Passive Energy Conservation Management in Retrofit Buildings: An Integrated Assessment-optimization Approach under Cost Uncertainty

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ABSTRACT

Passive Energy Conservation Management in Retrofit Buildings: An Integrated Assessment-optimization Approach under Cost Uncertainty

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A significant share of the total primary energy belongs to buildings. In many buildings, improving energy performance of buildings is of particular importance in new construction and existing buildings. Building refurbishment is considered a practical pathway towards energy efficiency as the replacement of older buildings is at a slow pace. There are various ways of incorporating energy conservation measures in buildings through refurbishment projects. In doing so, we have to choose among various passive or active measures. The energy usage can be significantly reduced by adopting passive measures. These methods might not need additional capital investment. An integrated building renovation approach, in which passive methods are implemented, can reduce the energy consumption of building, compensating the additional cost of new technologies. This thesis aims at developing an integrated assessment-optimization framework to provide a decision support for prioritization and selection of building refurbishment measures with energy conservation potentials by considering the cost uncertainty.

Firstly, a literature review is carried out to ascertain the state of the art in the retrofit decisions in buildings at the presence of several decision criteria. possible and available passive measures are investigated and identified based on four energy control principles. Secondly, the analytic network process (ANP) is reviewed as a multiple criteria decision-making method capable of incorporating the interdependencies among decision criteria to arrive at an overall assessment (relative scores) for alternative retrofit measures. To incorporate uncertainties in formulating the initial cost of materials, a fuzzy set approach is adopted. Then, the scores resulted from the assessment phase are formulated a utility objective function to be maximized alongside the cost objective function(s) that are minimized. The fuzzy numbers representing the cost uncertainties are incorporated into the cost objective function using alternative methods of graded mean integration, aggregate approach and interval approach. Various Solution approaches are then utilized for the multi-objective models to deal with the conflicting objectives including distance to ideal, compromise programming and goal programming. The cases of linear and integer assumptions about decision variables are investigated. The applicability of the proposed three-stage assessment-optimization approach under uncertainty is then illustrated through the case study of a typical building in order to verify its applicability and usefulness and the solution scenarios are explored and compared The proposed framework can assist decision makers in choosing the best passive measures in the planning phase of the building refurbishment addressing the complexities arising from multiplicity of feasible measures and their varied characteristics.Finally, in terms of the impact of the above research, it worth mentioning that 40% of final energy is used in buildings and the use of passive measures as a means of refurbishment for building stocks could create significant energy efficiency gains.

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I dedicate this dissertation to my beautiful wife, Shabnam Loghman and my lovely daughter, Anahita, for her all welcoming distractions over conducting this research. This would not have been possible without their support and patient. And special thanks to my mom, Monireh Norouzkhani for her endless love, support and encouragement.

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Articles Published in journals:

[1] **F. Amiri Fard** and F. Nasiri, "A Bi-Objective Optimization Approach for Selection of Passive Energy Alternatives in Retrofit Projects under Cost Uncertainty," *Energy Built Environ.*, vol. 1, no. 1, pp. 77–86, 2020.

[2] **F. Amiri Fard,** A. Jafarpour, and F. Nasiri, "Comparative assessment of insulated concrete wall technologies and wood-frame walls in residential buildings: a multi-criteria analysis of hygrothermal performance, cost, and environmental footprints," *Adv. Build. Energy Res.*, pp. 1–33, 2019.

[3] **F. Amiri Fard** and F. Nasiri, "Integrated Assessment-Optimization Approach for Building Refurbishment Projects : Case Study of Passive Energy Measures," *J. Comput. Civ. Eng.*, vol. 32, no. 5, pp. 4–9, 2018

[4] **F. Amiri Fard,** S. A. Sharif, and F. Nasiri, "Application of passive measures for energy conservation in buildings–a review," *Adv. Build. Energy Res.*, vol. 13, no. 2, pp. 282–315, 2019.

Article published in refereed conference proceedings

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[6] **F. Amiri Fard** and F. Nasiri, "Passive energy conservation management in retrofit projects," in *Proceedings of the International Conference of World Sustainable Energy Days (WSED'19)*, Wels, Austria, 2019.

CONTRIBUTION OF CO-AUTHORS

Mr. Amirhosain Sharif (PhD candidate at Concordia University, BCEE) had a contribution in chapter 2, in writing two paragraphs, adding the potential of phase change materials to improve the Trombe wall concept and the impacts of life cycle assessment in building sector.

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LIST OF ABBREVIATIONS

ANP	Analytic network Process
AHP	Analytic Hierarchy Process
HVAC	Heating, Ventilation, and Air Conditioning
LHTES	Latent Heat Thermal Energy Storage
PCM	Phase Change Material
ETICS	External Thermal Insulation Composite Systems
NPV	Net Present Value
LCC	Life Cycle Cost
IRR	Internal Rate of Return
SIR	Saving to Investment Ratio
AAC	Autoclaved Aerated Concrete
LCA	Life Cycle Assessment
SSF	Single-Skin Façade
MSF	Multi-Skin Façade
DSF	Double System Façade
CRFS	Climate Interactive Façade System
DSE	Double Skin Envelope
LPSHW	Lattice Passive Solar Heating Walls
CFD	Computational Fluid Dynamics
MLP	Mirror Light Pipe
SHGC	Solar Heat Gain Coefficient
HPI	High Performance Insulation
SHGC	Solar Heat Gain Control
DL	Daylighting
SPD	Suspended Particle Device
HOE	Holographic Optical Elements

PVC	Polyvinyl Chloride
GFRP	Glass Fiber Reinforced Polyester
MCDM	Multicriteria Decision Making
QFD	Quality Function Deployment
MAVT	Multiple-Attribute Value Theory
EPIQR	Energy Performance/Indoor Environmental Quality Retrofit
EATT	Environmental Assessment Trade-Off Tool
EPH	Energy Performance for Heating
TOBUS	Tool for Selecting Office Building Upgrading Solutions

Chapter 1 : INTRODUCTION

1.1 BACKGROUND, RESEARCH MOTIVATION AND PROBLEM STATEMENT

The primary objective of an energy-efficient refurbishment project is to reduce energy consumption by maintaining or enhancing the indoor thermal comfort condition, as well as reducing CO_2 emissions (Güçyeter & Günaydin, 2012). By implementation of energy conservation measures, natural resources will be conserved, adverse environmental impacts will be reduced, and operational costs of buildings will also be alleviated (Al-Homoud, 2005) and these will, in turn, enhance the living conditions and improve the comfort of the building's occupants. A significant share of the total primary energy is spent on buildings, which is strongly reliant on the characteristics of the buildings. For illustration, the residential sector makes up more than 60 percent (Balaras et al., 2007). Improving the energy performance of buildings is of particular importance in both new construction and existing buildings. There is a growing need to implement energy conservation measures in existing buildings due to their low replacement rate (Poel, Cruchten, & Balaras, 2007). Therefore, most of these buildings will still be functional until 2025 or even 2050 (ürge-Vorsatz, Danny Harvey, Mirasgedis, & Levine, 2007). For instance, in the United Kingdom, it is predicted that nearly 75% of all dwellings in the year 2050 are already functional (Weiss, Dunkelberg, & Vogelpohl, 2012) The majority of these buildings were constructed before the rise of concerns and awareness about the importance of energy efficiency and conservation in buildings (Huang, Niu, & Chung, 2013). According to a Canadian study, houses which were constructed before the 1940s have an energy-saving potential of about 25 to 30 percent compare to 12 percent for houses built in the 1990s (Ürge-Vorsatz, Danny Harvey, Mirasgedis, & Levine, 2007).

There is a wide variety of energy efficient measures. The literature points to over 400 passive or active measure options applicable to the existing building. In this sense, the challenge would be to evaluate these options and to choose the most effective ones that could best match with the environmental, financial, legal and social factors as well as characteristics of a building. The needs of stakeholders and occupants in the building retrofit projects should also be incorporated into such selection decisions.

This selection problem can be interpreted as a multi-objective optimization problem featured by the existence of multiple and conflicting objectives from qualitative characteristics such as occupants' behavior to quantitative criteria such as cost. Furthermore, ignoring the associated uncertainties by using simplified models and unrealistic assumptions could undermine the energy efficiency measure selection. For some of energy management parameters, there is an intrinsic uncertainty (e.g. climate change uncertainty) which needs to be decently addressed. Despite the existence of rich literature in this area, there are still some gaps in the assessment and optimization of building retrofit projects. The literature is particularly limited when multiple aspects and criteria are considered in the selection process. Although the use of a multi-objective optimization approach has been advocated, however, most of the existing models are just cost-based optimization; therefore, they are ignoring many other aspects of the energy retrofitting project. For those models that more objective functions were added in the optimization step, the model is being very complex to solve and/or creating several solution scenarios complicating the retrofit decision making when it comes to implementation.

In this sense, there is a need for a filtering method to prioritize selected alternative retrofit measures. As such, only a select number of measures will be qualified for consideration in the optimization models. In addition, by considering a range of decision criteria in the assessment phase, the number of objective functions in the optimization model will be reduced. Addressing and incorporating the uncertainty parameters in the optimization is also crucial. This helps in selecting the best retrofit alternatives and maximize building energy efficiency in line with these variations. In construction, the cost estimation is regarded as the main factor for the success of a project. In reality, the estimated costs mostly deviate from the actual costs; therefore, the cost uncertainty analysis is required. This requirement becomes more critical especially when a project constrained by initial investment as the main driver (Ökmen & Öztaş, 2010). In most construction projects, the initial cost estimate was substantially below what was ultimately spent as the final budget (Doloi, 2013; Welde & Odeck, 2017) and there is a high factor risk in the initial capital cost in the retrofit projects (Feng, Rukmal, Karunathilake, Sadiq, & Hewage, 2020). Reviewing the literature revealed that most of the existing models for selection of energy measures, do not consider cost ranges and contingency; thus, if the construction cost exceeds the available budget, the selected energy measures have to be changed to meet the available fund or the whole project is halted.

1.2 RESEARCH OBJECTIVES

This research aims at developing an integrated assessment-optimization framework to provide decision support for prioritization and selection of building refurbishment measures, maximizing energy conservation potentials and minimizing the associated costs (under costing uncertainties). This objective can be decomposed into the following sub-objectives:

- Investigation of the optimized energy measures technologies from a large available number of options in the market,

- Development of an energy decision management model that can assist decision-makers in choosing the best measures in the early phase of the building refurbishment,
- Incorporation of uncertainties with respect to cost estimations for retrofit alternatives.

1.3 RESEARCH METHODOLOGY

Firstly, possible and available passive measures are investigated and identified based on four energy control principles including 1) Heating/cooling flow control, 2) Water vapor transport control, 3) Air transport control, 4) Natural/solar heating, and cooling and lighting control. Secondly, a multiple criteria decision-making method is identified capable of incorporating the interdependencies among a comprehensive list of decision criteria (identified through the literature review) to establish a relative ranking (scores) of alternative retrofit measures. These scores will be used to formulate a utility function representing a non-monetary qualitative (value-driven) objective function that will be maximized alongside minimization of costs. To formulate cost objective function, the fuzzy theory is explored incorporating uncertainties related to experts' opinions about the initial cost of materials. Then, considering the above two objectives, a multi-objective optimization model is constructed. Three categories of, solution approach is explored for the above multi-objective optimization, including distance to ideal, compromise programming and goal programming. The solution scenarios are investigated and compared. The applicability of the proposed three-stage assessment-optimization approach under uncertainty is then illustrated through the case study of a typical building to verify its applicability and usefulness. The proposed framework (Figure 1) can assist decision-makers in choosing the best set of passive measures given monetary and non-monetary qualitative objectives in the planning phase of the building refurbishment addressing the complexities arising from the multiplicity of feasible measures and their varied characteristics.

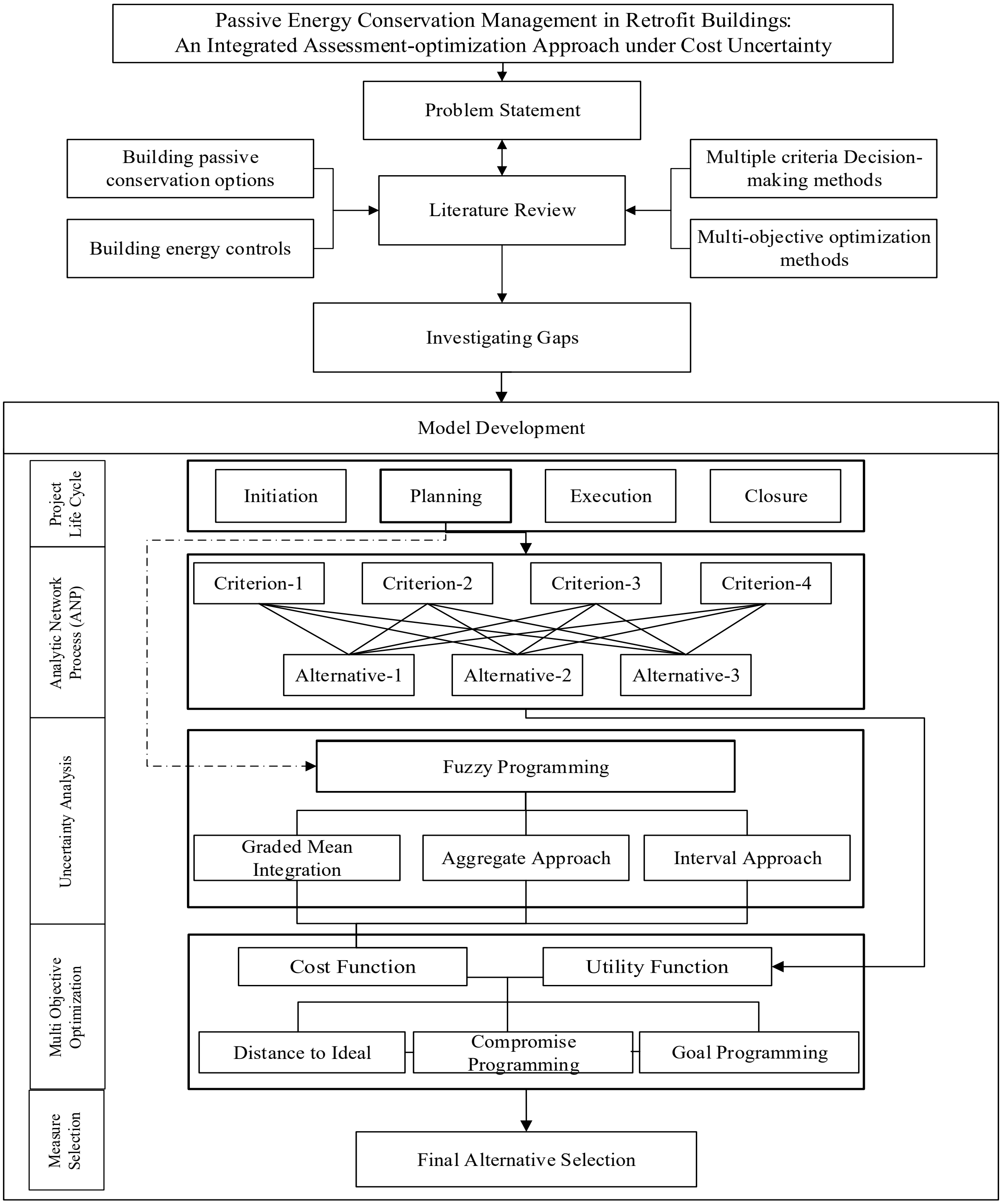

Figure 1, Research Methodology Flow Diagram

1.4 THESIS LAYOUT

This thesis is comprised of five chapters. The work described in Chapters 2, 3, and 4 have been written as three papers and a comprehensive reference list is prepared at the end of the thesis.

Chapter 2 presents a technical review of the passive measures in buildings. A categorization of passive energy measures is provided. The review explores several types of insulation materials along with their selection criteria. Application of thermal mass as a redeemable energy technique is also discussed. In addition, the performance of different techniques including heating and cooling flow control, optimum place and thickness of insulation, air transport control, water vapor control, natural heating, cooling, and lighting are presented. Advancements in these techniques including the naturally ventilated envelope, Trombe walls, sunspaces, natural daylighting, sun shading, fenestration, glazing materials and framing, are also discussed. It is concluded that despite their performance in decreasing energy consumption, implementing the most effective combination of these passive technologies, with respect to the characteristics of the buildings, has remained a big challenge for building designers/managers. This effort is published by the journal of Advances in Building Energy Research:

***Amiri Fard, F.**, Sharif, S. A., & Nasiri, F. (2019). Application of passive measures for energy conservation in buildings–a review. Advances in Building Energy Research, 13(2), 282–315. https://doi.org/10.1080/17512549.2018.1488617*

In chapter 3, first, the analytic network process (ANP) is identified and explored as a multiple criteria decision-making method capable of incorporating the interdependencies among decision criteria. Using ANP, the resulting relative scores of alternative retrofit measures will be fed into a bi-objective optimization model forming a utility objective function to be maximized alongside a cost objective that is minimized. This effort was published by the American Society of Civil Engineering (ASCE) Journal of Computing in Civil Engineering:

***Amiri Fard, F.**, & Nasiri, F. (2018). Integrated Assessment-Optimization Approach for Building Refurbishment Projects: Case Study of Passive Energy Measures. Journal of Computing in Civil Engineering, 32(5), 4–9. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000785*

Second, the developed model is extended by uncertainty incorporation. In doing so, the analytic network process (ANP) is again explored for ranking of alternative retrofit measures. Fuzzy theory is applied toward treating uncertainties that widely exist in experts' opinions about the initial cost estimation practice for retrofitting technologies and materials. Then, the scores resulting from the assessment phase and the fuzzy values from costing step are used to construct a multi-objective optimization model. Former results are used to formulate a utility objective function to be maximized alongside the latter results, which are forming a set of cost objective function (optimistic, pessimistic and mean) will be minimized.

This extension was also written in a paper format and published by the journal of Energy and Built Environment:

***Amiri Fard, F.**, & Nasiri, F. (2020). A Bi-Objective Optimization Approach for Selection of Passive Energy Alternatives in Retrofit Projects under Cost Uncertainty. Energy and Built Environment, 1(1), 77–86. https://doi.org/10.1016/j.enbenv.2019.11.005*

In chapter 4, the applicability of the proposed two-stage and three-step assessment-optimization approaches are then illustrated by adapting two case studies. The different solution results are explored and compared.

Chapter 5 summarizes research contributions and, highlights, limitations, key assumptions and insights for future research.

Chapter 2 : REVIEW AND SYNTHESIS OF LITERATURE

This chapter provides a full review of the application of passive measures for energy conservations, developed model for selecting energy management measures from a set of available options and alternative approaches for uncertainty formulation. The content of this chapter has been published in the following journals:

Amiri Fard, F.*, Sharif, S. A., & Nasiri, F. (2019). Application of passive measures for energy conservation in buildings–a review. Advances in Building Energy Research, 13(2), 282–315. https://doi.org/10.1080/17512549.2018.1488617*

Amiri Fard, F.*, & Nasiri, F. (2018). Integrated Assessment-Optimization Approach for Building Refurbishment Projects: Case Study of Passive Energy Measures. Journal of Computing in Civil Engineering, 32(5), 4–9. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000785*

Amiri Fard, F.*, & Nasiri, F. (2020). A Bi-Objective Optimization Approach for Selection of Passive Energy Alternatives in Retrofit Projects under Cost Uncertainty. Energy and Built Environment, 1(1), 77–86. https://doi.org/10.1016/j.enbenv.2019.11.005*

2.1 BACKGROUND

"The building sector is responsible for more than 40% of the total final energy consumption and more than 30% of the greenhouse gas emissions in developed countries, more than the industry and transportation sectors (Yang, Yan, & Lam, 2014). From this share of energy use, residential sector makes up more than 60% (Balaras et al., 2007). Improving energy performance of buildings is of particular importance in new construction and existing buildings. There is a growing need to implement energy conservation measures in existing buildings due to their low replacement rate, which is only 0.07% annually (Poel et al., 2007). Therefore, most of these buildings will still be functional until 2025 or even 2050 (ürge-Vorsatz et al., 2007). For instance, in the United Kingdom it is predicted that nearly 75% of all dwellings in the year 2050 are already functional (Weiss et al., 2012) The majority of these buildings were constructed before the rise of concerns and awareness about the importance of energy efficiency and conservation in buildings (Huang et al., 2013). According to a Canadian study, houses which were constructed before the 1940s have an energy saving potential of about 25 to 30 percent compare to 12 percent for houses built in the 1990s (Ürge-Vorsatz et al., 2007).

To minimize the energy inefficiency and waste in commercial buildings, different performance strategies have been promoted. The challenge is the fact that the surging innovations in building sector should be examined to ensure that the targeted energy efficiency is acquired. This needs attention to a combination of influencing parameters related to climate and configuration of the building envelope.

Energy efficiency practices in buildings consist of passive or active measures. Active measures include improving HVAC systems, efficient appliances, efficient lighting systems, and utilization of renewable energy, and distributing the energy as effectively as possible while maintaining the comfort of occupants. Passive measures, on the other hand, aim at reducing energy demand by increasing the use of natural heating, cooling, and lighting potentials as well as reducing the energy losses through the building envelope (Konstantinou, 2014). Although passive measures in building sector have been widely practiced, we require knowledge about available alternatives and how to choose among them to achieve the best performance and efficiency gains in building refurbishment projects.

Sadineni et al. (Sadineni, Madala, & Boehm, 2011) reviewed alternative passive energy conservation measures by categorizing them based on building elements such as walls, fenestration, and roofs. Quesada et al. (Quesada, Rousse, Dutil, Badache, & Hallé, 2012a, 2012b) investigated the reflection and radiation of solar energy in three different envelopes: opaque, transparent and translucent façades, which cannot transfer solar heat into the building directly. Schiavoni et al. (Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016) provided a review of available insulation material in the market by considering some of the material's features and environmental aspects and compared them to unconventional insulations which are not commercialized yet. Zhou and Chen (Zhou & Chen, 2010) reviewed the existing methods on the thermal performance of double-skin façade as a passive solar system and the controlled shading devices. Jelle et al. (Jelle et al., 2012) in a review paper conducted a research for high performance fenestration products including: glazing, spacers and frames. A list of manufactures' specifications of different fenestration products are also provided. The impact of window glazing system on the energy consumption of building and the techniques for choosing a decent glazing have been reviewed by Hee et al. (Hee et al., 2015). Saadatian et al.(Saadatian, Sopian, Lim, Asim, & Sulaiman, 2012) Reviewed various types of Trombe walls and discussed the two characteristics of them including configuration and technology. Aflaki et al. (Aflaki, Mahyuddin, & Mahmoud, 2015) reviewed studies on the operation of natural ventilation in buildings as a passive design method in order to find the most effective architectural elements and techniques in building facades and ventilation openings in tropical climates.

To the best of the authors' knowledge, passive energy can be the first approach to reduce energy demand in existing buildings. However, in most of previous studies, the focus is solely on a specific type of passive measure, while these measures could be interlinked and affect each other's performance, and should be categorized in line with their function. Our focus will be on available alternative passive measures that can be implemented in the building section (whether new construction or retrofit project) to reduce overall energy consumption based on energy control principles as relate to functions of heating and cooling control, air transport control, water vapor transport control and natural/solar heating, cooling and lighting control. In section 2 to 5 available passive measures which should be controlled to design a building envelope efficiently with respect to its functions and impact on the energy of buildings are sorted. Section 6, a conclusion and presentation of future work are detailed.

2.2 HEATING AND COOLING FLOW CONTROL

Dylewski and Adamczyk (Dylewski & Adamczyk, 2011), and Al-Homoud (Al-Homoud, 2005)believe that among all energy efficiency passive measures, thermal insulation is the most efficient and main energy-saving contributor especially as it pertains to building envelope. Based on research conducted by Papadopoulos et al. (Papadopoulos, Theodosiou, & Karatzas, 2002) on 42 residential buildings, space heating and cooling is responsible for more than 80% of total energy consumption. U-value (thermal transmittance) measured in W/m^2 K is the overall heat flow coefficient that shows the rate of heat transfer through a unit area or one square meter of a building component as a result of 1 degree Kelvin temperature gradient. R-value (thermal resistance) is the reverse of U-value, which should be considered when selecting insulation (Schiavoni et al., 2016).

The most significant factors in choosing an appropriate type of insulation are building factors of targeted thermal conductivity and targeted thermal inertia as well as technology factors of price, availability and feasibility/ease of application. Health-related issues, flammability, and benefit to cost ratio are also some parameters taken into consideration when selecting appropriate insulation.

For instance, fiberglass batt insulation contains materials hazardous for human health, and in particular, for the installation crew(Sadineni et al., 2011). Schiavoni et al. (Schiavoni et al., 2016), reviewed the characteristic of insulation materials, including thermal properties, acoustic properties, reaction to fire or water, vapor resistance and environmental issues. Consequently, their research categorizes the available materials in the market into three categories: conventional, alternative, and advanced, and lists subsets for each category (Table 1)

Table 1, List of available insulation materials in the market (Schiavoni et al., 2016)

Category	**Sample insulation type**
Conventional	Stone wool, glass wool, expanded polystyrene, extruded polystyrene, cellulose, cork, wood fiber, mineralized wood fiber, LECA, vermiculite, perlite
Alternative	Hemp, Kanaf, flax, sheep's wool, coir fiber, recycled rubber, jute fiber, recycled cardboard
Advanced	VIP, GFP, aerogel

Al-Homoud (Al-Homoud, 2005) believes that selecting the adequate type and form of insulation materials are dependent on the place of insulation, building elements, and the performance of insulation and aesthetic matters. Tingley et al. (Densley Tingley, Hathway, & Davison, 2015) assessed and compared three types of insulation based on 16 environmental impact criteria. Sadineni et al. (Sadineni et al., 2011) categorized the type of insulation based on their material type into four groups and respective subgroups. (Table 2)

Table 2, Types of thermal insulation based on different materials(Sadineni et al., 2011)

Type of insulation	Type of material	Name of insulation in the market
Inorganic	Cellular materials	Calcium silicate, bonded perlite, Vermiculite, ceramic products
	Fibrous materials	Glass wool, rock wool, slag wool
Organic	Cellular materials	Cork, foamed rubber, polystyrene, polyethylene, polyurethane, polyisocyanurate, other polymers
	Fibrous materials	Cellulose, cotton, sheep wool, wood, pulp, cane, synthetic fiber
Metallic/Metalized reflective membranes	Rolled foil (aluminum), reflective paint, reflective metal shingles, foil faced plywood sheathing	
Advanced material	Transparent material (aerogel), PCM (phase change materials)	

2.2.1 Optimum Place of Insulation

The building envelope, especially its external walls, plays a significant role in energy conservation. In this sense, using a passive system, energy is stored during the daytime in the outer surfaces and this energy can be used to warm up the indoor at night. The heat storage capability of a building can be identified as its thermal mass , especially in passive solar spaces design techniques(Rempel, Rempel, Gates, & Shaw, 2016) (M. Ozel & Pihtili, 2007). Therefore, there must be integration between thermal mass and insulation place (to compensate the thermal bridges) to reach the high indoor thermal comfort condition. Many studies have been done to determine the optimum location of insulation. Thermal bridges essentially define the conditions in a building envelope in which thermal resistance varies considerably. Therefore, it causes a significant amount of heat gain (in summer) and heat loss (in winter) through the building envelope. One of the common ways is to put an insulation layer on different surfaces of the wall (inner surface, outer surface or in the middle) with different thicknesses and calculate the thermal mass capability of the wall by considering the maximum time lag and minimum decrement factor. In this sense, we provide an overview of the thermal mass and thermal bridge concepts.

