ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A PERFORMANCE BASED DECISION-MAKING APPROACH FOR INSULATION MATERIAL SELECTION:
A SOCIAL HOUSING CASE

Ph.D. THESIS

Burcu Çiğdem YILMAZ

Department of Architecture

Construction Science Programme

JULY, 2018

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A PERFORMANCE BASED DECISION-MAKING APPROACH FOR INSULATION MATERIAL SELECTION:
A SOCIAL HOUSING CASE

Ph.D. THESIS

Burcu Çiğdem YILMAZ
(502102014)

Department of Architecture

Construction Science Programme

Thesis Advisor: Assoc. Prof. Dr. Seden ACUN ÖZGÜNLER

JULY, 2018

ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YALITIM MALZEMESİ SEÇİMİNDE PERFORMANS ODAKLI BİR KARAR VERME YÖNTEMİ: SOSYAL KONUT ÖRNEĞİ

DOKTORA TEZİ

Burcu Çiğdem YILMAZ
(502102014)

Mimarlık Anabilim Dalı

Yapı Bilimleri Programı

Tez Danışmanı: Doç. Dr. Seden ACUN ÖZGÜNLER

TEMMUZ, 2018

Burcu Çiğdem YILMAZ, a Ph.D. student of İTU Graduate School of Science Engineering and Technology student ID 502102014, successfully defended the thesis/dissertation entitled “A PERFORMANCE BASED DECISION MAKING APPROACH FOR INSULATION MATERIAL SELECTION: A SOCIAL HOUSING CASE”, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Seden ACUN ÖZGÜNLER** ....
İstanbul Technical University

Jury Members : **Prof. Dr. Gül KOÇLAR ORAL** ....
İstanbul Technical University

Assoc. Prof Dr. Gülten MANİOĞLU ....
İstanbul Technical University

Prof. Dr. Mustafa ÖZGÜNLER ....
Mimar Sinan Fine Arts University

Prof. Dr. Nihal ARIOĞLU ....
Beykent University

Date of Submission : 20 June 2018
Date of Defense : 17 July 2018

To my family,

FOREWORD

It is exciting to finalize this work and a honor to present it herewith. It has been a long way that many great people have joined. I would like to thank these people, respectively.

Particularly and first of all, I want express my gratitude to my supervisor Assoc. Prof. Dr. Seden ACUN ÖZGÜNLER for her priceless support and guidance.

Secondly, I would like to thank to the jury members Prof. Dr. Gül KOÇLAR ORAL and Prof. Dr. Mustafa ÖZGÜNLER for their collaboration and contribution. This study is enriched thanks to their valuable comments during the thesis progress.

I owe a very big and special thank you to my mother Gülsüm ÇELİK and my father Hasan ÇELİK. Writing this thesis without their endless support was impossible. And my sister, Pınar, thank you for holding my hand ever since I can remember.

Finally, I want to present a lovely thank to my husband Yiğit YILMAZ. I remember the first days we started to set forth our PhDs. He was with me since those days and encouraged me whenever I surrendered and indeed I was about to give up. And my little daughter, Tuna; you are my soul, my future..and definitely everything is for you and much beautiful when You two are with me.

June 2018

Burcu Çiğdem YILMAZ
(M. Sc. Architect)

TABLE OF CONTENTS

Page

ABBREVIATIONS

AHP : Analytical Hierarchy Process
ANSI : American National Standards Institute
App : Appendix
ASHRAE : American Society of Heating, Refrigerating and Air-Conditioning Engineers
BC : Before Christ
BEP : Building Energy Performance
BEP-TR : Building Energy Performance – Turkey
CED : Cumulative Energy Demand
CG : Cellular Glass
CIB : International Council for Research and Innovation in Buildings
COPRAS : Complex Proportional Assessment
CO : Cost
CPD : Construction Products Directive
DMs : Decision Makers
ELECTRE : Elimination and Choice Translating Reality
EN : European Norm
EP : Expanded Perlite
EPBD : Energy Performance of Buildings Directive
EPS : Expanded Polystyrene
GC : Global Cost
GHG : Green House Gas
GW : Glass Wool
GWP : Global Warming Potential
HVAC : Heating Ventilating and Air Conditioning
LCA : Life Cycle Assessment
LCC : Life Cycle Cost
MADM : Multi Attribute Decision Making
MAUT : Multi Attribute Utility Theory
MCDM : Multi Criteria Decision Making
MODM : Multi Objective Decision Making
MW : Mineral Wool
NIST : National Institute of Standards and Technology
nZEB : Nearly Zero Energy Building
PB : Payback Period
PEU : Primary Energy Use
PF : Phenolic Foam Board
PMV : Predicted Mean Vote
PPD : Predicted Percentage of Dissatisfied
PROMETHEE : Preference Ranking Orgaization Method for Enrichment Evaluation
PUR : Polyurethane
RW : Rock Wool

SMART : Simple Multi Attribute Ranking Technique
TMY : Typical Meteorological Year
TOPSIS : Technique for Order Preference by Similarity to an Ideal Solution
TS : Turkish Standard
UNPF : United Nations Population Fund
XPS : Extruded Polystyrene
WASPAS : Weighted Aggregated Sum Product Assessment
WPM : Weighted Product Method
WSM : Weighted Sum Method

SYMBOLS

ϕ_e : External relative humidity
ρ_e : External vapour pressure
M_A : Metabolic rate
M_o : Metabolism
c : Specific heat capacity
ρ : Specific heat
$c\rho$: Volumetric specific heat
λ : Thermal conductivity
R : Thermal resistance
α : Absorptivity
e : Emissivity
r : Reflectivity
a : Thermal diffusivity
b : Thermal effusivity
ξ : Specific moisture ratio
$\rho\xi$: Specific moisture content
δ : Vapour permeability
μ : Vapour resistance factor
k_m : Moisture permeability
μd : Diffusion thickness
K_θ : Thermal moisture permeability
D_w : Moisture diffusivity
A : Unit area
ε : Hygric expansion
c_a : Specific air content
k_a : Air permeability
K_a : Air permeance
CG : Global cost
CO_a : Annual running costs
CO_{CO2} : CO_2 emissions cost
CO_{disp} : Disposal costs
T : Calculation period
D_f : Discount factor
VALfin(tTC) : Residual value
RATxx : Price development (Rate)
CO_{init} : Initial investment cost
CO_{inv} : Investment cost
CO_{run} : Running costs
CO_{ma} : Maintenance costs
CO_{op} : Operational costs
CO_{en} : Energy costs

CO_{per} : Periodic costs
PB : Payback period
RAT_{inf} : Inflation rate
RAT_{act} : Actualization rate
RAT_{re} : Real discount rate
RAT_{disc} : Discount rate
$f_{pv}(n)$: Present value factor
M_A : Metabolic rate
L : Load
PMV : Predicted Mean Vote
FU : Functional unit
d : Density
U : Thermal transmittance
WSM : Weighed sum method
a : Actual value
w : Weight factor
R : R value
k : Scaling constant
u : Utility function operator
RAT_{re} : Real discount rate
RAT_{disc} : Discount rate
$f_{pv}(n)$: Present value factor
M_A : Metabolic rate
L : Load
PMV : Predicted Mean Vote
FU : Functional unit

LIST OF TABLES

LIST OF FIGURES

Page

A PERFORMANCE BASED DECISION MAKING APPROACH FOR INSULATION MATERIAL SELECTION:
A SOCIAL HOUSING CASE

SUMMARY

Built environments have been evolving since the 500s BC, as we can observe aesthetic, social and environmental concepts in ancient Greek cities' performances. Performance can be explained as the ability to perform something, or the fulfillment of an obligation or a claim. The three principles of architecture; firmitas (durability), utilitas (utility) and venustas (beauty), introduced by Vitruvius (1960), are also early examples of the built environment and the evolution of its performance. Built environments and their performance have a great impact on human life, as we spend most of our times in them. Moreover, the performance of buildings have been frequently discussed in the last decades, mostly in terms of sustainability, energy, cost, health, etc.

Buildings, as the consumers of more than one third of global energy, have a significant impact on global warming, the depletion of resources, and emissions. The degree of environmental impact caused by buildings and their energy consumptions has been increasing rapidly, due to rising comfort needs and population growth. The high amount of energy consumption in buildings has led to the need for energy efficiency action in terms of buildings through legislative strategies such as energy efficiency regulations, energy certification of buildings according to energy classes, refurbishment of existing buildings, etc.

On the other hand, building design involves several decisions in different stages of the build process. Building design, in the form of the process of decision-making, involves decision makers such as investors, property owners, designers, experts, etc., with each decision maker, from different points of view, targeting the success of the project in terms of different concerns involving several dependent and independent parameters.

With the increase in building energy consumption levels worldwide, thermal insulation materials have become one of the key applications for building energy efficiency. When high performance buildings are targeted, thermal insulation materials become increasingly significant. Consequently, conflicts may occur between the efforts and the provisions due to thicker applications of the material, leading to higher costs and greater environmental impact. In addition, higher comfort levels are also expected as a feedback for such intensive efforts. Thus, the determination of the most effective thermal insulation material in terms of its properties for high performance building is a multiple criteria decision-making problem, since the thermal insulation materials are significant in terms of their impact on the energy, cost, thermal comfort, and environmental performance of a building.

Urbanization and social housing has an important impact on the embodiment of 'housings'. The requirements of social housing such as low investment cost for states and low operating costs for low-income group occupancies signify the importance of performance estimation for social housing. From this point of view, one of the most

significant performance indicators for social housing are cost and energy, since they are also significant with regard to current directives and regulations.

Besides, a comprehensive definition for social housing performance within a sustainability approach has an obvious importance for economic, social and environmental development. Nevertheless, current regulations and developments also regularly identify new criteria in order to expand the definition of building performance. EN 15459 (2017) introduced new revisions such as the cost of greenhouse gas emissions in order to evaluate the monetary value of environmental damage caused by CO2 emissions related to the energy consumption of buildings. Moreover, environmental product declarations (EPD) came into prominence in order to verify the information about the life-cycle environmental impact of products. EPBD (2018) also states the importance of building energy performance improvements while improving thermal and visual comfort. Thus, in addition to energy and cost performances, the environmental impact and user comfort performances should be also considered as determinative and descriptive for a sustainable social housing design.

Environmental impact has been discussed and evaluated since the 1960s. By the publication of the National Environmental Policy Act (NEPA, 1970) in U.S., environmental impact assessment obtained formal status. Today, environmental impact is evaluated either on material, component or building scale, depending on the purpose of the evaluation.

Thermal comfort is also a Twentieth Century discipline, focusing on a comfortable indoor environment in terms of thermal criteria. As a result of the evolution of space phenomenon and architectural theories and movements, occupancy became an important factor as an individual with a physical dimension in the design process. This evolution brought the need to evaluate and increase user comfort within the built environment.

In this study, “high performance” is evaluated in terms of energy, cost, thermal comfort, and environmental impact. Thus, the aim and scope of the study, beyond a consideration of cost optimal energy efficiency, is proposing a methodological approach for a performance-based decision-making method covering energy, cost, thermal comfort, and environmental performance.

Within this context, the methodological approach presented in this study includes the following main steps:

- Determination of the archetype
- Parameterization with the designated independent variables
- Calculation of the dependent variables
- Implementation of a multiple criteria decision-making process
- Determination of the best alternatives through the decision-making scores.

Different building functional typologies perform different energy consumption patterns in terms of activity types, occupied hours, internal gains, etc. The more detailed the sub-categories that buildings are divided into, the more accurate will be the analyses in terms of energy. In this study, a social housing archetype which has a 4 apartment/floor plan scheme was designated.

Firstly, the independent variables were determined for the parameterization process. The main independent variable was designated as the thermal insulation material used and its thickness, since the aim is the selection of the optimum thermal insulation material.

The dependent variables are identified as energy, cost, thermal comfort, and environmental impact performance. Energy consumption is calculated through the use of the Energy Plus simulation tool. Such consumption is based on an hourly basis, with 6 time steps per hour. Using this approach, the life cycle cost of the related components were calculated with a modified global cost formula as the sum of the initial investment cost, the net present value annual cost of the energy costs, transposed with the development rate of energy. In this approach, indoor environmental thermal comfort is evaluated based on the EN 15251 Adaptive comfort model, and evaluated within Category III. The influence of the material selection on the environmental impact performance of the building is calculated through the embodied carbon (kgCO2e/kg) and the embodied energy (Mje/kg) of the materials used.

In the proposed approach, all scenarios occurring by parameterization are calculated in terms of life cycle cost and primary energy consumption through a 30 year life span. The cost optimal point within the whole alternatives is obtained, and alternatives beyond the cost optimal level are listed for the purposes of multiple criteria decision-making. Alternatives were listed with the associated decision-making criteria for high performance building design in the form of investment cost, primary energy consumption, thermal comfort, and environmental impact values. In order to be compared with each other, all criteria values were normalized. Furthermore, the normalized values of the criteria were summed in order to obtain the total score of the alternatives. In this step, the weighting factors of each criterion were considered either as being equal or as the calculated weightings based on the AHP pairwise comparison method for criteria. Finally, best alternatives were determined for the decision maker, in order to develop a high performance building design.

The analysis show that the performance criteria that have been evaluated have an important impact on the alternatives and the results. Thus, it is meaningful to include the four determined performance criteria (energy, cost, thermal comfort, and environmental impact) in the decision-making process in order to select the best alternatives.

The results show that proper decision-making on the selection of thermal insulation building materials, with different environmental and economic attributes, ensure a higher performance with regard to buildings. The proposed approach influences the selection of the best alternative, which allows the personal preferences of the decision maker to be met, without digressing from the scope of EPBD.

It is clear that the methodology used in multiple criteria decision-making, and the weighting factors of the criteria, are quite substantial and effective in terms of the results of the decision-making process. The study should be improved by assigning different weighting factors to decision-making criteria, in order to identify the deviations resulting from the different weighting factors. Thus, further studies should be conducted incorporating different decision-making methods, and variations in terms of the criteria and the weighting factors should be analyzed. It is also possible that a tool can be generated by using the proposed methodology, to offer a quick analysis to meet further demands and for the design processes of different archetypes.

YALITIM MALZEMESİ SEÇİMİNDE KULLANILABİLECEK BİR PERFORMANS ODAKLI KARAR VERME YÖNTEMİ: SOSYAL KONUT ÖRNEĞİ

ÖZET

Antik Yunan şehirlerinde gözlemleyebildiğimiz estetik, sosyal ve çevresel tasarım kriterlerine bakıldığında, yapma çevrenin gelişimi MÖ500 yıllarına kadar dayandırılabilir. Aynı zamanda Vitruvius (1960)'ın tanımlamış olduğu mimarinin üç prensibi olan firmitas (dayanıklılık), utilitas (işlevsellik), ve venustas (estetik), yapma çevrenin gelişimi ve performansının öneminin erken örneklerindendir. Tarih boyunca elde edilen verilere bakıldığında ise, yapma çevre ve bina performansının, insanların günlük hayatının büyük kısmını geçirdiği çevreler olarak, insan hayatı üzerinde önemli etkiye sahip olduğu görülmektedir. Bina performansı; genellikle sürdürülebilirlik, enerji, sağlık ve maliyet konularında, son yıllarda sıklıkla ele alınmakta olan bir konudur.

Dünya'da tüketilen toplam enerjinin üçte birinden fazlasının tüketiminden sorumlu olan binaların, aynı zamanda sera gazı salımları, küresel ısınma ve doğal kaynakların tükenmesinde de önemli payı bulunmaktadır. Ayrıca, hızlı artmakta olan insan nüfusu ve bu nüfusun mekânsal konfor gereksinimlerinden dolayı binaların enerji tüketimi gün geçtikçe artmakta, bu durumdan kaynaklanan olumsuz çevresel etkiler de hızlı bir şekilde artış göstermektedir. Binalarda gerçekleşen yüksek orandaki enerji tüketimleri, binalarda enerjinin etkin kullanımını sağlamak amaçlı çıkarılacak yönetmeliklerin, binaların enerji performans sınıflandırılmasının ve var olan yapıların enerji etkin yenilenmesinin gerekliliğini ortaya koymaktadır. Avrupa Birliği Komisyonu tarafından yayınlanmış olan Bina Enerji Performansı Direktifi (EPBD) binalarda enerji performansı ve enerjinin etkin kullanımı konularında amaç, kapsam ve hedefleri tanımlayan, Avrupa Birliği ülkelerinin uymak ve uygulamakla yükümlü olduğu bir direktiftir. EPBD bir yandan binalarda enerji verimliliğinin arttırılmasını, asgari enerji verimliliği gereksinimlerinin belirlenmesini, binaların enerji sertifikasyonlarının planlanması ve yürütülmesini hedeflerken, aynı zamanda bina için yapılan yatırım ile binanın tüm yaşam döngüsü boyunca tasarruf edilen enerji maliyetleri arasındaki maliyet-optimal dengesi gibi yeni hükümler de ortaya koymuştur.

Bina tasarımı, farklı süreçleri ve bu süreçlerde alınan birçok kararı içermektedir. Yatırımcı, tasarımcı, yüklenici, uzmanlar, danışmanlar, vb. gibi karar vericiler bu sürece dahil olmaktadır. Karar vericilerin farklı bakış açıları, yatkinlikleri, alınan kararlardaki etkileri vb. projenin ulaşacağı başarı düzeyine ve binanın performansına doğrudan etki etmektedir.

Dünyadaki enerji tüketim düzeyinin artmasıyla ısı yalıtım malzemeleri ve ısı yalıtımı uygulamaları önemli uygulamalardan biri haline gelmiştir. Özellikle yüksek performanslı binalar hedeflendiğinde ısı yalıtım malzemesi daha önemli hale gelmekte, yüksek kalınlıklardaki uygulamalarda bağlı olarak yüksek yatırım maliyeti, malzeme kullanımına bağlı çevresel etki vb. nedenlerden dolayı ortaya konan çaba ve

kazançlar arasında uyuşmazlık oluşabilmektedir. Ayrıca, bu gibi uygulamalar sonuçunda yüksek termal konfor düzeyleri beklenmektedir. Bu nedenle, yüksek performanslı bina tasarımında doğru ısı yalıtım malzemesi ve uygulamasının belirlenmesi, enerji, maliyet, termal konfor ve çevresel etki performanslırını doğrudan etkileyen bir çok kriterli karar verme problemi olarak tanımlanabilir.

Kentleşme ve sosyal konut ihtiyacı, konut kavramının şekillenmesinde büyük öneme sahiptir. Bina performansına sosyal konut açısından bakıldığında ise, düşük yatırım maliyetleri ve düşük gelir grubu için düşük işletim giderleri, sosyal konutlar için performans değerlendirmelerini daha önemli hale getirmektedir. Bu açıdan, ilk yatırım maliyeti, bakım onarım maliyetleri, işletme giderleri ve enerji tüketim düzeyleri performans göstergeleri olarak öne çıkmaktadır. Buna ilaveten, sosyal konutlar için performans tanımının, sürdürülebilirlik başlığı altında, ekonomik, sosyal ve çevresel kalkınma için geniş bir çerçeveye oturtulması büyük önem taşımaktadır. Bununla birlikte, mevcut yönetmelik ve düzenlemeler, bina performansının tanımını genişletiecek yönde kriterler ortaya koymaktadır. EN 15459 (2017), binalarda enerji tüketimine bağlı CO_2 emisyonlarının neden olduğu çevresel zararın parasal değerini değerlendirmek için 'sera gazı emisyonu maliyeti' tanımını ortaya koymuştur. Ayrıca, ürünlerin yaşam döngüsü çevresel etkilerinin beyanı için 'çevresel ürün deklerasyonu' günümüzde ön plana çıkmaktadır. EPBD (2018) ise enerji performansının iyileştirilmesinin termal ve görsel konuforun arttırılması ile bir arada düşünülmesinin önemini vurgulamaktadır. Sonuç olarak, öne çıkmakta olan enerji ve maliyet performanslarına ek olarak, çevresel etki ve kullanıcı konforu performanslarının da sürdürlebilir bir sosyal konut tasarımı için belirleyici ve tanımlayıcı performans göstergeleri olarak değerlendirlmesi önemi doğmaktadır.

Çevresel etki, 1960larda tartışma konusu olmaya başlamış ve Ulusal Çevre Politikası Yasası'nın (NEPA, 1970) yayınlanması ile birlikte resmiyet kazanmıştır. Günümüzde, çevresel etki değerlendirme sistemleri, malzeme, bileşen, bina, proje, vs. ölçeklerinde değerlendirilebilmektedir. Buna örnek olarak, Çevresel Ürün Deklerasyonu (EPD), gönüllü yeşil bina sistemleri, vs verilebilir.

Termal konfor ise 20. yüzyılda doğmuş bir disiplin olup, iç mekan koşullarının termal kriterler açısından uygunluğuna ve kullanıcı tatmin düzeyine odaklanmaktadır. Mekan olgusunun gelişimi ve bireyin mekan içerisinde önemli bir faktöre dönüşmesi ile kullanıcı memnuniyeti önem kazanmıştır. Bu gelişim, yapılı çevrede kullanıcı konforunu değerlendirme ve artırma ihtiyacını getirmiştir.

Kentleşme ve sosyal konut ihtiyacının artması, konut kavramını oldukça etkilemiştir. Günümüzde Türkiye'deki konut stokunun %10'unu sosyal konutlar oluşturmakta ve bu oran sosyal konut yatırımları ile hızla artmaktadır. Bu nedenle önerilen karar verme yaklaşımı tüm bina tipolojilerine uygulanabilir olup bu çalışma kapsamında örneklem bir sosyal konut arketipinin tasarımı veya iyileştirmeleri için uygulanmıştır. Önerilen yaklaşımda "yüksek performans" kavramı enerji ve maliyet performansı, termal konfor ve çevresel etki açılarından değerlendirilmiştir. Böylece, çalışmanın amacı, maliyet optimum enerji etkin bina tasarımının ötesine geçmektedir. Bu bağlamda önerilen yaklaşımın ana adımları aşağıda sunulmaktadır:

- Örneklemin belirlenmesi
- Belirlenen bağımsız değişkenlerle örneklemin parametrelendirilmesi,
- Bağımlı değişkenlerin hesaplanması
- Çok kriterli karar verme yöntemi aracılığıyla en iyi alternatiflerin belirlenmesi

Farklı fonksiyon taşıyan bina tipolojileri; bina tipolojisine göre farklılaşan aktivite türleri, kullanım saatleri, binanın iç kazançları gibi enerji kullanımı etkileyen faktörlerden dolayı farklı enerji performans davranışları göstermektedir. Bu yüzden daha detaylı olarak alt kategorilere ayrıştırılabilen binaların enerji analizlerinden daha doğruya yakın sonuçlar elde edilebilir. Bu çalışmada örneklem olarak 11 katlı ve her katta 4 apartman dairesinin yer aldığı plan şeması, arketip olarak seçilmiştir.