Thermal Mass

Thermal mass is defined as the ability of a construction material to store and absorb heat energy. Dense material like bricks and concrete have high thermal mass, on the contrary, lightweight materials have low thermal mass. By this feature, during the day, solar energy can be stored in a building element, and during the night, it can be released. Thermal mass can be highly beneficial in regions with high outdoor temperature differences between day and night(Reardon, McGee, & Milne, 2013) Two key features of thermal mass are time lag and decrement factor of structure elements. The time lag is the amount of time it takes for heat to diffuse from outside surface to indoor space. During this process, the reduction ratio of its amplitude is called decrement factor. These two features are considered very essential to measure the heat storage capabilities of materials(Asan, 2000).

Some recent studies have shown that from the thermal performance viewpoint, dividing the insulation at two places out of three possible places (internal, external, middle) with the same thickness works better than the installation of just a single location. Ozel and Pihtili (M. Ozel & Pihtili, 2007) investigating the optimal placement of wall insulation, addressed 12 different kinds of walls. They reported two major findings. Firstly, the best results were achieved when insulation of the same thickness was placed on the outside wall surface, middle wall surface, and indoor wall surface. Secondly, in comparing between placing two equal layers on either side of the wall or placing two layers with different thicknesses, the former provided a longer time lag and shorter decrement factor. Kolaitis et al. (Kolaitis et al., 2013) point out that the comparison between external insulation and internal insulation shows that external insulation configurations have 2 to 11% higher time lag and 29 to 63% lower decrement factor values compared to internal insulation. In research conducted by Asan (Asan, 2000) the insulation placement in six different configurations is analyzed with calculation of maximum time lag and minimum decrement factor. Al-Homoud (Al-Homoud, 2005) believes that, to reach the best insulation performance, the insulation should be placed closest to the point of entry of heat flow. This means that for regions where winter heating is dominant, it is better to install insulation inside, whereas for areas with dominant summer cooling, outside insulation is preferable.

In new construction, the best place for insulation is in between two wall layers or a cavity, however, this is not feasible in an existing building during a refurbishment project. Soares et al. (Soares, Costa, Gaspar, & Santos, 2013) have focused on implementing passive construction solutions, such as latent heat thermal energy storage (LHTES) systems, to improve building's energy performance. They applied phase change materials (PCMs) in passive LHTES. It was concluded that PCM passive LHTES systems provide the potential for decreasing energy consumption by reducing/shifting the heating and cooling loads, as well as decreasing the indoor temperature fluctuations, which improves the internal thermal comfort of existing buildings.

Thermal Bridge

To reduce energy consumption, the enhancement of insulation levels and thermal mass are not enough. Creating thermal bridges in the building envelope should also be avoided (Baba & Ge, 2016). In a building envelope, thermal resistance is not fixed due to the fact that most of the materials are not homogeneous and they mostly have different thermal resistances or different thermal conductivity. The zones in which thermal resistance are lower than the other zones are called thermal bridges (Branco, Tadeu, & Simoes, 2004). Thermal bridges are the main reason for reducing the thermal resistance of a building envelope wall and roof, especially in framing, as well as and junctions (Kośny & Kossecka, 2002). Heat loss during winter and heat gain during summer occurs across the thermal bridges (Cuce & Cuce, 2016). Research conducted in British Columbia, Canada, shows that reducing thermal bridge failure in a building envelope could reduce energy consumption by up to 10% which is equal to utilizing triple-glazed windows and increasing insulation levels (Baba & Ge, 2016). Theodosiou and Papadopoulos (Theodosiou & Papadopoulos, 2008) showed that despite existing building codes for insulation, energy consumption for buildings is 35% higher than what is predicted in the design phase because of the impact of thermal bridges. Double brick walls used widely in construction are vulnerable to thermal bridge occurrence, which is mostly not taken into consideration in energy demand estimations. Furthermore, the thermal conductivity of steel, which can create thermal bridges, is one of the main disadvantages of Lightweight Steel Framed (LSF), which could penalize the energy efficiency and thermal behavior of steel buildings. In case of new buildings, thermal bridge mitigation techniques such as External Thermal Insulation Composite Systems (ETICS) are applicable to reduce thermal bridges and improve thermal inertia (Santos, Martins, & da Silva, 2014).

Thermal bridges can be categorized into two types. Linear thermal bridges are placed at the intersection of two or more building elements which are characterized by a linear thermal transmittance (or Ψ-value in W/m K). The second type is the point or 3D type, situated at three-dimensional corners and characterized by a point thermal transmittance in W/K (or x-value in

W/K)(Cuce & Cuce, 2016). Thermal bridges can be evaluated by experimental methods or numerical methods. Former methods are time-consuming, difficult to implement, appropriate for critical projects and sometimes used for checking the reliability of a simulation. Latter can be done by Finite Element and Finite Difference. Although, there are computer programs for a specific type of Finite analysis methods (Larbi, 2005), they are generally very complex. Also, there are two main problems for current energy simulation programs. Firstly, heat flow is assumed to be linear and one-directional but in reality heat flow through the thermal bridge is multi-directional. Secondly, in building energy simulations, if the thermal bridges are not identified or their impact are not evaluated, the simulation scenarios will be less realistic (BrumĂ, Moga, & Moga, 2016).

According to research by Kosney et al. (Kośny & Kossecka, 2002) in many building energy modeling software (such as DOE-2, BLAST or ENERGY PLUS) are just one-dimensional and only parallel path descriptions of building envelope could be defined. Therefore, the result of building energy load estimations for many buildings might be incorrect due to the three-dimensional impact of thermal bridges. WUFI Plus and ESP-r are capable of modeling 3D thermal bridges. Ge and Baba (Ge & Baba, 2015) investigated the impact of thermal bridges on the energy performance of a residential building by simulating two climates with different insulation levels in WUFI Plus using three methods called equivalent U-value method, equivalent wall method, and direct 2D/3D modeling method. Ascione et al. (Ascione, Bianco, De Masi, De'Rossi, & Vanoli, 2013) proposed a new method by simplifying the conduction transfer function procedure to improve the capabilities of energy simulation software for implementing three-dimensional heat transfer in thermal bridges. The accuracy of the simplified CTF method was verified by a numerical analysis using the finite volume method showing that the maximum errors under hourly-variable outdoor temperature and solar radiation were not higher than 4.5%. Cuce and Mert Cuce

(Cuce & Cuce, 2016) tried to assess thermal bridges in refurbished houses dating back to the 1930s with uninsulated separating walls when external walls were insulated by Aerogel as a thermal superinsulation material. The results showed that after refurbishment, the amount of heat loss is remarkably increased due to the impact of thermal bridges around the junctions of external walls and separating walls.

2.2.2 Optimum Thickness of Insulation

By increasing the thickness of insulation, the initial implementation cost will increase but the energy loss, and consequently, energy cost will be reduced. In contrast, if the thickness of insulation decreases, the initial implementation cost will drop but the energy cost will surge for both cold and hot climate conditions. Therefore, the optimum thickness of insulation for a building should be calculated by maintaining a balance (tradeoff) between initial costs and potential energy savings. The widely accepted rule of thumb is that the optimal thickness of insulation is the one that enhances energy-saving over the lifetime of a project which is mediating the marginal cost of the added insulation (Al-Homoud, 2005). In this sense, the optimum thickness of thermal insulation is dependent on several factors such as structure, climate conditions, indoor thermal comfort targets, external wall orientation, the lifetime of the building, insulation type and cost, energy resources and costs, the type and capacity of HVAC system, and inflation and discount rates of refurbishment investments in building sector (Al-Homoud, 2005), (Axaopoulos, Axaopoulos, & Gelegenis, 2014).

To determine the best tradeoff between initial costs and energy savings for choosing insulation scenarios, most of the researchers have used one or a combination of various economic evaluation methods such as net present value (NPV), LCC, internal rate of return (IRR), saving to investment ratio (SIR) and p_1-p_2 methods. The heating and cooling requirements (yearly heat or cooling transmission loads) are the most valuable input for calculation of insulation thickness. Most of the researchers used degree-days or degree-hours methods (Çomakli & Yüksel, 2003), (Dombayci, Gölcü, & Pancar, 2006), (Sisman, Kahya, Aras, & Aras, 2007). Performing this method under a static condition (e.g. fixed thermal condition without considering temperature distribution) with or without considering solar radiation is very simple. Again, to address the issue of accuracy, some researchers used a numerical method or an analytical method. The first category is based on the implicit finite difference method under steady periodic conditions (Al-Sanea & Zedan, 2002), (Meral Ozel, 2011a). The second category is based on Complex Finite Fourier Transform (Meral Ozel, 2011b). Bolattürk (Bolattürk, 2008) calculated the optimum insulation thickness on external walls based on a degree-hour method, which shows that the use of insulation in building walls for cooling degree-hours and cooling loads is much more efficient than for heating hours and heating loads in Turkey's warmest zone. Daouas (Daouas, 2011)considered different wall orientations without taking into account wind direction and velocity, calculated optimum insulation thickness in Tunisia. The results showed that the south orientation is the most economical orientation. Axaopoulos et al. (Axaopoulos et al., 2014) investigated the wind speed and direction and their impacts on calculation of the optimum insulation thickness for heating and cooling loads for three types of composite external walls in the city of Athens, Greece. The method for analyzing economic aspect was LCC. A similar study has been done by Axaopoulos et al. (Axaopoulos, Axaopoulos, Panayiotou, Kalogirou, & Gelegenis, 2015) in the city of Larnaca, Cyprus. The optimum thickness of external walls was different due to the fact that these two regions have different climate profiles. Ozel Meral (Meral Ozel, 2011b) considered five different wall structures including concrete, briquette, brick, and Autoclaved Aerated Concrete (AAC), and two different insulation materials, which are extruded polystyrene and expanded polystyrene. They used the Net Present Value (NPV) of energy consumption over ten year's lifetime to identify the optimal thickness of insulation.

Life Cycle Assessment (LCA) is a comprehensive and systematic approach to evaluating environmental impacts of a product or process during its entire life cycle (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014). LCA reflects the extraction of raw materials, manufacturing, operation, removal and reuse. LCA can incorporate the selection of environmentally preferable materials and the optimization and evaluation of the construction processes(Asdrubali, Baldassarri, & Fthenakis, 2013). The implementation of LCA in the building sector has become a focus of research in the last ten years. The number of published studies on the implementation of LCA in buildings has more than doubled in the last five years (Anand & Amor, 2017). Despite the significant contribution of research on LCA, there is limited research combining all aspects of the building simultaneously.

2.3 AIR TRANSPORT CONTROL

Air transport is a fundamental building property as a result of air movement through the building envelope. Heat and moisture move in and out of a building due to the air movement through the cracks, openings, chinks and holes in the envelope. Air transport can compromise the impact of thermal insulation as heat and cooling losses cause an increase in heating and cooling demands, noise, reduction of thermal comfort, condensation, mold growth problems on the wall surfaces, movement of air contaminants and increment of infiltration rate and ventilation(Chen, Levine, Li, Yowargana, & Xie, 2012; Hassan, 2013; M. H. Kim, Jo, & Jeong, 2013; Sherman, Logue, & Singer, 2011). To the best of the authors' knowledge very limited research has been done in analyzing air movement and airtightness within building envelopes. A building's airtightness is directly linked to the choice of envelope technology, the quality of its implementation and the air permeability of the envelope(Šadauskienė, Banionis, & Paukštys, 2014). Air inflow and outflow happen in a building because of different pressures caused by three mechanisms: wind effect, stack effect (natural buoyancy) and, combustion and ventilation effect (resulting from mechanical air handling equipment and appliances) (Figure 2) (John F Straube, 2005)

Urquhart et al. (Urquhart, Richman, & Finch, 2015) state that most of the previous research in building refurbishment emphasizes thermal insulation and amount of energy that can be saved in the application of energy retrofit measures. However, the envelope's enclosure functionality can be improved by securing airtightness as it accounts for 5 to 15 percent of energy demand in a building.

Straube and Burnett (John F Straube, 2005) point out that in a well-insulated building about 30% to 50% of energy consumption for space conditioning is due to air leakage through the building envelope. Gillott et al. (Gillott et al., 2016) believe that due to air infiltration and exfiltration happening through gaps in the old building's envelope, heat losses can contribute up to one third of total heat losses. In addition, using a bar chart for normalized maximum air leakage, it was illustrated that France has the highest air change rate of 11 followed by the UK and the USA at around 8 ACH at 50 Pa.

Airtightness retrofits can minimize energy loss and save a considerable amount of energy. They are cost effective in comparison to the other energy efficiency measures and can be undertaken without a major refurbishment such as draught stripping or sealing(Roberts, 2008). By implementing appropriate retrofit measures, the rate of infiltration can be reduced by up to 77%

(Hong, Ridley, Oreszczyn, & Group, 2004). Montoya et al. (Montoya, Pastor, Carrié, Guyot, & Planas, 2010) identified the critical parameters that have the greatest impact on airtightness based on an assessment of the air leakage distribution of single family dwellings in France and Spain.

Air retarders are also used to increase the airtightness of buildings with impeding heating or cooling leaks from building envelopes. The main duty of air retarders is to block airflow but allow moisture flow unless the condensation happens. In this sense, the permeability rating of air retarders should be high (more than 5 m3/h.m2). A common problem for well-tightened buildings is poor indoor air quality which can be solved by providing sufficient ventilation. Air ventilation prevents moisture levels from rising while allowing a sufficient amount of fresh air to circulate(Al-Homoud, 2005)

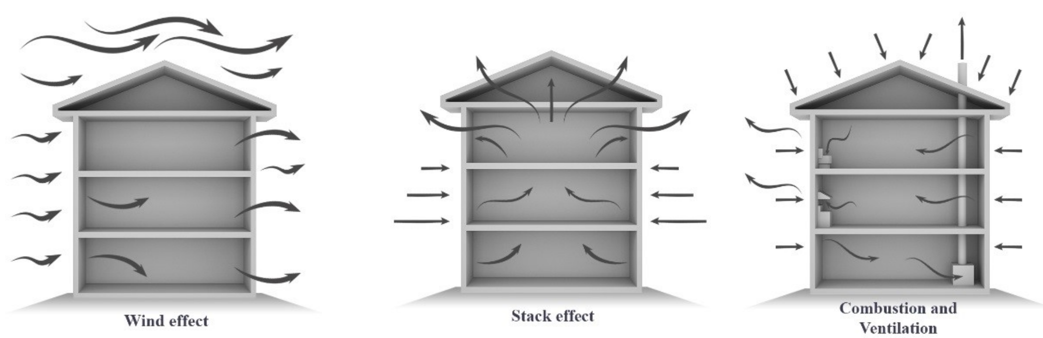

Figure 2, Three factors causing air inflow and outflow throughout a building enclosure (John F Straube, 2005)

2.3.1 Types, Requirements and Location of Air Retarders

A combination of different materials, assemblies and joints provide airtightness in buildings but unlike vapor retarders, multiple air barrier layers are preferable. For the air barrier, five main criteria have been considered including continuity, strength, durability, stiffness, and impermeability(Straube & Ph, 2002). There are other properties proposed in the literature such as elasticity, thermal stability, and flammability resistance, ease of fabrication, installation and joint sealing. The categorization of air barriers is based mostly on location, type and water vapor permeance of the air barrier system(John F Straube, 2005). Some materials need additional coating to be considered as an appropriate air barrier including uncoated concrete block, plain and asphalt impregnated fiberboard, expanded polystyrene, batt and semi-rigid fibrous insulation, perforated house-wraps, asphalt impregnated felt, 15 lb. or 30 lb. tongue and groove planks, vermiculite insulation, and cellulose spray-on insulation(Wagdy Anis, 2016).

The preferred placement for an air barrier system is on the warm-humid side of the insulation similar to the vapor barrier. However, proper construction practice and the types of materials have a greater impact than for the location of an air retarder. When an air retarder is installed on the cold drier side of the insulation, the focus should be on its vapor permeability performance. In this case, air retarders have to be ten to twenty times more permeable compared to vapor diffusion and the vapor barrier systems, otherwise condensation is most likely to occur(Quirouette, 1982).

2.3.2 Airtightness Measuring Methods

For rating of airtightness in buildings, there are three methods of fan pressurization including blower door method (M. H. Kim et al., 2013),(Jeong, Firrantello, Bahnfleth, Freihaut, & Musser, 2008) tracer gas method (Pressurization, 2010) and simple acoustical method (Hassan, 2013). The fan pressurization including blower door method determines flow rate over the inner building envelope at different pressures, especially at 50 Pa pressure difference. When using this method, results are not impacted by climatic conditions(Sfakianaki et al., 2008),(Finch, Straube, & Genge, 2009). However, the main drawback of this method emerges when building size increases and the air leakage of a high rise building needs to be measured. In that case, it is required to consider stack and wind effects and the large flow rate by many blower fans should be used to attain a pressure difference of at least 50 Pa (William, Grenville, & Brian, 1999). Some modified methods have been suggested efforts to tackle this problem including “The US Army Corps method”(Zivov, Bailey, & Herron, 2009), The German “Fachverband Luftdichtheit im Bauwesen e.V.”(Erhorn-Kluttig, Erhorn, & Lahmidi, 2009) method and the “guarded-zone method”(Finch et al., 2009; Urquhart et al., 2015) All of these methods are based on the fan pressurization method with some modifications to make it applicable for high-rise buildings with varying numbers of units.

The tracer gas method gives more reliable and accurate results (an indication of accuracy is decent distribution as indicated by the uniformity of tracer gas concentration values(Pressurization, 2010)); however, its implementation is costly and requires specialized experience (M. H. Kim et al., 2013),(Jeong et al., 2008) The acoustical method is a simple and quick diagnostic method to assess the whole building envelope for air leakage (just a noise source, a microphone and a computer are needed). It is not costly to implement and requires basic tools. However, the estimations might need several hypothetical assumptions leading to uncertainties and imprecisions(Hassan, 2013). Table 3, provides a summary of the airtightness measurement methods with their advantages and drawbacks.

Further, Chen et al. (Chen et al., 2012) used the blower door method in two buildings in the cold zone of China. The results show that airtightness performance for dwellings in the middle of a building is considerably better than dwellings at the end of the building. The same situation applies to families living on the middle floor which have a lower infiltration rate than families living on the top floors. Litvak et al. (A. Litvak, M. Kilberger, 2000) classified 64 French dwellings built within the last 10 years, based on the type of frames (masonry or timber frame) and occupancy type (multi-or single-family). They used the fan pressurization method to evaluate the airtightness rate for each class of buildings. They comprehended that apartments are more air tightened than townhouses. Sfakianaki et al. (Sfakianaki et al., 2008) investigated 20 houses in the area of Attica, Greece to calculate airtightness using two methods, the fan pressurization including blower door method with less than 50 Pa pressure difference and the tracer gas method under the natural ventilated building. The results were checked to find their homogeneity. The sample buildings in the category group called ‘‘low airtightness level’’ were considered as homogeneous and samples in ‘‘medium/high air tightness level’’ were considered uneven. Some reasons behind of this fact are due to different construction performances, temperature differences between inside and outside and wind velocity variations.

Table 3, Advantages and disadvantages of airtightness measuring methods

Methods	ADVANTAGE	DISADVANTAGE
Fan pressurization	-Simple and low cost implementation -climatic condition does not impact the results -applicable to low-rise buildings	-Not suitable for high-rise or multi-unit buildings -Interior leakage paths from the testing floor to all other building components (e.g. stair case, elevator), between floors and through shafts must be sealed which is nearly impossible -"Stack effect " and "wind effect" are ignored or limited
Tracer gas	-Reliable results -Accurate results	Very expensive to implement Requires specialized experience to implement
Simple acoustical	-Simple and low cost implementation -Climatic condition does not impact the results	-Need to several assumptions

2.4 WATER VAPOR CONTROL

Water vapor is transferred by various transport mechanisms including water vapor diffusion as well as displacement of water vapor by air movement. A small flux of air can carry a considerable amount of vapor which can be prevented by increasing the airtightness of buildings. Creating a low vapor permeance is the main function of a water vapor retarder. To incorporate vapor retarders in buildings, the literature points to the following requirements: mechanical strength, adhesion, elasticity, thermal stability, fire and flammability resistance, ease of fabrication, installation and joint sealing (Owen, 2013). In addition, water vapor barriers must be selected with a specific level of vapor permeance to control water vapor diffusion and decrease the occurrence of condensation. A small crack split or rip will not have a significant effect on its performance. However, use of a water vapor barrier could eliminate the need to use an air barrier. As such, the vapor performance of existing air barriers has to be considered before implementing water vapor barriers.

Some materials due to their nature can be used as an air barrier and vapor barrier at the same time such as sheet metal and glass. Some materials, like sealed gypsum board, house wraps or wood sheathing, are effective air barriers but provide little water vapor diffusion control. Torn or unsealed polyethylene cannot be used as an air barrier but could perform well as a vapor barrier(John F Straube, 2005). To determine the water vapor transmission properties of construction materials, two methods are commonly used: the dry and wet cup methods. The first method is associated with a mean relative humidity of 25% and the second method with a 75% relative humidity. Kumaran extended the cup methods at varying relative humidity levels and tested them for three materials: perlite insulation board, calcium silicate insulation board, and plywood sheathing(Petersen, Link, & Kumaran, 1998). Kunzel (Künzel, 1999) evaluated the use of smart retarders by conducting field tests. According to the results, a smart vapor retarder will increase the moisture load tolerance of materials which can effectively decrease the risk of damage to the building envelope. Wilkinson et al. (Wilkinson, Ueno, Rose, Straube, & Fugler, 2007) tested below-grade and above-grade wall assemblies in southern Ontario with and without polyethylene sheeting to determine the pros and cons of each approach. Kumaran et al. (Kumaran, Lackey, Normandin, & Reenen, 2005) evaluated 18 building membranes (paper-based and polymer-based materials) that were available in North American markets as to their level of water vapor permeance, air permeance, and the water absorption coefficient. Saneinejad (Saneinejad, 2009) performed experimental research to assess hygrothermal performance under conditions leading to inward moisture flow. Based on the results, the presence of vapor tight interior finishes causes accumulation of moisture in the interior gypsum board. Moreover, a vapor tight sheathing does not prevent moisture accumulation in the interior gypsum board and the wood studs. Table 2-4 illustrates vapor retarder's classification based on permeance and rigidity.

2.4.1 Hygrothermal Performance

There are two methods to improve the thermal performance of walls in refurbishment projects: internal insulation and external insulation and each of them has their own pros or cons. External insulation is not applicable to buildings with heritage value or historical buildings. The internal method changes the hygrothermal performance of the walls. However, it is associated with many problems including water condensation, mold growth, and frost damage(Vereecken, Van Gelder, Janssen, & Roels, 2015). Penetration and condensation of moisture are two of the most significant factors in hygrothermal performance of a building. Accordingly, moisture can be controlled by mechanical devices or by finding a proper place for installation of a vapor retarder within the building envelope. Moisture penetration has a direct impact on the energy consumption, comfort condition, and durability, conductivity, and productivity of building insulation. Finding a proper location or a suitable material for moisture retarders is always a challenging issue depending on climate condition and moisture level of the region. Diffusion of water vapor from warm and humid inside air to cold outside air through the building envelope occurs in predominantly cold climate regions. Therefore, vapor retarders should be installed on the interior surfaces of the envelope within the internal insulation. Conversely, in predominantly hot regions, vapor diffuses from warm and humid outside air to cold inside air; therefore, retarders prevent moisture penetration if placed on the exterior surfaces of the wall within the external insulation (Al-Homoud, 2005).

As for the disadvantage of the first case, high indoor humidity causes the unwanted thermal condition, which can be rectified by implementing adequate ventilation or using hydrophilic materials. The weakness of the latter case most likely comes from the vapor retarder failure, which can be damaged by incidence(Kolaitis et al., 2013) such as hanging a picture on a wall by a nail or hook causing vapor condensation, altering the performance of the vapor retarder. Hydrophilic materials allow water to move through the shell quickly. Therefore, water cannot condense in the insulation layer, however, moisture damage is possible within the structural elements which are exposed to condensation. Toman et al.(Toman, Vimmrová, & Černý, 2009) measured the hygrothermal performance of an internal thermal insulation system using hydrophilic mineral wool basis (without water vapor barrier) for a period of four years.

Table 4, Vapor retarder's classification

Vapor retarders classifications	Permeance or rigidity	Available products
Canadian General Standards Board (CGSB)	Type I retarders with permeance of 15 ng/(Pa· s ·m^2)	Polyethylene plastic sheet, aluminum foil , paper-backed aluminum,
	Type II retarders with permeance of 45 ng/(Pa· s ·m^2) or less before aging	Asphalt-impregnated, asphalt coated Kraft
	Type III retarders with permeance of 60 ng/(Pa· s ·m^2) or less after aging	Plywood
Classification based on rigidity	Rigid retarders	Reinforced plastics, aluminum and stainless steel
	Flexible retarders	Metal foils, laminated foil and treated papers, coated felts and papers, and plastic films or sheets
	Coating retarders	Semifluid, mastic, paint, hot melt (thermofusible sheet materials)
2009 IRC R601.3 Standard	< 0.1 perm	Polyethylene sheet, sheet metal, , non-perforated aluminum foil, foil-faced insulation sheathing, glass, rubber membrane
	: 0.1 < perm < 1.0 perm	Coated kraft paper,fiberglass batts, low-perm paint, fiber-faced polyisocyanurate, expanded or extruded polystyrene, 30-pound asphalt coated paper, plywood
	1.0 < perm < 10 perm	Latex, enamel paint, gypsum board, fiberglass insulation, cellulose insulation, board lumber, concrete block ,brick, 15-pound asphalt-coated paper, house wrap

2.5 NATURAL HEATING, COOLING, AND LIGHTING CONTROL

In the past, traditional buildings were constructed with consideration of climatic conditions and passive methods for natural cooling in summer and natural heating in winter. Nowadays, most buildings rely on mechanical or active strategies for heating, cooling, and lighting which require a significant amount of energy(Tyagi & Buddhi, 2007). By using passive methods such as use of solar energy or creative design of the building, total energy consumption in a building can be reduced considerably. Nowadays, passive solar energy is in practice. In 1974, in New Mexico, a large south facing window was used as a pioneer pilot passive solar heating system(Bataineh & Fayez, 2011). Use of direct or indirect passive solar energy is a classical method to alleviate heating, to improve cooling capacities and to decrease the energy consumption of a building by taking the advantage of free solar energy(Sánchez-Ostiz, Monge-Barrio, Domingo-Irigoyen, & González-Martínez, 2014). In winter, solar energy is used for heating the indoor environment to reach thermal comfort condition. In a direct way, solar radiation is absorbed through the transparent elements of the building envelope, in particular, the ones located in the south orientation. This radiation is converted into heat which raises the indoor temperature. Solar radiation can also be used as a natural lighting system. Solar radiation in winter season can also be used in an indirect way. Prominent technologies for indirect solar gains include multi or double-skin façade, Trombe wall, and attached sunspaces(Konstantinou, 2014). In the next section, we review available measures for natural space heating, cooling, and lighting through passive solar energy.

2.5.1 Naturally-ventilated Envelope

Passive solar façades convert sunlight into thermal energy and uses wind pressure and natural convection, without the use of any active mechanical or electrical equipment, to ventilate the indoor environment depending on the season and the geographical region(Quesada et al., 2012a). Façade systems, based on specific structure systems, are divided into two main systems: the single-skin façade (SSF) and the multi-skin façade (MSF). The double system façade (DSF) and the climate interactive façade system (CRFS) are two subsets of the latter system(Radhi, Sharples, & Fikiry, 2013). The double skin façade has two layers with different glazing materials – one internal façade and one external façade, – which are divided by a ventilated air cavity called channel. The exterior layer protects the building against the outdoor weather and outside noises. The mechanism for the DSF system is different in winter and summer. The ventilated cavity is utilized to evacuate or collect the solar irradiance which is absorbed by an envelope. In cold weather, the DSF system performs like a heat exchanger and collects heated air inside the cavity to warm up the indoor environment saving heating energy. In hot weather, a shading tool is installed inside the cavity to act as a blind protecting the interior rooms from solar radiation. In this case, the remaining heated air in the cavity can be evacuated. There are three modes of ventilation inside this cavity including natural, forced or mixed. The natural mode is due to wind pressure and thermal buoyancy (caused by the difference in temperature between interior and exterior layers of the cavity). The forced mode functions via mechanical ventilation devices. According to Figure 3, DSF system can be categorized into three types. In type-A, ventilation air enters the cavity, flows up and comes back to the duct network of the HVAC system. In type-B, fresh air enters the cavity preheated by solar radiation and goes to the room in the winter. In type-C, the fresh air enters the cavity after pre-heating and is exhausted to the outdoors in the summer when the window in the internal façade is closed. In the winter time, the pre-heated air goes into the indoor space when the window in the internal façade is open. The first two types are mechanically ventilated façades, and type-C is a naturally-ventilated façade(Zhou & Chen, 2010).

Alonso et al. (Alonso, Oteiza, García-Navarro, & Martín-Consuegra, 2016) explored and compared three different construction envelope systems including the conventional façade, a tile-based ventilated enclosure, and an external thermal insulation system. Among all these three systems, the external thermal insulation system saved 15% more energy than the first option and the ventilated façade saved approximately 13% more energy than the first conventional enclosure. In summer, ventilated systems perform better than insulation systems in saving energy, but in winter, insulation options could save more energy compared to the ventilated façade.

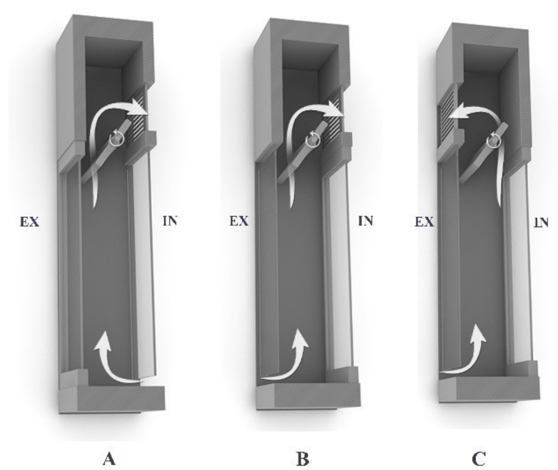

Figure 3 Three different applications of the double skin façade(Zhou & Chen, 2010)

The contribution of a Double Skin Envelope (DSE) to the heating energy savings was examined by Kim et al. (Y. M. Kim, Kim, Shin, & Sohn, 2009) in office buildings with different wall-facings. Balocco estimated the energy performance of a naturally-ventilated double façade using dimensional analysis. The 14 independent non-dimensional parameters considering a variety of fluid thermo-physical properties were reviewed and utilized to investigate energy and thermal performance of different façades. Saelens et al. (Saelens, Roels, & Hens, 2004) demonstrate that a correct modeling of the inlet temperature of ventilated multiple-skin façades requires a proper implementation of the boundary conditions and modeling parameters. Moreover, they showed that the assumption of an inlet temperature, which is equal to the interior or exterior air temperature, is not usually valid. The importance of the inlet temperature as a boundary condition for numerical multiple-skin façade models was investigated using a sensitivity analysis. Eicker et al. (Eicker, Fux, Bauer, Mei, & Infield, 2008) analyzed the performance of single and double façades with sun shading systems in summer empirically and in a real project in Germany. The results showed that in a ventilated façade the thermal energy production is between 50-100 kWh/m^2. Høseggen et al. (Høseggen, Wachenfeldt, & Hanssen, 2008) modelled a building with and without a double skin façade with controllable windows and hatches for natural ventilation in a simulation program called ESP-r. According to the results, energy demand by improving U-value of windows in single-skin option and double skin façade alternative will be the same.

Hien et al. (Hien, Liping, Chandra, Pandey, & Xiaolin, 2005) compared the effects of a double-glazed façade with a single glazed façade system and investigated their impact on the energy consumption, thermal comfort, and condensation by simulation. The results indicated that energy consumption is minimized in double glazed façade with natural ventilation and thermal comfort improved simultaneously. Condensation problem can be solved by mechanical fans. Pasquay (Pasquay, 2004) evaluated the energy performance of three different buildings with double-skin façades for one year. In one building all the air conditioning facilities were removed and replaced by a double skin façade, one building had cooling equipment without mechanical ventilation, and one building had cooling equipment combined with mechanical ventilation. The results showed that in the long term, double skin façades would be economically efficient for high- rise buildings and the problem of heat gain.

Gratia and Herde (Gratia & De Herde, 2007) analyzed eight double skin façades using TAS simulation software. According to the results, the use of a double skin façades reduces the heating loads and raises the cooling loads. Pérez-Grande et al. (Pérez-Grande, Meseguer, & Alonso, 2005) studied the impact of the glass properties on the performance of double glazed façades. Ten different façades formed by various glass combinations were designed and the total heat rate in the building for each of them was calculated. The results showed that from a thermal balance point of view, a suitable combination of the glasses forming the channel can decrease the thermal load of the building significantly. Tanaka et al. (Tanaka, Okumiya, Tanaka, Young Yoon, & Watanabe, 2009) conducted research on the three-dimensional thermal characteristics of double-skin façades and found that the impact of the ventilation openings and the shade conditions on the temperature distribution of double-skin façades is considerable. Furthermore, for the cooling load, this system can also decrease the energy consumption considerably.

Zerefos (Zerefos, 2007)compared a double skin façade and a single skin façade for the heating and cooling loads in contrasting climates, and calculated their thermal and lighting properties. According to their results, in climates with high sunshine duration, the heating and the cooling loads difference for a double skin façade are less than that of a single skin façade. Carlos et al. (Carlos, Corvacho, Silva, & Castro-Gomes, 2010) characterize the thermal performance of a double window system when converted into a ventilated double window as a passive system. The outside air circulates through the channel between the windows and, from the top of the window's case, enters the building. A series of empirical measurements in a test cell exposed to real weather conditions in Portugal was conducted to determine the relationship between the solar irradiance, the air flow rate and the temperature of the air entering the room.

Chan et al. (Chan, Chow, Fong, & Lin, 2009) reported findings on the energy performance of a double skin façade in a typical office building in Hong Kong considering climatic condition. The theoretical model was developed using the Energy Plus simulation program to evaluate the energy performance of a double skin façade with different configurations including glazing type (clear, absorptive or reflective glass), glazing position (inner or outer pane) and glazing layers (single or double glazing material). An annual savings of approximately 26% in building cooling energy was reported by a double skin façade system with single clear glazing as the inner pane, and double reflective glazing as the outer pane. However, from an economic perspective, a long payback period of 81 years was reported for this configuration.

Zhou and Chen (Zhou & Chen, 2010) investigated the available methods on the thermal performance assessment of double skin façades and shading tools. They concluded that an efficient way to fulfilling the agenda of sustainable building design practices in the commercial buildings would be to implement ventilated double-skin facades (DSF) with controlled shading device systems. In a research by (Xu & Ojima, 2007), the application of a double skin façade for a two-story house in Kitakyushu, Japan was proposed. They investigated the stack effect in a double skin space during the summer, the greenhouse effect during the winter and the availability for free air-conditioning during the autumn. They also measured thermal performance in a double skin space and its impact on air-conditioning load in the rooms.

2.5.2 Trombe Wall

The Trombe wall is with a thickness of 20 to 40 cm, usually dark in color, with a high thermal mass, which has south orientation. The air cavity in the Trombe wall has a thickness ranging from 2 to 15 cm. The sunlight is absorbed by the wall, a portion of it radiates into the space and transmits by convection, the other portion of heat absorbed by the cavity space conducted to the wall slowly, heating the room space for many hours after the sunset.

The main aim of designing a Trombe wall is to gain heating energy during winter (Figure 4). Smolec et al. (Smolec, 1993) calculated the temperature distribution of a Trombe wall analytically and compared their results with empirical findings. Fang et al. (Fang & Li, 2000) compared Lattice Passive Solar Heating Walls (LPSHW) with a conventional Trombe wall. They concluded that the LPSHW perform better than the Trombe wall in terms of energy efficiency gains. Sodha et al. (Sodha, M. S.; Kaushik, S. C.; Nayak, 1981) used numerical analysis to evaluate the thermal performance of Trombe walls and roof pond systems during summer and winter time. Buzzoni et al. (Buzzoni, Olio, & Spigab, 1998) employed finite difference method to analyze the performance of a passive solar system for heating consisting of a Trombe wall with thermal insulation on the southern wall surface. Mootz and Bezian (Mootz, F; Bezian, 1996)investigated an energy-saving façade panel structured using a composite Trombe wall including a glazing, an absorber plate, insulation a dead air space and a convection channel between absorber and insulation considering two options. The results showed that during a day, large spacing works better for energy recovery for both alternatives. However, during night hours, Heat losses decreases for the second option. By using the Computational Fluid Dynamics (CFD) technique, Gan (Gan, 1998), investigated the impact of the distance between the Trombe wall and glazing, wall height, glazing type and insulation. The results showed that for summer cooling, the insulation should cover the interior surface of a Trombe wall to maximize the ventilation rate. Raman et al.(Raman, Mande, & Kishore, 2001) investigated the integration of a Tromble wall and sackcloth cooling concepts to provide thermal comfort conditions. Chel et al. (Chel, Nayak, & Kaushik, 2008) assessed the possible energy conservation, passive heating potential and co_2 energy reduction by utilizing a Trombe wall in a honey storage building. The results revealed that 3312 kWh/year could be conserved along with a 33 ton/year co_2 emission reduction. Özbalta and Kartal (Özbalta & Kartal, 2010) estimated the passive heating potential of a Trombe wall in Turkey by using the unutilizability method. The Trombe wall was tested with different kinds of materials including reinforced concrete, brick, and autoclaved aerated concrete, with various surface colors to estimate the capability of heat gain from solar energy for each option. Shen et al. (Shen, Lassue, Zalewski, & Huang, 2007) compared a traditional Trombe wall and a composite Trombe wall – an insulating wall paired with a traditional one. The results show that regarding energy saving potentials, the composite wall has a better performance in cold and cloudy weather.

Tyagi and buddhi (Tyagi & Buddhi, 2007) presented and compared an innovative form of a Trombe wall that integrates phase change materials (PCM). The results showed that for saving a specific amount of energy, the PCM-Trombe wall requires less space and is lighter in weight compared to a traditional Trombe wall.

The implementing PCMs in new buildings have provided opportunities for implementation of innovative Trombe wall systems, which are movable, portable, rotating systems, and lightweight (Basecq, Michaux, Inard, & Blondeau, 2013). For instance, Moghiman et al. (Moghiman, Hatami, & Boghrati, 2011) design a new and efficient Trombe wall compared to the classical solar walls. In this system, a series of rotating storage wall segments that rotates around their vertical shafts mimics a classic Trombe wall. During the day, the rotating walls segments act as a good absorber, while overnights they become a good radiator. Nwachukwu and Okonkwo (Nwachukwu & Okonkwo, 2008) investigated ways to enhance heat transfer across a Trombe wall by applying a coating on the heat-receiving surface of the wall. This technique resulted in higher heat absorption capacity in comparison with other conventional alternatives.

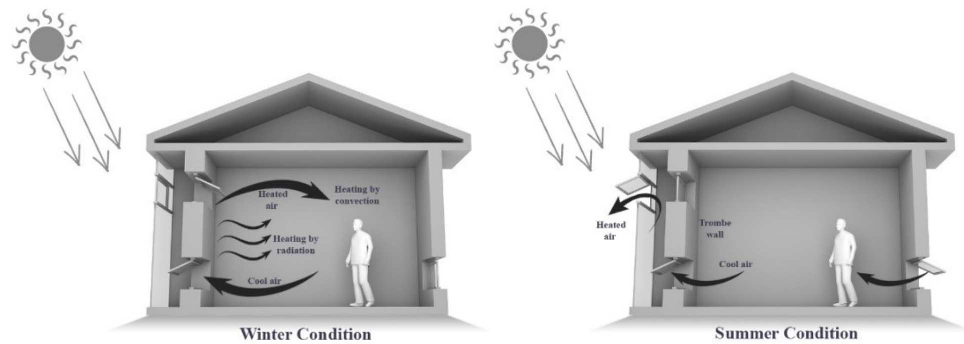

Figure 4, Trombe wall application in winter and summer time(Chel et al., 2008)

2.5.3 Sunspace

Attached sunspaces or conservatories are often referred to as sunrooms and function similar to Trombe walls. The only difference between the two systems is the availability of more space between the wall and the glass in the latter case, which could create a comfortable living space while affording energy efficiency advantages (Kesik & Simpson, 2002) (Figure 5). The majority of the studies on sunspaces try to find solutions to maximizing the benefits of heating load in winter and avoiding overheating in the summertime. Aside from overheating in summer, one drawback of passive heating is that it could only happen through the south façade, although this issue can be addressed by facilitating heating energy distribution across the space (Konstantinou, 2014).

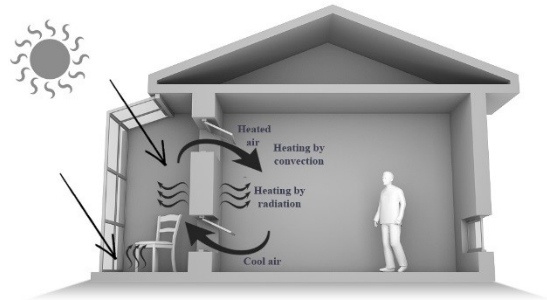

Figure 5, Sunspace indirect heating mechanisms

Schoenau et al. (Schoenau, Lumbis, & Besant, 1990) examined the thermal performance of four sunspaces in Saskatoon, Canada. In order to validate an analytical model, performance was monitored hourly while a simulation was conducted to account for the annual energy performance estimations. Aelenei et al. (Aelenei, De Azevedo Leal, & Aelenei, 2014) used a numerical approach to investigate the thermal performance of a sunspace in a residential building in Portugal. Orientation, sunspace configuration, natural ventilation of the sunspace and position and radiative properties of the shading devices were considered as design variables and their influence on thermal behavior and the possible amount of energy saving were analyzed.

Bataineh and Fayez (Bataineh & Fayez, 2011) investigated the thermal performance of an attached sunspace to a building in Amman, Jordan. Furthermore, they evaluated the impact of the orientation of the sunspace, opaque wall and floor absorption coefficients and the number of glass layers on thermal performance. Based on their results, sunspace can decrease heating load considerably in winter. However, it causes serious overheating in summer. Bakos et al. (Bakos & Tsagas, 2000) explored the thermal and economic aspects of an attached sunspace in Greece. Thermal load was calculated by the degree-day method and, for economic performance, the LCC method was used. Oliveti et al. (Oliveti, Arcuri, De Simone, & Bruno, 2012) calculated the solar gains of the sunspace and the adjacent spaces in different regions of Italy based on several geometric configurations including a system of windows made up of clear double-glazing. They considered and analyzed the impact of factors such as different level of exposure, optical properties and thermal aptitude of the opaque areas, the ventilation capacity and the shading mechanism.

Sánchez-Ostiz et al. (Sánchez-Ostiz et al., 2014) investigated thermal performance and design of two passive solar systems including attached sunspace with horizontal heat storage and an attached sunspace with vertical thermal storage. These two sunspaces were tested under the real conditions in two residential buildings in Spain. Monge-Barrio and Sánchez-Ostiz(Monge-Barrio & Sánchez-Ostiz, 2015) studied the behavior of sunspaces as passive elements in summer for different climatic regions in Spain. The results show that sunspaces can be configured to perform efficiently in summer, even in extremely hot conditions. Zhu et al. (Zhu, Liu, Yang, & Hu, 2014) evaluated the thermal performance of new Yaodong dwellings by adding an attached sunspace to the old building located in the Zaoyuan village in Yanan City, China. By using Energy-Plus software, they conducted numerical simulations of heating and cooling energy consumption.

Fernández-González (Fernández-González, 2007) assessed the thermal performance of five passive solar test-cells including Direct Gain, Trombe wall, Waterwall, Sunspace, and Roofpond by considering a control test-cell in Muncie, Indiana in order to identify the limitations of these passive solar heating systems. Rempel at al. (Rempel et al., 2016) modeled a series of field-validated sunspaces in Pacific Northwest to quantify their thermal mass design issues and to investigate the impact of factors such as the sizing and ground configuration of floor-based thermal mass. Lucas et al.(Lucas, Hoese, & Pontoriero, 2000) analyzed and compared the thermal performance of three passive systems including Trombe wall, direct gain and sunspace, in a region with a continental Mediterranean climate. The results show that all mentioned passive systems gained solar radiation throughout all the seasons of the year. Among them, the Trombe wall joined to a sunspace provided the best results, with small energy gain in summer and high energy contribution in winter.

Mottard and Fissore (Mottard & Fissore, 2007) proposed a new thermal simulation model for an attached sunspace by paying attention to the internal long-wave radiation exchanges and solar radiation distribution within the sunspace. For validation, the calculated results were compared to the empirical data. Furthermore, a sensitivity analysis was used to determine the parameters of the model with the strongest impacts on energy performance. Babaee et al. (Babaee, Fayaz, & Sarshar, 2016) proposed a design modification for sunspaces to enhance the thermal performance of dwellings in Tabriz, Iran which has a cold climate. Six sunspace configurations with different ratios of glazed to opaque surfaces were modeled and simulated to identify an optimum dimension of the sunspace. The orientation, the number of glazed surfaces, the direction and inclination angle of the surfaces, the glazing material, and the common wall material of the sunspace as design criteria were also assessed.

2.5.4 Natural Daylighting

Daylighting can be an appropriate substitution for electric lighting. Electricity used for lighting accounts for 10% to 20% of total electricity consumption in buildings. Using daylighting can help reduce electricity consumption for lighting by up to 75 percent (Edwards & Torcellini, 2002). In the hot seasons, using less energy for electric lighting results in less indoor heat production lowering the cooling load. Furthermore, daylight entering a building can make an attractive and pleasant atmosphere and allows the occupants to have a visual connection with the outside world (Li & Tsang, 2008). Apart from some advantages in energy saving and structural aspects, daylighting has a psychological and physiological impact on the occupants(Edwards & Torcellini, 2002). In this regard, Plympton et al. (Plympton, Conway, & Epstein, 2000) revealed that students in daylight classrooms performed notably better in their education. Various methods have been developed in daylight collection and distribution. Littlefair (Littlefair, 1990) reviewed available systems for gaining and trapping daylight in a building and provided recommendations for designing the proposed systems including the light pipe, mirror system, prismatic systems, lens systems, holographic diffracting systems and light shelves. Yun et al. (Yun, Shin, & Kim, 2010) installed a light pipe system in a windowless space of a case study building located in Korea. Indoor illuminance distribution and concurrent outdoor illuminance were monitored for two months. They showed that a light pipe system can be an efficient tool for indoor daylighting with respect to both the daylighting performance of the light-pipe system and the indoor illuminance. However, distribution of space can be affected by clouds, solar altitudes and external total illuminances. Zhang and Muneer (Zhang & Muneer, 2000) proposed a modified form of daylight factor for light pipe systems. Two weeks of measurements have been done to illustrate the performance of the light pipe. The findings show that for a given design of light pipe, its penetration factor is a function of solar altitude, sky clearness index and the distance between the point of illuminance measurement and the light pipe diffuser. Paroncini et al. (Paroncini, Calcagni, & Corvaro, 2007) monitored the performance of a light pipe system for one year in Italy. To perform the test, a light pipe was mounted on the roof of a windowless test room which was equipped with some indoor sensors to measure internal illuminance as well as outdoor sensors to record external illuminance.

Jenkins and Muneer (Jenkins & Muneer, 2003) proposed a model that determines the level of light from a light pipe. Moreover, to calculate the illuminance resulting from a given luminous flux in overcast skies, they proposed a method and tested its applicability using data collected from different locations in the UK. Shin et al.(Shin, Yun, & Kim, 2012) developed a performance assessment method for a light pipe system based on the amount of daylight and electric lighting energy saved. The proposed method was tested against experimental data under Korean climate conditions to illustrate its robustness and applicability.

Li et al. (Li, Tsang, Cheung, & Tam, 2010) investigated the applicability of light pipe systems in Hong Kong. They measured daylight illuminance in a corridor with installed light pipes. They demonstrated that a light pipe system can enhance the daylight uniformity and has high potential to decrease the electric lighting needs while providing sufficient illuminance.

Rosemann et al. (Rosemann, Mossman, & Whitehead, 2008) proposed a novel system called the solar canopy illumination system, which collects direct sunlight from a structure attached above the windows on each floor. The collected sunlight is distributed throughout the building through a series of special purpose light guides. Based on the amount of energy savings, this system has the potential to be profitable. Tai Kim and Kim (J. T. Kim & Kim, 2010) evaluated the performance of two optical daylighting systems: light pipe systems and mirror sun-lighting systems. They concluded that visual comfort could be obtained, and energy can be saved considerably if the optical daylighting systems are designed according to the characteristics of the building, climate, lighting needs, and the space. Oakley et al. (Oakley, Riffat, & Shao, 2000) monitored the performance of six light pipes in three cases: a workshop, a residential building, and a small office. Their results confirm that light pipes are proficient tools for bringing daylight into buildings. Also, the most efficient light pipes are straight and short ones with low aspect ratios. Also, light pipes with larger diameters were shown to be more efficient. Additionally, results of laboratory measurements of illuminance for various angle configurations of a deflecting sheet coupled to a mirror light pipe (MLP) were presented by Venturi et al.(Venturi, Wilson, Jacobs, & Solomon, 2006). The results pointed out that the performance of the sheet is subject to its angle, which could vary to maximize the output for every month of the year. For low elevations during the winter months, a substantial improvement was achieved. However, simultaneously, the measurements showed a reduced performance in the summer months and a remarkable decrement under diffuse light. One of the main reasons behind ignoring natural light benefits and features in design of buildings is the lack of proper assessment tools. In this sense, Krarti et al. (Krarti, Erickson, & Hillman, 2005) provided a simplified method to assess electricity saving potentials of daylighting for some combinations of building geometry, window opening size, and glazing type in four different locations in the United States. The influence of daylighting performance was further investigated and the above method was validated by Ihm et al. (Ihm, Nemri, & Krarti, 2009)with an experimental analysis. They also investigated the impact of dimming and stepped daylighting controls.

Onaygil and Guler (Onayg & Guler, 2003) compared conventional lighting systems with natural daylighting by collecting and assessing data for a representative year in Istanbul, Turkey. Their results show that in regions with similar climate conditions, energy consumption can be reduced by about 30% using daylighting. Moreover, there is potential for further energy savings using high quality lighting equipment. Tregenza et al.(Tregenza & Wilson, 2011), explored the Radiosity and Monte-Carlo methods for daylighting modeling. Li and Tsang (Li & Tsang, 2008) presented field measurements on daylighting and presented an integrated method of electric lighting and daylighting in office buildings in Hong Kong. They analyzed electricity consumption by the fluorescent luminaires, indoor illuminance levels and the impact of room parameters on daylighting designs.