Çalışmada ilk olarak parametrelendirilme aşaması için bağımsız değişkenler belirlenmiştir. Önerilen yaklaşımda amaç ısı yalıtım malzemesinin seçim kararı üzerine olduğu için ana bağımsız değişken olarak ısı yalıtım malzemesi ve bu malzemenin uygulanma kalınlığı seçilmiştir. Bağımlı değişkenler olarak ise enerji, maliyet, ısıl konfor ve çevresel etki performansları belirlenmiştir.

Enerji tüketimleri detaylı dinamik hesaplama yöntemine dayanan Energy Plus simülasyon programı kullanılarak, ısıtma ve soğutma birincil enerji tüketimi üzerinden değerlendirilmiştir. Daha sonra bağımsız değişkenlerin yaşam döngüsü maliyeti hesaplanabilmesi için EN 15459'da verilen global maliyet hesaplama yöntemi kullanılmış, global maliyet formülü çalışmanın kapsamı açısından düzenlenerek hesaplamalarda kullanılmıştır. Düzenlenmiş yönteme göre yaşam döngüsü maliyeti; ilk yatırım maliyeti ile bakım ve enerji maliyetlerinin bugünkü değerlerinin toplanması sonucunda hesaplanmaktadır. Önerilen yaklaşımda parametrelendirme ile meydana gelen tüm senaryolara ait yaşam döngüsü maliyeti ve birincil enerji tüketimi, 30 yıllık yaşam süresi dikkate alınarak hesaplatılmıştır. Sonraki aşamada iç konfor koşulları EN 15251'de tanımlanan "adaptif konfor" modelindeki III. kategoriye göre analiz edilmiştir. Son olarak, ısı yalıtım malzemesi seçiminin binanın çevresel etki performansı üzerindeki etkisi, malzemelerin gömülü karbonu (kgCO2e/kg) ve gömülü enerjisi (Mje/kg) üzerinden hesaplanmıştır.

Karar verme sürecinde birinci adım, tüm senaryo alternatifleri için maliyet optimum noktanın belirlenmesi ve maliyet optimum noktanın ötesindeki senaryoların çok kriterli karar verme yönteminin uygulanabilmesi için ayrıştırılması ile başlar. Maliyet optimum noktanın ötesinde yer alan enerji etkin alterantifler, yüksek performanslı bina tasarımı için enerji, maliyet, ısıl konfor ve çevresel etki değerleri ile listelenir. Kriterlerin birbirleri ile kıyaslanabilmesi için tüm kriterlere ait değerler, o kritere ait en yüksek ve en düşük değere ait uzaklığı hesaplanarak normalize edilmekte ve normalizasyon sonucunda 0 ile 1 arası değer almaktadır. Sonrasında o kritere ait normalize edilen değerler eşit ağırlık faktörleri ile değerlendirilerek senaryo alternatiflerine ait toplam skor elde edilmektedir. Sonraki aşamada ise kriterlerin ağırlık faktörlerini elde etmek için bir anket çalışması üzerinden karar vericilerden bilgi toplanmakta ve toplanan veriye göre AHP metoduna göre ağırlık faktörleri hesaplanmaktadır. Son olarak, yüksek performansa sahip bir bina tasarımı geliştirmek amacıyla, karar verici için en iyi alternatifler belirlenmektedir.

Sonuçlar göstermektedir ki, farklı çevresel ve ekonomik özelliklere sahip ısı yalıtım malzemeri ve uygulamaları içerisinden doğru alternatifin belirlenmesi, daha yüksek bina performansına ulaşılmasına katkı sağlamaktadır. Bunun yanı sıra, kullanılan karar verme yöntemi ve ağırlık faktörlerinin karar üzerindeki etkisi oldukça fazladır. Ağırlık faktörlerine bağlı hassasiyetin daha kapsamlı değerlendirilebilmesi için, farklı ağırlık faktörleri kullanılarak çalışma genişletilebilir. Aynı zamanda önerilen yöntem ve yaklaşım, performans kriterlerinin artırılmasına uygun bir yapıdadır. Analitik Hiyerarşi Süreci (AHP) yöntemi ile kriter sayısı arttırılabileceği gibi, kirterler arasında hiyerarşik bağıntı kurularak ağırlık faktörlerinin detaylı hesaplanması da sağlanabilecektir. Önerilen yöntemin bir yazılım aracına dönüştürülmesi ise, yöntemin kullanılabilirliği için gerekli görülmektedir.

Çalışmanın detaylı aktarımı şu şekilde kurgulanmıştır:

Çalışmanın birinci bölümünde, konuya genel bir giriş ile birlikte, çalışmanın amaç ve kapsamı detaylı olarak açıklanmış, konu ile ilgili detaylı literatür özeti sunulmuştur.

İkinci bölümde, enerji ve maliyet performansı, ısıl konfor ve çevresel etki değerini etkileyen parametreler ve hesaplama yöntemleri teorik bilgiler ile açıklanmış, devamında ısı yalıtım malzemelerin çevresel etki değerlerine ait bilgiler verilmiştir.

Üçüncü bölüm, performans odaklı bina tasarımında karar verme yöntemleri ile ilgilidir. Literatürde yer alan ve en çok kullanılan karar verme yöntemleri ile ilgili detaylı bilgiler verilmiş, kendi aralarında güçlü ve zayıf yanları değerlendirilmiştir.

Dördüncü bölümde, yukarıda yer alan metodoloji adımlarına ait teorik bilgiler ve metodolojide kullanılan adımlar detaylı olarak çıklanmıştır.

Beşinci bölüm, dördüncü bölümde açıklanmış olan metodolojinin örneklem üzerinde uygulanması adımlarını içermektedir.

Altıncı bölüm, tüm çalışma adımlarının ve sonuçlarının özetlenerek yorumlandığı sonuç bölümünden oluşmaktadır.

1. INTRODUCTION

Architecture and built environment concepts have been evolving since 500s (BC), where the ancient Greek cities were designed with aesthetic, social and environmental aspects. The Roman architect and author Vitruvius asserted on his treatise “De Architectura”, today known as “The Ten Books of Architecture”, the three principles of architecture as firmitas (durability), utilitas (utility) and venustas (beauty) (Vitruvius, 1960). Thus, he dedicated an evaluation of building performance with these three quality criteria then.

The performance of built environments has a great impact on human life, as we spend most of our times in built environments in order to shelter and sustain our lives. Thus, the design of the built environment plays a critical role in achieving a better performance, while providing the requirements of its users (Yılmaz, 2017). Today, buildings are analyzed, evaluated and even graded according to several subjective and objective performance aspects such as, accessibility, durability, energy, health, cost, etc. Moreover, it is targeted and forced to evaluate and assign the performance levels of buildings on specific objective criteria, such as energy performance.

Estimation of building performance might be essential in building projects where the indicators of building performance are crucial. Housings, which are buildings such as apartments or units assigned for residence, are one of the main cases, since the amount of housing stock within the whole building stock has a great amount. Moreover, housing stock is expanding rapidly due to migration, politics about housing development and public housing. According to the IV. Building Census applied in Turkey, 7,838,675 buildings were counted where the number of buildings were counted as 4,387,971 in 1984. Moreover, according to the results of the building census in 1984, 7,096,277 housing units were counted where 16,235,830 housing units were identified in 2000, with an increase of 129% (Building Census, 2000).

As analyzed, urbanization and social housings has an important impact on the embodiment of ‘housings’. In Turkey, Housing Development Administration (TOKI) is the governmental organization for social housing planning and construction. Social housing program of TOKİ targets the low and middle-income people who cannot own a housing unit under the existing market conditions. The beneficiaries of the social housing projects of TOKİ make their down payments on the start of the constructions after the tender or at a certain stage and continue monthly payments according to a single-indexed reimbursement plan. Additionally, the maturities of the loan repayments of TOKİ are set as 8-25 years in average depending on the financial capabilities of the target groups. (Url-1).

The requirements of social housings such as low investment costs for states and low operating costs for low-income group occupancies signify the importance of performance estimation for social housings. From this point of view, one of the most significant performance indicators for social housings can be cost and energy, since they are also significant with the current Directive and Regulations. Besides, a comprehensive definition for the social housing performance within a sustainability approach has an obvious importance for economic, social and environmental development.

Beyond the energy and cost performance, a comprehensive description of social housing performance requires a sustainability approach, which has three main contents such as economic, social and environmental sustainability. Nevertheless, current regulations and developments also point out new criteria regularly, in order to expand the definition of building performance. EN 15459 (EN 15459, 2017) introduced new revisions such as cost of greenhouse gas emissions to evaluate the monetary value of environmental damage caused by CO2 emissions related to the energy consumption in buildings. Moreover, environmental product declarations (EPD) came into prominence in order to verify the information about the life-cycle environmental impact of products. EPBD (2018) also states the importance of building energy performance improvement while improving thermal and visual comfort. Thus, in addition to the energy and cost performances, the environmental impact and user comfort performances should be also considered as determinative and descriptive for a sustainable social housing design.

Energy was not even a concern until the first energy crisis of 1973. While soil mechanics, structural mechanics, building materials, building construction and HVAC were seen essential, designers only sought advice on room acoustics, moisture tolerance, summer comfort or lighting when really needed or when, after construction, problems arose. (Hens, 2011). The Montreal Protocol, authored in 1987, was one of the first international agreements, which aims to phase out substances destructive to the ozone layer.

In the last decades, energy consumption and energy performance became one of the most significant performance indicators in buildings. Buildings, as the consumers of more than one third of global energy, have a significant impact on global warming, depletion of resources, and emissions. The amount of environmental impacts caused by buildings and its energy consumptions has been increasing rapidly due to comfort needs and population growth as well. According to the United Nations Population Fund reports, as summarized in Figure 1.1, from the beginning of time until 1950, the world population grew to almost 2.5 billion people; from 1950 to 1990, that population doubled; and it is expected by 2050, the world will add almost 2.5 billion people, an amount equal to the world's total population in 1950 (UNPF, 2004; Spiegel & Meadows, 2012).

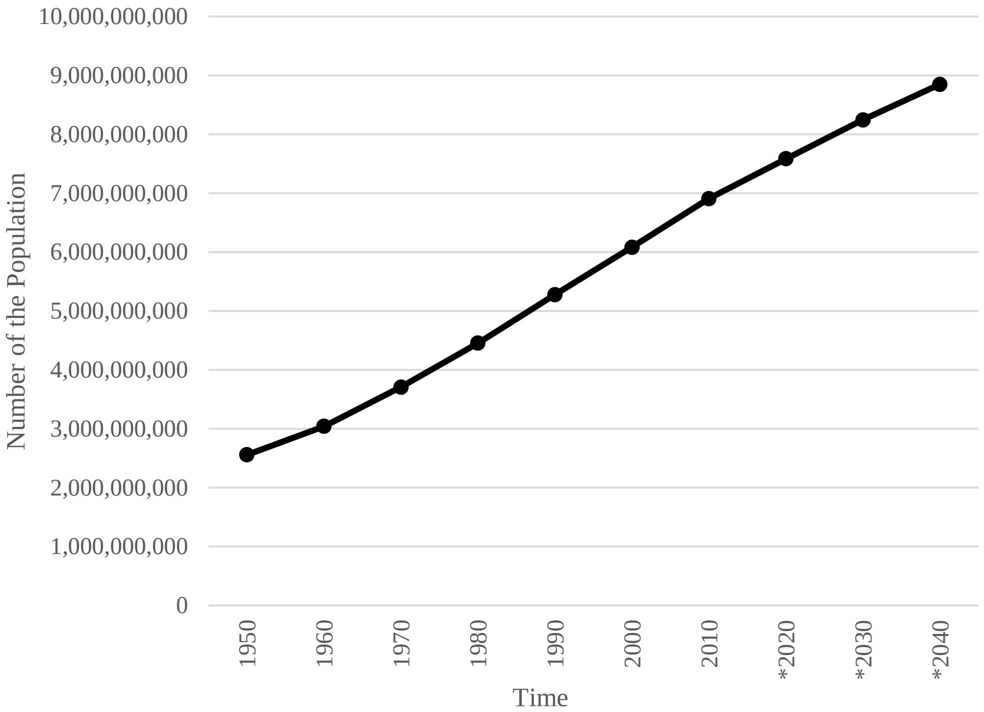

Figure 1.1 : World population between 1950 – 2010 and future projection (Url-2).

In accordance with the world population growth, the report presented by (IEO, 2016) shows the increase of energy consumption between 1990 and 2012 and the future projection for energy consumption until 2040. As given in Figure 2.2, there occurs a 70% increase in energy consumption in non-OECD countries between 2012 and 2040, where the increase level is 18% in OECD countries. This study also highlights the importance of population growth on the increased energy consumption levels.

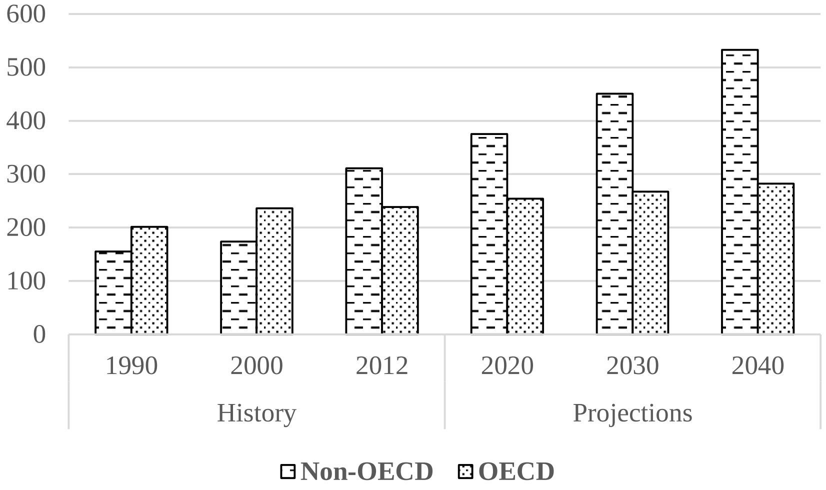

Figure 1.2 : World energy consumption, 1990-2040 (quadrillion Btu) (IEO, 2016).

Today, buildings represent nearly the 31% of the overall energy consumption, as given in Figure 1.3. The high amount of energy consumption in buildings brought the necessity of energy efficiency action in buildings through legislative strategies such as energy efficiency regulations, energy certification of buildings according to energy classes, refurbishment of existing buildings, etc.

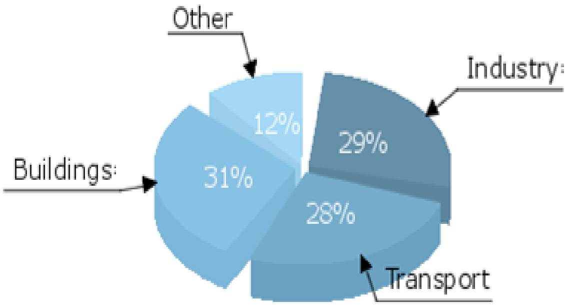

Figure 1.3 : Global energy consumption per sector (*International Energy Agency*).

Agenda 21, held in 1992 at the Earth Summit in Rio de Janeiro, is a United Nations action concerning sustainable developments (Agenda 21, 1992). The aim of Agenda 21, referring to 21st century, was to develop sustainable developments by adopting and implementing policies concerning issues such as recycling, energy efficiency, conservation, etc.

In the EU countries, the Energy Performance of Buildings Directive (EPBD) is the main document that is defining the framework of energy performance and efficiency in buildings (Directive, 2002). The aim of the EPBD is to improve the energy efficiency levels by defining the minimum energy performance requirements for new and existing buildings. Moreover, a calculation methodology was defined to determine the performance level and its related energy class in order to certificate the buildings. So that, the publication of EPBD represents and regulates the occasion for obtaining a definitive answer in terms of building energy performance certificate, which is a mandatory document when a building is constructed, sold or rented out.

Besides, The Directive 2010/31/EU of the European Parliament and of the Council (Directive, 2010) has been published as the up-to-date document which highlights new targets as a 20% reduction of energy consumption and emissions, and 20% introduction of renewable energy use in buildings until 2020, in comparison with 1990. Additionally, all new buildings should be designed as nearly zero energy buildings by 2020, according to EPBD Recast.

In Turkey, the regulation is published in December 2008 in Turkey as “Regulation for Building Energy Performance” (BEP, 2009), in order to set a strategy and methodology to run the project of the national calculation methodology for building energy performance certification, putting into order the main requirements of the certification procedure and the general boundary of the scope of the certificate. The methodology (BEP-TR, 2010) is based on simple hourly dynamic method as defined in “EN ISO 13790:2008 – Energy performance of buildings – Calculation of energy use for space heating and cooling” (EN 13790, 2008). The methodology represents a simple reference building for Turkey defined by the same geometry and orientation as the estimated building but with thermal envelope properties and mechanical requirements limited by standards such as “TS 825 Heating Energy Conservation Standard for Buildings” (TS 825, 2008).

Life cycle cost, whole-life cost, global cost are the commonly used terms in order to define the cost performance of buildings. In general, these terms include the recurring (operating costs, maintenance costs, etc.) and non-recurring costs (investment costs, installation cost, remaining value, etc.) in order to represent the overall cost of an idea, design or project. Life cycle cost method is especially used when several alternatives with the same performance levels having different initial and operating costs are compared and analyzed.

EPBD Recast accompanies new provisions such as cost optimal energy performance levels of buildings which is based on the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. (Regulation, 2012), published in January 2013, provides clarification to the calculation of building energy related costs. Regulation (2012) refers to the EN 15459-1:2017, which is a part of a series of standards representing the methodology for the energy performance assessment of buildings. EN 15459 (2017) is based on the global cost, which is the sum of the present value of the initial investment costs, annual running costs, replacement costs and disposal costs.

Moreover, new revision of EPBD (2018) levels the targets as short-term (2030), mid-term (2040) and long-term (2050) objectives. According to these steps, greenhouse gas emissions should be reduced at least 40% by 2030, and 80-95% by 2050. Besides, a highly energy efficient and decarbonized building stock is targeted by 2050, including the cost-effective transformation of existing buildings and design of new buildings as nearly zero-energy buildings.

On the other hand, while decarbonizing the building stock and designing new nearly zero-energy buildings, investments are required with a great effort and well-balanced decisions. These investments and decisions also have a great impact on the whole life carbon emissions and environmental impact of the building. Herein, the importance of considering not only the building, but also the investments' carbon emissions and environmental impact comes into prominence.

Environmental impact has been in discussion and evaluation since 1960s. By the publication of the National Environmental Policy Act (NEPA, 1970), the environmental impact assessment obtained a formal status. In European Union, the European Union Directive (85/337/EEC) on Environmental Impact Assessments (Directive, 1985) is published on the assessment of the effects of certain public and private projects on the environment and amended in 1997 (Directive, 1997). Strategic Environmental Assessment (SEA Directive, 2001) is the enlarged Directive for the assessment of plans and programmes, which is now in force.

Thermal comfort is also a twentieth century discipline, focusing on the comfortable indoor environment in terms of thermal criteria. By the evolution of the space phenomenon and architectural theories and movements, occupancy became an important factor as an individual with ap hysical dimension in the design process. The thermal comfort model defined by Fanger (1970), is the most common method in order to evaluate the indoor condition of thermally well-being and satisfaction. ANSI/ASHRAE Standard 55, first published in 1966 (ASHRAE, 1966) is the standard to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space. Similar with ASHRAE Standard 55, EN 15251 and ISO 7730 also defines the thermal comfort criteria, conditions and methodologies for calculations of thermal comfort.

1.1 Research Objective

Building design comprises several decisions in different stages of the process. In this process, multiple stakeholders take part to make decisions on problem solving. Moreover, these decisions may require either multiple decision makers or multiple criteria to evaluate. Building design, as a process of decision-making, involves decision makers such as investors, property owners, designers, experts, etc. where each decision maker, form different points of view, targets the success of the project with different concerns on several dependent and independent parameters. The problem solving becomes more complex when there are more decision makers and more criteria. Therefore, a gap occurs in decision-making with multiple criteria in a building design.

Voluntary and mandatory environmental guidelines developed at the local, national, and international levels are increasingly applicable to building design and construction (Spiegel & Meadows, 2012). In general, knowing that the building is designed in accordance with the building code requirements or above the requirements provide safety in terms of building performance. For example, a strong structured building will stand to extreme loads such as earthquakes or windstorms, or a high-insulated building will perform better in cold climates in terms of thermal comfort. However, while providing the high degree of safety, it may not be feasible in other terms such as cost, environment, etc. So that, concerning the performance criteria of a design with an integrated approach has led to a paradigm shift in the field of building design. It is often no longer sufficient to simply conform to minimum requirements prescribed by building codes. Thus, performance-based design comes into prominence where multiple stakeholders work together to achieve the best solutions providing a balance between the decision criteria.

When high energy efficiency levels in building are targeted, conflicts may occur on the high amount of investments causing high costs, high amount of material and technology use and related higher environmental impact levels. By the increase on the building energy consumption levels worldwide, thermal insulation materials became one of the key applications for building energy efficiency. When high performance buildings are targeted, the thermal insulation materials become more significant, due to thicker applications of the material, so as with higher costs, higher environmental impacts. Besides, higher comfort levels are also expected as a feedback of those intensive efforts. Thus, determination of the proper thermal insulation material and its properties for a high performance building is a multiple criteria decision-making problem, since the thermal insulation materials are significant with their impact on the energy, cost, thermal comfort, and environmental performance of a building.

In this research, it is aimed to find answers on how to fill the multiple criteria decision-making gap on building material selection. It is foreseen that a proper multiple criteria decision-making, with multiple environmental and economic attributes, ensures higher performances for buildings. Thus, the main aim of the study is to propose an approach in order to increase the building performance.

The proposed approach is applied to a residential building archetype, since there is a huge residential building stock and high amount of new buildings are introduced to the building stock every year. The percentage of new residential buildings between 2002 and 2012 is around 86% (nearly 900.000 buildings in the last 10 years), with 24% of one dwelling buildings and 62% of 2 and more dwelling buildings, as given by Tüik (TUIK Report). These values increase the importance of residential buildings on energy consumption reduction targets.

Many studies on existing residential building stock analysis are introduced to the literature. The stocks have been analysed according to the climatic zone, construction year, type and form of the buildings, etc. In Turkey, residential building stock has a wide range of variability in terms of construction technology, shape, adjacency, number of floors and number of apartment units per floor Thus, the study is limited with social housings in Turkey, where the number of social housing units are represented with 10% within the total residential stock as given in Figure 1.4. The analysis are limited with the building construction year (from 2002 to 2012) due to the construction technology difference based on earthquake regulations and available statistical data.