2.5.5 Sun Shading

The main duty and most efficient application of sun shading systems is to prevent solar radiation and the resulting overheating in summer conditions (Bellia, De Falco, & Minichiello, 2013). There are a variety of forms and shapes for sun shading from projecting eaves to Venetian blinds and curtains. The choice depends on their applications, function and aesthetic designs. The sun shading devices can be categorized into exterior shading and interior shading. Exterior shading is more efficient in comparison to interior shading, however, it is associated with higher maintenance costs(Konstantinou, 2014).

Kischkoweit-Lopin (Kischkoweit-Lopin, 2002) illustrated shading systems with sketches and short descriptions of their elements including attachment and the criteria for selecting the proper daylighting system for a given climatic condition. Palmero-Marrero and Oliveira (Palmero-Marrero & Oliveira, 2010) studied the impact of louver shading devices in different locations and different façades of a building. They quantified energy requirements of a building in the cooling and heating seasons in Mexico City, Cairo, Lisbon, Madrid and London. The results showed that using louver shading devices can improve thermal comfort conditions and a significant amount of energy can be saved compared to a building without any sun shading devices.

Kim et al. (G. Kim, Lim, Lim, Schaefer, & Kim, 2012) investigated an experimental configuration of an external shading device for a building in South Korea. For heating and cooling energy saving, some conventional daylighting devices were examined to identify the advantages of external shading devices. The results showed that the external shading devices have two main benefits. Firstly, they could improve the energy performance with various adjustments of the slat angle. Secondly, they provide better views for the building occupants. By using IES-VR software, Hammad and Abu-Hijleh (Hammad & Abu-Hijleh, 2010) explored the impact of external dynamic louvers on the energy consumption of an office building located in Abu Dhabi. Based on the results, the optimal static angle for the south-oriented façade was −20◦ and for the east- and west-oriented façades 20◦. Using the fixed façades can save slightly less energy than the dynamic façades, however, fixed façades have lower initial investment, maintenance and operation costs. In this regard, Carbonari et al. (Carbonari, Rossi, & Romagnoni, 2002) studied the optimal orientation of buildings regarding their control logic and the type of adopted shading devices. They compared the impact of three different shading element configurations (without external shading element, external fixed louvers with 45tilted and automatically adjustable louvers with control logic) in three Italian climates (Venice, Rome, and Trapani).

Kim et al. (J. H. Kim, Park, Yeo, & Kim, 2009) compared the application of an automated Venetian blind to a manual or motorized Venetian blind to determine the their energy performance and the associated level of occupant comfort. Cheng et al. (Cheng, Chen, Chou, & Chan, 2007) pointed out that an appropriate setting for a shading device could conspicuously promote the room lighting performance. They showed that natural daylight, which includes directional sunlight, diffused skylight and reflected light can further enhance the energy conservation. The results revealed that when considering a proper altitude and azimuth, the area of the daylight zone could also be increased and shading can be obtained as well. The application of using overhang on electrochromic windows was analyzed for commercial buildings by Lee and Tavil (E. S. Lee & Tavil, 2007). For comparing the thermal and visual efficacy of different types of solar shadings, David et al. (David, Donn, Garde, & Lenoir, 2011) proposed simple indices for non-residential buildings. They studied a typical office to evaluate the efficiency of the various types of solar protections. Gratia and Herde (Gratia & De Herde, 2007) examined the impact of the position and the color of the blinds on the cooling demands in an office building with a double skin façade. According to the results, cooling demand can be decreased up to 23.2%. Three factors play a crucial role in this performance: the position of the blinds, the blinds' color and the opening of the double-skin. They also investigated the impact of the blinds' characteristics on the human comfort.

Kuhn et al. (Kuhn, Bühler, & Platzer, 2000) recommended a new simple, reliable and realistic method for internal and external shading to evaluate overheating protection of several sun shading systems in combination with glazing. This approach includes the angle-dependent determination of the total solar energy transmittance based on ray-tracing methods. Datta (Datta, 2001) investigated the influence of fixed horizontal louver shading devices on thermal performance of a building by TRNSYS simulation for four different cities in Italy. The optimization of the shading devices for the entire year was performed to minimize primary energy loads. The investigation revealed two main findings. Firstly, the optimum design is dependent on location and weather conditions. Secondly, shading factor varies with time of day and is different for summer and winter. Ho et al. (Ho, Chiang, Chou, Chang, & Lee, 2008) studied the feasibility of fitting windows with sun-shadings in four different building designs to reduce the lighting costs in daylight-illuminated classrooms in Taiwan. The results revealed that a double-layered sun shading could best achieve a uniform illumination distribution within the classroom yielding a 71.5% saving in lighting energy. By using a coupled lighting and thermal simulation module, Tzempelikos and Athienitis (Tzempelikos & Athienitis, 2007) calculated the influence of glazing area, shading device (an exterior roller blade) and shading control on cooling and lighting demands of a building located in Montreal. Furthermore, they quantified and analyzed the influence of shading device types, properties, and control on energy demand. They applied an integrated approach for automatic control of motorized shading with controllable electric lighting systems which resulted in considerable reduction of energy demand.

Bellia et al. (Bellia et al., 2013), evaluated the impact of external solar shading devices on the energy demands (including heating, cooling, and lighting) of a typical air conditioned office building by use of building energy simulation for a whole year in Italian climate conditions. For warm summer climates, the solar shading devices have shown the highest energy efficiency. Abu-Zour (Abu-Zour, Riffat, & Gillott, 2006) presented a new collector integrated into louvered shading devices. They considered a variety of solar louver collectors with several design aspects. The results showed that the compatibility of louvers with different building sizes and shapes could enhance solar control and the aesthetics of building façades. Charde and Gupta (Charde & Gupta, 2013) analyzed the impact of static sunshade solid brick , and brick cavity wall with projections of their impact on indoor air temperature in summer and winter. According to the results, the static winter sunshade had a better performance compared to horizontal static sunshades. However, in summer, the brick cavity wall with brick projections performed better than a solid brick wall.

2.5.6 Fenestration

Among the means of energy transfer, the exterior windows are responsible for 25 percent to 28 percent of the total heat gain in summer. This number increases to 40 percent we include infiltration (Yu, Yang, & Tian, 2008). Thermal performance of windows and doors also plays a significant role in energy efficiency in buildings in winter, 30 percent to 50 percent of heat losses occurs from fenestration (Gustavsen, Grynninga, Arasteh, Jelle, & Goudey, 2011). The design arrangement and proportions of windows, skylights, and doors is called fenestration. Fenestration can be considered a visual and physical connection to the outdoors. Fenestration could improve the energy performance of a building in several ways including the use of glazing to reduce heat loss by conduction, daylight to offset daylighting needs, implementation of low air leakage, the use of glazing and shading methods to balance heat gain during cold or hot seasons, provision of natural ventilation to save cooling energy. From a physical point of view, glazing material, framing, dividers, shading devices are all fenestration components(Engineers, 2013).

There are several types of glazing systems designed to limit heat loss from windows to the environment and, when needed, facilitate heat gain from the outside environment. Glazing devices are often most impactful when it comes to maximizing solar heat gain but also minimizing heat loss. Using an inappropriate glazing system in certain climates can drastically increase the energy usage within that building by elevating the heating and cooling loads. Current technological developments in glazing focus on elements such as glass, air and other gas, insulation spacing, emissivity and reflective coatings, high visibility assemblies, and thermally improved framing systems. On the other hand, using proper glass reflects UV radiation during the summer and prevents buildings from becoming overheated(Vern’s Glass, 2015).

Susorova et al. (Susorova, Tabibzadeh, Rahman, Clack, & Elnimeiri, 2013) evaluated factors related to the role of geometry in building energy performance in a commercial office building. The study included window orientation, window to wall ratio, and room width to depth ratio to assess total annual energy consumption. To do so, they used an energy analysis program called “Design-Builder” to model a room in a typical office building for six climate zones in the United States. The results showed an approximate range of 3 percent to 14 percent energy savings in hot climates and around 1% in temperate and cold climates. It can be explained that rooms with large window area in hot climate require less artificial lighting energy and conversely, they lose more heat energy through the large window areas in cold climate. Jelle et al. (Jelle et al., 2012) reviewed the thermal performance of different components of a window system including glazing, spacer, and framing. Based on their finding, 0.28 and 0.30 W/m^2-K was found to be the lowest U-value for the center of glass for a suspended coating glazing product and an aerogel glazing product, respectively. The lowest U-value for the frame was 0.61 W/m^2-K. Which shows that there is a priority to research on the frame's material to reduce frame U-values.

Arasteh et al. (Arasteh, Goudey, Huang, Kohler, & Mitchell, 2006) evaluated typical window products as part of a whole house energy modeling in five US climates and compared them to the requirements for net-zero energy buildings. The results showed that windows with U-factors of 0.57 W/m2 –K are energy neutral in hot climates. However, a low U-factor is not as important as the ability to modulate from high SHGCs (heating season) to low SHGCs (cooling season) in mixed climates. Song et al. (Song, Jo, Yeo, Kim, & Song, 2007) evaluated the surface condensation in three different double glazing window systems with a conventional aluminum spacer and insulation spacer made of thermally broken aluminum and thick-walled plastic, respectively. An evaluation method and judgment criteria were suggested for preventing surface condensation.

Tahmasebi et al. (Tahmasebi, Banihashemi, & Hassanabadi, 2011) assessed the thermal performance of different windows subject to changing certain components and characteristics such as glazed layers, filled gases, sizes and orientations of the windows. They pointed out that the type of gas used in double and triple glazed windows and an increase in the size of the windows ratio from 34 percent to 41 percent do not change the thermal performance significantly. Jaber and Ajib (Jaber & Ajib, 2011) studied the impacts of windows' U-value, window orientation, and window size on annual heating and cooling energy demands in three different climatic zones: Amman, Aqaba, and Berlin. They investigated four types of windows including single glazed, double glazed L, double glazed H and triple glazed. The results revealed that heating energy requirement is more sensitive to window types and sizes compared to the cooling load. Energy savings of 21%, 20% and 24% can be attained using glazed window in Amman, Aqaba, and Berlin, respectively.

2.5.7 Glazing Materials

The most important part of a fenestration system is the glazing as it has the largest area of the constituent parts. Thus, its U-value impacts the overall U-value of a window (Jelle et al., 2012). Recently glazing technologies have progressed tremendously. Glazing materials are presented in different forms such as multilayer glazing, suspended films, vacuum glazing, smart windows, solar cell glazing, self-cleaning glazing solar control glasses, insulating glass units, low emissivity (Low-E) coatings, evacuated glazing, aerogels and glazing cavity gas fills, just to name a few. Additional to glazing materials developments, many studies focus on improvements in frame and spacer designs (Quesada et al., 2012b). Both glass and plastic are common glazing material and can be clear, tinted, coated, laminated and obscured. There is a wide variety of tinted glass such as blue, gray, green and bronze. The high absorption rate of solar radiation by tinted glass can lead to reduction of the solar heat gain, visible transmittance, and glare. Coating of glasses is another method to improve the performance of glazed coating, which is typically applied in one or two surfaces of a glazing unit. The coating can be categorized in Low-Emissivity Coatings, Reflective Coatings, and Spectrally Selective Coatings. Laminated glass is made by sticking two panes of glass together, with a layer of clear, tinted or coated plastic placed in between. Obscured glass is used mostly for privacy and is translucent or decorative (Engineers, 2013). Sadineni et al. (Sadineni et al., 2011) categorized glazing material based on their functions that include high performance insulation (HPI), solar heat gain control (SHGC), daylighting (DL), or a combination of these functions. They applied the above categorization to aerogel glazing, vacuum glazing, switchable reflective glazing, suspended particle devices (SPD) film and holographic optical elements.

Buratti and Moretti (Buratti & Moretti, 2012) investigated innovative glazing systems with silica aerogel to estimate its light transmittance, solar factor and color rendering index. According to their results, aerogel windows pose a higher performance in comparison with the windows normally used in Italy and EU countries from the energy saving point of view. Bahaj et al. (Bahaj, James, & Jentsch, 2008) explored technical, economic, environmental and indoor comfort implications of energy control in highly glazed buildings in Middle Eastern climates. For two case study buildings, they predicted the impact of using electrochromic glazing, holographic optical elements (HOE), aerogel glazing, and thin photovoltaic films on cooling demand.

By using an analytical thermal network and a numerical finite difference model, Manz et al. (Manz, Brunner, & Wullschleger, 2006) investigated heat transfer in triple vacuum glazing. They considered the impact of four parameters on thermal transmittance: emittances of glass sheet surfaces, support pillar radius, support pillar separation and thermal conductivity of support pillar material. Based on their findings, the thermal transmittances can be reduced by utilizing the triple vacuum glazing concept. Hassouneh et al. (Hassouneh, Alshboul, & Al-Salaymeh, 2010) investigated the energy performance of windows of an apartment building in Amman to find the most energy efficient window that can save more energy and decrease heating demand in winter. They used eight types of glazing. According to the results, the flexibility of selecting the glazed area and orientation increases by utilizing energy efficient windows. Using glazing type A and clear glass in a large area facing south, east and west reduce heating costs and save more energy. Using glazing type B in the north direction can also save energy and reduce costs.

2.5.8 Framing

The impact of framing on the total heat transfer rate of a window is much more than the area rate of the frame to the overall window area which is approximately 20 percent to 30 percent. The impact in highly insulated windows is even larger (Gustavsen et al., 2011). Wood, metal, and polymers are commonly used as framing materials for fenestrations and are often combined. Wood has a high insulating value and structural integrity but low resistance to moisture, warpage, organic degradation and weather condition. Metal frames have very poor thermal performance, but high durability and structural characteristics. Aluminum is the best choice of metal for fenestration because it is easy to manufacture, and it is low weight. Polymer frames are mainly made of vinyl or fiberglass. Their thermal and structural performance are similar to wood but vinyl frames must be reinforced in large fenestrations and are mostly hollow and can be filled by insulation materials (Owen, 2013).

Gustavsen et al. (Gustavsen et al., 2011) analyzed the impact of frames and edge-of-glass on U-factor in different surfaces, frame material and spacer conductivities to develop some performance benchmarks based on the available products on the market. They concluded that for the improvement of the thermal performance of window frames, the following strategies have to be taken into consideration: development of new spacer technologies, identification of alternative thermal break materials, development of new thermal break materials, development of structural insulating materials, development of low-emissivity coatings for PVC/aluminum window frames with many cavities, development of alternative frame designs/technologies and alternative window designs.

The development of a glass fiber reinforced polyester (GFRP) material for window frames was presented by Appelfeld et al. (Appelfeld, Hansen, & Svendsen, 2010) In doing so, three configurations of these frames were investigated and energy and structure of them were compared to the conventional frames. They concluded that a window made of GFRP can save heating energy remarkably more than reference conventional frames.” (Amiri Fard, Sharif, & Nasiri, 2019)

In this section, the passive measures have been categorized in according to the four energy control principles. However, designing a model to help the retrofit designers to select possibly the most effective choices among a large variety of them is still in demand and need which is discussed in the next section.

2.6 SELECTION OF PASSIVE ENERGY MESURES

“Multi criteria decision-making, single/multiple objective optimization methods, simulation tools and/or sensitivity analysis methods have been sought to deal with the challenge of selecting a set of energy management measures from a set of available options (Senel Solmaz, Halicioglu, & Gunhan, 2018)” (Amiri Fard & Nasiri, 2020).

Simulation methods are based on the scenario definition. To find the best possible scenario in a building, a set of energy measures are selected, a base-building model is created and evaluated by simulation tools (e.g. DesignBuilder, eQUEST...) to identify the best combination of measures. The main drawbacks of using a simulation approach is that modeling different scenarios for energy efficiency in each building is a time-consuming process. Thus, the application of simulation tools for decision making in the early phase of building retrofitting is regarded as infeasible (Senel Solmaz, Halicioglu, & Gunhan, 2018). Building simulation tool includes dynamic simulation modeling methods (energy simulation programs) and static simulation modeling methods (mathematical methods). The dynamic models can consider dynamic behavior of building and its components. However, finding the best scenario is time consuming with a high discrepancy between the results of actual and predicted models. On the other hand, static simulation methods are mostly over simplified in building modeling (Hashempour, Taherkhani, & Mahdikhani, 2020).

Sensitivity analysis belongs to the category of methods that aim at finding the input-output relationships to identify the input parameters with the highest influence on outputs. The application of sensitivity analysis methods in the context of building analysis is categorized into two sub-groups of local and global approaches. The interactions between inputs are not explored in the former approach without self-verification in the process. The latter approach is categorized into three groups of regression, screen, and variance-based Meta models. These models are computationally intensive and their accuracy highly depends on the model assumptions (Tian, 2013).

Multi-objective optimization methods are useful in dealing with conflicting objectives. It has been widely used to optimize building energy performance in the different phases of construction. Multi-objective optimization methods work well for a complicated problem. However, the derived results need to be screened and filtered before using them in building energy analysis. Otherwise, the number of inputs can highly extend the optimization run time (Senel Solmaz et al., 2018). "Furthermore, it could create several solution scenarios complicating the retrofit decisions when it comes to implementation" (Amiri Fard & Nasiri, 2020).

"In this sense, Diakaki et al. (Diakaki, Grigoroudis, & Kolokotsa, 2008) compared the performance and outcomes of three different optimization techniques: the compromise programming, the global criterion method, and the goal programming. Roberti et al. (Roberti, Oberegger, Lucchi, & Troi,

2017) developed a multi-objective optimization model coupled with analytical hierarchy process (AHP) to identify optimal retrofits for a historical building. Shao et al. (Shao, Geyer, & Lang, 2014) designed an integrated model as a hybrid framework by combining analytical hierarchy process (AHP), quality function deployment (QFD), Non-dominated Sorting Genetic Algorithm II, and multiple-attribute value theory (MAVT) approach in order to incorporate human judgments and other qualitative aspects of a retrofit project. The analytic network process (ANP) was used by Zhao et al. (Zhao, Wu, & Zhu, 2009) to develop a three-grade evaluation system for energy efficiency retrofits of existing buildings in China. Pohekar and Ramachandran (Pohekar & Ramachandran, 2004) and Løken (Løken, 2007) reviewed multi-criteria decision-making techniques and analyzed their applicability in energy planning problems. The use of an analytic hierarchy process (AHP) was explored by Si et al. (Si, Marjanovic-Halburd, Nasiri, & Bell, 2016) for assessment of retrofitting measures considering the characteristics of buildings. Jaggs and Palmer (Jaggs & Palmer, 2000) developed an energy performance and indoor environmental quality retrofit (EPIQR) methodology to assist building owners in choosing the most effective retrofit actions while considering a maximum allocated budget. To assess a number of retrofitting scenarios, Flourentzou and Roulet (Flourentzou & Roulet, 2002) used two multi-criteria analysis approaches of EPIQR and a decision-making tool for selecting office building upgrading solutions (TOBUS). Rey(Rey, 2004) also employed a multi-criteria assessment methodology to identify the best retrofit scenarios for a case study building. Lohet et al. (Loh, Crosbie, Dawood, & Dean, 2010) introduced a model called EATT (environmental assessment trade-off tool) incorporating AHP model considering energy performance and different design criteria in the early building design decisions. In order to help designers select the most operationally feasible energy measures, Alanne (Alanne, 2004) proposed a multi-criteria ‘‘knapsack’’ model, which first utilizes an

MCDM approach to calculate utility scores or weights alternative retrofit measures based on specific criteria. Then, using a knapsack optimization method, they identified the best implementation scenario for these retrofit actions" (Amiri Fard & Nasiri, 2020).

It is observed that the cost estimate in many cases was substantially below what was ultimately spent as the final budget (Welde & Odeck, 2017). Therefore, cost contingency considerations should be sufficiently addressed in an attempt to develop an energy efficiency model which is undertaken in the next section

2.7 COSTING CONSIDERATIONS FOR PASSIVE ENERGY MEASURES

"In real-world cases, many parameters and factors influence energy management optimization, mostly associated with varied degrees of uncertainty. However, in conventional methods, for simplification, those parameters or coefficients were usually specified as deterministic, whereas uncertainties in design variables, coefficients and parameters are not taken into consideration (Yao, Chen, Luo, Van Tooren, & Guo, 2011). Uncertainties could directly affect the selection of retrofitting measures and the success of a retrofit project. A decent prediction/formulation approach to address uncertain parameters is crucial to achieve a maximum building energy efficiency during the whole lifespan of buildings (Ma, Cooper, Daly, & Ledo, 2012). However, on the negative side, formulating an optimization model under uncertainty could lead to a computationally intensive model. By definition, uncertainty is regarded as the lack of knowledge and intrinsic variability of a model and its environment (Yao et al., 2011). The main aim of uncertainty analysis is to investigate the reliability of the results and to establish the occurrence likelihood of particular states of a model (Mechri, Capozzoli, & Corrado, 2010). In energy optimization models there are different sources of uncertainty; variables, vagueness in constraints, highly variable climate and environmental parameters, and future building performance and operation decisions (Hopfe, Emmerich, Marijt, & Hensen, 2012)(Nguyen, Reiter, & Rigo, 2014).

For planning of energy retrofit applications, Gabrelli and Ruggeri (Gabrielli & Ruggeri, 2019) developed a retrofit decision model for building portfolios in contrast to a single building. They employed several approaches such as regression analysis, life-cycle costing, multi-attribute optimization, discounted cash flow analysis, and the Monte Carlo simulation. A weakness of their model was the lack of consideration of qualitative attributes as well as their associated weights. Tian et al (Tian et al., 2018) reviewed adopted uncertainty analysis methods in building energy assessments. Das et al. (Das, Van Gelder, Janssen, & Roels, 2017) used a retrofit case study in Sweden and investigated the impacts of admitting uncertainties in evaluation of energy efficiency measures. Verderame et al. (Verderame P. M. , Elia J. A. , Li J., 2010) conducted a review of planning and scheduling approaches utilized in different applications (including energy planning) highlighting the role and importance of uncertainty analysis. Zeng et al. (Zeng, Cai, Huang, & Dai, 2011) provided a review of literature on energy systems optimization by considering the approaches adopted to address potential uncertainties. Mavrotas et al. formulated a mixed integer linear programming model, comprising both linear and integer variables, representing energy flows and discrete energy technologies for a case study hotel in Greece, respectively. Ultimately, a number of fuzzy parameters have been suggested to handle uncertainties in energy costs and fuel prices (G Mavrotas, Demertzis, Meintani, & Diakoulaki, 2003). They also proposed an integrated modelling and optimization framework where the minimization of costs and the maximization of demand satisfaction are considered as objective functions. The energy demand uncertainties were formulated using fuzzy set theory (George Mavrotas, Diakoulaki, Florios, & Georgiou, 2008).

Rezvan et al. (Rezvan, Gharneh, & Gharehpetian, 2012) used a multi-objective optimization method subject to uncertainties in energy demand to calculate the optimum capacity of distributed generation technologies for a stock of buildings.

Liu et al. (Liu et al., 2009) integrated chance-constrained programming, interval linear programming and mixed integer linear programming to address the uncertainties associated with estimation of probability density functions and intervals. They proposed an inexact model for long-term planning of power systems. Diwekar (Diwekar, 2003) developed an integrated multi-objective optimization model under parameter uncertainties using probability distributions associated with green engineering concepts in material selection stage. Mazur (Mazur, 2007) developed a fuzzy non-linear programming framework in which a maximum energy efficiency and a minimum total cost rate, as well as different constraints, are formulated using fuzzy set theory. Borges and Antunes (Borges & Antunes, 2003) proposed a fuzzy multi-objective linear programming approach to incorporate the uncertainties and imprecision associated with the coefficients of an input-output energy economy planning model. Sadeghi and Hosseini (Sadeghi & Mirshojaeian Hosseini, 2006) demonstrated an application of fuzzy linear programming for optimization of an energy supply system in Iran comprising fuzzy coefficients for investment costs. Yokoyama et al. (Yokoyama, Ito, & Murata, 2003) developed a multilevel linear programming method under uncertain energy demands based on the minimax regret criterion. A fuzzy multi-objective mathematical programming was employed by Bitar et al. (Bitar, da Costa Junior, Barreiros, & Neto, 2009) to find a compromise between different objective functions simultaneously dealing with potential uncertainties and subjective information. An optimization modelling approach using fuzzy set theory was developed by Nguene and Finger (Nguene &

Finger, 2007) to measure potential losses and gains of decision makers when aiming for optimal policies for energy allocations over different time horizons." (Amiri Fard & Nasiri, 2020).

"The formulation of uncertainties in optimization problems is widely studied in the literature. There are three classes of methodologies explored namely, stochastic, interval and fuzzy approaches. Stochastic programming is considered when parameters or coefficients are not known but can be defined as probabilities or chances. Using stochastic methods could lead to computational and modeling complexities in the related mathematical programming problems. However, these methods could capture the impact of uncertainties and the correlation among them. Chance-constrained programming and two-stage stochastic programming are two alternative methods under stochastic mathematical programming (Zeng et al., 2011). The main goal of the former method is the reliability of a system (i.e. in an uncertain environment how a system is able to meet feasibility) which is defined as a minimum requirement on the probability of satisfying constraints (Sahinidis, 2004).The latter is concerned for optimization problems in which the related data are mostly uncertain and analysis of policy scenarios is desired (Zeng et al., 2011). Some parameters, such as energy price, can be stated as probability distributions over a specific period, according to available literature and historical data. These probability distributions can be expressed by either discrete values or continuous functions (Cai, Huang, Yang, & Tan, 2009).

An alternative way to formulate uncertain parameters is to express them as intervals with unknown distributions. Interval programming generates interval solutions with improved applicability through addressing interval information in the coefficients of the constraint and objective function. (Lin & Huang, 2011) An uncertain parameter is replaced with an interval range and the value fluctuates within a minimum and maximum range without distribution information of this interval. Consequently, a range of optimal solution is obtained and shows how the variables effect it (Kontogiorgos, Chrysanthopoulos, & Papavassilopoulos, 2018). The following features are added to an optimization method by using Interval programming: 1) it promises uncertainties to be directly communicated into the optimization and solution processes; 2) it does not make a model more complicated; therefore, the model will have relatively low computational requirements; and 3) it does not need membership or distributional information for parameters due to lack of distribution information and the membership functions(Zeng et al., 2011). Furthermore, defining fluctuation interval is typically much easier for decision makers and engineers to specify a distribution (Cai, Huang, Lin, Nie, & Tan, 2009).

Finally, fuzzy programming can be used to formulate uncertainties (captured by fuzzy numbers) in optimization problems. Uncertainty in parameters and constraints in this approach are treated as fuzzy numbers. This is reflecting the fact that with the presence of uncertainties, the parameters can be expressed by a range of values associated with membership degrees. These degrees could represent the extent of decision-makers' beliefs in the corresponding value (Plebankiewicz, Zima, & Wieczorek, 2015). In case of the constraints of the optimization problem, a degree of satisfaction of each constraint can also be designated as the membership function of the constraint (Sahinidis, 2004). The rationale behind using fuzzy set theory to represent these uncertainties (instead of adopting a probabilistic approach) is a reflection of the characteristics of these uncertainties. The cost estimations are obtained with respect to experts' opinion, and as such, the uncertainties are related to beliefs of experts in the expressed values instead of associating these values with degrees of randomness (statistically estimated or experimentally observed) in a probabilistic approach (Ruparathna, Hewage, & Sadiq, 2017). A higher membership for a cost value represents a stronger belief (opinion) about it (Lin & Huang, 2011). To incorporate parameters with fuzzy values in mathematical programming models a fuzzy programming approach is utilized (Kontogiorgos et al., 2018). These parameter values are incorporated into optimization models using value intervals and their associated benchmark fuzzy membership distributions, such as triangle or trapezoidal (Cai, Huang, Yang, et al., 2009; Amiri Fard & Nasiri, 2020).

Although one of the best options to decrease energy consumption in buildings is through renovation, however, there is a high level of risk in estimation of initial capital cost (Feng et al., 2020). In practice, in many cases, it is observed that the initial cost estimates were substantially below what was ultimately spent (Welde & Odeck, 2017). "In the case of residential buildings, the capital cost is sought as the most important factor for implementing a retrofit project. This is due to the fact that having less initial investments needed for a retrofit project with a single owner is sought more desirable in comparison with the preference for having a long-term return-on-investment in larger industrial projects (Kontogiorgos et al., 2018)" (Amiri Fard & Nasiri, 2020).

2.8 SUMMARY AND GAP ANALYSIS

"Energy efficiency practices in buildings consist of passive or active measures. Passive energy strategies, by reducing the energy demand in buildings, could lead to less dependency on fossil energy and capital-intensive renewable energy technologies. However, an effective application of these measures is highly depending on acquiring knowledge on building science concepts and energy control principles. This chapter reported on the state of the art in application of passive energy measures in buildings from an energy conservation perspective.

The reviewed studies were divided into four energy control principles; heating and cooling control, air transport control, water vapor transport control and natural heating, cooling and lighting control. Each of these control principals were linked to a number of technologies. A classification of passive measures was proposed (according to their types of energy control mechanism) that could help the building designers/managers arrive at an informed decision in selecting the best matching technologies with respect to characteristics of the building envelope and its functions. This classification contains a wide variety of passive measures applicable to buildings. Thus, selecting the most effective combination of passive measures is a challenging task for building designers/managers." (Amiri Fard, Sharif, et al., 2019)

"Despite the existence of literature, there are still a number of gaps in assessment and optimization of building retrofit projects. In particular, using a multi-objective optimization method could create several solution scenarios complicating the retrofit decisions when it comes to implementation. There is a need for a filtering method to prioritize selected alternative retrofit measures. In this sense, only a select number of measures will be considered for consideration in the optimization phase. In addition, by considering a range of decision criteria in the assessment phase, the number of objective functions in the optimization model will be reduced. A decent prediction of uncertainty parameters associated with optimization is also needed to help select the best retrofit alternatives maximizing building energy efficiency".(Amiri Fard & Nasiri, 2020)

Table 5, Methods used and identified gaps in the literature

Author-Year	Method used-Objective Function	Gap
(Najjar, Figueiredo, Hammad, & Haddad, 2019)	Multi-objective optimization Objective function: 1-Cost minimization 2-Constructability of building maximization	• Focused on just cost and constructability of building only • Uncertainty was not considered
(Verbeeck & Hens, 2005)	Multi-objective optimization Objective function: 1-Cost minimization 2-Building Load Minimization	• Focused on heating energy reduction • Uncertainty was not considered
(Ruparathna et al., 2017)	Fuzzy-based LCCA method Cost based model (economic perspective)	• Limited to just two energy retrofit alternative (Roof insulation and heat pump) • Disposal costs, service life of the new component and the remaining service life of the building in LCCA have been ignored, • The model does not consider non-monetary and/or qualitative benefits of building energy retrofits.
(Antipova, Boer, Guillén-Gosálbez, Cabeza, & Jiménez, 2014)	Systematic tool for the optimal retrofit Objective function: 1-Cost minimization 2-Environmental impact minimization	• Only two criteria were considered • Uncertainty was not considered
(Asadi, da Silva, Antunes, & Dias, 2012)	Tchebycheff programming-predicted mean vote (PMV) based on Fanger's model Objective functions: 1-Cost minimization 2-Thermal comfort Maximization	• The same priority was given to all EEMs • Thermal comfort was added as an objective in the optimization model However other aspects of energy retrofit were neglected such as environmental impacts, Resource use… • Uncertainty was not considered
(Asadi, Da Silva, Antunes, & Dias, 2012)	Tchebycheff programming	• Other Aspects of energy retrofit neglected such as social (human comfort, environmental impacts, … • Uncertainty was not considered

	Objective functions: Investment retrofit cost Energy saving	• just focuses on required energy for heating
(Chidiac, Catania, Morofsky, & Foo, 2011)	Screening Approach Objective functions: 1-Payback period minimization	• NPV was not considered • By using simulation, made the model very complex
(Mauro, Hamdy, Vanoli, Bianco, & Hensen, 2015)	SLABE methodology Objective functions: 1-Life Cycle Cost minimization	• Limited number of variables was considered • The other aspects of the retrofitting project were ignored
(Murray, Walsh, Kelliher, & O'Sullivan, 2014)	Multi-objective optimization model Objective functions: 1- Cost minimization 2-Carbon emission minimization	• The other aspects of the retrofitting project were ignored • Uncertainty was not considered
(Jafari & Valentin, 2017)	Optimization framework Objective functions: 1- Cost minimization	• Just cost based optimization model • Cost estimation uncertainty was not considered
(Alanne, 2004)	Multi-criteria ''knapsack'' model	• Just two criteria considered (environmental value and functionality) • Just one objective considered • Cost is regarded as a constraint • Based on pre-defined action and scenarios; therefore, there is no guarantee an optimal result to be achieved • Results do not demonstrate a specific solution for the renovation action • In the defined five scenarios, it is clear that in completely environment-oriented case, the result would completely be different from functionality-oriented case
(Diakaki et al., 2008)	Multi-objective optimization techniques	• There is no method to prioritize selected alternative measures (Filtering)

		• According to the aim of the paper it is supposed to consider as many retrofit measures as possible without any dependency to MCDM methods or simulation but there is not any proposed mechanism • Uncertainty was not considered
(Shao et al., 2014)	Hybrid framework (AHP- QFD (quality function deployment)- Non dominated Sorting Genetic Algorithm II- MAVT) Objective functions: • Initial investment cost • Energy consumption • Global warming potential	• By using AHP ,the authors ranked criteria and selected the first three with highest weight; therefore, the role of other criteria would be neglected in the next steps • Three steps out of 4 are based on human judgment • Uncertainty was not considered
(Penna, Prada, Cappelletti, & Gasparella, 2015)	Genetic Algorithm coupled with a simulation tool Objective functions: • Economic performance • Indoor thermal comfort	• All EEMs considered to be as the same priority • Other Aspects of energy retrofit neglected such as environmental impacts, Resource use… • Uncertainty was not considered
(Flourentzou & Roulet, 2002)	EPIQR and TOBUS	• Both approaches are the analysis toola which are based on building audit the results have to be judge by a human again(sorting software) • There is no guarantee that proposed action is the optimum one • Uncertainty was not considered

This chapter has highlighted a number of research pathways, gaps and shortcomings in the literature:

1) Most of the existing developed models for the selection of energy measure options are emphasizing on cost minimization, missing other qualitative and non-monetary decision criteria. Accounting for other objectives in the optimization step could lead to a decision model that is very complex to solve or create many solution scenarios. (See Table 5, i.e. (Jafari & Valentin, 2017; Murray, Walsh, Kelliher, & O'Sullivan, 2014; Najjar, Figueiredo, Hammad, & Haddad, 2019))

2) Consideration of cost ranges and cost estimation contingency were also seen as a gap in the most decision support frameworks developed for energy measure selection. A decision model developed for selection of passive energy measures as part of refurbishment projects shall account for and incorporate these uncertainties in order to adopt a more realistic selection process. (See Table 5, i.e. (Asadi, Da Silva, Antunes, & Dias, 2012; Diakaki, Grigoroudis, & Kolokotsa, 2008; Penna, Prada, Cappelletti, & Gasparella, 2015; Rabani, Madessa, & Nord, 2017; Shao, Geyer, & Lang, 2014))

The above research gaps as identified through the literature review serve as the main rationale behind adoption of the research objectives presented in chapter 1. The following chapter will be devoted to proposing a decision support approach that 1) integrates qualitative and quantitative decision criteria through a two-stage integrated assessment-optimization model, and 2) implements and analyzes several means of incorporating costing uncertainties into the above mentioned model using fuzzy set theory.

Chapter 3 : METHODOLOGY

3.1 MODEL DEVELOPMENT

In this chapter, first, a two-stage assessment-optimization approach is proposed. This effort was published by the American Society of Civil Engineering (ASCE), journal of computing in civil engineering:

***Amiri Fard, F.**, & Nasiri, F. (2018). Integrated Assessment-Optimization Approach for Building Refurbishment Projects: Case Study of Passive Energy Measures. Journal of Computing in Civil Engineering, 32(5), 4–9. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000785*

3.1.1 Background

"Improving energy conservation and efficiency as well as enhancing the indoor thermal comfort for occupants are two of the main targets in building refurbishment projects (Calcerano, Cecchini, & Martinelli, 2017; Güçyeter & Günaydın, 2012). The building sector consumes over 40% of total final energy and accounts for over 30% of greenhouse gas emission in developed countries (Dixit, Fernández-Solís, Lavy, & Culp, 2012; Yang et al., 2014). The stock of existing buildings poses a high potential for energy performance improvement as the replacement of them has been at a slow pace(Hamdy, Hasan, & Siren, 2013). By promoting energy conservation, natural resources will be conserved, adverse environ-mental impacts will be reduced, and the operational costs of buildings will be alleviated (Al-Homoud, 2005). In addition, building refurbishments could enhance the living conditions and improve the overall comfort of the occupants (Corgnati, Cotana, D'Oca, Pisello, & Rosso, 2017). In doing so, there are two pathways of achieving energy conservation through building refurbishment; application of active measures or opting for passive measures.

The former deals with producing energy from renewable technologies mostly with the help of government incentives and support at the building scale (Nasiri, Mafakheri, Adebanjo, & Haghighat, 2016). The latter is concerned with reducing energy demand at the building scale. The literature points to over 400 passive measure options applicable to existing buildings (Shao et al., 2014). In this sense, the challenge would be to evaluate these options and identify the ones that best match with the characteristics of a building and its occupants (Asadi, Da Silva, et al., 2012; Rabani et al., 2017). This evaluation requires an integrated (collective) assessment of the benefits associated with retrofit measures to provide a basis for comparison with the required expenditures (Sun, Gou, & Lau, 2018).The chapter aims at presenting an integrated assessment-optimization framework as a decision support for prioritization of building refurbishment measures related to energy conservation."(Amiri Fard & Nasiri, 2018)

"First, an analytic network process (ANP) is used to calculate the relative weights of alternative retrofit measures according to a set of identified non-monetary qualitative criteria. These relative weights will be used in formulating the Utility function. This function is maximized, and the total refurbishment cost is minimized simultaneously. This setting presents a bi-objective optimization subject to different constraints with respect to retrofit targets, needs, and standards. This pre-optimization integration of non-monetary qualitative decision criteria using ANP method reduces the computational complexity of decision making in multi option retrofitting projects through integrating these criteria into one representative utility function.

3.1.2 Multi-criteria assessment

The literature review points to several nonmonetary attributes of retrofit measures, as categorized in Figure 6, with several related sub-criteria. Using an ANP approach (Saaty, 2001), alternative retro-fit measures can be compared (and scored) according to such criteria and sub-criteria called clusters and nodes, respectively. The nodes in a cluster can impact some or all of the nodes of other clusters. After identifying the relationships among nodes and clusters, the nodes of each cluster are compared pairwise with respect to their impacts on other nodes in that cluster.

The relative preference weights are calculated using a scale from 1 to 9, where 1 stands for equal importance, 3 for moderate importance, 5 for strong importance, 7 for very strong importance, and 9 for extreme importance. The even values 2, 4, 6, and 8 reflect intermediate nuances in this scale system. On this basis, the local priority vectors are obtained for each pairwise comparison matrix by using the eigenvector method. These local priority vectors will then form an initial supermatrix where each segment represents the relationship between two clusters. This matrix is transformed into a weighted one which convergences to a limit supermatrix, capturing the direct and indirect influences of each node on every other nodes (H. Lee, Kim, & Park, 2010). As such, the composition of these influence weights generates the ranking scores of the alternatives. These scores can be used as relative weights of alternatives in a utility function, representing an aggregated value score for the retrofit project.

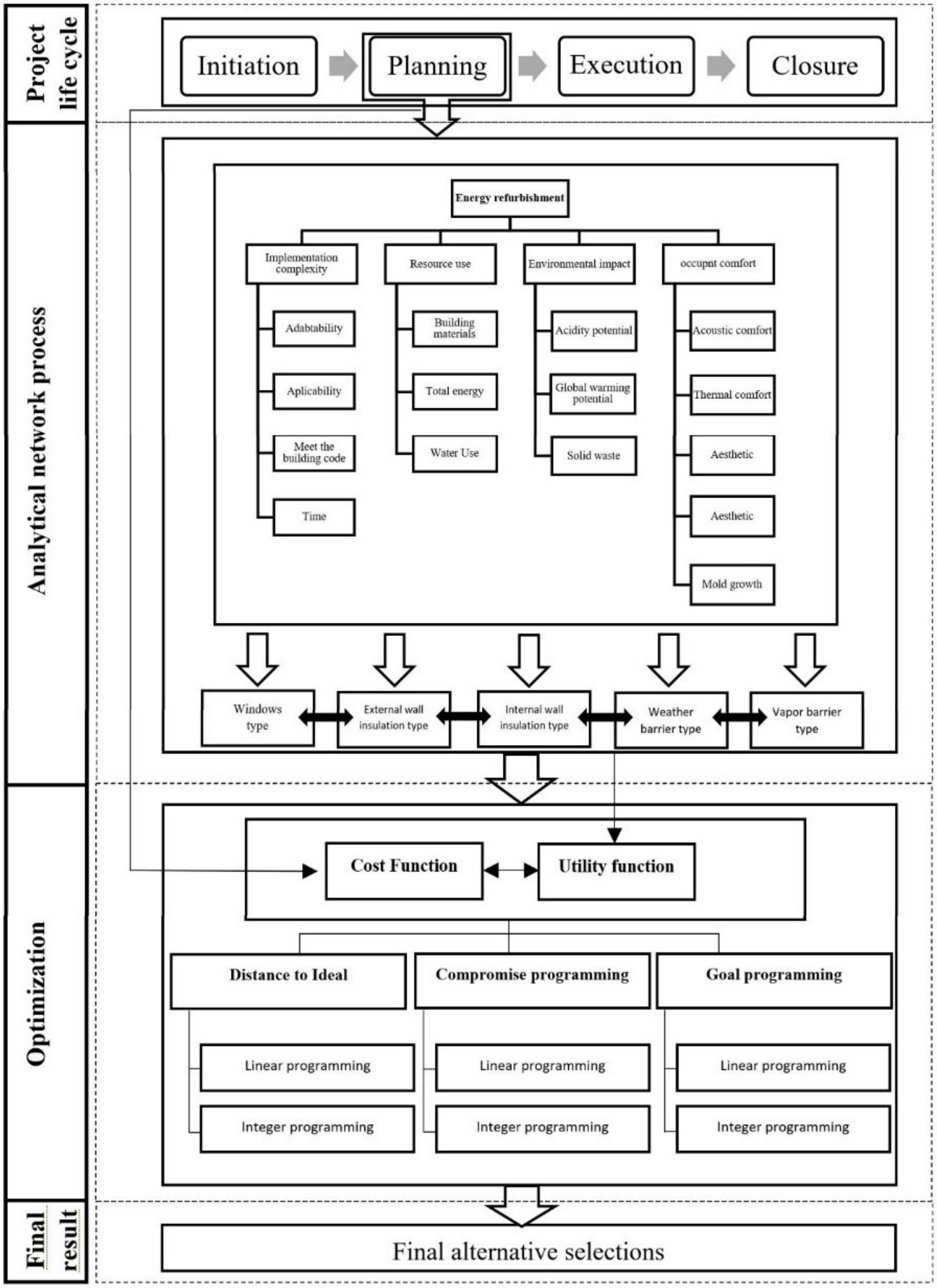

Figure 6, Proposed approach and its phases.

3.1.3 Bi-objective optimization

Optimizing the cost and utility functions associated with the retrofit project, simultaneously, will direct the selection of retrofit measures. This framework is presented in Figure 6. Further, three alternative solution approaches for this bi-objective optimization problem are explored: distance to ideal, goal programming, and compromise programming. The solution approaches consider integer and linear variable scenarios. The former one is associated with the case of having go/no-go decisions for alternative retrofit measures and the latter allows for partial inclusion of these measures in the solution.

In distance to ideal method (Mafakheri, Breton, & Ghoniem, 2011), the cost and utility objectives are combined to form a single objective, on the basis of the distance of each objective function to its best possible value as follows:

$$Minimize\ Z = \left\{\left(\frac{f1\,max - f1(x)}{f1max - f1min}\right) + \left(\frac{f2(x) - f2min}{f2max - f2min}\right)\right\} \quad (1)$$

where f_1 and f_2 correspond to the utility and cost functions, respectively. The term f_1max is the maximum value of utility when optimized individually, and f_2min represents the minimum cost when solely optimized. The terms f_1min and f_2max correspond to worst case values of these functions, respectively, calculated when the opposite objective function is at its best value.

In goal programming approach, one objective is optimized subject to considering the other one as a constraint. In the first scenario, the utility function is placed as the objective and maximized, whereas cost is managed as a constraint with a target such as a budget value or a certain percentage deviation from its minimum value (for example 5%). In the second scenario, cost is considered as the objective and the utility function becomes a constraint subject to a target, such as a certain percentage deviation from its maximum value (for example 5%):

Goal programming: Scenario 1

Maximize utility $f_1(x)$

s.t.

$f_2(x) \leq 1.05\ f_{2\ min}$ (2)

Goal programming: Scenario 2

Minimize cost $f_2(x)$

s.t.

$f_1(x) \geq 0.95\ f_{1max}$ (3)

In compromise programming method, the objective functions are both converted to constraints while optimizing a common compromise objective of λ (Collette & Siarry, 2014).

Maximize λ

s.t.

$f_1(x) \geq \lambda\ f_{1\ max} + (1-\lambda)\ f_{1min}$ (4)

$f_2(x) \leq \lambda\ f_{2min} + (1-\lambda)\ f_{2max}$ (5)

Based on Eqs. (4) and (5), if λ is maximized, then $f_1(x)$ will be closer to its maximum value and $f_2(x)$ will be closer to its minimum. In this sense, the concept of λ, capturing the best compromise, is similar to distance-to-ideal approach without the need to account for the sum of distances." ."(Amiri Fard & Nasiri, 2018)

3.2 MODEL DEVELOPMENT-UNCERTANITY INCPRPORATION

As an extension to the two-step developed model, the three-stage assessment-optimization approach under uncertainty is presented and tested through the case study of a typical building. This section was published by the journal of Energy and Built Environment:

***Amiri Fard, F.**, & Nasiri, F. (2020). A Bi-Objective Optimization Approach for Selection of Passive Energy Alternatives in Retrofit Projects under Cost Uncertainty. Energy and Built Environment, 1(1), 77–86. https://doi.org/10.1016/j.enbenv.2019.11.005*

3.2.1 Background

"In an attempt to alleviate the consequences of climate change, a temperature goal and a global peak of greenhouse gas emissions have been suggested in the recent UN climate change report (Meteorological, Wmo, Nations, & Programme, 2018). One of the main approaches to realistically achieving reduced greenhouse gas emissions and building energy consumption is retrofitting (Ma et al., 2012). In developed countries, the stock of existing buildings is regarded for over 30 percent of greenhouse gas emissions, and consumes more than 40 percent of total final energy. The primary objective of an energy-efficient retrofit project is to reduce energy consumption with maintaining or enhancing the indoor thermal comfort condition, as well as reducing greenhouse gas emissions. By implementation of energy conservation measures, natural resources will be conserved, adverse environmental impacts will be reduced, and operational costs of buildings will also be alleviated. These will, in turn, enhance the living conditions and improve the comfort of the building's occupants (Amiri fard & Nasiri, 2018). A significant share of the total primary energy is spent on buildings (more than 60 percent), which is strongly reliant on the characteristics of the buildings

(Amiri Fard, Sharif, et al., 2019)(Amiri Fard, Jafarpour, & Nasiri, 2019). Improving energy performance of buildings is of particular importance in new construction and existing buildings. There is a growing need to implement energy conservation measures in existing buildings given the fact that globally the replacement rate of existing buildings with new buildings is approximately 1 to 3 percent annually (Fan & Xia, 2018). According to a U.S. research, more than 60 percent of the U.S. housing inventory has over 30 years old and majority of them are energy inefficient (Jafari & Valentin, 2017). In Canada, houses which were built before the 1940s, if retrofitted, have an energy saving potential of about 25 to 30 percent (Ürge-Vorsatz et al., 2007).

Based on the triangle of Energy (Trias Energetica) (Konstantinou, 2014), there are three solutions to achieve energy conservation: 1) reduction of energy demand by adopting passive strategies; 2) application of renewable energy (active strategies); and 3) using fossil energy as efficiently as possible. More than 400 different energy measures can be categorized as passive and active strategies which illustrate the existence of numerous alternatives that can be undertaken. Studies show that nearly 80% of energy efficiency measures are intuitively selected from these alternatives according to the characteristics of the building, the location, environmental factors, etc. (Shao et al., 2014). Therefore, choosing the right combination of refurbishment actions among possible passive measures is a timely issue as well as a real challenge (Senel Solmaz et al., 2018).

This selection problem can be interpreted as a multi-objective optimization problem featured by the existence of multiple and conflicting objectives including qualitative criteria such as occupants' behavior and quantitative criteria such as cost (Asadi, Da Silva, et al., 2012). The purpose of this chapter is to develop an integrated assessment-optimization approach comprised of two stages of multiple-criteria assessment and multi-objective optimization that can direct the retrofitting efforts in buildings. The aim is to assist in prioritization and identification of the best set of passive measures in retrofit projects. The authors emphasize on the application of passive measures to reduce energy demand. Passive technologies are the ones that contribute to reducing energy losses through the building envelop or to increasing the use of natural heating, cooling and lighting. In this definition, other alternative measures such as renewable energy resources, as active measure, are excluded. In addition, by taking into account the uncertainties in cost estimations (materials, labor, installation, delivery etc.), the proposed multi-objective model is formulated using a fuzzy programming approach (Amiri Fard & Nasiri, 2020)."

"The analytic network process (ANP) is reviewed as a multiple criteria decision-making method capable of incorporating the interdependencies among decision criteria and of arriving at an overall assessment (relative scores) for alternative retrofit measures. Simultaneously, fuzzy theory is explored to incorporate uncertainties using alternative fuzzy programming methods. Then, the scores resulted from the assessment phase, as well as uncertainty formulations, will be fed into a multi-objective optimization model. The assessment results are incorporated into a utility objective function to be maximized alongside the latter results which form a cost objective function that is minimized. Three different solution scenarios are explored and compared. The applicability of the proposed assessment-optimization approach is then illustrated through a case study of a typical building (Amiri Fard & Nasiri, 2020)"

3.2.2 Assessment-optimization approach under uncertainty

"The literature review identified several criteria that reflect the non-monetary qualitative values associated with retrofit measures as presented in Figure 7. Each of these criteria can be further broken down into several sub criteria. Reflecting on the multiplicity of these criteria and the gaps identified in the literature review, a three-step approach is proposed for investigation of passive energy technologies for adoption in retrofit projects. Firstly, an analytic network process (ANP) is utilized to calculate the relative weights of alternative retrofit measures according to a set of identified criteria from the literature, namely environmental, occupancy, resource (energy) efficiency, and implementation feasibility. The ANP is an extension of the AHP approach with consideration of interdependencies among decision criteria (Zhao et al., 2009).