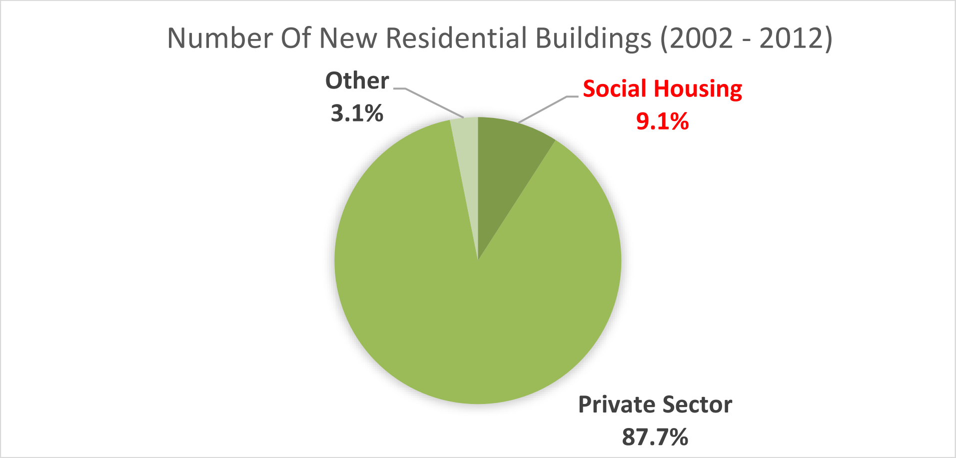

Figure 1.4 : Percentage of social housing represented in existing residential building stock between 2002 and 2012 (TUIK Report).

Distribution of the number of social housings within 10 years is given in Figure 1.5. In addition to 500.000 social housing units built between 2002 and 2012, 700.000 new social housing units are targeted to be built until 2023.

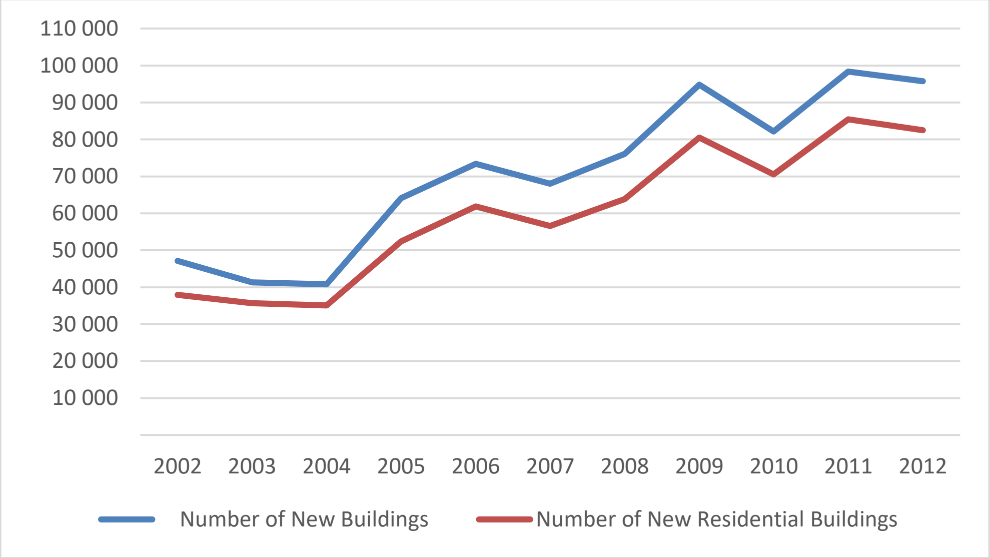

Figure 1.5 : Distribution of number of social housing units into years *(TUIK Report).*

Throughout the researches on the current social housing projects, it was observed that 4 apartment/floor plan scheme is one of the most common plan configuration within the whole social housings. Thus, in this study, an archetype which has a 4 apartment/floor plan scheme was designated. Some examples of 4 apartment/floor social housing plans are given in Figure 4.4 below.

Figure 1.6 : Typical 4 apartment/floor social housing plans.

In this study, "high performance" is evaluated in terms of energy, cost, thermal comfort, and environmental impact. Thus, the aim and scope of the study, beyond the cost optimal energy efficiency, is an approach proposed for performance based decision-making method covering the energy, cost, thermal comfort, and environmental performances.

Within this context, the approach of the methodology presented in this study includes the following main steps:

- Determination of the archetype
- Parameterization with the designated independent variables
- Calculation of the dependent variables
- Implementation of the multiple criteria decision-making
- Determination of the best alternatives through the decision-making scores.

Each step of the methodology has its own sub steps that are defined in methodology section of the thesis. Determination of the archetype is explained in section 4.1 based on statistical analysis. In section 4.2, parameterization of the base case with the designated independent variables is given. Calculation of the dependent variables (performance criteria) are explained in section 4.3.1, 4.3.2, 4.3.3, and 4.3.4 for energy, cost, thermal comfort and environmental impact, respectively. Finally in section 4.4, the proposed multiple criteria decision-making model is presented.

1.2 State-of-the-Art

Thermal insulation materials, with its several properties such as thermal conductivity, fire protection, mechanical strength, robustness, water resistance, environmental impact, etc., have a great impact on the overall performance of buildings. It is known that, there exists no insulation material that can provide all crucial requirements at the maximum level. Therefore, it is important to determine the crucial requirements and its limitations and impact on the performance of the building.

The literature review on the subject is studied in two parts as impact of thermal insulation material on building performance and decision making on high performance building design. An extensive literature review is made to observe and find out the current knowledge as well as the theoretical and methodological data. Since a gathered state-of-the-art is presented in this section, the collected data has a great efficacy on the overall study.

1.2.1 Impact of thermal insulation material on building performance

By the increasing actions on the energy efficiency of buildings, thermal insulation materials have become one of the key applications in promoting the energy efficiency of housings. By the progress in the thermal insulation material industry and material properties, the influence of thermal insulation on building energy performance has still been investigated in recent researches (Mohsen and Akash, 2001; Dombaycı et al, 2006; Tettey et al, 2014a; Tettey et al 2014b; Aditya et al, 2017; Braulio and Bovea, 2017; Lee et al, 2017; Lucchi et al, 2017; Menyhart and Krarti, 2017; Nematchoua et al, 2017; Simona et al, 2017;).

Mohsen and Akash (2001) emphasized the lack of insulation in residential buildings of Jordan’s urban areas. They calculated and pointed out that energy savings in heating, of up to 76.8% can be achieved with wall and roof insulation with polystyrene in a typical single house. Additionally, orientation and glazing approaches were also investigated in order to maximize the solar gains during winter. This study represents an example of evaluating the thermal insulation material through single performance criteria as energy performance such like Simona et al (2017), where they studied on increasing energy efficiency in collective residential buildings by applying a further insulation on the outher surface of the walls.

Rakhshan et al (2013) emphasized the fact of real estate focusing on reducing costs, while neglecting long-term operational considerations such as environmental, economic and energetic points. Besides, higher initial investments can reduce the carbon footprint and greenhouse gas (GHG) emissions of buildings, while requiring more insulation materials. In their study, they also included the embodied energy and GHG emissions associated with the full lifecycle of EPS insulation material on a two-story semi-detached villa case study in Dubai.

Tettey et al (2014a & 2014b) studied a cold climate region and calculated the primary energy for the production of insulation materials and their impact on the primary energy for operation of Swedish building code level insulated cases and passive house case. They also highlight that as more stringent energy-efficiency standards are introduced and high performance buildings are built, more attention must be paid to the choice of building materials such as thermal insulation.

Aditya et al. (2017) presented a wide review on insulation materials and discussed potential reductions on energy consumption and emissions in buildings through the application of proper insulation materials. They state that *"by increasing the insulation thickness the thermal conductivity will be reduced, while the insulation cost will be increased until it exceeds the savings, which this additional thickness will not bring any economic benefit. Therefore, the optimum insulation thickness exists where the savings start to drop by increasing the thickness of insulation. Building insulation is also by means an energy saving method as well as reducing negative environmental impact of the greenhouse gas the buildings emit."*

Braulio and Bovea (2017) studied the thickness optimization of envelope insulation materials and found out that 40% reduction in energy demand can be achieved by the optimum insulation compared to regulations.

Nematchoua et al (2017) calculated the optimum insulation thickness, energy saving and payback period for buildings in Yaounde´ and Garoua cities, located in two climatic regions in Cameroonpoint. They found out that, wall orientation had a significant effect both on the optimum insulation thickness and on energy savings. In equatorial region (Yaounde´), for south orientation, the optimum insulation thickness was 0.08 m for an energy savings of 51.69 \$/m2. Meanwhile, in tropical region (Garoua), for north orientation, the optimum insulation thickness was 0.11 m for an energy savings of 97.82 \$/m2.

The studies conducted for Turkey and their key findings are as below:

Dombaycı et al (2006) studied the subject with two performance criteria as life cycle cost and energy savings through different insulation materials and energy sources for Denizli. They found out that when the optimum insulation thickness is used for polystyrene, the life cycle saving and payback period are 14.09 \$/m^2 and 1.43 years, respectively.

Moreover, Ucar and Balo (2009) calculated the energy savings over a lifetime of 10 years and payback periods for four different climate zones of Turkey through five different energy types and four different insulation materials. Optimum insulation thickness is found as between 1.06 and 7.64 cm and energy savings between 19 \$/m2 and 47 \$/m2, and paybac periods between 1.8 and 3.7 years.

Özel (2012) also conducted a study to find the optimum thickness of thermal insulation for Elazığ, the cold climate region of Turkey, for 20 years lifetime. According to the results, the range of optimum insulation thickness varies between 5.4 and 19.2, with energy saving between 86,26 and 146,05 \$/m^2, and payback period between 3,56 and 8,85 years.

Afterwards, Ekici et al. (2012) studied the optimum insulation thickness for different external wall types in four different climate regions of Turkey. Optimum insulation thicknesses, energy savings and payback periods were calculated as 0.2 to 18.6 cm, 0.038 to 250.415 \$/m2, and 0.714 to 9.104 years, respectively, depending on the insulation material, city,, fuel type and cost.

Another study conducted by Özel et al. (2015) focused on rockwool and glasswool insulation materials. They calculated the optimum insulation thickness through environmental impact as between 0.15 and 0.064m for glasswool and rockwool and through life cycle cost as between 0.012 and 0.007 m for glasswool and rockwool, respectively.

1.2.2 Decision making on high performance building design

Previous literature review studies on decision-making methods and applications exist, from different point of views. Some studies present a general overview of decision-making methods applied on a wide range of subjects (Huang et al, 1995; Zhou et al, 2006; Huang et al, 2011; Cinelli et al, 2014; Wang and Poh, 2014; Mardani et al, 2015), some are focused on a specific decision-making method applied on several subjects (Behzadian et al, 2010; Behzadian et al, 2012; Russo and Camanho, 2015; Stefano et al, 2015; Govindan and Jepsen, 2016), where the others handle the subject as decision-making method(s) used only on a specific area such as energy planning, energy supply, renewable energy systems, building design, construction, etc. (Pokehar and Ramachandran, 2004; Loken, 2007; Wang et al, 2009; Macharias et al, 2014; Jato-Espiro et al, 2014; Strantzali and Avarossis, 2016). This part of the literature review focuses on the previous studies where decision-making methods are used for decision-making on high performance building design.

Mela et al. (2012) present 6 different multiple criteria decision-making methods, applied on 3 cases as office building, hall design and single family residential house. The Pareto optimal results of cases are collected from previous studies and analysed in order to select the best option within the optimal alternatives. It is discussed in this paper with the advantages and required attentions for different methods, and highlighted that, from the point of view of additional information required, the simplest method for the user is PEG, since it does not need any preference data form the decision maker such as weights of the multiple criteria that are evaluated.

Zavadskas et al. (2013) applies 3 multi-criteria methods (WSM, WPM, and WASPAS) on assessment of facades. Four facades’ alternatives in terms of twelve criteria, involving physical, structural, economic, environmental and performance properties, were evaluated. They analysed that WASPAS is the most suitable method for the structure of the decision matrix and sandwich panel façade is the best alternative. Additionally, they compared the findings with a multiple objective optimization model and the best ranked alternative decisions coincided in the current case and “sandwich” I panels were preferred.

Motuziene et al. (2016) investigated 3 envelope alternatives for a single-family house in terms of cost, energy use, greenhouse gases and ozone layer depletion. In order to find the most rational alternative, the AHP and COPRAS methods have been applied.

Blondeau and Allard (2002) presents a multi-criteria analysis of ventilation on a university building during summer period. Possible actions are investigated by ELECTRE and MAUT in terms of thermal comfort, indoor air quality and energy consumption.

Several papers on building performance related studies by using decision-making methods, are investigated and summarized in Table 1.1. In some studies only one single method is applied for the analysis [Hopfe et al, 2013; Hsieh et al, 2004; Shu et al, 2010; Alwear and Clements-Croome, 2010; Arroyo et al, 2016; Woo and Menassa, 2014; Akadiri et al, 2013; Rey, 2004; Roulet et al, 2002; Kim et al, 2014; Lapinskiene and Martinaitis, 2013; Kaklauskas et al 2006), where some other used multiple methods (Mela et al, 2012; Zavadskas et al, 2013;Motuziene et al, 2016; Blondeau and Allart, 2002) in order to make a comparison between the methods and the applicability of the methods on the structure of the cases.

It is shown the commonly used decision-making methods used on this topic and highlights the methods which are most commonly used in the last decade.

According to this analysis, AHP is the most common method used for building related studies such as; building performance assessment (Hopfe et al, 2013), planning and design tender selection (Hsieh et al, 2004), HVAC system decision-making (Shu et al, 2010 , Arroyo et al, 2016), sustainable building indicators (Alwear and Clements-Croome, 2010) building retrofit analysis (Woo and Menassa, 2014), construction solution selection (Motuziene et al, 2016) material selection (Akadiri et al, 2013), etc.

(Hsieh et al, 2004) focuses on selection of planning and design alternatives of public office buildings by using Fuzzy AHP method considering multiple criteria from building layout to system requirements. (Wong and Li, 2008) used an AHP survey method to assign the important weightings of the criteria for selection of intelligent building systems. In (Shu et al, 2010), a decision-making of district cooling and heating systems for blocks of buildings in cold climate is investigated by using AHP method. In (Alwear and Clements-Croome, 2010), a consensus-based model (Sustainable Built Environment Tool- SuBETool), which is analysed using the analytical hierarchical process (AHP) for multi-criteria decision-making is used for assessing sustainable intelligent buildings. A general building performance assessment (cost, indoor temperature, overheating, floor area, space height, energy consumption, etc.) is studied in (Hopfe et al, 2013) through an AHP method under uncertainty. Akadiri et al. (2013) focused on the selection of sustainable materials for building projects by using AHP. They evaluated the material alternatives in terms of environmental impact, life cycle cost, resource efficiency, waste minimization, performance capability and social benefit. (Woo and Menassa, 2014) developed a model for retrofitting of commercial building stock and used AHP for evaluation of a number of HVAC alternatives, regarding cost, time, quality and environmental issues.

2. PERFORMANCE BASED BUILDING DESIGN APPROACH

Performance can be explained as the ability to perform something, or the fulfillment of an obligation or a claim. Arguably, the design goals of firmitas (being durable and remain in good condition), utilitas (being of use and function well for the people using it), and venustas (being delightful and raising the spirits of people) have existed at least since Roman Architect Vitruvius wrote about them in 15 BC in his book De Architectura (Vitruvius, 1960). Yet, until the last several decades, these Vitruvian virtues have been recognized mainly at an intuitive level, rather than measured in any systematic way. (Mallory-Hill, Preiser,Watson, 2012)

Building's physical properties and qualities plus possible functional qualities become performance metrics, which are predictable during design and controllable during and after construction. The difference between properties and qualities is quite subtle. The first do not reflect a graded judgement whereas the second do (Hens, 2011). For example, thickness of a material is a property, but the thermal conductivity of the material figures as a quality.

Performance requirements turn the functional demands into the engineering metrics. These metrics are predicted during design, when the building exists on paper, which is why calculation, computer simulation and prototype testing are used (Hens, 2011).

In the nineteen seventies, a Belgian inter-industrial study group wrote a first 'Performance Guide for Buildings', which today can be seen as an early trial to produce coherent sets of performance-based specifications (Hens, 2011). The metrics given below were based on the functional demands advanced by ISO DP 6241;

1. Structural integrity
2. Fire safety
3. Safety at use
4. Tightness (water and air)
5. Thermal comfort
6. Indoor air quality
7. Acoustical comfort

8. Visual comfort
9. Contact comfort
10. Vibratory comfort
11. Hygiene
12. Functionality
13. Durability
14. Economy

The building sector is important due to the intensive manufacturing process of building materials with several properties, content, purpose of the use, etc. Thus, the building performance is directly interrelated with the building sector's performance and its outcomes.

The international interest in a performance-based approach grew from the eighties on. Within CIB (International Council for Research and Innovation in Buildings) a working group 'Performance Concept in Buildings' was established. A real break-through came with the European CPD's (Construction Products Directive) which differentiated between six groups of functional demands (Hens, 2011):

1. Structural safety
2. Fire safety
3. Health, hygiene, environment
4. Safety at use
5. Acoustical comfort
6. Energy efficiency

In the framework of a research project by the International Energy Agency's Executive Committee on Energy Conservation in Buildings and Community Systems, performance metrics were proposed at different levels as building and building components as given in Table 2.1 and 2.2, respectively.

As given in Table 2.1 and 2.2, performance evaluation varies according to the level such as building, component, etc. However, performance of the building components directly affect the building performance. Thus, it is important to evaluate the performance with the indicators at different levels.

Table 2.1 and Table 2.2 present the performance metrics at the building level and building component level, respectively. There is also a great importance on the performance of the individual building materials. However, the independent performance of building materials are inadequate to determine and define the performance of the building. Thus, it is important to signify the performance at multiple and proper levels, whne necessary.

As observed from the Tables, building physics have a great importance within the whole performance metrics. Besides, a building can be measured in many ways. Mainly, there is a significant focus on the building energy performance and its related carbon footprint, nowadays.

Table 2.1 : Performance metrics at the building level.

Field		**Performances**
Functionality		Safety when used
		adapted to usage
Structural adequacy		Global stability
		Strength and stiffness against vertical loads
		Strength and stiffness against horizontal loads
		Dynamic response
Building physics	Heat, air, moisture	Thermal comfort in winter
		Thermal comfort in summer
		Moisture tolerance
		Indoor air quality
		Energy efficiency
	Sound	Acoustical comfort
		Room acoustics
		Overall sound insulation
	Light	Visual comfort
		Day-lighting
		Energy efficient artificial lighting
	Fire safety	Fire containment
		Means for active fire fighting
		Escape routes
Durability		Functional service life
		Economical service life
		Technical service life
Maintenance		Accessibility
Costs		Total and net present value, life cycle costs
Sustainability		Whole building life cycle assessment and evaluation

Table 2.2 : Performance metrics at the building component level.

Field		**Performances**
Structural adequacy		Strength and stiffness against vertical loads
		Strength and stiffness against horizontal loads
		Dynamic response
Building physics	Heat, air, moisture	Air tightness
		▪ Inflow, outflow
		▪ Venting
		▪ Wind washing
		▪ Indoor air venting
		▪ Indoor air washing
		▪ Air looping
		Thermal insulation
		▪ Thermal transmittance (U Value)
		▪ Thermal bridging
		▪ Thermal transmittance of doors and windows
		▪ Mean thermal transmittance of the envelope
		Transient response
		▪ Dynamic thermal resistance, temperature damping and admittance
		▪ Solar transmittance
		▪ Glass percentage in the envelope
		Moisture tolerance
		▪ Building moisture and dry-ability
		▪ Rain-tightness
		▪ Rising damp
		▪ Hygroscopic loading
		▪ Surface condensation
		▪ Interstitial condensation
		Thermal bridging
		▪ Temperature factor
		Others (i.e. the contact coefficient)
	Acoustics	Sound attenuation factor and sound insulation
		Sound insulation of the envelope against noise from outside
		Flanking sound transmission
		Sound absorption
	Lighting	Light transmittance of the transparent parts
		Glass percentage in the envelope
	Fire safety	Fire reaction of the materials used
		Fire resistance
Durability		Resistance against physical attack
		Resistance against chemical attack
		Resistance against biological attack
Maintenance		Resistance against soiling
		Easiness of cleaning
Costs		Total and net present value
Sustainability		Life cycle analysis profiles

In this part of the study, the energy, cost, thermal comfort and environmental impact are explained as the performance metrics. The theoretical information, definitions, and required data and information for the calculations used in the literature are given in the following sections.

In Section 2.1, the energy performance of buildings and its related information are presented.

Section 2.2 presents a detailed definition of terminology used in building cost performance calculations.

Thermal comfort and comfort performance calculation methods are given in section 2.3.

Section 2.4 includes information on environmental impact, impact of building materials and environmental performance evaluation methods.

Finally, in the Section 2.5, these performance metrics are discussed and evaluated in terms of building thermal insulation materials. Moreover, thermal insulation material categorization methods and detailed information on commonly used thermal insulation materials are presented in the Section 2.5, comprehensively.

2.1 Building Energy Performance

Buildings are domain energy consumers all over the world with around 40% of total energy consumption (EPBD, 2010). The energy used in buildings is mainly used in three processes, as construction, operation and demolishment. Operation process takes the longest phase along others with an average 30 years life span and holds the highest energy consumption for mostly heating, cooling and lighting, which are possible to be improved by decisions maker and especially architects, by designing a proper building in terms of form, orientation and envelope compatible with local climate conditions. Therefore, due to potential high energy conversation, many researchers have recently focused on building form, orientation and envelope according to local climate conditions as to redound energy consumption.

Building design figures as key factor in energy efficiency, among others because most parameters of influence are under the control of the design team (Hens, 2011). In other words, buildings' relation with environmental factors via orientation, form and envelope of building, which are determined in design process, sets the energy performance of the building.

In this section, these design principles and their relation with energy performance are discussed.

2.1.1 Building orientation

Orientation of buildings is a vital subject to determine surfaces’ and namely zones’ direction, and also collimate sun and wind effects on buildings. So that, in design process, decision makers should take local climate conditions and dominancy upon energy consumption withal into consideration to properly receive solar radiation, daylight and wind to the envelopes and the rooms.

Spanos et al. 2005 indicate that proper orientation, location of building and landscaping factors may potentially improve the energy performance by 20% with increasing contribution of solar radiation, daylight and wind to the zones. Moreover, building orientation is also crucial to constitute passive climatisation and lighting strategies in order to have higher energy efficiency from pre-supported lighting and HVAC systems.

Efficient building orientation may shift among climate zones, where dominancy on energy needs can alter entirely for buildings. Studies on energy efficiency conducting along northern hemisphere for regions with high HDDs indicate that best orientation of building is towards the south due to high solar radiation. Whereas, for regions with high CDDs the best orientation turns to between north and dominant wind direction.

2.1.2 Building form

Building form constitutes shape or configuration of a building through surfaces and spaces reciprocally. In other words, building form defines the compactness of the shape. The compactness of a building form equals the ration between the condition volume in m^3 and the envelope surface in m^2.

Reaction of a building against environmental conditions is mainly considered by designing of building form, in which exposure of sun and of wind on surfaces is determined as to have passive heating or cooling strategies, and so to decrease energy demands according to climate. Form of a building, namely, effecting on energy use, has been taken into consideration in many studies to ameliorate energy performance and interior comfort conditions (Alanzi et al, 2009; Catalina et al, 2011; Faizi e al, 2011; Fallahtaft, and Mahdavinejad, 2015). Building form as a passive response to local weather conditions is taken into consideration to improve energy efficiency with space configuration (Yeang, K., 2006). Building form, thereby, alters energy demand as building orientation and configuration of building envelope. Optimum form of buildings differs with each other in accordance with location, climate, function, spatial layout, and occupied hours etc. Studies on cold climate indicate that net energy demand for heating a space increases with a less compact building form, where all other parameters are equal. Therefore, compact forms are preferred to decline heat loss where heating loads are domain on energy use. Whereas, it is known that decision makers opt linear forms in order to benefit wind as to have ventilation and to decrease humidity, which causes uncomforted conditions.

2.1.3 Building envelope

The building envelope is perhaps one of the most interesting subjects with regard to multidisciplinary design. Envelopes have a major role in the building’s exposure to the elements; they have a great impact on energy efficiency and indoor environmental quality. Envelopes are also an important component in the building structure and are a big part of their budget (Echenagucia, Capozzoli, Cascone, Sassone 2015).

Some of the important measures used in the retrofitting process of the building envelope include: external walls’ insulation, windows’ glazing type, air tightness (infiltration) and solar shading (El-Darwish, Gomaa 2017).

In general, building envelopes include the resistance to air, water, heat, light, and noise transfer. As for thermal envelopes, they include outer walls, roof, foundation, windows and doors. The purpose of the thermal envelope is to prevent heat transfer form interior of a house to its exterior in winter and vice versa in summer. For instance, windows in educational spaces should be located at the sides and if subject to solar gain should be tinted glass with a ‘‘low E” rating to reduce heat transfer (El-Darwish, Gomaa 2017).

2.1.4 Climate

Climate is defined as a statistical combination of weather situation during a long period (minimum 20 or 30 years) for an issued place (Heerwagen, 2004). Whereas, weather can be introduced a collection of atmospheric phenomena on some place for a short period. Thus, climate comprises, as distinct from weather, not only average of air temperature, precipitation rates, wind speeds, and solar radiation intensities, etc. but also the frequency of specific occurrences, range of climatic values and the extreme values and the variability of climatic values or occurrences. Whereby, Climatic data is distinctly useful for decisions making on environmental control of buildings in order to design buildings in accordance with climatic requirements over the place.

2.1.4.1 Outdoor air temperature

Outside air temperature, one of the essential climatic data is taken into consideration for thermal behaviour of buildings. Outside temperature mainly varies according to the location, time and local environmental factors. Firstly, location initially determines degree of solar exposure to the earth according to distance between the location and equator, which rises the degree towards 90^o and temperature, while the location comes closer to equator. Secondly, there are two sort of temperature changes due to time, as daily and seasonal temperature changes. Daily temperature changes occurs while the world revolves around itself and then this movement varies relation between the location and sun. World revolves on its tilted axis as it orbits the sun. Therefore, the tilted axis shifts degree of sun exposure on northern and southern hemisphere according to the location of word on sun orbit. Thus seasons and seasonal temperature changes occurs. Lastly, local environmental factors varies outside air temperature as temperature differences occur between urban and countryside in the same time and the meridian. Moreover, Puddles such as seas, lakes, rivers etc. have explicit impact on local outside temperature so forests and altitude of the location do.

The name of climate in a region is generally designated through dominancy on outside temperature and humidity. They are subjects to handle with so as to generate comfortable zones for occupants. So that, the air temperature plays a significant role in the annual heating, cooling energy uses of buildings and indoor thermal comfort as well. The design principles to have sustainable buildings are varied to integrate passive systems and hybrid systems among climates.

2.1.4.2 Solar radiation

It is short wave electromagnetic radiation emitted by sun. Direct solar radiation, diffused solar radiation and reflected radiation constitute types of solar radiation, which are absorbed by buildings and, therefore, warm building elements and indoor air temperature as well. It is the main source to either heat building or support heating system via passive climatisation strategies.

Solar radiation directly effects the heat gains of a space or a building. These decrease the end energy needed for heating but increase the end energy needed for cooling (Hens, 2011).

2.1.4.3 Relative humidity and vapour pressure

Relative humidity is calculated according to the ratio between the pressure of water vapour and the equilibrium vapour pressure of water at the same temperature. Relative humidity (ϕ_e) and vapour pressure (ρ_e) impact the moisture response of building enclosures and buildings in a straightforward way. (Hens, 2011).

On the average, relative humidity remains constant between summer and winter, where the vapour pressure differs a lot. In temperate climates, the inverse occurs between day and night: large difference in relative humidity and quite constant vapour pressure (Hens, 2011).

A sudden temperature rise lowers relative humidity whereas a sudden temperature drop may push relative humidity to 100% with mist as result (Hens, 2011).

During rainy weather, the outside wet bulb temperature closely follows raindrop temperature. When as warm as air, 100% relative humidity will be measured (Hens, 2011).

2.1.4.4 Wind

The building envelope provides protection from the main elements such as heat, cold, rain, wind, etc. Wind affects the hydrothermal response of building enclosures. At local level, wind speed and wind direction get shaped by the built environment (Hens, 2011). For example, the surrounding buildings, trees, etc. can block the wind or the high-rise buildings may create a tunnel effect and change the direction or increase the speed of the wind. Moreover, the proper usage of wind by a proper design provides a natural ventilation advantage for the built space.

Arens and Williams (1997) explained the wind influences on building energy consumption in four ways as below:

- air infiltration and exfiltration

- surface heat transmission
- mechanical systems efficiency
- necessity for enclosing outdoor space.

Thus the pattern of the wind, the speed and the direction, is an important input for defining the climate of the region in micro and macro scale.

2.1.4.5 Precipitation

Precipitation is used to describe the amount of water precipitation at the region, climate or site over a unit of time. Precipitation may include both the rain and the equivalent content of snow (Energy Plus, 2015).

2.1.4.6 Typical meteorological year

The typical meteorological year (TMY) is a generated data from the weather data recorded for a long period. Commonly, depending on the sensitivity of the TMY, hourly or monthly data is used to generate a TMY. A typical TMY includes the informative data of dry bulb temperature, dew point temperature, wind speed, wind direction, total global solar radiation, direct radiation, diffuse radiation, etc.

TMY is used to estimate and assess the building energy consumption in a regular period. It is used by designers for decision making on building design, solar system design, etc. Since the TMY represents the typical situation of the climate, by removing the extremes, it can not be used for calculation the peaks.

2.2 Cost Performance of Buildings

Building costs are one of the most significant criteria in a decision making of a building design. When it comes to building, the main concern for the principal is the investment. Of equal importance, however less obvious because distributed over time, are the benefits generated, though not all can be translated into financial value. In terms of physical quality, the costs are the extra investments for better performance while the benefits are the advantages generated by the upgraded performance (Hens, 2011).

In a social housing design, costs become more significant due to the constraints on the project budget. On the other hand, considering the costs from the life cycle point of view is quite substantial in social housing systems in order to evaluate the advantages of the investments on the expected low-cost operation of the building. For this purpose, the methodology given in *"EN 15459 Energy performance of buildings – Economic evaluation procedure for energy systems in buildings."* Is used for the cost calculations of this approach.

EN 15459:2017 uses the global cost approach, which is based on the whole expenses during the life span of the building. According to EN 15459, global cost (CG) is calculated by equation (2.1), considering the sum of the initial investment costs (CO_{inv}), the present value of annual running costs, replacement costs (CO_a) and CO_2 emissions cost ($CO_{CO2(i)}$(j)) as well as disposal costs ($VAL_{ft_{TC}}t(j)$) within the calculation period (T) by applying discount rate ($D\_f(i)$). Then, the present value of residual value ($VAL_{fin(tTC)}$(j)) of the components are subtracted from the sum of costs to obtain the CG. Furthermore it is available to involve price development (RAT_{xx}(j)) of annual costs into calculation.

$$CG(T) = CO_{inv} + \sum_j \left[\sum_{i=1}^{TC} \left(CO_{a(i)}(j) * (1 + RAT_{dev(i)}(\mathrm{j})) + CO_{CO2(i)}(j)\right) * D\_f(i) + CO_{disp(TLS)}(j) - VAL_{ft_{TC}}t(j)\right] \tag{2.1}$$

As also stated in EN 15459:2017, depending on the objectives of the investor, the calculation method may be applied considering only selected specific cost items, systems or products. In the proposed approach, in order to obtain the cost performance of the alternatives, only the investment costs and the energy costs are considered. This allows a proper evaluation for an envelope analysis, on which the residual values, maintenance costs, etc. are not dominant and can be ignored.

2.2.1 Initial investment costs

Based on the EN 15459 description, initial investment cost (CO_{init}) is the cost incurred up to the building (or the building element) is delivered to the customer, ready to use. In other terms, initial investment costs are those that are presented to the customer as the design, material, construction, commissioning costs.

In the proposed approach, initial investment cost is the material and installation of the building elements that are evaluated for the decision-making. As aforementioned, the methodology presents a whole approach for the building envelope. Thus, the scope of the investment cost is considered as the whole cost of the envelope, including the opaque (wall) and the transparent (window) building elements.

2.2.2 Annual costs

Annual costs (CO_a) refer to the running costs, periodic costs or the replacement costs of building systems, elements in a certain year.

The annual costs (running costs of maintenance, operation and energy, periodic costs, and disposal costs) described in EN 15459 and their provisions in the proposed approach are explained and discussed below.

2.2.2.1 Running costs

Running costs (CO_{run}) include maintenance cost, operational cost and energy cost for the time step considered. Within the equation, all running costs of the n^{th} year are summed to be included in the annual cost (CO_a).

2.2.2.2 Maintenance costs

Maintenance costs (CO_{ma}).are representing the expenses due to the necessary cleaning, repair, adjustment, etc. in order to preserve and restore the desired quality of the building or building element.

In the proposed approach, the maintenance of the building envelope is ignored since it is considered that all alternatives will have similar requirements such as regular cleaning, re-painting, replacement of window insulation bands etc. that does not affect the building performance directly.

2.2.2.3 Operational costs

Operational costs (CO_{op}).are the expenses linked to the operation of the building, including annual costs for insurance, utility charges and other standing charges and taxes (EN 15459:2017).

Operational costs are commonly interest of the whole building approaches. Since only the building envelope is evaluated, operational costs are excluded in this approach.

2.2.2.4 Energy costs

Energy costs (CO_{en}) are the costs based on the energy consumption and the tariff of the energy source as well as the fixed and peak charges and national taxes. The costs mostly consists of electricity and natural gas bills to ensure indoor comfort conditions for user in terms of illumination, cooling, heating and ventilation.

2.2.2.5 Periodic costs

Periodic costs ($CO_{per(i)}$).substitute the necessary replacement costs for components or systems that occur on year I, for age reasons.

Within the whole building envelope approach, all required replacements are considered under the maintenance costs, since these replacements are not related with main building elements but the small parts of them. Thus, period costs are excluded from the scope of the proposed approach.

2.2.2.6 Disposal costs

Disposal costs (CO_{disp}) refer to the cost for deconstruction at the end of life of a building or building element. It also includes the removal cost of the building elements that have not yet come to the end of their lifetime, transport and recycling.

2.2.3 Cost of green house gas emissions

Cost of greenhouse gas emissions is used to represent the monetary value of environmental damage caused by CO_2 emissions related to the energy consumption in buildings. In this content, CO2 emissions encounter effects of all greenhouse gases weighted with their global warming potential expressed as an equivalent to CO_2 during a 100 year period (EN 15978).

In Turkey, the CO_2 taxes and expenses are not defined yet. Thus, in the proposed approach, the environmental impact of the building elements and systems are calculated as a I performance index and evaluated in the decision-making approach.

2.2.4 Residual (final) value

From the building envelope point of view, it is considered that all elements come to end of their lifetime within 30 years. Besides, there exists an amount of residual value of the envelope elements such as glazing. On the other hand, the compared alternatives does not have a significant different in terms of residual value. Thus, residual value are excluded in the scope of the proposed approach.

2.2.5 Payback period

Payback period (PB) is the time when the investment costs are balanced with the monetary savings occurring (EN 15459: 2017). Payback period is an important determinant, as longer payback periods signify economically unfeasible investments, where shorter payback periods makes the investment more desirable from the investor point of view.

In (EN 15459:2017), the payback period presents the time when initial investment is expected to be recovered compared to a reference situation. The proposed approach in this study makes the comparison of alternatives to the reference case which is the current requirement level.

When there is not a significant influence of replacement costs on the annual costs, the discounted payback period is calculated with the equation (2.2) below.

$$PB = \ln\left[\frac{1}{\left(1-\frac{\left(CO_{init}-CO_{init,ref}\right)*RAT_{disc}}{CF}\right)}\right].\frac{1}{\ln(1+RAT_{disc})}\ [year] \qquad (2.2)$$

2.2.6 Economic parameters

2.2.6.1 Inflation rate

Inflation rate (RAT_{inf}) is the increase rate of the prices over a defined time, which causes a decrease on the purchasing value of the money.

2.2.6.2 Actualization rate (Market interest rate)

Actualization rate (RAT_{act}) is the inflation of the money placed on the market. The reference actualization rate is declared by the Commissions yearly.

2.2.6.3 Real discount rate (Real interest rate)

The real discount rate (RAT_{re}) is the actualization rate reduced from the inflation rate. Real discount rate can be expressed by the equation (2.3) below, when the 30nalyzing rate and actualization rate are low and close to each other. Otherwise, it is advised in the literature to use the equation (2.3) in order to obtain more accurate results.

$$RAT_{re} = RAT_{inf} - RAT_{act} \tag{2.3}$$

2.2.6.4 Discount rate

Discount rate (RAT_{disc}) is the definite value for comparison of the value of money at different times expressed in real terms (EN 15459:2017). Practically, discount rate is the real interest rate that is charged to commercial and national banks. In this methodology, discount rate is considered equal to the real discount rate.

2.2.6.5 Discount factor

Discount factor (D_f_i) is a multiplicative number which is used to convert a cash flow occurring at a given point in time (year i) to its equivalent value at the starting point and which is derived from the discount rate (EN 15459:2017).

The discount factor for a given period (year), based on the number of years "i" and the discount rate (RAT_{disc}) is calculated by the equation (2.4) below.

$$D\_f_i = \left(\frac{1}{1+ RAT_{disc}}\right)^{i} \tag{2.4}$$

2.2.6.6 Present value factor

The present value factor ($f_{pv}(n)$), calculated by equation (2.5) is used to transform the sum of n^{th} year annual costs to the present value. Discount rate is used in the calculations,

$$PVAL\_f_{t_{TC}} = \frac{1-(1+RAT_{disc})^{-t_{TC}}}{RAT_{disc}} \tag{2.5}$$

2.2.6.7 Price development rate / / Price escalation rate

Price development rate (RAT_{dev}) is introduced to represent the development of prices over time, such as energy, product, system, labour, etc. prices, as those prices may be different from the inflation rate. Besides, energy price development rate may also differ between different energy sources such as electricity, natural gas, etc.

The evolution of annual costs are included in the EN 15459:2017, as one of the main updates of the Standard. So that, the calculation of the costs at year *n* should be based on the evolution rate for that specific cost, where the evolution rate of the cost category is different from the inflation rate. The evolution rates also takes place in (NIST, 1995) as the “price escalation rate”.

2.3 Thermal Comfort Performance of Buildings

Building performance has been evaluated through the centuries with different concerns. Up until the last decades, technical and aesthetic merit were the significant indicators for the building quality. Thus, stakeholders of the building design process were qualified on these topics. Today, it is known that the built environment has an impact on its users in terms of behaviour, perception, etc. that constitutes the user comfort. In this section, one of the most important comfort indicators, the thermal comfort, is investigated and discussed.

Feeling comfortable is typically defined as a condition of mind that expresses satisfaction (Hens, 2011). From the thermal comfort point of view, thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55).

2.3.1 Parameters effecting thermal comfort

Thermal comfort depends on both environmental and personal parameters. The thermal environment can be expressed by its environmental parameters as air temperature, radiant temperature, air velocity and relative humidity. Besides, being thermally comfortable vary greatly between individuals depending on the personal parameters as clothing level, activity level (metabolic rate), age, gender, etc. Table 2.3 presents the parameters that are considered for thermal comfort evaluation. The parameters are defined in detail in the following sub sections.

Table 2.3 : The ASHRAE thermal sensation scale.

Indoor environmental parameters	Personal parameters
Air temperature	Clothing
Radiant temperature	Metabolic rate
Air speed / velocity	Age – Gender
Relative humidity	

2.3.1.1 Indoor environmental parameters

As given in Table 2.3, the indoor environmental parameters affecting the thermal comfort are such as air temperature, radiant temperature, air speed or velocity, and relative humidity, as described here.

Air temperature

The air temperature, also known and used as dry-bulb temperature, is the average temperature of the air within the space that is surrounding the occupant. The temperature is measured with a dry-bulb thermometer.

Radiant temperature

The radiant temperature (mean radiant temperature) is related with the temperature and emissivity of the surfaces based on the view factor (amount of the surfaces affecting) around the occupant. So the mean radiant temperature represents the mean average value of the surface temperatures that are in contact with the occupant body by radiant heat transfer.

Air speed (velocity)

The air speed it is the average speed of the air to which the body is exposed, with respect to location and time (ASHRAE 55:2017). Air speed directly affects the amount of heat transfer through the skin.

Relative humidity

Relative humidity is the amount of water vapour in air expressed with the percentage (% 0 – 100). Humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy, however, long term high humidity indoors will cause microbial growth, and very low humidity (EN 15251, 2007).

Either High or low relative humidity can cause occupant discomfort into a building. For example, in summer conditions human body perspire to exhaust surplus heat from body by evaporating to cool body, whereas high relative humidity lows evaporation of perspiration on the body. Therefore, the body, at high humidity, impose higher distress of surplus heat then at lower humidity.

2.3.1.2 Personal parameters

The main personal parameters affecting the sensation of thermally comfort are as clothing level, metabolic rate or the activity level, age, gender, etc. as described here.

Clothing level (clo)

Clothing level describes the thermal insulation level occurring by the clothes worn by a person. The clothing level, represented by the unit (clo), directly affects the heat loss through the body. 1 clo is equal to 0.155 m^2K/W (0.88°F·ft^2·h/Btu), which corresponds to trousers, a long sleeved shirt, and a jacket.

Metabolic rate /activity level (met)

The metabolic rate of people is related with their activity level such as sleeping, walking, running, etc. The term basic metabolism ($M_o \approx 73$ W) relates to the energy needed by a 35 years old male, 1.7 m tall, weighting 70 kg, who is sleeping in a thermally neutral environment, 10 hours after his last meal. When waking up, metabolism increases A metabolic rate (M_A) of 58 W per m^2 body surface is called 1 *met* (Hens, 2011). Table 2.4 presents the metabolic rates of different activities.

Table 2.4 : Metabolic rates (ASHRAE 55).

Activity	Metabolic rate (M_A) W/m^2	Heat produced W
Sleeping	41	41
Lying	46	46
Sitting	58 (=1 *Met*)	58
Standing	70	70
Teaching	93	93
Studying	78	78
Cooking	96 – 116	96 – 116

Age, gender, etc.

The perception of comfort also vary between different age, gender and genetic diversities.

2.3.2 Comfort evaluation models

Using the words of the European standard EN 15251: “An energy declaration without a declaration related to the indoor environment makes no sense. There is therefore a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings”. Thus, the specification about thermal comfort objectives that a building must achieve is a prerequisite for its design (Attia and Carlucci, 2015).

Within the literature, there are different thermal comfort evaluation models. The commonly used models are the PMV model and the adaptive model. These models are defined by standards such as “ANSI/ASHRAE Standard 55:2017 Thermal Environmental Conditions for Human Occupancy” (ASHRAE 55) and “EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics” (EN 15251).

PMV model is commonly applied for mechanically conditioned spaces, where the adaptive comfort model is more applicable for spaces such as naturally conditioned or ventilated.

In the proposed approach of this study, Fanger method is applied to evaluate the thermal performance of the spaces. The method developed by Ole Fanger is based on the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) levels defined. The detailed definition of the method is given in section 2.3.2.1 below.

2.3.2.1 Predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD)

The statistical approach that was developed by P. O. Fanger combines three concepts:

1. The Load (L). Equals the difference between the metabolic heat produced and the heat lost. The larger the load, the more the conditions drift away from a comfortable situation. A negative load marks environments that are colder than desired for a given activity and dress. A positive load instead marks environments that are warmer than desired for a given activity and dress. A load zero marks environments that fit with the comfort equations for a given activity and dress (Hens, 2011).
2. The Predicted Mean Vote (PMV).

   The thermal comfort level is characterized using the thermal sensation scale given in Table 2.5. According to this scale, “0” represents the neutral sensation, where the + (1-3) range represents the warmth and – (1-3) represents the cold.

$$PMV = [\, 0.303 \exp(-0.036\, M_A\,) + 0.28]\, L$$

$$\text{If } PMV > 3, \text{ then } 3, \;\text{ if } PMV < -3, \text{ then } -3 \qquad (2.6)$$

Table 2.5 : The ASHRAE thermal sensation scale.

Vote	Thermal sensation
3	Much too warm
2	Too warm
1	Slightly warm
0	Neutral
-1	Slightly cold
-2	Too cold
-3	Much too cold

The predicted percentage of dissatisfied is a non-linear function of PMV as given in equation (2.7), below.

$$PPD = 100 - 95\exp[-(0.03353\ PMV^4 + 0.2179\,PMV^2)\,] \tag{2.7}$$

2.4 Environmental Impact Performance

Life Cycle Assessment (LCA) is a methodology, which is used to assess the environmental impacts of products, processes, services, etc. LCA allows measuring the environmental impact of materials through some indicators such as:

- Cumulative Energy Demand (CED): The primary energy consumed directly and indirectly during the considered life cycle of the material or product.
- Global Warming Potential (GWP): The impact to the global warning through gas emissions in terms of kilograms of CO_2 equivalent. Burning fossil fuels produces CO_2, ≈ 1.75 kg per m^3 gas and ≈ 2.8 kg per litre oil or kg coal. Once in the atmosphere CO_2, just as water vapour, CH_4, NO_2, SF_6 and all CFC’s, absorbs the terrestrial and solar infrared radiation and re-emits both, half of it back to the earth. There, the infrared maintains the moderate temperatures needed for life. However, when the concentration of global warming gases increases, the re-emitted infrared also augments, resulting in a slow increase in terrestrial mean temperature: the global warming effect (Hens, 2011).

There are three commonly used approaches that are used to perform LCA:

- Cradle to cradle: considers the overall stages starting with the product stage and including the use stage, reuse-recycle stages, etc.