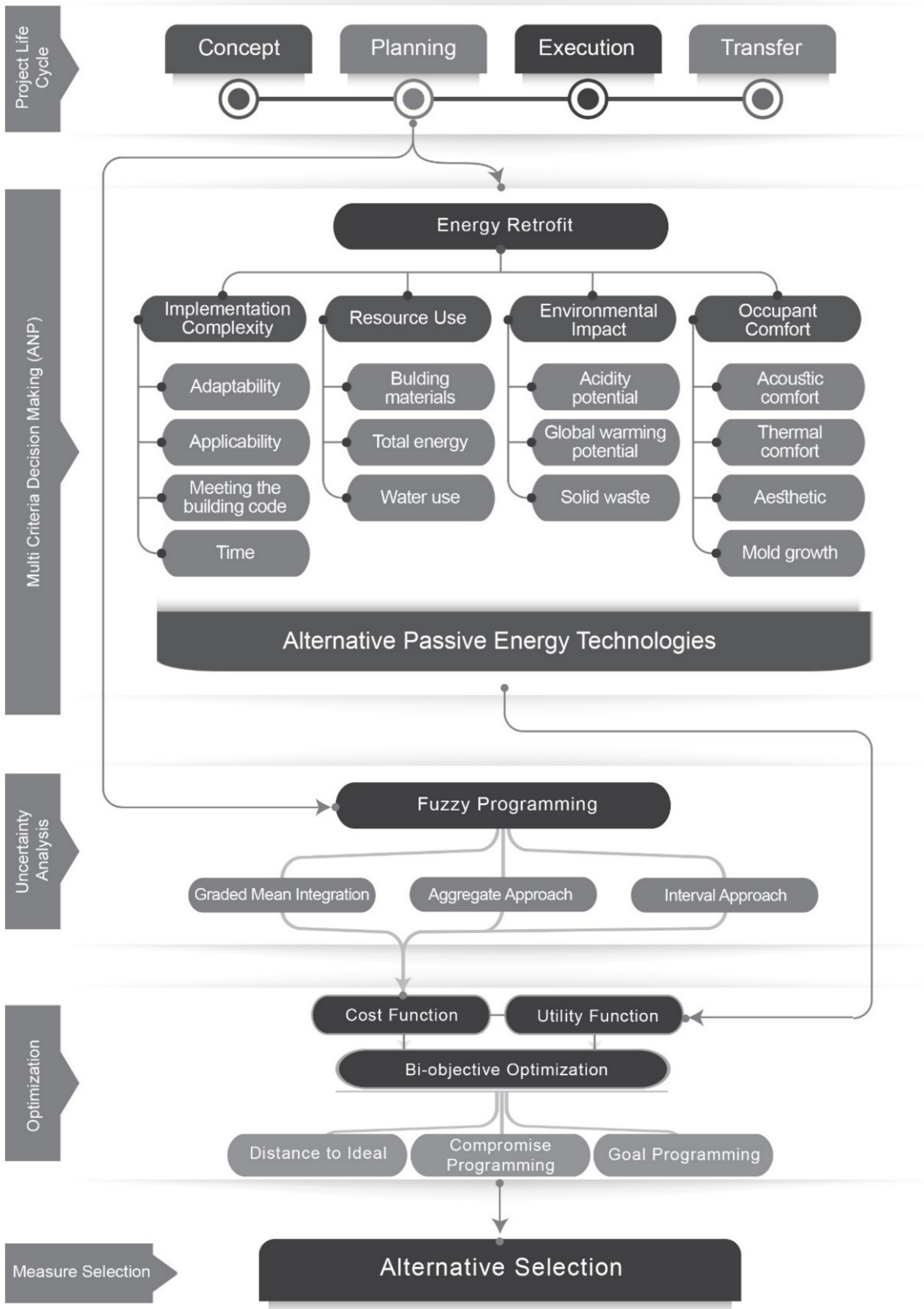

Figure 7, Proposed extended approach and its phases.

These relative weights will be used in formulating a utility function capturing and integrating the non-monetary decision criteria. Secondly, an optimization phase is explored, in which the above formulated "Utility" function is maximized while the "Retrofit Cost" is minimized. In this multi-objective optimization problem, we employ and compare two mathematical programming approaches; linear programming in which allows a partial implementation of retrofit measures, and integer programming which considers 0-1 decision variables representing go/no-go decisions for alternative passive measures. We also explore consideration of different constraints according to retrofit targets, needs and standards. Thirdly, in terms of monetary (costing) considerations, fuzzy theory is explored to incorporate uncertainties in estimation of material costs, forming a cost objective function. The following section is providing a detailed description of the proposed methodology (Amiri Fard & Nasiri, 2020)":

3.2.3 Multi-criteria assessment

"Adopting an analytic hierarchy process (ANP) as the multiple criteria assessment approach, the criteria and sub criteria, called clusters and nodes, form an ANP network. The nodes in a cluster can impact some or all of the nodes of any other cluster. The dependencies are illustrated by arcs with different directions. In some cases, there is interdependency among nodes in the same cluster which is shown by a looped arc. After assigning and finding the relationships among nodes and clusters. The nodes of each cluster are pair-wisely compared with respect to their impacts on the other nodes in the cluster. The same comparison applies for any possible interdependencies. The relative preference weights are calculated using a scale from 1 to 9, where 1 is for equal importance, 3 for moderate importance, 5 for strong importance, 7 for very strong importance, and 9 for extreme importance. In addition, the even values 2, 4, 6, and 8 are used to reflect intermediate nuances in this scale. Then local priority vectors are obtained for each pairwise comparison matrix by employing the eigenvector method. All these local priority vectors are formed an initial supermatrix which is a partitioned matrix where each segment represents a relationship between two clusters. Then, the supermatrix is transformed into the weighted supermatrix which allows convergence to occur in the limit supermatrix. Finally, the weighted supermatrix is transformed into the limit supermatrix by raising it to powers to capture the transmission of influence along all possible paths of the supermatrix. Raising the weighted supermatrix allows convergence of the matrix and the resulting matrix is called the limit supermatrix, which generates limit priorities capturing all of the direct and indirect influences of each nod on every other nod (H. Lee et al., 2010). The composition of these weights generates the ranking scores of alternatives." (Amiri Fard & Nasiri, 2018)

3.2.4 Bi-objective optimization

"We use the above-mentioned scores as relative weights of alternatives to form a utility function, representing an integrated value score associated with each retrofit project. In that sense, an optimization problem can be formulated targeting a maximum utility while minimizing the associated costs. The following bi-objective optimization model can serve this purpose:

$$\text{Maximize } U = u \cdot X \quad (6)$$

$$\text{Minimize } C = c \cdot X \quad (7)$$

Subject to:

$$AX \leq b \quad (8)$$

$$X \geq 0$$

Where $c = (c_1, c_2, c_3 \dots c_n)$ and $u = (u_1, u_2, u_3 \dots u_n)$ are the cost and relative utility vectors associated with the decision alternatives and $X = (x_1, x_2, x_3 \dots x_n)$ is the vector of the decision variables representing the alternatives. Equation 3 represents a series of typical technical constraints that could include capacity constraints, budget constraints, etc(Amiri Fard & Nasiri, 2020)".

3.2.5 Uncertainty formulation/analysis

To incorporate cost estimation uncertainty into the model, "the cost function is formulated as follows:

$$\text{Minimize } C = \tilde{c}\, X \tag{9}$$

Subject to:

$$AX \leq b$$

$$X \geq 0$$

Where $\tilde{c} = (\tilde{c}_1, \tilde{c}_2, \tilde{c}_3 \dots \tilde{c}_n)$ is the fuzzy vector of the objective function cost coefficients.

These fuzzy parameters can be specified through a membership function $\mu_{\tilde{c}_i} = (x, \tilde{c}_i^o, \tilde{c}_i^m, \tilde{c}_i^p)$, $\tilde{c}_i$ are fuzzy triangular numbers. These fuzzy coefficients are denoted by $\tilde{c}_i = (\tilde{c}_i^o, \tilde{c}_i^m, \tilde{c}_i^p)$ where $\tilde{c}_i^m$ is mean and $\tilde{c}_i^p$, $\tilde{c}_i^o$ are pessimistic and optimistic cost estimations respectively. Thus, the cost function can be rewritten as follows:

$$\text{Minimize } C = [(\tilde{c}^m - \tilde{c}^p)X, \tilde{c}^m X, (\tilde{c}^o - \tilde{c}^m)X] \tag{10}$$

Subject to:

$AX \leq b$

$X \geq 0$

The above optimization problem has to deal with three objective functions (depending on which set of estimates is used). Different methods were employed to combine these three objectives and form a single objective optimization, including fuzzy graded mean integration, fuzzy aggregation approach, and fuzzy interval approach. We explore the formulation of uncertainties in the above proposed bi-objective optimization problem using these three approaches, and will compare the outcomes to seek insights on their differences and similarities with respect to formulation of uncertainties and the obtained solutions. A fuzzy graded mean integration approach (Kutlu & Ekmekçioğlu, 2012) defuzzyfies the fuzzy numbers and transforms them into crisp numbers, transforming the multi-objective optimization problem, presented in Eq. 10, into a single objective one. A common approach is to use a Beta (distribution) mean equation as follows:

$$\text{Minimize } C = \frac{[(\tilde{c}^m - \tilde{c}^p) + 4\,\tilde{c}^m + (\tilde{c}^o + \tilde{c}^m)]}{6} X \tag{11}$$

Subject to:

$AX \leq b$

$X \geq 0$

Alternatively, a fuzzy aggregation approach (Sadeghi & Mirshojaeian Hosseini, 2006) can be utilized to integrate the multi objective problems presented in Eq. 10 into one objective as follows:

$$\text{Minimize } C = [\tilde{c}^m + \omega(\tilde{c}^o - \tilde{c}^m) + (1 - \omega)(\tilde{c}^p - \tilde{c}^m)]X \tag{12}$$

Subject to:

$AX \leq b$

$X \geq 0$

Where ω is a weight that corresponds to decision maker's degree of optimism. Higher value of ω reports a decision maker with higher acceptance of optimistic cost estimation. A risk averse decision maker prefers to take pessimistic cost estimation into consideration.

In addition, a fuzzy interval approach (Zimmermann, 2001) can be utilized which assumes a bell-shape fuzzy distribution for the cost parameters. As such, for each membership function, two fuzzy coefficients exist, as lower and upper estimates, on two sides of the mean value. In that sense, three optimization objectives can be identified, the mean $\tilde{c}^m$.X, right spread ($\tilde{c}^p$-$\tilde{c}^m$).X (that will be minimized) and left spread ($\tilde{c}^m - \tilde{c}^o$).X (that will be maximized):

$$\text{Min } C_1 = \tilde{c}^m X \tag{13}$$

$$\text{Min } C_2 = (\tilde{c}^p - \tilde{c}^m)X \tag{14}$$

$$\text{Max } C_3 = (\tilde{c}^m - \tilde{c}^o)X \tag{15}$$

The fuzzy interval approach not only guarantees the optimization based on mean, optimistic, and pessimistic estimates, it accounts for the distribution of these estimations and the variations among them. In this case, we have to deal with a multiple objective optimization problem. In this sense, three alternative multi-objective optimization methods are explored to the problem represented by Eqs. 13-15; "distance to ideal", "goal programming" and "compromise programming". The solution approaches consider integer and linear variable scenarios. The former one is associated with the case of having go/no-go decisions for alternative retrofit measures and the latter allows for partial inclusion of these measures in the solution. In distance to ideal method (Mafakheri et al., 2011), the cost and utility objectives are integrated to form one single objective, incorporating the distance of each objective function to its best possible value. To identify best cost value, the model is optimized only with a cost minimization objective function. To calculate the best value for the utility function, we optimize the model only with a utility maximization objective function. The following equation can then demonstrate the concept of integration, in which the sum of distances to ideal solutions is minimized as a single objective function:

$$Minimize\ Z = \left\{ \left(\frac{f1\,max - f1(x)}{f1max - f1min} \right) + \left(\frac{f2(x) - f2min}{f2max - f2min} \right) \right\} \quad (16)$$

In goal programming approach, one of the objectives is placed as the main objective, and the second objective is transformed to a constraint by considering a target value for it. In doing so, in the first scenario, the utility function is placed as the main objective which has to be maximized and cost would be added as a constraint with a target that captures a certain percentage deviation (v) from its minimum value:

Maximize utility $f_1(x)$

Subject to:

$$f_2\,(x) \leq (1+v)\ f_{2\,min} \quad (17)$$

In the second scenario, cost could be considered as the principal objective and the utility function is added to the constraints with a target that captures a certain percentage deviation (y) from its maximum value:

Minimize cost $f_2(x)$

Subject to:

$$f_1(x) \geq (1-y)\, f_{1max} \tag{18}$$

In scenario 1, when we model uncertainty using the fuzzy interval approach, the main objective is maximizing the utility function whereas cost is managed as a constraint with a certain percentage deviation from its minimum value (v). In this situation, due to the existence of three cost functions, it is needed to identify a balance solution between feasibility degree of constraint and satisfaction degree of the objective function which allows a decision maker to decide a compromise solution. The degree of feasibility can be calculated as follows:

$$Degree\ of\ Fesibility = \begin{cases} 1 & b \geq C_p \\ 1 - \frac{(Cp-b)^2}{(C_p-C_m)*(C_p-C_o)} & C_m \leq b \leq C_p \\ \frac{b-C_o}{C_m-C_o} & C_o \leq b \leq C_m \\ 0 & b \leq C_o \end{cases} \tag{19}$$

Where $b = (1+v)\, f_{2\,min}$

Using a compromise programming approach, the multi-objective problem will be aggregated into a single objective one considering a set of compromise constraints (Collette & Siarry, 2014). In this sense, both objectives are rewritten by using a common weight of λ and added to the set of existing constraints:

Maximize λ

Subject to:

$$f_1(x) \geq \lambda\, f_{1\,max} + (1-\lambda)\, f_{1min} \quad (20)$$

$$f_2(x) \leq \lambda\, f_{2min} + (1-\lambda)\, f_{2max} \quad (21)$$

Based on Eq. (20) and (21), if λ as the single objective function is maximized then $f_1(x)$ will be closer to its maximum value and $f_2(x)$ will be closer to its minimum (Charles ReVelle, 1997). In this sense, the concept of λ, capturing the best compromise, is very similar to distance to ideal approach without the need to account for the sum of distances (Amiri Fard & Nasiri, 2020).

3.2.6 Summary

Due to synergy effects or cross effects of energy conservation measures employed in building retrofit projects, an appropriate selection of them plays a vital role in improving the energy saving potentials of buildings. The proposed model aims at taking into account both qualitative and quantitative decision criteria as well as various types of constraints and uncertainties to provide a comprehensive decision aid for prioritization/selection of passive energy conservation measures in retrofit projects. A novel aspect of the proposed approach rests in development of a utility function, representing multiple non-monetary (qualitative) assessment criteria. In addition, a comparative analysis of various combinations of uncertainty formulations and bi-objective optimization solution approaches were explored. The similarity of the outcomes from every combination scenario shows a convergence towards the selected set of measures representing a robust approach in identifying the best tradeoff between utility and cost objectives.

There are several avenues for future research. A combined assessment of active and passive measure can be conducted (Nasiri et al., 2016). In doing so, a life-cycle cost approach needs to be taken into consideration accounting for initial (capital) costs as well as expected maintenance/operational expenditures. In addition, the proposed approach was applied to a case study which was rather a generic one. In a real-world case, the model shall be modified to some extent including adoption of higher variations in values of uncertain parameters. Based on the level of available information, application of simulation tools and sensitivity analysis approach can be explored to a wide range of future replacement and maintenance scenarios(Amiri Fard & Nasiri, 2020)."

Chapter 4 : CASE STUDY

4.1 CASE STUDY I AND RESULTS

"An illustrative case study of a three-story residential building is considered with a dimension of 8 m by 10 m and a height of 3 m. Thus, the total floor area for each level is 80 m^2 and the total wall area and window area of the building are 204 and 12 m^2, respectively, representing 15% of the floor area.

According to Fig. 6, an ANP structure is considered to consist of retrofit complexity, resource use, environment impact, and occupant comfort as the main decision criteria, clustered into 14 sub-criteria. Five alternative passive energy measures are considered: window improvement, external wall insulation, internal wall insulation, vapor barrier, and weather barrier. A questionnaire survey has been conducted among a group of local energy experts and facility users, with 16 respondents, posing a consistency ratio of less than 0.08. These weights obtained from ANP can be interpreted as the relative utilities (benefits) associated with alternatives forming a utility function. Assuming that there are a alternative types of windows windows (a=1, 2,…,A), "b" alternative types of external wall insulation (b=1, 2,…,B), "c" alternative types of internal wall insulation (c=1, 2,…,C), "d" alternative measure types of vapor barrier (d=1, 2,…,D)and "e" alternative measure types of weather barrier (e=1, 2,…,E), the bi-objective optimization model is written as follows:

$$\text{Maximize}U=\sum_{a=1}^{A} U_a^{WIN}\, x_a^{WIN} + \sum_{b=1}^{B} U_b^{EWALL}\, x_b^{EWALL} + \sum_{c=1}^{C} U_c^{IWALL}\, x_c^{IWALL} + \sum_{d=1}^{D} U_d^{VB}\, x_d^{VB} + \sum_{e=1}^{E} U_e^{WB}\, x_e^{WB} \quad (22)$$

$$Minimize C = A_{WIN} \sum_{a=1}^{A} C_a^{WIN}\, x_a^{WIN} + A_{EWALL} \sum_{b=1}^{B} C_b^{EWALL}\, x_b^{EWALL} + A_{IWALL} \sum_{c=1}^{C} C_c^{IWALL}\, x_c^{IWALL} + A_{VB} \sum_{d=1}^{D} C_d^{VB}\, x_d^{VB} + A_{WB} \sum_{e=1}^{E} C_e^{WB}\, x_e^{WB} \quad (23)$$

To diversify the choice of retrofit measures, it can be assumed that at least one retrofit measure is selected from each category. On that basis, Eq. (24) presents the set of constraints that govern this model

$$\sum_{a=0}^{A} x_a^{WIN}=1,\ \sum_{b=0}^{B} x_b^{EWALL}=1,\ \sum_{c=0}^{C} x_c^{IWALL}=1,\ \sum_{d=0}^{D} x_d^{VB}=1,\ \sum_{e=0}^{E} x_e^{WB}=1,\ x_b^{EWALL}+x_c^{IWALL}=1 \quad (24)$$

where U_a^{WIN}= utility weight of window type a; U_b^{EWALL}= utility weight of external insulation material type b; U_c^{IWALL}=utility weight of internal insulation material type c; U_d^{VB}= utility weight of vapor barrier type d; U_e^{WB}= utility weight of weather barrier type e; x_a^{WIN} = windows type decision variable; x_b^{EWALL} = external insulation material type decision variable; x_c^{IWALL} = internal insulation material type decision variable; A_{WIN} = window area (m^2); C_a^{WIN} = initial cost of window type a (\$/m^2); A_{EWALL} =exterior wall surface to be insulated (m^2); C_b^{EWALL}=initial cost of exterior wall insulation material type b (\$/m^2); A_{IWALL}=interior wall surface to be insulated (m^2); C_c^{IWALL}= initial cost of interior wall insulation material type c (\$/m^2); A_{AIRT}= vapor barrier surface area (m^2); C_d^{VB}= initial cost of vapor barrier material type d (\$/m^2); A_{WB}= weather barrier surface area (m^2) and C_e^{WB} =initial cost t of weather barrier type e (\$/m^2). Tables 6 to 10 illustrate the characteristics of these alternative retrofit measures and their subcategories derived from the 2016 RS Means building construction cost data (Data Reed Construction 2016). The cost for each energy measure Includes, capital cost, labour cost, installation and delivery. The relative weights of alternative passive measures are calculated through the ANP, as presented in Table 11. Considering alternative options in each category of passive measures, there are a minimum of 1,500 combinations of passive measures for implementation in the case study building. This multiplicity of choices clearly reflects the importance of integrating the non-monetary qualitative criteria, to depart from an optimization problem with several objectives and to arrive at a bi-objective one using ANP. Table 12 demonstrates the optimization results when objective functions are optimized individually (i.e., Pareto solutions). These objectives are conflicting. If the utility function reaches its optimal value, the cost is not optimal, and vice versa. Turning to a bi-objective optimization problem, with an integer programming approach, the values of x_a^{WIN} , x_b^{EWALL} , x_c^{IWALL} , x_d^{VB} , x_e^{WB} is 1 if alternative type is selected, otherwise it is 0. With a linear programming approach, the value of these variables can be a number between 0 and 1.

Table 6, Characteristics of window types

N	Window type	Cost($/m^2)
1	Vinyl double hung window- one insulated glass	330
2	Vinyl double hung window- double insulated glass	460
3	Vinyl casement window- one insulated glass	396
4	Vinyl casement window- one insulated glass	565

Table 7, Characteristics of external wall insulation materials

N	External Insulation type	Thickness(m)	Thermal resistance	Cost($/m^2)
1	Rigid insulation-Expanded polystyrene	0.076	R11.49	16.90
2	Rigid insulation-Extruded polystyrene	0.05	R10	20.88
3	Rigid insulation-Extruded polystyrene	0.076	R15	26.08
4	Rigid insulation- Iso cyanurate	0.05	R6	17.76
5	Semi rigid insulation- Stone wool	0.089	R15	10.87

Table 8, Characteristics of internal wall insulation materials

N	Internal Insulation type	Thickness	Thermal resistance	Cost($/m^2)
1	Semi-rigid insulation-Un faced Fiberglass	0.089	R13	9.04
2		0.089	R15	10.76
3	Rigid insulation-un faced Fiberglass	0.05	R8.3	11.52
4		0.076	R12.4	14.31
5	Rigid insulation-Perlite	0.05	R5.55	16.90

Table 9, Characteristics of vapor barrier types

N	Vapor barrier type	Thickness (mm)	Cost($/m^2)
1	Aluminum foil	0.025	1.23
2	Polyethylene	0.051	0.85
3	Polyvinyl chloride	0.051	1.02
4	Polyester	0.025	1.47
5	Cellulose acetate	0.25	2.12

Table 10, Characteristics of weather barrier types

N	Weather Barrier type	Cost($/m^2)
1	House wrap spunbonded polypropylene	3.34
2	Building wrap spunbonded polyethylene	3.12
3	Asphalt felt paper	2.26

Table 11, Utility weights of alternative passive measures and their subtypes obtained from ANP

Alternatives	N=1	N=2	N=3	N=4	N=5
Windows	0.318717	0.176531	0.331851	0.235978	-
External wall insulation	0.290399	0.146591	0.209394	0.253376	0.261584
Internal wall insulation	0.286399	0.401457	0.303417	0.324157	0.377231
Vapor barrier	0.043380	0.236147	0.103121	0.186489	0.361185
Weather barrier	0.061105	0.039274	0.052217	-	-

Table 12, Pareto optimal solutions

Solution No.	Type of solution	Utility	Cost ($)	WIT	EWALL	IWALL	VB	WB
1	Max $f_1(x)$	0.713601	$6811.92	1	1	0	2	3
2	Min $f_2(x)$	0.709601	$6438.60	1	0	1	2	3

Table 13, Optimal solutions for different bi-objective formulations and solution approaches

Optimization method	Liner/integer	Z	λ	Utility	cost	Windows improvement Type	External wall insulation	Internal wall insulation	Vapor barrier type	Water barrier type
Distance to ideal	Linear Pr.	0.999745	-	0.70960	$6438.60	1	0	1	2	3
	Integer Pr.	0.999745	-	0.70960	$6438.60	1	0	1	2	3
Compromise programming	Linear Pr.	-	0.500062	0.713601	$6625.237	1	5 (0.49993 %)	1 (0.50006%)	2	3
	Integer Pr.	-	0.000000	0.713601	$6811.92	1	1	0	2	3
Goal programming: Scenario 1	Linear Pr.	-	-	0.713050	$6760.53	1	5 (0.862343%)	1 (0.138657 %)	2	3
	Integer Pr.	-	-	0.709601	$6438.60	1	0	1	2	3
Goal programming: Scenario 2	Linear Pr.	-	-	0.70960	$6438.60	1	0	1	2	3
	Integer Pr.	-	-	0.70960	$6438.60	1	0	1	2	3

Table 14, Deviations from best single objective solutions

Optimization method	Liner/integer	Percent change for Utility	Percent change for cost
Distance to ideal	Linear Pr.	-0.56%	0
	Integer Pr.	-0.56%	0
Compromise programming	Linear Pr.	0	+2.89%
	Integer Pr.	0	+5.79%
Goal programming: Scenario 1	Linear Pr.	-0.07%	+4.99%
	Integer Pr.	-0.56%	0
Goal programming: Scenario 2	Linear Pr.	-0.56%	0
	Integer Pr.	-0.56%	0

A summary of bi-objective optimization solutions are shown in Table 13. The variable values resulted from distance to ideal method in both linear and integer cases, goal programming#2 for both linear and integer cases, and goal programming#1 for integer programming case are the same. In addition, the optimal selections for compromise programming and goal programming#1 are the same but the assigned shares for them are different. The minimum costs among these cases will be $6625.23 and $6760.53, respectively. Thus, nearly half of internal wall and half of external wall are insulated. In compromise method, in case of integer programming, the value of cost objective is slightly higher than that of linear programming (due to restricting the values to binary). It is also observed that most of the solutions represent the same selection of measures which confirms the robustness of the outcomes. Selecting window Type 1, internal wall insulation Type 1, vapor barrier Type 2, and weather barrier Type 3 were recommended in most of cases. Table 14 indicates the deviations from maximum utility and minimum cost. In all cases, a deviation of less than 8% is guaranteed. In five out of eight cases, the cost has reached to its minimum value, whereas the utility function deviates less than 1% from its maximum value" (Amiri Fard & Nasiri, 2018).

4.2 CASE STUDY II AND RESULTS

"To investigate the applicability of the proposed model, we consider a generic case study. The case study is a three-story residential building, situated in Montreal, Canada which is a cold climate region with minimal retrofit since its construction, the size is 8 m by 10 m and its height is 3 m floor by floor, the total floor area for each level is 80 m^2 and the total wall area and window area of the building is 204 m^2 and 12 m^2, respectively, representing 15% of the floor area.