- Cradle to grave: evaluation performed taking into account the entire life cycle of the product/service, from the extraction of the raw materials to the disposal of the product (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016).
- Cradle to gate: the analysis does not consider the life of the product/service after the transportation to consumers, i.e. the use phase and the disposal (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016).

For the evaluation of the LCA indicators, a functional unit, f.u., is used. The functional unit for the assessment is defined as mass (kg) of insulation material needed to cover a 1 m^2 area at a thickness providing an average thermal resistance (R value) of 1 m^{2}K/W for a building service life of 60 years. The functional unit (f.u., kg) can be expressed as (Biswas, Shrestha, Bhandari, Desjarlais, 2016),

$$FU = R\,.\,\lambda\,.\,\rho\,.\,A \tag{2.8}$$

Where R is the unit thermal resistance (1 m^{2}K/W), λ is the thermal conductivity (W/mK), ρ is the density (kg/m^3), and A is a unit area (1 m^2).

2.5 Building Thermal Insulation for High Performance Building Design

Thermal insulation is the reduction of heat transfer between objects in thermal contact or in range of radiative influence (Url-2). Thermal insulation materials, achieved with specially engineered methods or processes with suitable materials, are used in buildings in order to reduce the heat transfer through the envelope. Application of thermal insulation materials is an efficient method for reducing energy consumption in buildings, especially where the heating energy is dominant.

Thermal insulation materials became significantly used in buildings after 1950s, due to the high consumption of non-renewable energy sources and the fact of depletion of resources in the mids of 21st century (Toydemir, Gürdal & Tanaçan, 2000). Thus, energy efficiency in buildings have come to the agenda and thermal insulation became the key action in regulatory applications.

Buildings influence the Earth directly and indirectly in many ways. Spiegel & Meadows (2012) exemplifies this influence as follows:

- Buildings influence the Earth directly through their use of resources.

- They work directly on the quantity and quality of the Earth's resources – the amount they use and the degree to which they contaminate what they use.
- Buildings impact the Earth directly through their performance and through their effect on the performance of adjacent structures.
- Buildings impact the Earth indirectly through design decisions that help drive the market.

Thermal insulation materials, by their usage of resources, by their impact on the environment, and by their effect on the building energy consumption, influence the Earth either directly and indirectly. Moreover, the selection of the thermal insulation material, decisions on the thermal insulation material application has a great impact on the investment and life cycle cost of the building. Therefore, the multi-attribute structure of thermal insulation materials requires a proper decision making process during the building design.

In this part of the study, thermal insulation materials are analysed through their properties, classifications, and commonly used materials are introduced.

In section 2.5.1, thermal insulation materials are analysed according to their main properties such as thermal, moisture, air, fire, mechanical behaviours and environmental characterizations. The classification of thermal insulation materials according to their structure is presented in section 2.5.2. Finally, conventional thermal insulation materials and new innovative thermal insulation materials are introduces in section 2.5.3 and 2.5.4, respectively.

2.5.1 Thermal insulation material properties

Thermal insulation materials, as not having a history as long as other materials, but has a necessity of usage as long as the history of humanity. Bozasky (2010) stated that, people have built shelters to protect themselves from the elements, originally using organic materials and later more durable substitutes. However, people discovered and introduced many materials that are suitable for insulation, besides the organic materials. Processing organic materials produced the first insulated panels in the 19th century: meanwhile an increasing range of artificial materials were developed (rock wool, 38nalyzing38, foam glass, hollow bricks, expanded perlite).

Materials can be evaluated according to their properties. (Hens, 2012) categorizes the material properties according to their thermal properties as in Table 2.6.

Within a building with a traditional construction of concrete frame and brick walls, the most significant materials with different properties are the thermal insulation materials. A material is called ‘insulating’, when its dry apparent thermal conductivity does not pass around 0.07 – 0.10 W/(m.K). Thus, the thermal behaviour of the insulation material, besides its mechanical, fire, etc behaviours, is the most significant attribute to be discussed.

Table 2.6 : Array of thermal, hygric and air-related material properties (Hens, 2012).

	Heat	**Moisture**	**Air**
Storage	Specific heat capacity c Volumetric specific heat $c\rho$	Specific moisture ratio ξ Specific moisture content $\rho\xi$	Specific air content c_a
Transport	Thermal conductivity λ Thermal resistance R Absorptivity α Emissivity e Reflectivity r	Vapour permeability δ Vapour resistance factor μ Diffusion thickness μd Moisture permeability k_m Thermal moisture permeability K_θ	Air permeability k_a Air permeance K_a
Combined	Thermal diffusivity a Thermal effusivity b	Moisture diffusivity D_w Water absorption coefficient A	
Consequences	Thermal expansion coefficient	Hygric expansion ε	

Table 2.7 reports a list of the most used international standards for the given properties of materials above (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016)

Table 2.7 : List of methods for the evaluation of material properties.

Parameter	**Unit**	**Evaluation method**	**Note**
Thermal conductivity (λ)	W/m.K	EN 12664	Low thermal resistance
		EN 12667	High thermal resistance
		EN 12939	Thick materials
		ASTM C518	Heat flow meter apparatus
		ASTM C177	Guarded hot plate apparatus
		ISO 8990	Hot box method
Density	kg/m^3		
Fire behaviour		EN ISO 1182 EN ISO 1716 EN 13823 EN ISO 11925-2	
Moisture behaviour (μ)		EN 12086 EN 12088	

In the following sub sections, technical information on the thermal insulation material properties, which are more significant in accordance with the scope of the study, are explained.

2.5.1.1 Physical behaviour

Thermal insulation materials have some physical properties constituting physical behaviour of material such as density, moisture behaviour and air behaviour. Furthermore, these properties are used to designate the limits by either national or international standards such as EN 13162, EN 13163, EN 13164, EN ISO 6946, BS 476 etc. for more than 30 years (Papadopoulos, 2008).

Density

Density can be defined as a ratio between mass of the unit volume and the unit volume of a material. So that, density is expressed as a numeric value in kg/m^3. Density of thermal insulation also influences on other significant properties, such as compressive strength, thermal conductivity. Usual behavior of the density, while the thickness increasing, tends to improve thermal behavior and strength of insulation material (i.e. improvement is going on till 5 kg/m^3 for thermal conductivity) (Burns, 1984). Furthermore, density of and also strength of the material is related with design of the proper support frame and calculation of the load of a building.

Moisture behaviour

Moisture behaviour of thermal insulation materials can be defined by its water vapour permeability (or resistance), moisture permeability (or resistance), diffusion thickness, etc.

Water vapour resistance factor (μ), which is dimensionless, defines the vapour permeability of building materials in comparison to the unitary value assigned to air; the higher the μ value the lower the permeability. Water vapour diffusion thickness may also be used as the multiplication of the μ value with the material thickness in meters.

Insulation materials are generally non-hygroscopic, due to their pore surface. Thus, only closed-pore insulation materials guarantee imperviousness, while limiting vapour diffusion across the pores. That favours foams as opposed to fibrous materials, which are vapour permeable, pervious for water heads and non-capillary only when treated with a hydrophobic resin. Whether insulation materials lose strength and stiffness, degrade biologically and rot when moist, depends on the matrix material. (Hens, 2012)

Air behaviour

Air-tightness is directly related with the pores of the material. Closed pores are required for a good air-tightness. Thus, foam materials have good air-tightness, where fibrous materials are air permeable.

2.5.1.2 Thermal behaviour

Thermal conductivity

Thermal insulation materials were developed in order to minimize the heat losses through the building envelope. That requires reducing thermal conductivity (λ) to the utmost. Thermal conductivity is the main key property of an insulation material, where the goal is to reduce the heat losses through the envelope of a building.

Thermal conductivity is described as the heat flow that passes through a unit area of a 1 meter thick homogeneous material, per unit time for 1 K temperature difference. Thermal conductivity (λ) is expressed in W/m K. A low thermal conductivity enables the lower thicknesses of insulation material applications to achieve high thermal resistance (m^2 K/W) and a low thermal transmittance value (W/m^2 K). To achieve the highest possible thermal insulation resistance, new insulation materials and solutions with low thermal conductivity values have been and are being developed, in addition to using the current traditional insulation materials in ever-increasing thicknesses in the building envelopes (Jelle, 2011).

For a building component with multiple layers of materials, the thermal properties are expressed by the thermal transmittance (U value), the heat flow that passes through a unit area of the component, due tu the temperature difference of 1 K, expressed in W/m^2K. The inverse of the U-value (1 / U-value) refers to the thermal resistance of the component (R-value), expressed in (m^2K/W). The equations of U-value and R-value are as given below.

$$U = R\,.\,\lambda\,.\,\rho\,.\,A \tag{2.9}$$

In the equation 2.9, d refers to the density of the material (kg/m^3), which directly effects the thermal performance (U-value) of the building material and the component.

Specific heat (ρ) is the heat capacity of a material. As a measurable physical quantity, specific heat is the amount of heat (Joules) added to 1 kg of mass material to the resulting temperature change as 1 Kelvin, expressed by J/kg.K.

Fire behaviour

Insulation materials can be categorized according to their performance and reaction against fire, which can be named as the fire behaviour of the material. The fire behaviour of the thermal insulation materials may cause serious safety (ignition temperature, etc.) and health (production of smoke) issues. Thus, when selecting a thermal insulation material, it is important to consider the fire behaviour of the material.

2.5.1.3 Mechanical behaviour

Due to their very high porosity, insulation materials have limited strength and stiffness. The mechanical behaviour of a material is generally defined by its pressure and temperature resistance.

Synthetic materials have higher sensitivity to temperature whereas organic and non-organic materials hardly give problem. Moreover, the pressure resistance of the material increases when the density of the material is increased. Besides, the thermal conductance may also increase parallel with the density. Thus, a material with low thermal conductance while maintaining good mechanical resistance is an important task to be optimized.

2.5.1.4 Environmental characterization

In the context of sustainability, Life Cycle Assessment of building components and also of entire buildings become more and more important, in order to take into account the whole energy uses starting from the construction up to the demolition. Insulating materials must guarantee acceptable performance throughout the whole life cycle of the building, but thermal performance is not the only parameter that should be addressed when selection an insulator; the choice of these materials in the building sector is starting to be inspired by a holistic approach, which considers also non-thermal features such as sound insulation, resistance to fire, water vapour permeability and impact on the environment and human health. (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016).

Environmental impact of materials can be evaluated under two categories as the direct and indirect. Direct environmental impacts are based on the environmental attributes of materials such as embodied energy, global warming potential, etc. Indirect impacts are the result of the contribution of materials to the energy efficiency of buildings, as the reduced energy consumption.

2.5.2 Thermal insulation materials according to their structures

Given in Table 2.8, (Hens, 2012) groups insulation materials according to their structure as; organic isolation materials, inorganic isolation materials, plastic foams, and mixed materials. (Toydemir, Gürdal & Tanaçan, 2000) group insulation materials in two different classification categories as materials according to their existence in nature and their origin, and materials according to their body structure. Materials according to their structure (Hens,

Table 2.8 : Materials according to their structure (Hens, 2012).

Group	Material	Acronym
Organic isolation materials	Cork	K
	Cellulose fibre	C
	Sea grass, wool, straw, flax	
Inorganic isolation materials	Glass fibre	MW
	Mineral wool	MW
	Cellular glass	CG
	Perlite, vermiculite	
Plastic foams	Expanded polystyrene	EPS
	Extruded polystyrene	XPS
	Polyurethane foam	PUR
	Polyisocyanurate foam	PIR
	Phenol, ureumformaldehyde and polyethylene foam	
Mixed materials	Pressed perlite boards	PPB

Thermal insulation materials that are commonly used (conventional) and applicable on the façade are discussed in detail, below.

2.5.3 Conventional thermal insulation materials

In this section, commonly used thermal insulation materials are introduced and explained with their physical, thermal, mechanical, etc. properties. Conventional thermal insulation materials in this section are also limited with the commonly applied materials in housing projects such as EPS, XPS, PUR, RF, RW, GW, CG, and EP.

2.5.3.1 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is made from smapp spheres of polystyrene containing an expansion agent, e.g. pentane C6H12, which expand by heating with water vapour (Jelle, 2011). The process may be a single step or double, according to the product. The two step process passes the blowing agent though the polystyrene beads during, or after, 44nalyzing4444ion. The resultant beads are then subjected to steam heating to above their glass transition temperature resulting in the beads expanding (by 40 to 80 times) and produce the cellular form. The resulting product is then moulded. The one step process employs direct thermal extrusion of the material after blowing and is mostly used for sheet and film manufacture (Url-3)

The general properties of EPS are as summarized below:

- Physical properties: Density of the EPS material is ≥15 kg/m^3 and generally up to 75 kg/m^3. The closed-cell structure of EPS provides a high level of moisture resistance and breathability.
- Thermal properties: Thermal conductivity values of EPS materials vary between 0.035 and 0.040 W/(m.K) with a specific heat around 1.25 kJ/kgK. The material is easily flammable and burning releases dangerous gases. It is generally defined in Class E in terms of fire behaviour. Fire retardant is often added in the manufacturing process.
- Mechanical properties: Tensile strength of EPS is between 0.15 and 0.52 N/mm^2. EPS has fair resistance to water absorption and good resistance to moisture damage, whereas poor resistance to direct sun (Papadopoulos, 2008).
- Environmental properties: EN 14040 defines a methodology, in which Life Cycle Assessment (LCA) is used to calculate environmental impact of a material as numerical data. All the gas emissions during designated period of the life span are assessed in terms of kilograms of CO_2 equivalent. Global warming potential of XPS is calculated as approximately medium value (5.05 kgCO_{2eq}/f.u.) in terms of cradle to gate (CTGA) among insulation materials in the market (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016). Foam produced with pentane gas, may contribute smog and ground level ozone (Papadopoulos, 2008).

2.5.3.2 Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is produced from melted polystyrene (from crude oil) by adding an expansion gas, e.g. HFC, CO_2 or C_6H_{12}, where the polystyrene mass is extruded through a nozzle with pressure release causing the mass to expand (Jelle, 2011).

The general properties of XPS are as summarized below:

- Physical properties: Density of the XPS material generally varies between 30 and 45 kg/m^3. The closed-cell structure of EPS provides a high level of moisture resistance and low water absorption.
- Thermal properties: Thermal conductivity values of XPS are between 0.030 and 0.040 W/(m.K). XPS has higher specific heat than EPS material (between 1.3 and 1.7 kJ/kgK). It is defined in Class E in terms of fire behaviour.
- Mechanical properties: XPS has good behavior mechanically with minimum 0.30 and maximum 0.35 N/mm^2 tensile strength. The material’s resistance to water absorption and moisture damage is excellent, but the resistance to direct sun is poor (Papadopoulos, 2008).
- Environmental properties: Global warming potential of XPS is calculated as 13.22. $kgCO_{2eq}$/f.u. during CTGA which is the highest value in the market (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016). EPS, which is manufactured with Hydro chlorofluorocarbons, depletes stratospheric ozone to some extent (Papadopoulos, 2008).

2.5.3.3 Polyurethane (PUR)

Polyurethane (PUR) is formed by a reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups) (Jelle, 2011).

The general properties of PUR are as summarized below:

- Physical properties: PUR density varies from 15 to 45 kg/m^3. And PUR material has high moisture resistance.
- Thermal properties: Thermal conductivity of PUR are between 0.020 and 0.030 W/(m.K). PUR specific heat varies from 1.3 to 1.45 kJ/kgK. Even if PUR materials are safe in use (B or C class), it releases hazard gases when burning.

- Mechanical properties: Tensile strength of Polyurethane foam is from 0.16 to 0.3 N/mm^2 (Arvidson, Sparks, & Guobang, 1983). PUR’s resistance to water absorption and moisture damage is excellent, but the resistance to direct sun is poor like the XPS (Papadopoulos, 2008).
- Environmental properties: Global warming potential value of PUR is 6.51 kgCO$_{2eq}$/f.u, that is around in the middle of the range (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016). The urethane is mostly manufactured with HCFCs, which precisely deplete stratospheric ozone, probable substitute blowing agent but with decreased thermal properties (Papadopoulos, 2008).

2.5.3.4 Phenolic foam board (PF)

Phenolic insulation board insulation material is produced by mixing high solids and phenolic resin with a surface acting agent.

The general properties of PF are as summarized below:

- Physical properties: Phenolic foams come in varying densities in the range of 35 kg/m^3 to 200 kg/m^3.
- Thermal properties: The thermal conductivity of phenolic closed cell insulation material is generally between 0.018 W/m.K and 0.023 W/m.K.
- Mechanical properties: PF has over 95% closed cell formation, thus has a good stability and moisture resistance. This feature also makes it non–wicking and highly resistant to moisture penetration. Tensile strength of the material is around 0.18 N/mm^2 for perpendicular section.
- Environmental properties: Assessing the life cycle of phenolic foam board in term of environmental properties indicates that two impact categories have negative effects such as water depletion and freshwater ecotoxity due to phenolic resin inside. Whereas it has lower embodied energy per unit thermal performance compared to other insulation materials (Tingley, Hathway, Davison, Allwood, 2014).

2.5.3.5 Rock wool (RW)

Rockwool is produced from melting stone (diabase, dolerite) at about 1500 ^{o}C, where the heated material is hurled out from a wheel or disk and thus creating fibres (Jelle, 2011).

The general properties of RW are as summarized below:

- Physical properties: Density of the rockwool material can vary from 40 to 200 kg/m^3. Researches demonstrated that the thermal insulation performance of stone wool materials for building application is negatively affected by water vapour condenses (Schiavoni, D'Alessandro, Bianchi & Asdrubali, 2016; Karamanos et al., 2008).
- Thermal properties: Thermal conductivity of rock wool are between 0.033 and 0.040 W/(m.K). RW specific heat varies from 0.8 to 1.0 kJ/kgK.
- Mechanical properties: Tensile strength of the material is mostly between 0.18 and 0.28 N/mm^2 up to the density. Furthermore it has good resistance to water absorption and excellent resistance to moisture damage and direct sun (Papadopoulos, 2008).
- Environmental properties: Global warming potential of RW is one of the lowest value among the products in the market with 1.45 kgCO$_{2eq}$/f.u during cradle to grate (Schiavoni, D'Alessandro, Bianchi & Asdrubali, 2016). The insulation material is quite safe environmentally, but greater health concern with loose-fill 47nalyzing47 than 47nalyzing47 batts (Papadopoulos, 2008).

2.5.3.6 Glass wool (GW)

Glass wool is produced from borosilicate glass at a temperature around 1400 ^{o}C, where the heated mass is pulled through rotating nozzles thus creating fibres (Jelle, 2011). Glass fibre consists of well-ordered, long fibres.

Glass wool are applicable to low-slope roofs (dense boards), pitched roofs (bats, soft boards), cavity fill, exterior insulation finishing, floor insulation, etc.

The general properties of GW are as summarized below:

- Physical properties: Density of glass fibre varies from 10 to 150 kg/m^3. Researches demonstrated that the thermal insulation performance of glass wool materials for building application seems to be not affected by high temperature (Schiavoni et al., 2016). Due to the fibrous structure, vapour resistance factor of glass fibre is very low, around 1.2 to 1.5, and air permeability is high.

- Thermal properties: With a specific heat capacity of 840 J/(kg.K), better production methods have resulted in further lowering the thermal conductivity of the material to 0.032 W/(m.K). They are temperature resisting materials.
- Mechanical properties: Glass wool has high ultimate tensile strength with the value of between 0.005 and 0.015 N/mm^2. It has good waterproof, flameproof, and nonflammable properties.
- Environmental properties: Glass wool is required high energy to produce as 229.02 MJ_{eq} /f.u., so that global warming potential is also high with 9.89 $kgCO_{2eq}$/f.u. (Schiavoni, D'Alessandro, Bianchi & Asdrubali, 2016). Although it is quite safe for interior environment, some concern that fibres may In the nineties, there was some concern about the possible cancerous nature of mineral fibres. Where this is a fact for asbestos fibre, no proof was found for glass fibre and mineral wool. The fibres irritate skin and mucous membranes. During installation, wearing protective clothing and a mask is mandatory (Hens, 2012).

2.5.3.7 Cellular glass (CG)

The basic material is used glass bottles. These are melted and extracted as thin-walled pipes. After cooling, the pipes are ground and carbon dust added. That mixture is then poured in moulds that enter the furnace. While the glass melts, the carbon reacts explosively to form CO_2, giving a porous glass mixture that solidifies into cellular glass breads (Hens, 2012).

The general properties of CG are as summarized below:

- Physical properties: Density of cellular glass is between 100 and 500 kg/m^3. Due to the closed pore structure, vapour resistance factor of cellular glass is extremely and air permeability is very low (airtight).
- Thermal properties: With a specific heat capacity of 840 J/(kg.K), the thermal conductivity of the material is around 0.40 – 0.45 W/(m.K).

- Mechanical properties: Cellular glass is very temperature tolerant. Moreover, compressive strength of the material is from 0.8 to 1.6 N/mm^2, therefore it can compensate loads which crush most other insulating materials.
- Environmental properties: Global warming potential was calculated in terms of cradle to grave (CTGR) as 0.73 kg CO2eq per f.u (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016). The material is free of CFC’s and HCFC’s and has been formally categorized as a sustainable construction material.

2.5.3.8 Expanded perlite (EP)

Expanded perlite This material can be used loose, mixed with a binder to create panels, and in bricks (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016).

- Physical properties: Density of the material varies between 80 and 150 kg/m^3
- Thermal properties: Thermal conductivity of the expanded perlite is between 0.040 and 0.052 W/(m.K). Specific heat varies between 0.9 nad 1.0 kJ/kgK.
- Mechanical properties: Compressive strength of the material is between 2.76 and 4.34 N/mm^2 (Demirboga, Gül, 2003). Furthermore it has fair resistance to water absorption, good resistance to moisture damage and additionally excellent resistance to direct sun (Papadopoulos, 2008).
- Environmental properties: Global warming potential value of PUR is 3.99 kgCO$_{2eq}$/f.u. The value is around in the middle of the range (Schiavoni, D’Alessandro, Bianchi & Asdrubali, 2016). It is also very safe for health of occupants (Papadopoulos, 2008).

3. DECISION MAKING METHODS FOR PERFORMANCE BASED BUILDING DESIGN

The life of each person is filled with decisions made within alternatives since there occurs a number of alternatives in every step we take during the day and life. We may have to decide when to wake up, what to wear, how to travel, which food to eat, etc. In general, all these decisions come up with several alternatives to evaluate and requires a decision-making among them, which is based on the selection of the most preferable one.

Decision-making and problem-solving domains are introduced to the literature by (Simon, 1947). He states that, *"(If) there were no limits to human rationality administrative theory would be barren. It would consist of the single precept: Always select that alternative, among those available, which will lead to the most complete achievement of your goals".* (Simon, 1947) describes the decision process in three main stages as intelligence, design and choice as given in Figure 3.1. In some cases, a fourth step exists as implementation.

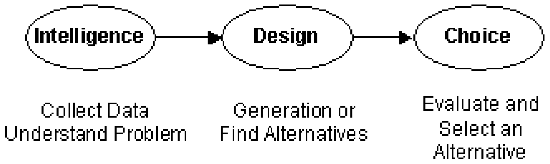

Figure 3.1 : Decision model by (Simon, 1947).

Making the "correct" decision means choosing such an alternative from a possible set of alternatives, in which, by considering all the diversified factors and contradictory requirements, an overall value will be optimized; that is, it will be favourable to achieving the goal sought to the maximal degree possible (Pedrycz, Ekel and Parreiras, 2011).

For a proper decision-making, the problem should be known and defined with its aim and scope. Before taking the steps of a decision-making process, it is important to identify the decision maker(s) and stakeholder(s) in the process, the structure of the problem, variables and the alternatives, and which model would best fit to the problem's situation. The properties that diversify the decision-making process can be as given below:

- In some cases, decision-making may require a singular goal (criteria) where in some cases a decision includes multiple goals (multiple criteria decision-making) to achieve. Thus, the number of goals determines the structure of the problem and the decision-making process.
- Additionally, it may be a personal or a group decision-making, based on the decision makers (DMs) involved to the process.
- The goals of the decision-making (as criteria) may be either subjective or objective, which effects the estimations on the alternatives.
- The decision-making problem may be a structured (quantitatively formulated), unstructured (qualitatively expressed) or a semi-structured (mixed) problem according to the features of the criteria.
- The "uncertainty" may come up due to the impossibility of obtaining reliable information, lack of data, unclear goals, etc.

Decision support consists of assisting a DM in the process of decision-making. For instance, this support may include (Trachtengerts, 1998):

- assisting a DM in the analysis of an objective component, that is, in the understanding and evaluation of the existing situation and constraints imposed by the surroundings;
- revealing DM preferences, that is, revealing and ranking priorities, considering the uncertainty in DM estimates, and shaping the corresponding preferences;
- generating possible solutions, that is, shaping a list of available alternatives;
- evaluating possible alternatives, considering DM preferences and constraints imposed by the environment;
- analysing the consequences of decision-making;
- choosing the best alternative, from the DM's point of view.

(Baker et al., 2002) describes the decision-making process as an eight step process as below;

- Step 1: Define problem,
- Step 2: Determine the requirements that the solution to the problem must meet,
- Step 3: Establish goals that solving the problem should accomplish,
- Step 4: Identify alternatives that will solve the problem,
- Step 5: Develop evaluation criteria based on the goals,
- Step 6: Select a decision-making tool,
- Step 7: Apply the tool to select a preferred alternative,
- Step 8: Check the answer to make sure it solves the problem.

The standard product selection process defined by (Spiegel & Meadows, 2012) includes the following steps:

1. Identify material categories.
2. Identify performance criteria.
3. Identify building material options.
4. Gather technical information.
5. Review submitted information for completeness.
6. Evaluate materials.
7. Select and document choice.

Before taking the steps of a decision-making process, it is important to identify the decision maker(s) and stakeholder(s) in the process, the structure of the problem, variables and the alternatives, and which model would best fit to the problem’s situation. In a decision model where only one optimal solution is obtained, the result may not be satisfactory and explanatory from multiple decision makers’ point of view. It is also discussed by (Wang et al., 2005) that, a mismatch between a specific optimization model and design practice may occur in terms of variables such that the exact thermal resistance value of a window may not exist in the market or a given time lag of a wall may not correspond to the solution of the designer.

Building projects can be evaluated under stages such as; early design stage, design stage, and construction stage. In some studies, it is described as conceptual design, main design and detailed design. Decision-making of a building project starts from the early design stage, where the most significant decisions are made from the building performance point of view and continues during the design stage and construction stage which also involve important decision-makings and these three stages should be evaluated simultaneously. It is widely recognized that most of the total cost and performance of the building is determined by the decisions made in the early design stage. Therefore, applying MLDM in this early stage can lead to considerable savings in the building project (Mela et al, 2012).

The early design stage of a building project involves mainly the selection of the land, determination of the building space needs, main building form and orientation, number of stories, window ratio etc. According to (Attia et al., 2012), conceptual early design stages can be divided into five sub-stages: (1) specifying performance criteria, (2) generating ideas, (3) zones-layout design, (4) preliminary conceptual design, and (5) detailed conceptual design, from the nZEB design point of view. The design stage mostly involves the material selections, detail solutions both from architectural, structural, mechanical and electrical point of view. On the construction stage, decisions are applied on the construction site, where there can be other decision-makings depending on human judgment and critical and practical problem solving.

Throughout the literature, decision-making methods can be classified based on;

- the complexity degree of the problem by (Turban et al., 2005) (structured, semi-structured, and unstructured),
- the levels of decision problems by (Zhang et al, 2015) (strategic planning, management control, and operational control),
- the reasoning process by (Simon, 1993) (rational or irrational).

Taking into account all the aspects listed above, it is clear that a decision-making support that fits with the structure of the decision is necessary for a proper decision-making. Decision-making, as a cognitive process of selecting an option or multiple options among several alternatives, can be addressed as a problem solving method within a situation. In other words, decision-making is described by (Harris, 1998), as the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Since there may be several alternatives to be considered, decision-making focuses on selection of the one that best fits with the aim, objectives, and limitations. A large number of psychological investigations demonstrate that DMs, not being provided with additional analytical support, use simplified and, sometimes, contradictory decision rules (Slovic, Fischhoff, and Lichtenstein, 1997).

In building design and construction, decision-making is a mandatory tool to obtain solutions. Whereas, most design professionals are unable to individually assess the available design options in order to achieve a high performance building. Moreover, when the task is a group decision-making, it becomes more difficult to determine the best alternative solution. Furthermore, the number of available alternatives, the variation on the expertise of the criteria, the cost of making errors, the flexibility due to the changes in the fluctuating environment and the uncertainties cause DMs to need a support for decision-making to achieve a high performance building.

Within the literature, there are several methods used for defining a decision-making method. However, not all methods are useful for every decision problem due to the structural differences between the decisions, which were mentioned above. Thus, determining the proper decision-making method to achieve proper results is essential.

In the following section 3.1., different decision-making methods, which are commonly used for decision-making in building design, are presented. Furthermore, a literature review is discussed in section 3.2 in the light of the theoric information. Finally, a conclusion is made in section 3.3 to highlight the key findings of the section for the proposed approach of this study.

As aforementioned, there are several methods used for defining a decision-making method. In this chapter, the decision-making methods which are commonly used in building design evaluation, optimization, and best alternative achievement. It is important to indicate that, the proper decision-making method can be determined only with considering the structure of the decision-making problem. Even if it is defined to use a decision-making method for building design, it is still important to evaluate the criteria of the evaluation, the features of the criteria, etc.

At this point, the most significant breaking point can be expressed by the difference between the optimization and decision-making. Optimization is a widely used method in building design, where you reach to the best solution within the alternatives. Pedrycz, et. al (2011) defines the optimization as associated with the search of an extremum (minimum or maximum, according to the essence of the problem) of a certain objective function, which reflects our interests, when observing diverse types of constraints (imposed on allowable resources, physical laws, standards, industrial norms, etc.). But they also highlight that, if numerical details of an optimization problem have been provided and we can obtain a unique solution without any guidance or assistance from a DM, than we are concerned with an optimization problem. Thus, it is sure that there is an intersection between optimization and decision-making. In a decision model where only one optimal solution is obtained, the result may not be satisfactory and explanatory from multiple decision makers' point of view. It is also discussed by (Wang et al., 2005) that, a mismatch between a specific optimization model and design practice may occur in terms of variables such that the exact thermal resistance value of a window may not exist in the market or a given time lag of a wall may not correspond to the solution of the designer.

However, this research is focused on the optimization problems where multiple decision makers play role, since a building design is not only a mathematical problem solution, but also a continuum where the decision-making is not a stand-alone tool, but a supportive tool for the stakeholders (decision makers) of the process to take decisions.

Mostly, the decisions in building design and construction require multiple criteria decision-making where there are multiple and conflicting criteria. Multi-criteria decision-making (MCDM) methods deal with the process of making decisions in the presence of multiple objectives (Pokehar, 2004). Objectives can be qualitative or quantitative, with the same or different levels of dependency. A MCDM can be either multi-attribute decision-making (MADM) or multi-objective decision-making (MODM). MADM problems are distinguished from MODM problems, which involve the design of a "best" alternative by considering the tradeoffs within a set of interacting design constraints (Baker et al, 2002). MADM is based on selecting the best alternative by ranking a finite number of alternatives, where MODM is expressed by a continuous function.

In the literature, there are several decision-making methods used on building performance evaluation. MCDM methods taking part in literature for evaluating the building performance can be listed as; weighted sum method (WSM) or multiplicative exponential weighting (MEW), weighted product method (WPM) or simple additive weighting (WPM), VIKOR, PROMETHEE, TOPSIS, ELECTRE, analytical hierarchy process (AHP), Edgeworth-Pareto principle, PEG, DEA, OCRA, MAUT, and SMART.

3.1 Decision Making Methods

There exists several decision making methods in the literature, serving for different type of problems. In this part of the study, decision-making methods are categorized in order to make a clear definition. Besides, this categorization may differ in detail or in other point of views. The categorization is as given below:

- Simple weighted criteria methods
- Pairwise comparison and outranking methods
- Combinatorial methods
- Compromise programming methods

3.1.1 Simple weighted criteria methods

Simple weighted criteria methods, commonly used in literature, are weighted sum method (WSM), weighted product method (WPM), and weighted aggregated sum product assessment (WASPAS) as explained and discussed below.

3.1.1.1 Weighted sum method (WSM)

Weighed sum method (WSM) is a MADM ranking method, where the best alternative is selected by the sum of n number of criteria ranking weights within m alternatives. It can be expressed by the following equation (3.1), where a and w are the actual value and weight factor of the jth criteria given for the ith alternative, respectively.

$$A_{WSM} = Max \sum_{i}^{j} \left(a_{ij} w_j \right) \tag{3.1}$$

3.1.1.2 Weighted product method (WPM)

Weighted product method (WPM) is a very similar method to WSM, where the only difference is that, actual values are not summed but multiplied. As expressed in the equation (3.2), alternatives are compared within each other by R value, which is the multiplication of the weighting factor power (w_j) of the relative weight (a_{Kj}/a_{Lj}) of each criteria within two cases. The comparison of the K and L alternatives is as below;

$$R(\frac{A_K}{A_L}) = \prod_i^j \left(a_{Kj}/a_{Lj}\right)^{w_j} \quad (3.2)$$

3.1.1.3)Weighted aggregated sum product assessment (WASPAS)

WASPAS is a similar method to WSM, as a method where there are two criterion of optimality as criterion of a mean-weighted success and multiplicative exponential generalized criterion, which are similar with WSM and WPM, respectively.

3.1.2 Pairwise comparison and outranking methods

For a long time people have been concerned with the measurement of both physical and psychological events (Saaty, 1987). Pairwise comparison method is first established by L.L. Thurstone (REF). Today, one of the most important pairwise comparison methods used for decision making in building evaluation is Analytic Hierarchy Process (APH).

3.1.2.1 Analytical hierarchy process (AHP)

Analytical hierarchy process (AHP), as a MADM method, is introduced to the literature by Saaty (1980). AHP is based on the pairwise comparison of the problem within the sub problems or sub-sub problems (criteria) defined. Pairwise comparisons of sub problems (sub-criteria) are translated into 1-9 scale due to their priority, where 1 represents an equal importance and 9 represents the most extreme importance within the comparison matrix. After calculation of the weighting factors of criteria, the weighting factors of each alternative with respect to each criteria is obtained and multiplied by the criteria’s weighting factor. The best alternative is selected according to the highest overall weighting factor within the alternatives.

$$R(\frac{A_K}{A_L}) = \prod_i^j \left(a_{Kj}/a_{Lj}\right)^{w_j} \quad (3.3)$$

3.1.2.2 Preference ranking organization method for enrichment evaluation (PROMETHEE)

Preference ranking organization method for enrichment evaluation (PROMETHEE) is an outranking method which uses pairwise comparison of alternatives in terms of criteria evaluated. The alternatives are compared with each other with the equation

(3.4), by calculating the difference between two alternatives a and b, for the jth criteria, with the values of the criteria f(a,j) and f(b,j), respectively.

$$d_j = f(a,j) - f(b,j) \tag{3.4}$$

The indifference and preference thresholds are also defined in this method, thus enabling an indifference within the alternatives if the difference of the values does not exceed the indifference threshold. The best alternative is the one which have the maximum value of the outranking within the comparison.

3.1.2.3 . Elimination and choice translating reality (ELECTRE)

The elimination and choice translating reality (ELECTRE) is also an outranking method as PROMETHEE, to be formulated that it chooses alternatives that are preferred over most of the criteria and that do not cause an unacceptable level of discontent for any of the criteria (Pokehar et al, 2004).

Another method, similar with ELECTRE, is ORESTE, which also takes part in the literature.

3.1.3 Combinatorial methods

3.1.3.1 Multi attribute utility theory (MAUT)

Multi attribute utility theory (MAUT) selects the best alternative through the maximization of satisfaction calculated by the utility function (3.5), where k is the overall scaling constant, k_i is the scaling constant of ith criteria, u is the overall utility function operator, $u_i$is the utility function operator of the ith criteria. The utility function can be either additive or multiplicative.

$$1 + ku(x_1, x_2, \dots x_n \ = \prod_i^j (1 + kk_i u_i \ (x_i)) \tag{3.5}$$

3.1.3.2 Simple multi attribute ranking technique (SMART)

The simple multi attribute ranking technique (SMART) is a variant of the MAUT method, which is based on simple utility relationships. The SMART methodology allows for use of less of the scale range if the data does not discriminate adequately so that, for example, alternatives which are not significantly different for a particular criterion can be scored equally (Baker et al, 2002).

3.1.4 Compromise programming methods

Compromise programming methods allow to reduce the set of efficient solutions to a more reasonable size without demanding any information from the decision maker. In this part, TOPSIS and VIKOR, which are the commonly applied methods in the literature, are explained.

3.1.4.1 Technique for order preference by similarity to an ideal solution (TOPSIS)

The technique for order preference by similarity to an ideal solution (TOPSIS) is developed by Hwang and Yoon (Hwang and Yoon, 1981). TOPSIS method, as a MODM method, is based on the evaluation of the alternatives according to the Euclidean distance to the ideal and the negative-ideal solution. The best alternative should have the shortest distance to the ideal, and the longest distance to the negative ideal solution.

3.1.4.2 VIKOR (VIKOR)

VIKOR method is a MODM method, used for multi-criteria optimization of complex problems. This method was developed by (Opricovic, 1998) focusing on selection by ranking from a set of alternatives in the presence of conflicting criteria (Opricovic and Tzeng, 2004). The ranking of the alternatives depends on the closeness of alternatives to the ideal solution point. In VIKOR method, the conflicting criteria's weights may be equal or vary, which is helpful for decision-maker to observe the change on the compromise solution.

The MCDM methods VIKOR and TOPSIS are based on an aggregating function representing closeness to the reference point(s). These two MCDM methods use different kinds of normalization to eliminate the units of criterion functions: the VIKOR method uses linear normalization, and the TOPSIS method uses vector normalization (Opricovic and Tzeng, 2004).

3.2 Evaluation of the Decision-Making Methods

Decision-making has to be considered as a continuous way of problem solving from the early design stage to the construction and operation of the building with multiple decision makers (stakeholders). Since the most effective decisions are made on the early design stage of a building project from the environmental point of view, it should be also taken into account that many decisions and parameters have a reevaluation potential through the further stages of the project. Also, many of the decisions (parameters) are quite difficult to be evaluated on the early design stages (such as the thermal bridge). Thus, the structure of the decision-making problem and the decision-making method used should be defined properly, in order to obtain appropriate results.

According to Baker et al. (2002) decision-making should start with the identification of the decision maker(s) and stakeholder(s) in the decision, reducing the possible disagreement about problem definition, requirements, goals and criteria. In the literature, the task of generating the alternatives for the decision-making is often left for the designer, who may or may not be the actual decision maker. In real case building projects, decision makers can be designers, project managers, investors, property owners or a combination of them. Each decision maker, form different points of view, targets the success of the project with different concerns on the same parameters. So that, a restricted solution of a parameter may be difficult to be established by multiple decision makers and entertains risks in case of self-assessments.

In building design process, it is required to combine different decisions by a multi-level structure. For example, representing multiple solutions for the optimality by Pareto optimal and using human-judgment techniques can be an alternative, instead of a restricted solution to the decision-makers, where multiple decision-makers exists. Thus, defining the decision makers in a project is also quite important to select the best decision-making method to implement.

According to the analysis of the literature, AHP is one of the most applied method for decision-making, where the definition of criteria and the calculation of their weight are central to assess the alternatives.

4. AN APPROACH ON PERFORMANCE BASED DECISION-MAKING FOR INSULATION MATERIAL SELECTION

“High performance building” is a common issue, concerning the decision makers such as investors, designers, professionals, technicians, operators, etc. As aforementioned in the previous sections, it is important to define the “high performance building” phenomenon in order to designate the stakeholders of the decision-making process. Moreover, estimation of building performance might be essential in building projects where the indicators of building performance are crucial. Additionally, decision-making on different stages of a project requires different analysis and concerns, thus the influence of the stakeholders on the decisions and the impact of the decision may vary.

This study proposes an approach on “performance based decision-making” in thermal insulation material selection for building design. “High performance” is defined in this study with the indicators as energy, cost, thermal comfort, and environmental impact. The proposed approach for performance based decision-making focuses on the social housing projects in Turkey, due to its’ representation of 10% of the housing stock.

As reviewed, there are several performance metrics varying according to the scope, level or content of the evaluation. Firstly, in this study, performance metrics are limited based on the EPBD scope, such as the energy and cost performances. Moreover, extensions as thermal comfort and environmental impact are also considered to develop a new approach where the performance indicators at the material level are more reflected on the evaluation at building level.

Based on the structure of the “building design”, several decisions are made through the design process. From selection of the site to the occupancy and operation level, all decisions affect the performance of the building with different incidence. This study investigates the material selections and their impacts on the performance metrics. Within the scope of the study, thermal insulation materials on the envelope are studied with a whole envelope design approach.

The methodology of the proposed approach has four main steps as given below:

- Determination of the archetype,
- Parameterization with the designated independent variables,
- Calculation of the dependent variables,
- Multiple criteria decision-making.

The methodology of the proposed approach for performance based decision making for insulation material selection is presented in Figure 4.1, as a flowchart.

In this section, the methodology of the proposed approach is explained systematically, with diagrams and flow charts. The methodology is adapted to the aim of the study, which was aforementioned in the previous sections.

4.1 Determination of the Archetype

Different building functional typologies perform different energy consumption patterns due to the activity types, occupied hours, internal gains etc. The more detailed the buildings are divided into sub-categories; more accurate will be the analyses in terms of energy. Thus, the first step of the methodology is set as the determination of the archetype, which may also affect the further steps as determination of the dependent and independent variables.

In this approach, the methodology is integrated with the determined archetype in terms of dependent and independent variables. For this reason, the determination of the archetype should be emphasized.

This study focuses on the social housings, so that an archetype which can represent a commonly applied social housing example will be analyzed and assigned.

.

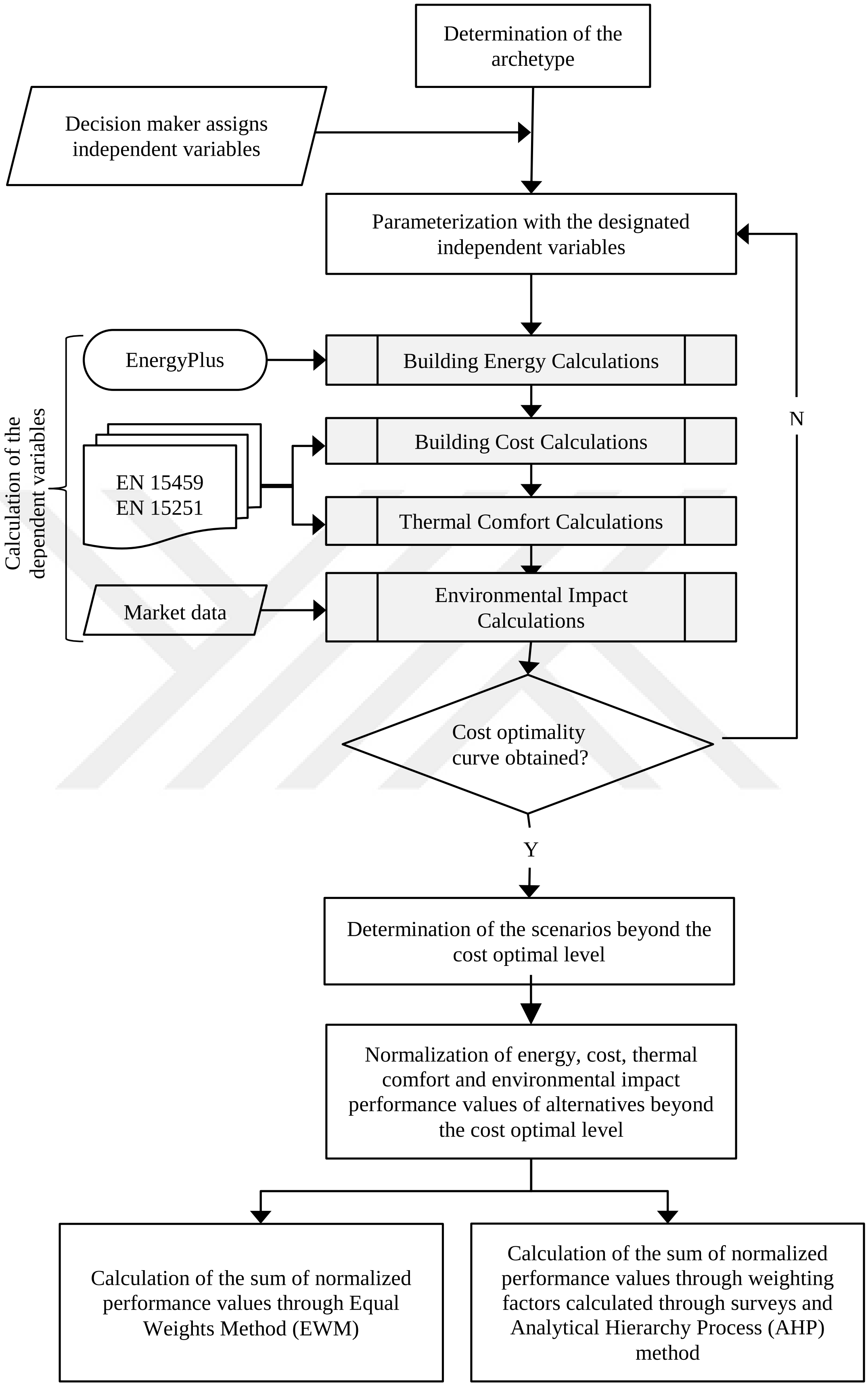

Figure 4.1 : The methodology of the proposed approach for performance based decision-making.