According to the framework presented in Figure 7, a list of possible energy efficiency measures is identified by the retrofit designer based on stakeholders' views about what they expect from a retrofit project. In the second step, ANP as a multiple criteria decision-making tool is used (see Figure 7) with implementation complexity, resource use, environmental impact and occupant comfort as main decision criteria clustered into 14 sub-criteria, assessing conservation energy technologies (ea. window improvement, external wall insulation, internal wall insulation, vapor barrier, and weather barrier). "A questionnaire survey has been conducted among a group of local energy efficiency experts and facility users, with 16 respondents, posing a consistency ratio of less than 0.08. These weights obtained from ANP can be interpreted as the relative utilities (benefits) associated with alternatives forming a utility function. Assuming that there are 'a' alternative types of windows (a = 1, 2,…, A), 'b' alternative types of external wall insulation (b= 1, 2,…,B), 'c' alternative types of internal wall insulation (c=1, 2,…, C), 'd' alternative types of vapor barrier (d=1,2,…, D), and 'e' alternative types of weather barrier (e= 1, 2,…, E), the bi-objective optimization model is written as follows"(Amiri Fard & Nasiri, 2018):

"Maximize

$$U=\sum_{a=1}^{A} U_a^{WIN}\, x_a^{WIN} + \sum_{b=1}^{B} U_b^{EWALL}\, x_b^{EWALL} + \sum_{c=1}^{C} U_c^{IWALL}\, x_c^{IWALL} + \sum_{d=1}^{D} U_d^{VB}\, x_d^{VB} + \sum_{e=1}^{E} U_e^{WB}\, x_e^{WB} \quad (25)$$

Minimize

$$C=A_{WIN} \sum_{a=0}^{A} C_a^{WIN}\, x_a^{WIN} + A_{EWALL} \sum_{b=0}^{B} C_b^{EWALL}\, x_b^{EWALL} + A_{IWALL} \sum_{c=0}^{C} C_c^{IWALL}\, x_c^{IWALL} + A_{VB} \sum_{d=0}^{D} C_d^{VB}\, x_d^{VB} + A_{WB} \sum_{e=0}^{E} C_e^{WB}\, x_e^{WB} \quad (26)$$

To diversify the choice of retrofitting measures, it is assumed that for one retrofit measure from each category could be selected. Equation 27 presents the set of constraints that address this assumption.

Subject to:

$$\sum_{a=0}^{A} \boldsymbol{x_a^{WIN}}=1;\ \sum_{b=0}^{B} \boldsymbol{x_b^{EWALL}} = 1;\ \sum_{c=0}^{C} \boldsymbol{x_c^{IWALL}}=1;\ \sum_{d=0}^{D} \boldsymbol{x_d^{VB}}=1;\ \sum_{e=0}^{E} \boldsymbol{x_e^{WB}}=1;$$

$$\boldsymbol{x_b^{EWALL} + x_c^{IWALL}=1} \quad (27)$$

Where A_{WIN}: Windows area (m^2), C_a^{WIN}, A_{EWALL} exterior wall surface to be insulated (m^2), A_{IWALL}: Interior wall surface to be insulated (m^2), A_{AIRT}: Vapor barrier surface area (m^2), A_{WB}: Weather barrier surface area where U_a^{WIN} = utility weight of window type a; U_b^{EWALL} = utility weight of external insulation material type b; U_c^{IWALL} = utility weight of internal insulation material type c; U_d^{VB}= utility weight of vapor barrier type d; U_e^{WB}= utility weight of weather barrier type e; x_a^{WIN}= window type decision variable; x_b^{EWALL}= external insulation material type decision variable; x_c^{IWALL}= internal insulation material type decision variable; x_d^{VB}= vapor barrier type decision variable; x_e^{WB}= weather barrier type decision variable; $\mathrm{C_a^{WIN}}$ = initial cost of window type a ($/m^2); $\mathrm{C_b^{EWALL}}$= initial cost of exterior wall insulation material type b ($/m^2); $\mathrm{C_c^{IWALL}}$ = initial cost of interior wall insulation material type c ($/m^2); $\mathrm{C_d^{VB}}$= initial cost of vapor barrier of material type d ($/m^2); and $\mathrm{C_e^{WB}}$= cost of weather barrier type e ($/m^2).

Tables 15 illustrates the characteristics of these alternative retrofit measures and their subcategories alongside possible optimistic and pessimistic costs for each measure where C_o, C_m, C_p are the most optimistic, the most possible and the most pessimistic values. The mean price has been derived from the 2016 RS Means building construction cost data which includes material and labour, installation and delivery for each energy measure (Data Reed Construction 2016). The relative weights of alternative passive measures are calculated through the ANP, as presented in Table 16. Considering alternative options in each category of passive measures, there is a minimum of 1,400 combinations of passive measures for implementation in the case study building. This multiplicity of choices clearly reflects the importance of integrating the non-monetary qualitative criteria, to depart from a multi-objective problem with several objectives and to arrive at one objective using ANP. Table 17 demonstrates the optimization results with respect to different fuzzy methods employed when objective functions are optimized individually (i.e., Pareto solutions). These objectives are conflicting. If the utility function reaches its optimal value, the cost is not optimal, and vice versa.

A summary of multi-objective solutions regarding different fuzzy set approaches and the associated values of selected variables are shown in the Tables 18 to 20. We have provided a comparative analysis of various combinations of uncertainty formulations and bi-objective optimization solution approaches. The similarity of the outcomes from every combination scenario shows a convergence towards the selected set of measures representing a robust approach in identifying the best tradeoff between utility and cost objectives. In graded mean integration approach, the variable values resulted from distance to ideal method in both linear and integer cases, and goal programming#1 for integer cases are the same. For the rest of optimization scenarios, there are similar decisions for at least in three of five measures. For window type, measure type 2 was selected in most of the cases as the higher cost savings outweigh the utility compromises. However, in goal programming#2 for integer case, and compromise programming linear and integer cases, window type 1 was selected to improve the utility. In all cases, vapor barrier type 5 was selected. This reflects the extent of the utility gains resulted from this measure compared to its elevated cost. External wall insulation as an alternative was not selected in this case project and in any solution. The weights were given to the internal wall insulation types by energy experts for the utility function were considerably higher than external insulation due to the fact that the case study building is situated in a cold climate region.

The goal programming scenario 2 demonstrates the highest minimum cost due to the restrictive constraint on utility with an allowance of 10 percentage deviation from the maximum utility value. It is also observed that all of the solutions almost represent the same selection of measures which confirms the robustness of the outcomes with respect to the choice of formulation and solution approach. Selecting window type 2 or 3, internal wall insulation type 2 or 4, vapor barrier type 5 and weather barrier type 1 or 2, were recommended which can be explained by the tradeoffs among their prices and utility values.

In Table 19, the results of optimization methods have been reported for the case of aggregate approach. Changing the weighting factor from 0.2 to 0.8 corresponds to the underlying investment conditions becoming more optimistic and a reduction in the total investment of retrofitting in all methods. It is notable that there is less sensitivity to the extent of uncertainty in the distance to ideal method with the decision makers' degree of optimism having no impact on technology selection. It is also observed that the options that fare best under a pessimistic costing assumption are the ones which provide the least distance to ideal. The aggregate approach leads to a series of similar results due to minimizing an aggregate cost function and maximizing the utility function. However, in interval approach, the solutions (as presented in table 20) for the choice of technology will change as the decisions are now dictated by optimizing three cost functions versus a utility function. This has led to a greater comprise from a costing perspective and even opting for lower utility in cases where there is no rigid constraint on the utility values.

Table 15, Characteristics and data for alternative passive energy technologies

Measure Type	N	Description	Thickness	Thermal resistance	Optimistic Cost($/m^2)	Cost($/m^2)	Pessimistic Cost($/m^2)
Window type	1	Vinyl double hung window- double insulated glass	-	-	500.00	550.00	585.00
	2	Vinyl double hung window- one insulated glass	-	-	215.00	245.00	282.00
	3	Vinyl casement window- double insulated glass	-	-	520.00	580.00	618.00
	4	Vinyl casement window- one insulated glass	-	-	412.00	460.00	541.00
External Insulation Type	1	Rigid insulation-Expanded polystyrene	0.076	R11.49	16.00	16.90	18.31
	2	Rigid insulation-Extruded polystyrene	0.05	R10	18.10	20.88	24.00
	3	Rigid insulation-Extruded polystyrene	0.076	R15	24.70	26.08	26.90
	4	Rigid insulation- Isocyanurate	0.05	R6	16.66	17.76	19.77
	5	Semi rigid insulation- Stone wool	0.089	R15	10.30	10.87	11.55
Internal Insulation Type	1	Semi-rigid insulation-Un faced Fiberglass	0.089	R13	13.31	14.31	15.80
	2	Semi-rigid insulation-Un faced Fiberglass	0.089	R15	15.90	17.20	19.00
	3	Rigid insulation-un faced Fiberglass	0.05	R8.3	10.40	11.52	12.95
	4	Rigid insulation-un faced Fiberglass	0.076	R12.4	8.00	9.04	9.90
	5	Rigid insulation-Perlite	0.05	R5.55	16.30	16.90	18.00
Vapor Barrier Type	1	Aluminum foil	0.025	-	1.23	1.30	1.10
	2	Polyethylene	0.051	-	0.85	1.00	0.77
	3	Polyvinyl chloride	0.051	-	1.02	1.15	0.98
	4	Polyester	0.025	-	1.47	1.60	1.25
	5	Cellulose acetate	0.25	-	2.12	2.18	1.95
Weather Barrier Type	1	House wrap spunbonded polypropylene	-	-	3.10	3.34	3.50
	2	Building wrap spunbonded polyethylene	-	-	0.77	0.90	1.05
	3	Asphalt felt paper	-	-	2.20	2.26	2.55

Table 16, Utility weights obtained from ANP

Alternatives	N=1	N=2	N=3	N=4	N=5
Windows	0.063743	0.035306	0.06637	0.047196	-
External wall insulation	0.058080	0.029318	0.041879	0.050675	0.052317
Internal wall insulation	0.057280	0.080291	0.060683	0.064831	0.075446
Vapor barrier	0.008676	0.047229	0.020624	0.037298	0.072237
Weather barrier	0.012221	0.007855	0.010443	-	-

Table 17, Pareto optimal solutions

Fuzzy programming		Type of solution	Utility	Cost ($)	WIT	EWALL	IWALL	VB	WB
Graded mean integration		Max $f_1(x)$	0.231119	$11259.82	3	0	2	5	1
		Min $f_2(x)$	0.155222	$4925.22	2	0	4	2	2
Aggregate approach	ω=0.2	Max $f_1(x)$	0.231119	$12063.34	3	0	2	5	1
		Min $f_2(x)$	0.155222	$5562.67	2	0	4	2	2
	ω=0.4	Max $f_1(x)$	0.231119	$11675.95	3	0	2	5	1
		Min $f_2(x)$	0.155222	$5303.54	2	0	4	2	2
	ω=0.6	Max $f_1(x)$	0.231119	$11288.57	3	0	2	5	1
		Min $f_2(x)$	0.155222	$5044.42	2	0	4	2	2
	ω=0.8	Max $f_1(x)$	0.231119	$10901.18	3	0	2	5	1
		Min $f_2(x)$	0.155222	$4785.29	2	0	4	2	2
Interval approach		**Type of solution**	**Best**	**Worst**	**WIT**	**EWALL**	**IWALL**	**VB**	**WB**
		Max $f_1(x)$	0.231119	0.155221	3	0	2	5	1
		Min $f_2(x)$	$5141.16	$13261.56	2	0	4	2	2
		Min $f_3(x)$	$638.28	$868.08	1	0	4	5	2
		Min $f_4(x)$	$615	$1346.28	3	3	0	4	1

Table 18, Optimal solutions for different multi-objective formulation with respect to Graded mean integration approach

Optimization method	Variables	Z	λ	Utility	Cost	Window type	External wall insulation	Internal wall insulation	Vapor barrier type	Water barrier type
Distance to ideal	Linear	0.711408	-	0.180229	$5184.30	2	0	4	5	2
	Integer	0.711408	-	0.180229	$5184.30	2	0	4	5	2
Compromise programming	Linear	-	0.604213	0.201204	$7448.18	2 (0.967) 3 (0.033)	0	2	5	1
	Integer	-	0.590713	0.200055	$7301.82	2	0	2	5	1
Goal programming Scenario 1	Linear	-	-	0.182419	$5417.74	2	0	2 (0.14) 4 (0.86)	5	2
	Integer	-	-	0.180229	$5184.30	2	0	4	5	2
Goal programming Scenario 2	Linear	-	-	0.208007	$8315.02	2 (0.74) 3 (0.26)	0	2	5	1
	Integer	-	-	0.208666	$8808.30	1	0	4	5	2

Table 19, Optimal solutions for different multi-objective formulation with respect to aggregate approach

Optimization method	ω	Variables	Z	λ	Utility	Cost	Window type	External wall insulation	Internal wall insulation	Vapor barrier type	Water barrier type
Distance to ideal	0.2	Linear	0.707540	-	0.180229	$5803.39	2	0	4	5	2
		Integer	0.707540	-	0.180229	$5803.39	2	0	4	5	2
	0.4	Linear	0.708285	-	0.180229	$5544.26	2	0	4	5	2
		Integer	0.708285	-	0.180229	$5544.26	2	0	4	5	2
	0.6	Linear	0.709061	-	0.180229	$5285.14	2	0	4	5	2
		Integer	0.709061	-	0.180229	$5285.14	2	0	4	5	2
	0.8	Linear	0.709869	-	0.180229	$5026.01	2	0	4	5	2
		Integer	0.709869	-	0.180229	$5026.01	2	0	4	5	2
Compromise programming	0.2	Linear	-	0.59802	0.200610	$8175.81	1 (0.02) 2 (0.98)	0	2	5	1
		Integer	-	0.590713	0.200055	$8105.74	2	0	2	5	1
	0.4	Linear	-	0.598219	0.200625	$7863.86	1 (0.02) 2 (0.98)	0	2	5	1
		Integer	-	0.590713	0.200055	$7792.75	2	0	2	5	1
	0.6	Linear	-	0.598449	0.201263	$7551.76	2 (0.9811) 3 (0.0189)	0	2	5	1
		Integer	-	0.590713	0.200055	$7479.77	2	0	2	5	1
	0.8	Linear	-	0.598696	0.200661	$7239.62	2 (0.9804) 3 (0.0195)	0	2	5	1
		Integer	-	0.590713	0.200055	$7166.78	2	0	2	5	1
Goal programming Scenario 1	0.2	Linear	-	-	0.183013	$6118.94	2	0	4	5	1 (0.64) 2 (0.36)
		Integer	-	-	0.182818	$6106.54	2	0	4	5	3

	0.4	Linear	-	-	0.182810	$5833.90	2	0	4	5	1 (0.59) 2 (0.41)
		Integer	-	-	0.180229	$5544.26	2	0	4	5	2
	0.6	Linear	-	-	0.182614	$5548.86	2	0	2 (0.15) 4 (0.85)	5	2
		Integer	-	-	0.180229	$5285.14	2	0	4	5	2
	0.8	Linear	-	-	0.182443	$5263.82	2	0	2 (0.14) 4 (0.86)	5	2
		Integer	-	-	0.180229	$5026.01	2	0	4	5	2
Goal programming Scenario 2	0.2	Linear	-	-	0.208007	$9110.41	1 (0.28) 2 (0.72)	0	2	5	1
		Integer	-	-	0.208666	$9396.19	1	0	4	5	2
	0.4	Linear	-	-	0.208007	$8785.34	1 (0.28) 2 (0.72)	0	2	5	1
		Integer	-	-	0.208666	$9093.86	1	0	4	5	2
	0.6	Linear	-	-	0.208007	$8454.78	2 (0.74) 3 (0.26)	0	2	5	1
		Integer	-	-	0.208666	$8791.54	1	0	4	5	2
	0.8	Linear	-	-	0.208007	$8122.75	2 (0.74) 3 (0.26)	0	2	5	1
		Integer	-	-	0.208666	$8489.21	1	0	4	5	2

Table 20, Optimal solutions for different multi-objective formulation with respect to interval approach

Optimization method	Variables	Z	λ	Utility	Cost	Window type	External wall insulation	Internal wall insulation	Vapor barrier type	Water barrier type
Distance to ideal	Linear	1.407117	-	0.213032	$9558.00	1	0	4	5	1
	Integer	1.407117	-	0.213032	$9558.00	1	0	4	5	1
Compromise programming	Linear	-	0.502463	0.193357	$9181.36	2 (0.0438) 3 (0.9562)	0	4	4 (0.4744) 5 (0.5256)	2
	Integer	-	0.473046	0.211293	$9420.24	3	0	4	5	2
Goal programming Scenario 1	Linear	-	-	0.182608	$5655.28	2	0	4	5	2 (0.08) 3 (0.92)
	Integer	-	-	0.180229	$5184.30	2	0	4	5	2
Goal programming Scenario 2	Linear	-	0.496103	0.208007	$9233.01	2 (0.0447) 3 (0.9553)	0	4	4 (0.0543) 5 (0.9457)	2
	Integer	-	0.473046	0.211293	$9420.24	3	0	4	5	2

In summary, in most cases, the bi-optimization approaches do not lead to significant variations over the utility objective function reflecting the small variations among the alternatives when it comes to the utility values. However, the cost variation is more remarkable in approaches that are emphasizing the utility. In compromise programming and the goal programming scenario 2, with rigid constraints on utility values, a small improvement in the utility has led to over 50% increase in the overall costs. In this sense, the choice of the optimization approach in the presence of two objective functions (and estimation uncertainties) for a retrofit project is subject to the extent of variations in expected utilities and costs for the alternative targeted technologies. If the utility values are not varying to a great extent, the distance to ideal and goal programming scenario 1 generate more promising solutions while a larger variation in the utility values can be accommodated using the compromise programming or goal programming scenario 2." (Amiri Fard & Nasiri, 2020)

Chapter 5 : CONCLUSIONS

5.1 SUMMURY

In this thesis, an integrated assessment-optimization framework was presented to direct a decision support for prioritization and selection of building refurbishment measures with energy conservation potentials under cost estimation uncertainty. To tackle the gaps found in the literature, the following steps were taken:

I: Available alternative passive measures, that could be implemented in the building section, (whether new construction or retrofit project) were identified and classified. In doing so, the attention was on overall energy consumption based on energy control principles as relate to functions of heating and cooling control, air transport control, water vapor transport control and natural/solar heating, cooling and lighting control were sorted.

II: An integrated assessment-optimization framework was proposed serving as a decision support for prioritization of building refurbishment measures

III: The above proposed model was extended by incorporation of cost estimation uncertainties to investigate their effects on the optimal decision. A fuzzy mathematical programming method was explored to formulate cost uncertainties. For cost estimation, three different scenarios, optimistic, pessimistic and mean have been considered. Three categories of solution approaches were investigated for the proposed multi-objective optimization model, including graded mean integration, aggregate and interval approach. The uncertainties in investment cost were expressed as fuzzy sets in forming fuzzy (cost) objective functions. The solutions for each scenario had been discussed and analyzed in comparison with initial solutions.

5.2 RESEARCH CONTRIBUTIONS AND HIGHLIGHTS

An exhaustive literature review in the second chapter could provide a robust foundation for future studies in the energy efficiency context. The proposed categorization of passive measures (according to their types of energy control mechanism) could help the building designers/managers to arrive at an informed decision in selecting the best matching technologies with regards to the characteristics of the building envelope and its functions. The proposed categorization of building technologies contains a wide variety of passive measures applicable to buildings. The weights obtained from the analytic network process method were used to formulate a utility function representing the non-monetary qualitative benefits of retrofit projects. The presented framework can assist in building refurbishment decision-makers in dealing with the multiplicity of passive measures and their varied characteristics. Also, it integrated qualitative and quantitative characteristics in the evaluation of such refurbishment projects. The obtained retrofitting solutions are the best trade-off between the utility maximization and cost minimization objectives. It shall be mentioned that these solutions were suboptimal with respect to the utility function and did not necessarily guarantee the lowest energy demand in building. The robustness of these trade-off solutions were investigated by comparing the outcomes of various bi-objective formulations (distance to ideal, goal programming, and compromise programming). Such a trade-off reflects the fact that the decision making on the choice of retrofit measures were bounded by cost, and as such, we had to compromise on utility attributes, such as energy conservation, occupants' preferences, and ease of implementation. The proposed methodology incorporated the effect of uncertainty on the optimal decision by the application of fuzzy theory. Fuzzy linear mathematical programming method that seeks to minimize cost uncertainties was a flexible tool for the energy efficiency measure selection model. For the cost of materials, three different scenarios, optimistic, pessimistic and mean were considered along with three alternative uncertainty formulation methods of fuzzy mathematical programming, graded mean integration, aggregate and interval approach.

The novelty of this model rests in the fact that it takes into account a wide range of qualitative and non-monetary criteria in the assessment step to satisfy all aspects of energy retrofitting. The relative scores obtained from the assessment step is represented as an objective function called "utility" function. The model does not restrict the addition of more criteria to cover more qualitative factors if needed. The proposed utility objective function is integrated into the optimization step along with the cost objective function and forming a bi-objective optimization problem. In doing so, unlike single objective cost minimization models, exhaustive aspects of energy retrofitting are incorporated. Furthermore, by considering a range of decision criteria in the assessment step, unlike a multi-objective optimization approach, the number of objective functions considered in the optimization step is reduced to only two, one to take care of costing dimension and one to represent qualitative aspects. This makes the proposed modeling approach more practical and easier to apply in real projects.

5.2.1 CONTRIBUTIONS: METHODOLOGICAL ASPECTS

- The proposed assessment-optimization approach provided a comprehensive methodology in considering different non-monetary criteria, generating representative weights for them, and incorporating these scored criteria into an optimization objective function called utility function,
- A contingency-based approach was proposed through the use of costing ranges in deriving the cost optimization objective function.

- The model formulation is rather generic with the possibility for the addition of other criteria, variables and constraints,
- A comparative analysis of various combinations of uncertainty formulations and bi-objective optimization solution approaches were explored.
- By using linear programming, partial implementation of a measure could also be directed, and as such, a combination of measures classified under one category of passive measures can be implemented leading to improving the cost efficiency of solutions.

5.2.2 CONTRIBUTIONs: PRACTICAL ASPECTS

- The proposed framework can assist decision-makers in choosing the best combination of measures in the early phase of the building refurbishment
- Using the approach proposed in the assessment phase helps a wide variety of influencing criteria to be considered which has not been feasible in practice before.
- Using the proposed cost contingency planning, an investor can make sure that his investment decision is reflective of uncertainties resulting from cost estimations.
- Identifying partial implementation strategies for the passive measures could result in more practical solutions as a combination of measures, under one category, can be adopted for implementation, leading to cost savings.

5.3 FUTURE WORK AND LIMITATIONS

- In terms of future research, a combined implementation of active and passive measures can be evaluated. However, especially for using renewable energy resources and new technologies, a life-cycle cost approach needs to be taken into consideration. In addition, the proposed approach was applied to a case study which was a generic one. In a real-world case, the model may need to be modified to some extent as follows. More uncertain parameters, and higher degrees of uncertainty, might be involved. The application of simulation tools and the sensitivity analysis approach can be adopted to analyze the future impacts of uncertainties. Application of simulation tools to perform comfort condition predictions for forming the utility function can also serve as a means of creating an automated decision support system reflective to changing conditions in terms of available technologies and costing. Finally, in the MCDM step, more criteria can also be considered to represent case-specific qualitative factors depending on the characteristics of building environment, users, and geography.

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APPENDIX A: QUESTIONNAIRE SURVEY

Dear Participant,

We are conducting an academic research project on application of passive measures in retrofit buildings, five types of passive energy measures including “window”, “External insulation”, “Internal insulation”, “Vapor barrier” and “Weather Barrier” for application in an illustrative building in Montreal, Quebec, Canada.

In this regards, experts’ opinion is needed on evaluating these passive alternative. The purpose of this study is to identify and evaluate preferred passive alternatives which could influence on energy reduction consumption while maintaining and/or enhancing the indoor thermal comfort condition. In the following pages we would like to obtain your opinion as an expert through a survey questionnaire. The information you provide will be of great value for this research, and accordingly, your participation is anticipated and very much appreciated.

We sincerely hope you can assist.

Farhad Amiri Fard
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Montréal, Québec, H3G 1M8
CANADA
Tel: (514) 848 2424 Ext. 7170
Room# 9.412

Information for participant

Key terms:

The case study is a hypothetic three-story residential building which has been assumed, situated in the following address: 800 Rue Lusignan Montréal, QC H3C 1Y9. It has been built in 1925 since its construction with minimal retrofit action, the size of the building is 8 m by 10 m and its height is 3 m floor by floor, the total floor area for each level is 80 m^2 with a concrete structure which the structure is in very good condition. The total wall area and window area of the building is 204 m^2 and 12 m^2, respectively, representing 15% of the floor area. According the client's mandate retrofit designer has selected 5 groups of passive measures as follow:

Passive energy alternatives: five types of passive energy measure are identified with different types and materials comprising:

- For window: Vinyl double hung window with one or double glass,
- For insulation: Rigid or semi Rigid insulation,
- For vapor barrier aluminum foil: Polyethylene, Polyvinyl chloride, Polyester and Cellulose acetate
- For weather barrier: House wrap spunbonded polypropylene, building wrap spunbonded polyethylene, Asphalt felt paper

In the following sheets, we would like to elicit your opinion in order to select amongst the criteria and alternatives. The pair wise comparison scale is used to express the importance of one element over another.

Example:

Given two Options, you can judge their relative importance as shown below example: if you think the option 'Acoustic comfort' is strongly more important than the option 'Aesthetic', then you mark strongly with (*) on the table. Also, if you think the option 'Mold growth" is extremely more important than 'Thermal comfort', then you mark extremely with (*).