4.2 Parameterization with the Designated Independent Variables

In this step of the methodology, the independent variables were determined for the parameterization. Independent variables represent the variation possibilities and opportunities in the design decision making. Thus, parameterization step is important in terms of defining the proper design alternatives in order to make a good decision-making.

According to the methodology, each independent variable (discrete variable) is coupled with all other discrete variables so that the total number of alternatives are equal to the multiplication of *n* number of variables with *m* number of alternatives.

Based on the methodology, thermal insulation materials are varied by their thermal properties, cost, and environmental attributes. Additionally, each thermal insulation material derives four new material options, according to the principle given in Figure 4.2. Finally, *m* number of thermal insulation materials create *m x 4* number of alternatives for the evaluation.

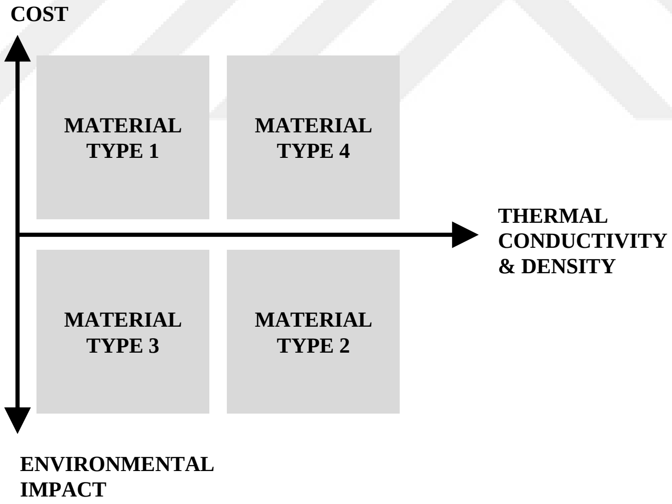

Figure 4.2 : Principle for derivation of thermal insulation materials.

Other independent variables of the methodology are as the thickness of the thermal insulation material and the window-to-wall ratio (WWR). In this methodology, the transparent components of the envelope (windows) are fixed in order to not to change the influence of the thermal insulation material on the results. However, windows can be integrated to the methodology and the parameterization when it is relevant for the project and decision-making.

4.3 Calculation of the Dependent Variables (Performance Criteria)

4.3.1 Calculation of the energy performance

Energy performance is the most determinative criteria that exist in this methodology. The influence of the material selection on the energy performance of the building is evaluated through the life cycle energy consumptions of the social housing archetype for 30 years life span.

Energy consumptions are calculated through Energy Plus simulation tool, on the hourly basis, with 6 time steps per hour. Conduction transfer function algorithm is used for heat balance calculations, with TARP algorithm for inside and DOE-2 algorithm for outside surface convection calculations.

Results of the energy calculations are evaluated in terms of primary energy use for heating and cooling. Conversion factors are 1 and 2.36 for natural gas and electricity, respectively.

It is considered to apply the methodology on a case located in the temperate dry climate region of Turkey. Temperate-dry climate region, which is represented by the capital city of Ankara is selected for this study. Latitude and longitude coordinates of Ankara is 40.12° N and 32.98° E, with 949m elevation.

4.3.2 Calculation of cost performance

In order to obtain more accurate decisions regarding building design and construction, not only initial investment costs of the potential implementation but also its expenses during life span are taken into calculation. Therefore, influence of the material selection on the cost performance of the building is evaluated through the life cycle costs of the case building for 30 years life span. Life cycle cost is calculated by the methodology presented in EN 15459:2007 and described in section 2.2.

EN 15459:2017 introduced the global cost approach, in which all related expenses and incomes such as investment costs, annual running and replacement costs, disposal costs and residual value during lifespan are summed with converting them to today's values by discount rate. In this approach, life cycle cost of the related components were calculated with a modified global cost formula $CGm(T)$ as sum of initial investment costs (CO_{inv}), net present value of annual costs $\left(CO_{a(i)}(j)\right)$and of energy costs

($CO_{en(i)}(j)$), which is transposed with development rate ($RAT_{dev(i)}$) of energy. In order to calculate today's value of further costs to involve in the sum, formula applies discount rate ($D\_f(i)$).

$$CGm(T) = CO_{inv} + \sum_j \left[\sum_{i=1}^{TC} \left(CO_{en(i)}(j) * (1 + RAT_{dev(i)}(\mathrm{j})) + CO_{a(i)}(j)\right) * D\_f(i)\right] \tag{4.1}$$

In this methodology, only the envelope costs are considered for investment costs and annual costs, in order to make a comparison between the scenarios due to the change of independent variable.

Envelope costs are evaluated in two parts as walls and windows.

4.3.2.1 Economic parameters

In Turkey, economic parameters are not steady for decades as EU Member States, such as inflation, market interest and nominal energy price escalation rates etc. Therefore, in order to reach more accurate results via life-cycle cost calculation, values of the economic parameters involving the calculation as aforementioned are accepted as an average of the annual values since 2005.

Unit prices of energy related facade elements are either designated from the unit prices list announced by government or requested from local market to obtain actual prices according to availablity of data for investment and maintenance costs.

Then, in order to define LCC formula of the façade options, other economic parameters regarding the rate of prices such as real interest rate, discount factor, present value factor and price escalation factor. Among these rates, price escalation factor regarding mostly energy prices is newly involved the GC by EN 15251. The rate is distinctly useful to reach more realistic results for such countries, in which the prices escalation is higher than inflation like Turkey for especially energy prices.

4.3.3 Calculation of thermal comfort performance

Thermal comfort is defined in ISO 7730 as "that condition of mind which expresses satisfaction with the thermal environment". Thermal performance is evaluated through the thermal comfort of the occupants. Thermal comfort is one of the most evident criteria to evaluate the performance of a building because an energy and cost efficient building can be effective only if the thermal comfort is provided to the occupants.

In this approach, indoor environmental thermal comfort is evaluated based on the operative temperature where the indoor air temperature and inside surface temperatures are both considered. Acceptable operative temperature range is set according to “EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics” European standard.

Thermal comfort is mostly a subjective measure which depends on either environmental and personal parameters which were aforementioned in the third section. In this methodology, adaptive comfort model is used in order to evaluate the thermal comfort level of the occupancies. The adaptive comfort models are based on the natural tendency of individuals to adapt their thermoregulation, clothing, metabolic rate and psychological conditions to the changing conditions of the outdoor climate under natural ventilation conditions. Unlike other comfort standards, this allows a greater range of temperatures related to the outside temperatures of the previous days. (Humpreys et al., 2013).

EN 15251 categorizes the type of buildings and the expectations of the occupants according to the Table 41 below. Based on the selected criteria form the Table 4.1, the corresponding comfort requirements given in Table 4.2 are considered to evaluate the indoor environmental comfort of occupants.

Table 4.1 : Categories in EN15251 and their extended explanations.

Category	Explanation
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons
II	Normal expectation for new buildings and renovations
III	A moderate expectation
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)

Table 4.2 : PMV and PPD values, operative temperature limits and maximum acceptable ppm levels for EN 15251 categories (given for sedentary activity).

Class	Thermal comfort requirements		Operative temperature range		Ventilation
	PPD [%]	PMV	Winter 1.0 clo / 1.2 met [^{0}C]	Summer 0.5 clo / 1.2 met [^{0}C]	CO_2 Above outdoor [ppm]
I	< 6	-0.2 < PMV < +0.2	21.0 – 23.0	23.5 - 25.5	350
II	< 10	-0.5 < PMV < +0.5	20.0 – 24.0	23.0 – 26.0	500
III	< 15	-0.7 < PMV < +0.7	19.0 – 25.0	22.0 – 27.0	800
IV	> 15	PMV > + 0.7	< 19.0 – 25.0 <	< 22.0 – 27.0 <	800 <

In this methodology, main output to represent the thermal comfort performance is the time (hour) not meeting the adaptive comfort model requirements during the occupied hours, within the acceptability limits of the Category III of EN 15251.

4.3.4 Calculation of environmental impact performance

Influence of the material selection on the environmental impact performance of the building is calculated through the embodied carbon (kgCO2e/kg) and embodied energy (Mje/kg) of the materials.

For the evaluation of the LCA indicators, commonly a functional unit, f.u., is used. The functional unit for the assessment is defined as mass (kg) of insulation material needed to cover a 1 m^2 area at a thickness providing an average thermal resistance (R value) of 1 m^{2}K/W for a building service life of 60 years. The functional unit (f.u., kg) can be expressed as (Biswas, Shrestha, Bhandari, Desjarlais, 2016),

$$FU = R\,.\,\lambda\,.\,\rho\,.\,A \tag{4.2}$$

Where R is the unit thermal resistance (1 m^{2}K/W), λ is the thermal conductivity (W/mK), ρ is the density (kg/m^3), and A is a unit area (1 m^2).

In this methodology, the functional unit is converted to the cm unit, in order to calculate the change of the environmental impact by the increase of the thickness.

4.4 Multiple Criteria Decision-Making

Decision-making, as a cognitive process of selecting an option or multiple options among several alternatives, can be addressed as a problem solving method within a situation. In other words, decision-making is described by (Attia et al, 2012) as the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Since there may be several alternatives to be considered, decision-making focuses on selection of the one that best fits with the aim, objectives, and limitations.

Before taking the steps of a decision-making process, it is important to identify the decision maker(s) and stakeholder(s) in the process, the structure of the problem, variables and the alternatives, and which model would best fit to the problem's situation. In a decision model where only one optimal solution is obtained, the result may not be satisfactory and explanatory from multiple decision makers' point of view. It is also discussed by (Wang et al, 2005) that, a mismatch between a specific optimization model and design practice may occur in terms of variables such that the exact thermal resistance value of a window may not exist in the market or a given time lag of a wall may not correspond to the solution of the designer.

Multi-criteria decision-making (MCDM) methods deal with the process of making decisions in the presence of multiple objectives. Objectives can be qualitative or quantitative, with the same or different levels of dependency. A MCDM can be either multi-attribute decision-making (MADM) or multi-objective decision-making (MODM). MADM problems are distinguished from MODM problems, which involve the design of a "best" alternative by considering the trade-offs within a set of interacting design constraints. MADM is based on selecting the best alternative by ranking a finite number of alternatives, where MODM is expressed by a continuous function.

In the methodology, all scenarios occurring by parameterization are calculated in terms of life cycle cost and primary energy consumption through the 30 years life span. Cost optimal point within the whole alternatives is obtained and alternatives beyond the cost optimal level are listed for the multiple criteria decision-making. Alternatives were listed with decision-making criteria for high performance building design as; investment cost, primary energy consumption, thermal comfort, and environmental impact values. In order to be compared with each other, all criteria values are normalized by dividing the value to the maximum value of that criteria. So that, the maximum value was normalized to 1, where the better alternatives have a value between 0 and 1. Further, normalized values of criteria were summed in order to obtain the total score of the alternatives. In this step, weighting factors of each criteria were considered as equal. Finally, best alternatives are determined for the decision maker, in order to develop a building design with high performance. Steps of the decision-making approach are figured as a flow chart in Figure 4.3.

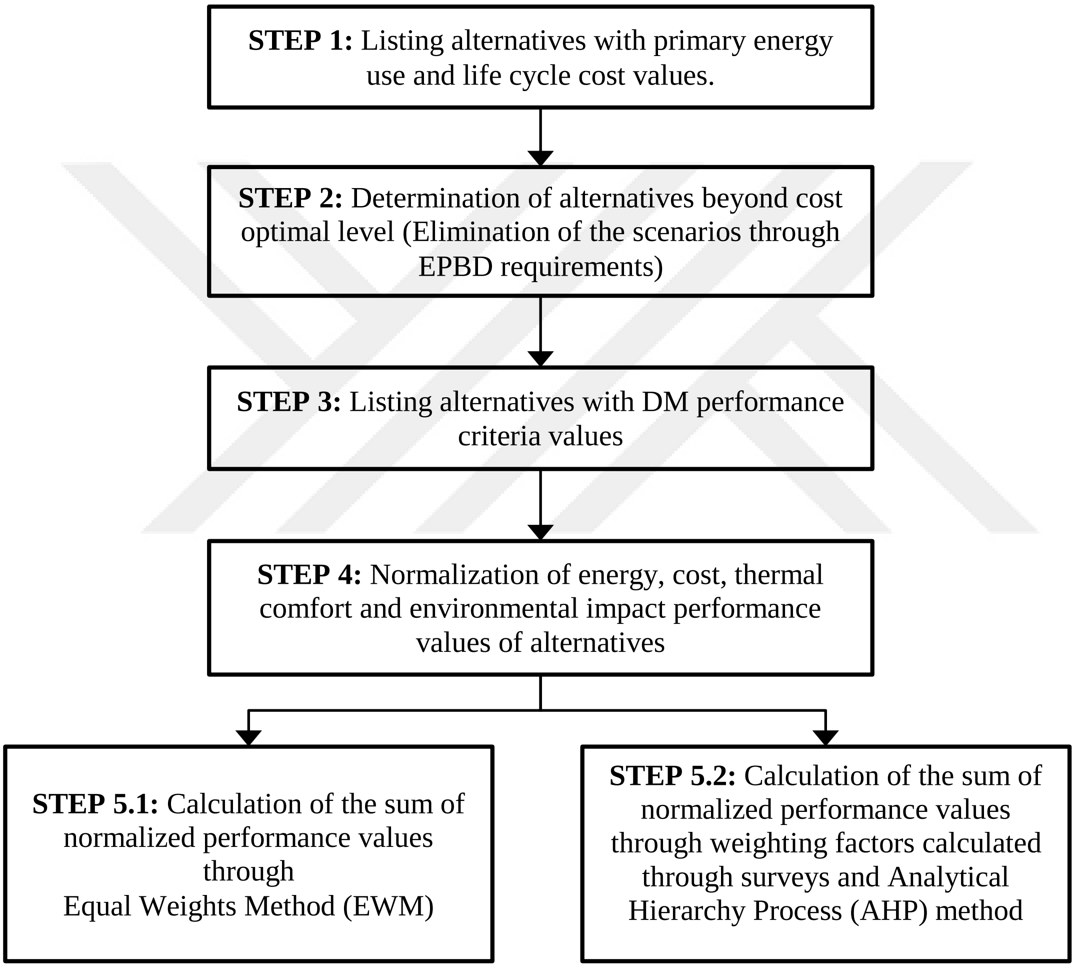

Figure 4.3 : Methodology for the decision-making process.

4.4.1 Listing alternatives with PEU and LCC values

In this step of the methodology, alternatives are evaluated by their primary energy use (PEU) and life cycle cost (LCC) values as calculated according to the presented method. The evaluation is made in accordance with (EPBD, 2010) cost optimality method.

4.4.2 Determination of alternatives beyond cost optimal level

The cost optimal case and the cost optimal level are determined in this step of the methodology. Cases which are beyond the cost optimal line are considered to be energy efficient cases, so that they are preferable in terms of energy efficiency targets of EPBD (2010).

In this methodology, the cost optimal range is considered as ±15%, due to the scope of the decision making and the width of the energy and cost ranges. Figure 4.4 shows the principle of economic optimal level and cost optimal range determination.

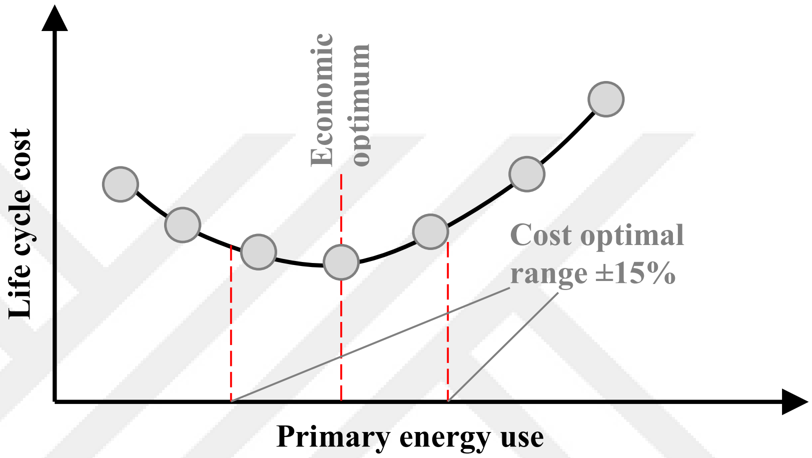

Figure 4.4 : Figuration of the cost optimality principles.

4.4.3 Listing the preferred alternatives with DM criteria values

Then, the alternatives that are determined in the second step given in section 4.4.2 are listed with the decision-making criteria values as investment cost, primary energy use for heating and cooling, thermal comfort, and environmental impact.

4.4.4 Normalization of DM criteria values

In most multi-criteria decision-making (MCDM) problems, criteria have different scales (e.g. comfort, fuel consumption, design, etc. in selecting a car). As such, pre-processing the data to obtain a common scale is required. Normalization is a technique that is used in multi criteria decision making in order to allow aggregation of criteria with numerical and comparable data. Thus, criteria can be used for rating and ranking decision alternatives. In this methodology the values of the energy, cost, thermal comfort and environmental impact criteria are normalized with the “feature scaling / min.-max. normalization” technique in order to obtain comparable data. The equation (4.3) used for the min. max. normalization is given below.

According to the equation (4.3), the difference between the value (x) and the minimum value of the data set is divided to the difference between the maximum and the minimum value of the data set and the normal. So that, the maximum value was normalized to 1, where the better alternatives have a value between 0 and 1.

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{4.3}$$

4.4.5 Determination of the best alternatives through Equal Weights Method (EWM)

Equal Weights Method (EWM), as a Weighted Sum Method (WSM), is the selected MCDM method for this study. WSM is a MADM ranking method, where the best alternative is selected by the sum of n number of criteria ranking weights within m alternatives. It can be expressed by the following equation, where a and w are the actual value and weight factor of the jth criteria given for the ith alternative, respectively.

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{4.4}$$

4.4.6 Determination of the best alternatives through AHP

In this part of the study, the proposed method to define the weighting factors of the performance indicators (criteria) is explained.

As discussed in Section 3, Analytical Hierarchy Process (AHP) is one of the most significant method used for decision making in building design. Thus, AHP method is used to evaluate the survey outputs and calculate the weighting factors of each performance indicator (criteria) indicated by the participants / project stakeholders. Detailed information on AHP method is given in section 4.4.6.4.

The main steps of the weighting factor calculation methodology are as follows:

- Defining the survey questions
- Determination of survey participants
- Evaluation of survey answers
- Calculation of weighting factors

- Calculation of sum of normalized DM criteria values

4.4.6.1 Defining the survey questions

Survey questions should be designed according to the type and the depth of the information that is needed. Additionally, there are different question types such as closed-ended questions, rating scale questions, multiple choice questions, rank order questions, dichotomous questions, open-ended questions.

In order to obtain data from project stakeholders, it is considered to collect the following information from the participants:

- the demographic data of the participants (decision makers)
- the interest of the decision maker on the subject
- the decision frequency of the participant on the subject
- the personal weighting factors of the participants.

The aim and scope of each information and the structure of the question that is asked to the participants are defined in detail below.

4.4.6.2 Part 1 – Demographic questions

In this part of the survey, the demographic questions are planned in order to determine what factors may influence the participant’s answers, interests, and opinions. The proficiency, educational level and employment status are determined as the required demographic data that should be obtained. The demographic data will be used to cross-tabulate the results with subgroups of the demographic divisions. The demographic questions are considered to be planed in a closed-ended structure where the participants will select the proper option as the answer to the question.

4.4.6.3 Part 2 – Measuring the participants’ (decision maker) interest on the subject

In this part of the survey, the personal interest of the participant on the researched subjects are asked. This information will be used to validate the answers by comparing the interest and importance levels obtained from Part 2 and Part 4. In this part of the survey, five point likert scale is used to measure the response of the survey participant to the question.

4.4.6.4 Part 3 – Measuring the impact of decision maker on decisions

The survey questions are composed based on the performance indicators (criteria) that are used in the method such as energy, cost, environmental impact and thermal comfort. This information will be used to validate the answers by comparing the impact/influence and importance levels obtained from Part 3 and Part 4. In this part of the survey, five point likert scale is used to measure the response of the survey participant to the question.

4.4.6.5 Part 4 – Measuring the personal weighting factors of the participant

In this part, survey questions should be grouped based on the performance indicators (criteria) that are used in the method such as energy, cost, environmental impact and thermal comfort. Additionally, the questions are planed to be asked in three different levels as the material, envelope and building. This provides to obtain an average value of the three levels and get a more certain result. Thus, it helps to understand and verify the answers of the participants.

4.4.6.6 Determination of survey participants

In order to apply the proposed approach, the participants of the survey are assumed as a group of stakeholders of a housing project, who are involved to the building design and decision-making process. Generally, stakeholders are the investor (project owner), managers, contractors, architect and engineers.

4.4.6.7 Evaluation of the survey results

Survey results for the questions given in Part 1 -3 are evaluated in order to obtain the key findings about the participants. Results are given in section 5.4.2.3.

4.4.6.8 Calculation of weighting factors through AHP

Analytical Hierarchy Process (AHP), first proposed by Myers ald Alpert, was developed later by Thomas Saaty in 1977 to be used in multiple criteria decision making.

According to this method, the main steps followed are as below:

<u>Step 1 - Developing a single pairwise comparison matrix for the criteria weights:</u> Evaluation phase of the AHP is based on the concept of binary comparison. In the

pairwise comparison, criteria are compared with each other in terms of intensity of importance. An example of the comparison matrix is given in Table 4.4. and the scale used for comparison is given and explained in Table 4.5. In this phase, the inter-factorial comparison matrix is constructed. The factorial comparison matrix is a square matrix of nxn dimensions. The matrix components on the diagonal assume the value 1.

Table 4.3 : Example of the single pairwise comparison matrix for the criteria weights.

	Criteria A	**Criteria B**	**Criteria C**	**Criteria n**
Criteria A	**1**	3x	x	5x
Criteria B	1/3x	**1**	5x	3x
Criteria C	1/x	1/5x	**1**	x
Criteria n	1/5x	1/3x	1/x	**1**

Table 4.4 : The fundamental scale for pairwise comparisons.

Intensity of Importance	Definition	Explanation
1	Equal important	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgment slightly favor one over the other.
5	Much more important	Experience and judgment slightly favor one over the other.
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity.
2, 4, 6, 8	Intermediate values	When compromise is needed.