	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort					*													**Aesthetic**

Mold growth	*																	**Thermal comfort**

With respect to **choose an exterior wall insulation**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																		**Aesthetic**
Acoustic comfort																		**Air quality**
Acoustic comfort																		**Health Aspect**
Acoustic comfort																		**Mold growth**
Acoustic comfort																		**Thermal comfort**
Aesthetic																		**Air quality**
Aesthetic																		**Health Aspect**
Aesthetic																		**Mold growth**
Aesthetic																		**Thermal comfort**
Air quality																		**Health Aspect**
Air quality																		**Mold growth**
Air quality																		**Thermal comfort**
Health Aspect																		**Mold growth**
Health Aspect																		**Thermal comfort**

Mold growth																			**Thermal comfort**

With respect to **choose an interior wall insulation**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**

With respect to **choose an water vapor barrier**

	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**

With respect to **choose a weather barrier**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**

With respect to **choose a window**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**

With respect to **choose an exterior wall insulation**

	Extremely	Very very strong	Very strong	Strong plus	Strong	Moderate plus	Moderate	Weak	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	strong	Very strong	Very very strong	Extremely	
adaptability																			**applicability**
adaptability																			**meet the building**
adaptability																			**time**
applicability																			**meet the building**
applicability																			**time**
meet the building																			**time**

With respect to **choose an interior wall insulation**

	Extremely	Very very strong	Very strong	Strong plus	Strong	Moderate plus	Moderate	Weak	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	strong	Very strong	Very very strong	Extremely	
adaptability																			**applicability**
adaptability																			**meet the building**
adaptability																			**time**
applicability																			**meet the building**

applicability																		**time**
meet the building																		**time**

With respect to **choose an water vapor barrier**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
adaptability																		**applicability**
adaptability																		**meet the building**
adaptability																		**time**
applicability																		**meet the building codes**
applicability																		**time**
meet the building																		**time**

With respect to **choose an air barrier**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
adaptability																		**applicability**
adaptability																		**meet the building**
adaptability																		**time**

applicability																		**meet the building codes**
applicability																		**time**
meet the building																		**time**

With respect to **a window type**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
adaptability																		**applicability**
adaptability																		**meet the building**
adaptability																		**time**
applicability																		**meet the building codes**
applicability																		**time**
meet the building																		**time**

With respect to **an exterior wall insulation**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Building materials																		**total energy**

Building materials																			**water use**
total energy																			**water use**
Acidity potential																			**GWP**
Acidity potential																			**solid waste**
GWP																			**solid waste**

With respect to **an interior wall insulation**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
Acidity potential																			**GWP**
Acidity potential																			**solid waste**
GWP																			**solid waste**

With respect to **a water vapor barrier**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	

Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
Acidity potential																			**GWP**
Acidity potential																			**solid waste**
GWP																			**solid waste**

With respect to **a weather barrier**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
Acidity potential																			**GWP**
Acidity potential																			**solid waste**
GWP																			**solid waste**

With respect to **a window type**

	Extremely	Very very strong	Very strong	Strong plus	Strong	Moderate plus	Moderate	Weak	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	strong	Very strong	Very very strong	Extremely	
Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
Acidity potential																			**GWP**
Acidity potential																			**solid waste**
GWP																			**solid waste**

With respect to **Acidity potential**

	Extremely	Very very strong	Very strong	Strong plus	Strong	Moderate plus	Moderate	Weak	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	strong	Very strong	Very very strong	Extremely	
Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**

External wall insulation																			**Windows improvement**
Internal wall insulation																			**Water vapor barrier**
Internal wall																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **GWP**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall insulation																			**Water vapor barrier**

Internal wall																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **Solid waste**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Building materials																			**total energy**
Building materials																			**water use**
total energy																			**water use**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall insulation																			**Water vapor barrier**

Internal wall insulation																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **building materials**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**

Air quality																		**Thermal comfort**
Health Aspect																		**Mold growth**
Health Aspect																		**Thermal comfort**
Mold growth																		**Thermal comfort**

With respect to **building materials**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acidity potential																		**GWP**
Acidity potential																		**SOLID WASTE**
GWP																		**SOLID WASTE**
External wall insulation																		**Internal wall insulation**
External wall insulation																		**Water vapor barrier**
External wall insulation																		**Weather barrier**
External wall insulation																		**Windows improvement**
Internal wall insulation																		**Water vapor barrier**
Internal wall insulation																		**Weather barrier**
Internal wall insulation																		**Windows improvement**

Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **Total energy**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acidity potential																			**GWP**
Acidity potential																			**SOLID WASTE**
GWP																			**SOLID WASTE**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall																			**Water vapor**
Internal wall																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**

Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **Water use**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acidity potential																			**GWP**
Acidity potential																			**solid waste**
GWP																			**solid waste**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall insulation																			**Water vapor barrier**
Internal wall																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**

Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **Adaptability**

	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**

Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall insulation																			**Water vapor barrier**
Internal wall																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **applicability**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**

Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
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Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall																			**Water vapor**

Internal wall																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **meet the building codes**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**

Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**
External wall insulation																			**Internal wall insulation**
External wall insulation																			**Water vapor barrier**
External wall insulation																			**Weather barrier**
External wall insulation																			**Windows improvement**
Internal wall insulation																			**Water vapor barrier**
Internal wall insulation																			**Weather barrier**
Internal wall insulation																			**Windows improvement**
Water vapor barrier																			**Weather barrier**
Water vapor barrier																			**Windows improvement**
Weather barrier																			**Windows improvement**

With respect to **time**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																			**Aesthetic**
Acoustic comfort																			**Air quality**
Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**

Mold growth																		**Thermal comfort**
External wall insulation																		**Internal wall insulation**
External wall insulation																		**Water vapor barrier**
External wall insulation																		**Weather barrier**
External wall insulation																		**Windows improvement**
Internal wall insulation																		**Water vapor barrier**
Internal wall insulation																		**Weather barrier**
Internal wall insulation																		**Windows improvement**
Water vapor barrier																		**Weather barrier**
Water vapor barrier																		**Windows improvement**
Weather barrier																		**Windows improvement**

With respect to **occupant comfort**																		
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Acoustic comfort																		**Aesthetic**
Acoustic comfort																		**Air quality**

Acoustic comfort																			**Health Aspect**
Acoustic comfort																			**Mold growth**
Acoustic comfort																			**Thermal comfort**
Aesthetic																			**Air quality**
Aesthetic																			**Health Aspect**
Aesthetic																			**Mold growth**
Aesthetic																			**Thermal comfort**
Air quality																			**Health Aspect**
Air quality																			**Mold growth**
Air quality																			**Thermal comfort**
Health Aspect																			**Mold growth**
Health Aspect																			**Thermal comfort**
Mold growth																			**Thermal comfort**

With respect to **alternatives**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Implementation complexity																			**Occupant comfort**
Implementation																			**Resource use**

Occupant comfort																			**Resource use**

With respect to **implementation complexity**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Alternatives																			**Occupant comfort**
Alternatives																			**Resource use**
Occupant comfort																			**Resource use**

With respect to **resource use**																			
	Extremely	**Very very strong**	**Very strong**	**Strong plus**	**Strong**	**Moderate plus**	**Moderate**	**Weak**	**Equal**	**Weak**	**Moderate**	**Moderate plus**	**Strong**	**Strong plus**	**strong**	**Very strong**	**Very very strong**	**Extremely**	
Environmental impact																			**Occupant comfort**
Environmental impact																			**Resource use**
Occupant comfort																			**Resource use**

Investigator: Farhad Amiri Fard, Ph.D student

Supervisor: Dr. Fuzhan Nasiri

CONSENT FORM

Dear Participant,

This is an academic research project regarding passive energy conservation management in buildings in Canada which is conducted by Farhad Amiri Fard under the supervision of Dr. Fuzhan Nasiri. In this study you are being asked to participate in this research.
In case of any question or need to clarification you should ask Mr. Farhad Amiri Fard to explain it. You can email your questions or call to investigator which his number is provided at the end of this form.
If you decide to participate in this research, please complete the survey and return it directly to the researcher
By completing and returning the attached survey, you are consenting to participate in this research.

Information for Participants

Participants

Experts are identified as key participants of this study. Experts include those identified as having an extensive knowledge of building envelope, passive building, sustainability in building sector, energy efficiency in building, and other relevant area in buildings. Experts are expected to include university academics, professional engineers, planners, and etc.

Participants' Right to Decline

Your participation is voluntary, and you can withdraw from the survey after having agreed to participate.
You are free to refuse to answer any question that is being asked in the questionnaire.

Confidentiality

The information provided by participants will not be disclosed. Participant's name, address and other personal data are not asked, however, if provided, they will be removed from the questionnaire and not known to others. The answers he or she gives will be only used for research purposes and for writing a report. Care will be taken to report information so as to minimize the readers' ability to identify the role and hence identity of the source of information.

Use of Information: The information and findings obtained will be used for completing the requirements for the degree of Ph.D thesis. In addition, they may be used in seminars, conference presentations and research publications.

Availability of Results

A summary of the results is expected to be available by October 2017. Participants wanting a copy upon request forward their request directly to Farhad Amiri Fard at Concordia University, by email to: farhad.amirifard@concordia.ca, or by phone: +1-5149984429.
Contact Numbers
For answers to questions about the research or to voice concern or complaint about the research, or to report a study-related problem:
Farhad Amiri Fard
Ph.D student at Concordia University
514-998-4429
farhad.amirifard@concordia.ca

APPENDIX B: ANP PAIRWISE COMPARITION

Respect to External wall insulation

Acoustic comfort	**9**	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Aeshtetic	9.000
Acoustic comfort	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Air quality	0.200
Acoustic comfort	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Health Aspect	0.250
Acoustic comfort	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	Mold growth	0.125
Acoustic comfort	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Thermal comfort	0.111
Aesthetic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Air quality	0.111
Aesthetic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	Health Aspect	0.125

Aesthetic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Mold growth	0.111
Aesthetic	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	**9**	Thermal comfort	0.111
Air quality	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Health Aspect	2.000
Air quality	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Mold growth	0.500
Air quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Thermal comfort	1.000
Health Aspect	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Mold growth	0.500
Health Aspect	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Thermal comfort	0.500

Mold growth	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Thermal comfort	1.000

	Acousrtic comfort	Aeshtetic	Air quality	Health Aspect	Mold growth	Thermal comfort
Acoustic comfort	1.00000	9.00000	0.20000	0.25000	0.12500	0.11111
Aeshtetic	0.11111	1.00000	0.11111	0.12500	0.11111	0.11111
Air quality	5.00000	9.00000	1.00000	2.00000	0.50000	1.00000
Health Aspect	4.00000	8.00000	0.50000	1.00000	0.50000	0.50000
Mold growth	8.00000	9.00000	2.00000	2.00000	1.00000	1.00000
Thermal comfort	9.00000	9.00000	1.00000	1.00000	1.00000	1.00000

Weighted							Priorities
0.036885246	0.2	0.041570439	0.039215686	0.038626609	0.029850746	0.386148727	0.064358121
0.004098361	0.022222222	0.023094688	0.019607843	0.034334764	0.029850746	0.133208624	0.022201437
0.18442623	0.2	0.207852194	0.31372549	0.154506438	0.268656716	1.329167068	0.221527845
0.147540984	0.177777778	0.103926097	0.156862745	0.154506438	0.134328358	0.874942399	0.145823733
0.295081967	0.2	0.415704388	0.31372549	0.309012876	0.268656716	1.802181437	0.300363573
0.331967213	0.2	0.207852194	0.156862745	0.309012876	0.268656716	1.474351744	0.245725291
1	1	1	1	1	1		

CLUSTOR NODE LABELS		Alternatives					Environmental impact			Resource use			Implementation complexity				Occupant comfort					
		External wall insulation	Internal wall insulation	Water vapor barrier	Weather barrier	Windows improvement	Acidity potential	GWP	SOLID WASTE	Building materials	total energy	water use	adabtability	applicability	meet the buiding codes	time	Acoustic comfort	Aeshtetic	Air quality	Health Aspect	Mold growth	Thermal comfort
Alternatives	External wall insulation	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.3809990	0.3420470	0.3967180	0.1903200	0.1942580	0.1321060	0.1950539	0.2857143	0.2000000	0.1111110	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Internal wall insulation	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.3809990	0.3420470	0.3967180	0.1903200	0.1743930	0.1321060	0.1950538	0.2857143	0.2000000	0.3333334	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Water vapor barrier	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0457230	0.0539840	0.0509330	0.0330170	0.0295760	0.0388260	0.0409738	0.0714286	0.2000000	0.1111110	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Weather barrier	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0746460	0.0908990	0.0537650	0.0482210	0.0418430	0.0786050	0.0409739	0.0714286	0.2000000	0.1111110	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Windows improvment	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.1176330	0.1710230	0.1017660	0.5381220	0.5599290	0.6183570	0.5279446	0.2857143	0.2000000	0.3333334	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Environmental impact	Acidity potential	0.0889830	0.0889830	0.1634240	0.0750570	0.1004980	0.0000000	0.0000000	0.0000000	0.0694878	0.0588235	0.6250130	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	GWP	0.3233860	0.3233860	0.5396150	0.5917270	0.4664700	0.0000000	0.0000000	0.0000000	0.3483628	0.4705882	0.2384870	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	SOLID WASTE	0.5876310	0.5876310	0.2969610	0.3332160	0.4330320	0.0000000	0.0000000	0.0000000	0.5821494	0.4705882	0.1365000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Resource use	Building materials	0.4705882	0.4705882	0.1575965	0.4285714	0.4444444	0.2307690	0.1391620	0.7785790	0.0000000	0.0000000	0.0000000	0.0000000	1.0000000	1.0000000	0.0973901	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	total energy	0.4705882	0.4705882	0.7607887	0.4285714	0.4444444	0.6923080	0.7731710	0.1428230	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5695406	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	water use	0.0588235	0.0588235	0.0816148	0.1428571	0.1111111	0.0769230	0.8766700	0.0785980	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.3330694	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Implementation complexity	adabtability	0.1504592	0.1504592	0.1683339	0.0855645	0.2488249	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	applicability	0.1504592	0.1504592	0.1095928	0.2512150	0.0933413	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	meet the buiding codes	0.6610411	0.6610411	0.6730984	0.6067932	0.6136143	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	time	0.0380405	0.0380405	0.0489749	0.0564273	0.0442194	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Occupant comfort	Acoustic comfort	0.0643581	0.0588254	0.0630185	0.0297143	0.0927193	0.0000000	0.0000000	0.0000000	0.0336026	0.0000000	0.0000000	0.1102353	0.2226831	0.0823419	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Aeshtetic	0.0222014	0.0200389	0.0224344	0.0297143	0.0302605	0.0000000	0.0000000	0.0000000	0.1191827	0.0000000	0.0000000	0.3482467	0.4536941	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Air quality	0.2215278	0.2128064	0.2046672	0.2603187	0.0909781	0.0000000	0.0000000	0.0000000	0.3288389	0.0000000	0.0000000	0.1102353	0.0809057	0.3150290	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000
	Health Aspect	0.1458237	0.1419387	0.1555055	0.2603187	0.1550394	0.0000000	0.0000000	0.0000000	0.0336026	0.0000000	0.0000000	0.1102353	0.0809057	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Mold growth	0.3003636	0.2949818	0.2964757	0.2603187	0.2401585	0.0000000	0.0000000	0.0000000	0.2984115	0.0000000	0.0000000	0.1102353	0.0809057	0.0000000	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	0.0000000
	Thermal comfort	0.2457253	0.2714088	0.2578987	0.1596153	0.3908442	0.0000000	0.0000000	0.0000000	0.1863616	0.0000000	0.0000000	0.2108120	0.0809057	0.6026290	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

CLUSTOR NODE LABELS		Alternatives					Environmental impact			Resource use			Implementation complexity				Occupant comfort					
		External wall insulation	Internal wall insulation	Water vapor barrier	Weather barrier	Windows improvement	Acidity potential	GWP	SOLID WASTE	Building materials	total energy	water use	adabtability	applicability	meet the buiding codes	time	Acoustic comfort	Aeshtetic	Air quality	Health Aspect	Mold growth	Thermal comfort
Alternatives	External wall insulation	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0544280	0.0488640	0.0566740	0.0190320	0.0215840	0.0146780	0.0358590	0.0214450	0.0150110	0.0125070	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Internal wall	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0544280	0.0488640	0.0566740	0.0190320	0.0193770	0.0146780	0.0358590	0.0214450	0.0150110	0.0375220	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Water vapor barrier	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0065320	0.0077120	0.0072760	0.0033020	0.0032860	0.0043140	0.0075330	0.0053610	0.0150110	0.0125070	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Weather barrier	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0106640	0.0129860	0.0076810	0.0048220	0.0046490	0.0087340	0.0075330	0.0053610	0.0150110	0.0125070	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Windows improvment	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0168050	0.0244320	0.0145520	0.0538120	0.0622140	0.0687060	0.0970570	0.0214450	0.0150110	0.0375220	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Environmental impact	Acidity potential	0.0222458	0.0222458	0.1069610	0.0491240	0.0657760	0.0000000	0.0000000	0.0000000	0.0486410	0.0457520	0.4861210	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	GWP	0.2116550	0.2116550	0.3531760	0.3872840	0.3053030	0.0000000	0.0000000	0.0000000	0.2438540	0.3660130	0.1854900	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	SOLID WASTE	0.3846030	0.3846030	0.1943600	0.2180980	0.2834190	0.0000000	0.0000000	0.0000000	0.4075050	0.3660130	0.1061670	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Resource use	Building materials	0.0971490	0.0971490	0.0325340	0.0884750	0.0917520	0.1978020	0.1192820	0.6673530	0.0000000	0.0972221	0.0925930	0.0000000	0.5917270	0.5917270	0.0864280	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	total energy	0.0971490	0.0971490	0.1570580	0.0884750	0.0917520	0.5934070	0.6627180	0.1224200	0.0833330	0.0000000	0.0185190	0.0000000	0.0000000	0.0000000	0.5054300	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	water use	0.0121440	0.0121440	0.0168490	0.0294920	0.0229380	0.0659340	0.0751420	0.0673700	0.0166670	0.0138899	0.0000000	0.0000000	0.0000000	0.0000000	0.2955770	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Implementation complexity	adabtability	0.0085120	0.0085120	0.0095230	0.0048410	0.0140770	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	applicability	0.0085120	0.0085120	0.0062000	0.0142120	0.0052810	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	meet the buiding codes	0.0733902	0.0733902	0.0387900	0.0343200	0.0347140	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	time	0.0021520	0.0021520	0.0027710	0.0031920	0.0025000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
Occupant comfort	Acoustic comfort	0.0048520	0.0048520	0.0051980	0.0024510	0.0076480	0.0000000	0.0000000	0.0000000	0.0033600	0.0000000	0.0000000	0.0899700	0.0742020	0.0274380	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Aeshtetic	0.0016530	0.0016530	0.0017400	0.0024510	0.0024960	0.0000000	0.0000000	0.0000000	0.0119190	0.0000000	0.0000000	0.2842250	0.1511780	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Air quality	0.0175540	0.0175540	0.0162830	0.0214730	0.0075050	0.0000000	0.0000000	0.0000000	0.0328840	0.0000000	0.0000000	0.0899700	0.0269590	0.1049739	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000
	Health Aspect	0.0117080	0.0117080	0.0128270	0.0214730	0.0127890	0.0000000	0.0000000	0.0000000	0.0033600	0.0000000	0.0000000	0.0899700	0.0269590	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	Mold growth	0.0243330	0.0243330	0.0244560	0.0214730	0.0198100	0.0000000	0.0000000	0.0000000	0.0298410	0.0000000	0.0000000	0.0899700	0.0269590	0.0000000	0.0000000	0.0000000	0.0000000	1.0000000	0.0000000	0.0000000	0.0000000
	Thermal comfort	0.0223880	0.0223880	0.0212740	0.0131660	0.0322400	0.0000000	0.0000000	0.0000000	0.0186360	0.0000000	0.0000000	0.1720540	0.0269590	0.2008061	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
		1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	1.0000000	0.0000000	1.0000000	1.0000000	0.0000000	1.0000000	0.0000000

Total	Average	Consistency measure		
0.3000820	0.01429		0.01971	1.37955
0.3228900	0.01538		0.01946	1.26588
0.0728340	0.00347		0.0031	0.89251
0.0899480	0.00428		0.00438	1.02213
0.4115560	0.0196		0.02221	1.13353
0.8468665	0.04033		0.02916	0.72308
2.2644300	0.10783		0.09768	0.90586
2.3447680	0.11166		0.12095	1.08326
2.8511931	0.13577		0.12338	0.90873
2.5174100	0.11988		0.12684	1.05808
0.6281469	0.02991		0.02339	0.78183
0.0454650	0.00217		0.00058	0.26889
0.0427170	0.00203		0.00044	0.21551
0.2546044	0.01212		0.00314	0.25891
0.0127670	0.00061		0.00014	0.22389
1.2199710	0.05809		0.02323	0.39994
0.4573150	0.02178		0.00266	0.12195
1.3351559	0.06358		0.06686	1.0516
0.1907940	0.00909		0.00144	0.15852
1.2611750	0.06006		0.06917	1.15171
0.5299111	0.02523		0.00682	0.2702
				15.2756

Alternatives		N=1	N=2	N=3	N=4	N=5
Windows		0.318717	0.176531	0.331851	0.235978	0
External wall insulation		0.290399	0.146591	0.209394	0.253376	0.261584
Internal wall insulation		0.286399	0.401457	0.303417	0.324157	0.377231
Vapor barrier		0.04338	0.236147	0.103121	0.186489	0.361185
Weather barrier		0.061105	0.039274	0.052217	0	0
		1	1	1	1	1

Normalized table

Alternatives		N=1	N=2	N=3	N=4	N=5
Windows		0.063743	0.035306	0.06637	0.047196	0
External wall insulation		0.05808	0.029318	0.041879	0.050675	0.052317
Internal wall insulation		0.05728	0.080291	0.060683	0.064831	0.075446
Vapor barrier		0.008676	0.047229	0.020624	0.037298	0.072237
Weather barrier		0.012221	0.007855	0.010443	0	0

APPENDIX C: OPTIMIZATION

Var. name	WIN-1	WIN-2	WIN-3	WIN-4	EWI-1	EWI-2	EWI-3	EWI-4	EWI-5	IWI-1	IWI-2	IWI-3	IWI-4	IWI-5	VB-1	VB-2	VB-3	VB-4	VB-5	WB-1	WB-2	WB-3	OBJECTIVE		
variables	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22			
coefficient	6430	2806	6764	5262	3369.06	4058.92	5245.52	2174.98	2174.98	2834.58	3403.4	2263.38	1779.56	3389.8	244.12	165.58	202.3	287.98	424.66	667.76	174.08	449.14	$ 5,184.30	>=	$ 4,925.22
solution	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	1.000	0.000			
CONSTRAINT 1	0.063743	0.035306	0.066370	0.047196	0.058080	0.029318	0.041879	0.050675	0.052317	0.057280	0.080291	0.060683	0.064831	0.075446	0.008676	0.047229	0.020624	0.037298	0.072237	0.012221	0.007855	0.010443	0.180229	<=	0.2311196
CONSTRAINT 3	1	1	1	1																			1	=	1
CONSTRAINT 4					1	1	1	1	1	1	1	1	1	1									1	=	1
CONSTRAINT 5															1	1	1	1	1				1	=	1
CONSTRAINT 6																				1	1	1	1	=	1
								Max $f_1(x)$	0.2311196				Z	0.71140874											
								Min $f_1(x)$	0.1552218																
								Max $f_2(x)$	$11,259.82																
								Min $f_2(x)$	$4,925.22																

Var. name	WIN-1	WIN-2	WIN-3	WIN-4	EWI-1	EWI-2	EWI-3	EWI-4	EWI-5	IWI-1	IWI-2	IWI-3	IWI-4	IWI-5	VB-1	VB-2	VB-3	VB-4	VB-5	WB-1	WB-2	WB-3			
variables	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22			
coefficient	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
solution	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0			
CONSTRAINT 2	6430	2806	6764	5262	3369.06	4058.92	5245.52	3517.3	2174.98	2834.58	3403.4	2263.38	1779.56	3389.8	244.12	165.58	202.3	287.98	424.66	667.76	174.08	449.14	$ 4,925.22		
CONSTRAINT 3	1	1	1	1																			1	=	1
CONSTRAINT 4					1	1	1	1	1	1	1	1	1	1									1	=	1
CONSTRAINT 5															1	1	1	1	1				1	=	1
CONSTRAINT 6																				1	1	1	1	=	1

Var. name	WIN-1	WIN-2	WIN-3	WIN-4	EWI-1	EWI-2	EWI-3	EWI-4	EWI-5	IWI-1	IWI-2	IWI-3	IWI-4	IWI-5	VB-1	VB-2	VB-3	VB-4	VB-5	WB-1	WB-2	WB-3			
variables	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22			
coefficient	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
solution	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0			
Objective function	0.063743	0.035306	0.06637	0.047196	0.05808	0.029318	0.041879	0.0506752	0.052317	0.05728	0.080291	0.060683	0.064831	0.075446	0.008676	0.047229	0.020624	0.037298	0.072237	0.012221	0.007855	0.010443	0.2311196		
CONSTRAINT 3	1	1	1	1																			1	=	1
CONSTRAINT 4					1	1	1	1	1	1	1	1	1	1									1	=	1
CONSTRAINT 5															1	1	1	1	1				1	=	1
CONSTRAINT 6																				1	1	1	1	=	1

window types

Optimistic Cost($/m²)	Cost($/m²)	Pessimistic Cost($/m²)	Defuzzified value of Cost
$ 500.00	$ 550.00	$ 585.00	$ 535.83
$ 215.00	$ 245.00	$ 282.00	$ 233.83
$ 520.00	$ 580.00	$ 618.00	$ 563.67
$ 412.00	$ 460.00	$ 541.00	$ 438.50

Façade area A
204

Windows area =A
12

External wall insulation

Optimistic Cost($/m²)	Cost($/m²)	Pessimistic Cost($/m²)	Defuzzified value of Cost
$ 16.00	$ 16.90	$ 18.31	$ 16.52
$ 18.10	$ 20.88	$ 24.00	$ 19.90
$ 24.70	$ 26.08	$ 26.90	$ 25.71
$ 16.66	$ 17.76	$ 19.77	$ 17.24
$ 10.30	$ 10.87	$ 11.55	$ 10.66

Internal wall insulation

Optimistic Cost($/m²)	Cost($/m²)	Pessimistic Cost($/m²)	Defuzzified value of Cost
$ 13.31	$ 14.31	$ 15.80	$ 13.90
$ 15.90	$ 17.20	$ 19.00	$ 16.68
$ 10.40	$ 11.52	$ 12.95	$ 11.10
$ 8.00	$ 9.04	$ 9.90	$ 8.72
$ 16.30	$ 16.90	$ 18.00	$ 16.62

Vapor barrier types

Optimistic Cost($/m²)	Cost($/m²)	Pessimistic Cost($/m²)	Defuzzified value of Cost
$ 1.10	$ 1.23	$ 1.30	$ 1.20
$ 0.77	$ 0.85	$ 1.00	$ 0.81
$ 0.98	$ 1.02	$ 1.15	$ 0.99
$ 1.25	$ 1.47	$ 1.60	$ 1.41
$ 1.95	$ 2.12	$ 2.18	$ 2.08

weather barrier types

Optimistic Cost($/m²)	Cost($/m²)	Pessimistic Cost($/m²)	Defuzzified value of Cost
$ 3.10	$ 3.34	$ 3.50	$ 3.27
$ 0.77	$ 0.90	$ 1.05	$ 0.85
$ 2.20	$ 2.26	$ 2.55	$ 2.20