Step 2 – Calculation of the weighting factors (priority vector): Assignment of the pairwise comparison matrix is based on the $m \ x \ m$ real matrix, where m is the number of performance criteria that are evaluated. Each entry a_{jk} of the matrix A represents the importance of the jth criterion relative to the kth criterion. If a_{jk} > 1, then the jth criterion is more important than the kth criterion, while if a_{jk} < 1, then the jth criterion is less important than the kth criterion. If two criteria have the same importance, then the entry a_{jk} is 1 (Saaty, 1980). The entries a_{jk} and a_{kj} satisfy the following constraint:

$$a_{jk} \,.\, a_{kj} = 1 \tag{4.5}$$

Once the matrix A is built, it is possible to derive from A the normalized pairwise comparison matrix A_{norm} by making equal to 1 the sum of the entries on each column, i.e. each entry □jk of the matrix A_{norm} is computed as:

$$a'_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \tag{4.6}$$

Finally, the criteria weight vector w (that is an m -dimensional column vector) is built by averaging the entries on each row of A_{norm}, i.e.

$$w_j = \frac{\sum_{l=1}^{m} a'_{jl}}{m} \tag{4.7}$$

In the proposed approach, weighting factors are firstly determined through the answers of the Part 4 questions. It is asked to the decision makers their personal weighting factors on the performance criteria for the project that they have involved. The answers are analyzed by calculating the average value of all decision makers' answers on the specific criteria. Due to the number of criteria that occurs due to the material, envelope and building levels, it is laborious to obtain answers from the decision makers in AHP pairwise format. Thus, the survey questions are asked in a regular 1-5 likert scale where the AHP methodology uses 1-9 likert scale as given in Table 4.5. Then, the obtained weighting factors are converted to a pairwise comparison, so that, each 0,5 difference between the weighting factors corresponds to one level of intensity of importance difference.

Step 3 – Calculation of the Consistency Ratio (CR):

The Consistency Ratio (CR) is used to validate the pairwise comparison matrix and tell the decision maker how consistent he/she has been. Calculation of the Consistency Ratio has three steps as described below.

In the first step of CR calculation method, the column addition of the pairwise comparison matrix are multiplied by the priority vectors for each criteria, and summed to obtain the $\boldsymbol{\lambda}_{max}$.

Then, the Consistency Index (CI) is calculated by the equation (4.8), where n is the number of the criteria.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.8}$$

Finally, the equation (4.9) is used to calculate the CR, by dividing the calculated CI to the Random Index (RI) which is obtained from Table 4.6 that can be used for small problems where $n \leq 10$.

$$CR = \frac{CI}{RI} \tag{4.9}$$

Table 4.5 : Values of the Random Index (RI) for small problems.

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

In this methodology, no pairwise comparison is conducted for the alternatives. The values of the performance criteria are obtained by calculations and the values are normalized as given in section 4.4.4, by equation (4.3).

4.4.6.9 Calculation of the sum of normalized DM performance criteria values

In this step of the proposed approach, normalized decision making criteria values are summed by multiplying with their weighting factors which are calculated through AHP method.

5. IMPLEMENTATION OF THE PROPOSED APPROACH

The study aims to present a new approach for performance based decision making on thermal insulation material selection. Specifically, the method is adapted to social housing design and the methodology is applied on a social housing archetype.

In this section, the implementation of the proposed approach on a determined archetype, which is a commonly applied social housing project, is presented with the results and key findings. Mainly, the implementation is made on a social housing archetype, considered as situated in temperate-dry climatic region of Turkey. 10 thermal insulation materials, five thickness variations, with three window to wall ratios are considered as the independent variables of the decision-making process and used for the parameterization, resulting with total 300 alternative scenarios. Four dependent variables as performance criteria (energy, cost, thermal comfort, environmental impact) are calculated through the methodology. Finally, the proposed approach for decision-making is applied on the results of 300 alternative scenarios.

As aforementioned, the approach of the methodology presented in this study includes the following main steps:

- Determination of the archetype
- Parameterization with the designated independent variables
- Calculation of the dependent variables
- Implementation of the multiple criteria decision-making
- Determination of the best alternatives through the decision-making scores.

5.1 Determination of the Archetype

Throughout the researches on the current social housing projects, it was observed that 4 apartment/floor plan scheme is one of the most common plan configuration within the whole social housings. Thus, in this study, an archetype which has a 4 apartment/floor plan scheme was designated.

The selected case study is a notional archetype for social housings applied in Turkey. Case study archetype is composed of 11 residential floors, each floor with 320 m^2 conditioned area (80 m^2 per apartment unit and 55 m^2 unconditioned area (circulation, core, etc.). Typical floor plan and the front façade of the archetype is given in Figure 5.1 and 5.2, respectively.

Figure 5.1 : Floor plan of the social housing archetype (Ankara Turkuaz Project B2 type floor plan) (Url-4)

Definition of the archetype in terms of optic and thermo physical properties of envelope are given in Table 4.6 and 4.7, below. Definitions are made through the reference values as minimum energy efficiency requirement values given in (TS 825, 2008; BEP-TR, 2010).

Figure 5.2 : Front facade of the social housing archetype (Ankara Turkuaz Project B2 front facade). (Url-4)

Table 5.1 : Transparent Component Thermal and Optical Properties.

Glazing type	**U Value (W/m^{2}K)**	**Solar heat gain coefficient (0-1)**	**Visible transmittance (0–1)**
	2.40	0.70	0.80

Table 5.2 : Opaque Component Thermal Properties

Opaque component	**Material**	**Thickness (m)**	**Conductivity (W/mK)**	**U Value (W/m2K)**
Exterior Wall	Plaster	0.020	0.970	Uextwall=0.57
	Insulation	0.060	0.035	
	Aerated brick	0.190	0.500	
	Gypsum plaster	0.020	0.970	

5.2 Parameterization with the Designated Independent Variables

In order to parameterize the base case archetype to obtain alternatives to be evaluated in the decision-making process, thermal insulation material data is collected from the market. The alternatives are representing thermal insulation materials with different attributes. In this case, five thermal insulation materials are selected to be applied such as XPS, EPS, GW, RW, and CG. Moreover, thermal insulation materials are varied in terms of high and low performance levels. For example, thermal insulation material 01 is representing the XPS material with lower thermal conductivity and density, where thermal insulation material 02 is representing the XPS with higher thermal conductivity. In sum, 10 variations are considered in this study, on order to represent a variation in terms of material attributes and attribute ranges. The thermal insulation materials that are involved in this study are given in the Table 5.3.

In addition to the variety of thermal insulation materials, variation of other design parameters may also change the performance of the thermal insulation material in terms of energy, cost, etc. In this study, one of the most effective envelope parameter as the window to wall ratio (WWR) is also considered. WWR of 10%, 15%, and 20% are considered as other independent variables in order to compose a whole approach for the envelope.

Finally, 10 thermal insulation materials with 5 thickness variations and 3 window-to-wall ratios are combined and 300 alternatives are obtained to be evaluated in the decision making process.

Table 5.3 : Properties of the insulation material alternatives.

Material No	Thermal Insulation Material	Thermal Conductivity (W/mK)	Density (kg/m3)	Specific Heat (J/kgK)	EI Embodied Carbon (kg.CO_2 eq /cm) (cradle to gate)	EI Embodied Energy (MJ/cm) (cradle to gate)	Material Cost	Thickness Alternatives (m)
1	**Extruded Polystyrene (XPS)**	01 XPS: 0.027	01 XPS: 30	1300	01 XPS: 1.365	01 XPS: 34.79	High	(0.04, 0.08, 0.12, 0.16, 0.20)
		02 XPS: 0.040	02 XPS: 50		02 XPS: 5.370	02 XPS: 70.80	Low	
		03 XPS: 0.027	03 XPS: 30		03 XPS: 5.370	03 XPS: 70.80	Low	
		04 XPS: 0.040	04 XPS: 50		04 XPS: 1.365	04 XPS: 34.79	High	
2	**Expanded Polystyrene (EPS)**	01 EPS: 0.035	01 EPS: 20	1250	01 EPS: 0.530	01 EPS: 15.80	High	(0.04, 0.08, 0.12, 0.16, 0.20)
		02 EPS: 0.040	02 EPS: 40		02 EPS: 2.550	02 EPS: 88.60	Low	
		03 EPS: 0.035	03 EPS: 20		03 EPS: 2.550	03 EPS: 88.60	Low	
		04 EPS: 0.040	04 EPS: 40		04 EPS: 0.530	04 EPS: 15.80	High	
3	**Glasswool (GW)**	01 GW: 0.035	01 GW: 15	1000	01 GW: 0.210	01 GW: 5.40	High	(0.04, 0.08, 0.12, 0.16, 0.20)
		02 GW: 0.050	02 GW: 150		02 GW: 1.350	02 GW: 28.00	Low	
		03 GW: 0.035	03 GW: 15		03 GW: 1.350	03 GW: 28.00	Low	
		04 GW: 0.050	04 GW: 150		04 GW: 0.210	04 GW: 5.40	High	
4	**Rockwool (RW)**	01 RW: 0.035	01 RW: 20	900	01 RW: 0.45	01 RW: 6.90	High	(0.04, 0.08, 0.12, 0.16, 0.20)
		02 RW: 0.050	02 RW: 160		02 RW: 1.05	02 RW: 16.80	Low	
		03 RW: 0.035	03 RW: 20		03 RW: 1.05	03 RW: 16.80	Low	
		04 RW: 0.050	04 RW: 160		04 RW: 0.45	04 RW: 6.90	High	
5	**Cellular Glass (CG)**	01 CG: 0.035	01 CG: 100	1000	01 CG: 1.54	01 CG: 6.60	High	(0.04, 0.08, 0.12, 0.16, 0.20)
		02 CG: 0.055	02 CG: 200		02 CG: 0	02 CG: 27	Low	
		03 CG: 0.035	03 CG: 100		03 CG: 0	03 CG: 27	Low	
		04 CG: 0.055	04 CG: 200		04 CG: 1.54	04 CG: 6.60	High	

5.3 Calculation of the Dependent Variables (Performance Criteria)

Calculation results of the energy, cost, environmental impact and thermal comfort are given in the following sections 5.3.1, 5.3.2, 5.3.3, and 5.3.4, respectively.

5.3.1 Calculation of energy performance

Energy performance of the alternatives are calculated through EnergyPlus simulation tool, according to the methodology explained in section 4.3.1.

It is assumed that 4 people are living in each apartment unit. Average lighting power density is fixed to 6 W/m2 for each apartment unit, with additional 5 W/m2 electronic equipment load. Since the building is a new construction, infiltration is considered to be low as 0.2 ach for apartment units and 0.5 for unconditioned zones such as apartment hall.

In this study, it is considered that the case study building is mechanically operated for heating and cooling through 24 hours. Set-point temperatures of the building are assumed as 20ºC for heating and 26ºC for cooling. Heating is provided by a central boiler, cooling is provided by unit packaged terminal air conditioners, and ventilation is provided naturally, related with the occupancy schedule.

Other concerted limitations on the determined archetype are as given below:

- 4 apartment/floor building typology
- Aspect ratio (1:1)
- Area of apartment units (100 m²)
- Internal gains (5 W/m²)
- Lighting power density (12 W/m²)
- Occupancy density (4 person/apt.)
- Occupancy schedule,
- Occupancy behavior & natural ventilation schedule,
- Operational schedule (24 hour constant)
- Infiltration rate (0.3 ach-1)

- Heating set point temperature (20°C)
- Cooling set point temperature (26°C)

Visuals of the energy model is given in Figure 5.3. Primary energy use results are given in Figure 5.4. Detailed outputs of the alternatives are given in Appendix B, figures form Figure B.1 to FigureB.10, in terms of heating and cooling primary energy uses.

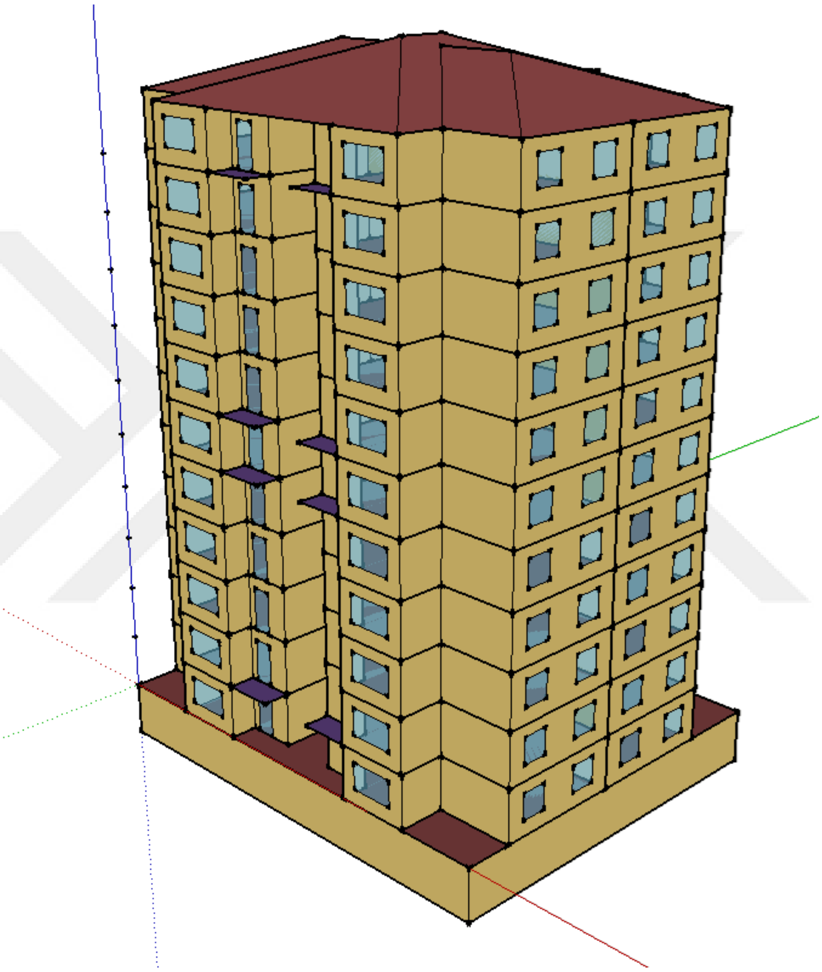

Figure 5.3 : Visualized energy model of the archetype.

In general, cases with no thermal insulation for WWR10%, WWR15% and WWR20% have primary energy use for heating and cooling as 127.35 kWh/m^2.a, 123.84 kWh/m^2.a, 123.03 kWh/m^2.a, respectively.

According to Figure B.1, total primary energy use for heating and cooling varies between 81,84 kWh/m^2.a and 53.41 kWh/m^2.a for 01-XPS thermal insulation material. Cases with no thermal insulation for WWR10%, wwr15% and WWR20% have primary energy use for heating and cooling as 127.35 kWh/m^2.a, 123.84 kWh/m^2.a, 123.03 kWh/m^2.a, respectively.

According to Figure B.2, total primary energy use for heating and cooling varies between 88.71 kWh/m^2.a and 57.69 kWh/m^2 for 02-XPS thermal insulation material.

According to Figure B.3, total primary energy use for heating and cooling varies between 86.33 kWh/m^2.a and 56.14 kWh/m^2.a for 03-EPS thermal insulation material.

According to Figure B.4, total primary energy use for heating and cooling varies between 88.71 kWh/m^2.a and 57.71 kWh/m^2.a for 04-EPS thermal insulation material.

According to Figure B.5, total primary energy use for heating and cooling varies between 86.33 kWh/m^2.a and 56.15 kWh/m^2.a for 05-GW thermal insulation material.

According to Figure B.6, total primary energy use for heating and cooling varies between 92.75 kWh/m^2.a and 60.59 kWh/m^2.a for 06-GW thermal insulation material.

According to Figure B.7, total primary energy use for heating and cooling varies between 86.33 kWh/m^2.a and 56.15 kWh/m^2.a for 07-RW thermal insulation material.

According to Figure B.8, total primary energy use for heating and cooling varies between 92.76 kWh/m^2.a and 60.60 kWh/m^2.a for 08-RW thermal insulation material.

According to Figure B.9, total primary energy use for heating and cooling varies between 86.31 kWh/m^2.a and 56.11 kWh/m^2.a for 09-CG thermal insulation material.

According to Figure B.10, total primary energy use for heating and cooling varies between 94.48 kWh/m^2.a and 61.88 kWh/m^2.a for 10-CG thermal insulation material.

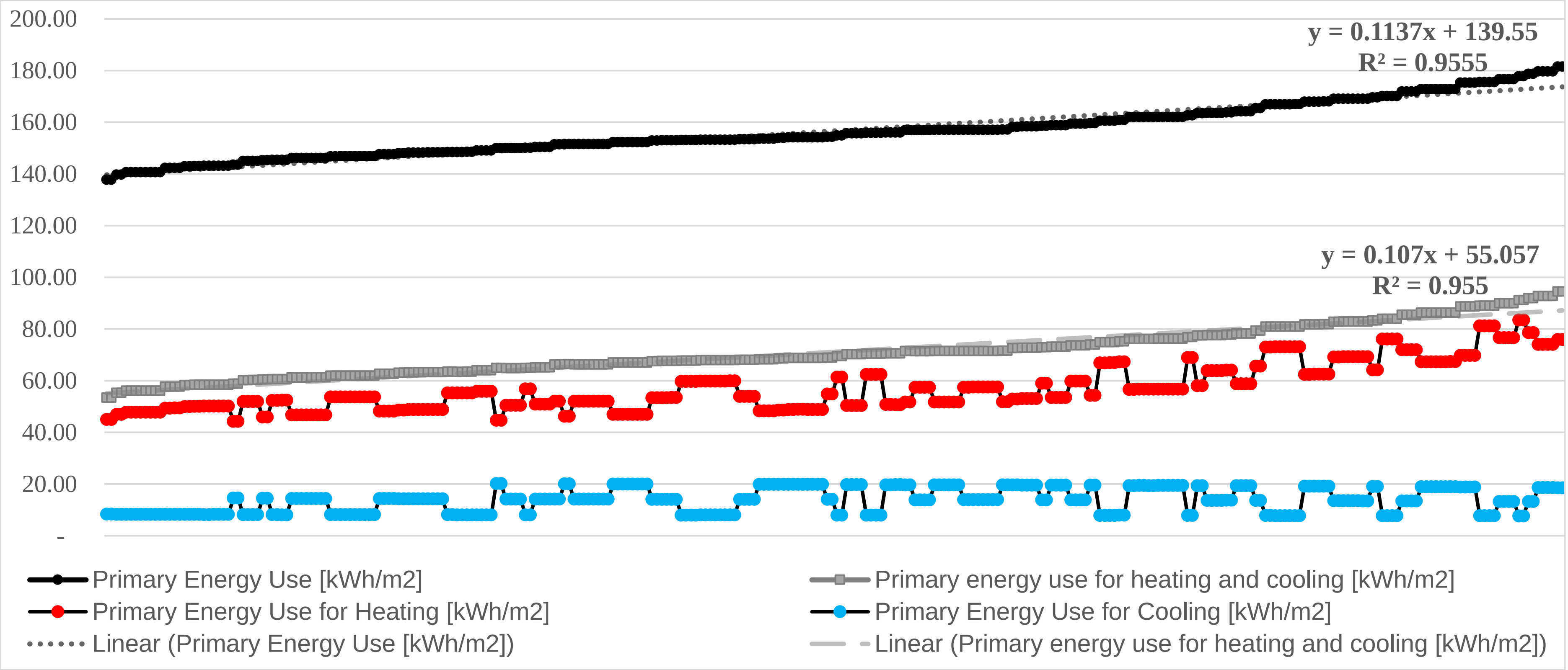

Figure 5.4 : Primary energy use of 300 alternatives [kWh/m^2]

5.3.2 Calculation of cost performance

Cost performance of the alternatives are calculated according to the methodology explained in section 4.3.2.

As aforementioned, in order to reach more accurate results via life-cycle cost calculation, values of the economic parameters involving the calculation as aforementioned are accepted as an average of the annual values since 2005. Economic parameters that are used in the calculations are explained in Table 5.5, below. Calculation results of all alternatives are presented in Appendix C, Figure C.1 to C.10, and discussed here.

Table 5.4 : Economic parameters for LCC.

Inflation rate, Ri ()	%	9.18
Market (Nominal) interest rate, R ()	%	11.67
Real interest rate, RAT_{re}	%	2.27
Nominal price escalation on natural gas, En ()	%	10.07
Nominal price escalation on electricity, Ee ()	%	13.09
Present value factor, $f_{pv}(n)$	%	28.64
Natural gas unit price*	TL/kWh**	0.11
Electricity unit price*	TL/kWh**	0.41
Calculation Period	Years	30

*Unit energy prices include all VATs.

According to the results, life cycle cost of “01 XPS” alternatives vary between 762.7 TL/m2 (8cm ins., 10% WWR) and 847.72 TL/m2 (20cm ins., 20% WWR), where the cost optimal cases are represented by 8cm insulation thickness for all WWR cases.

Life cycle cost of “02 XPS” alternatives vary between 756.19 TL/m2 (8cm ins., 10% WWR) and 821.20 TL/m2 (20cm ins., 20% WWR), where the cost optimal cases are represented by 8cm and 12 cm insulation thickness for all WWR cases with reasonably similar LCC values.

Results of “03 EPS” thermal insulation material shows that the life cycle cost of alternatives vary between 756.83 TL/m2 (12cm ins., 10% WWR) and 821.14 TL/m2 (4cm ins., 20% WWR) where the cost optimal cases are represented by 12cm insulation thickness for all WWR cases.

Life cycle cost of “04 EPS” alternatives vary between 745.18 TL/m2 (12cm ins., 10% WWR) and 812.56 TL/m2 (4cm ins., 20% WWR), where the cost optimal cases are represented by 12 cm insulation thickness for all WWR cases.

“05 GW” thermal insulation material alternatives have a LCC variation between 791.22 TL/m2 (8cm ins., 10% WWR) and 887.00 TL/m2 (20cm ins., 20% WWR), where “06 GW” thermal insulation material alternatives have a LCC variation between 803.16 TL/m2 (8cm ins., 10% WWR) and 880.05 TL/m2 (20cm ins., 20% WWR). cost optimal cases are represented by 8cm insulation thickness for all WWR cases

According to the results, life cycle cost of “07 RW” alternatives vary between 781.00 TL/m2 (8cm ins., 10% WWR) and 871.33 TL/m2 (20cm ins., 20% WWR), where the cost optimal cases are represented by 8cm insulation thickness for all WWR cases.

Life cycle cost of “08 RW” alternatives vary between 779.61 TL/m2 (8cm ins., 10% WWR) and 864.03 TL/m2 (20cm ins., 20% WWR), where the cost optimal cases are represented by 8cm insulation thickness for all WWR cases.

“09 CG” thermal insulation material alternatives have a LCC variation between 806.37 TL/m2 (8cm ins., 10% WWR) and 915.69 TL/m2 (20cm ins., 20% WWR), where the cost optimal cases are represented by 4 cm and 8 cm insulation thickness for all WWR cases with reasonably similar LCC values.

“10 CG” thermal insulation material alternatives have a LCC variation between 809.58 TL/m2 (8cm ins., 10% WWR) and 910.95 TL/m2 (20cm ins., 20% WWR). cost optimal cases are represented by 8cm insulation thickness for all WWR cases.

In general,when the investment and maintenance costs increase, the total energy costs decrease due to higher insulation level and decreased heating energy use. The balance between the investment and maintenance costs and energy costs are given in Figure 5.5.

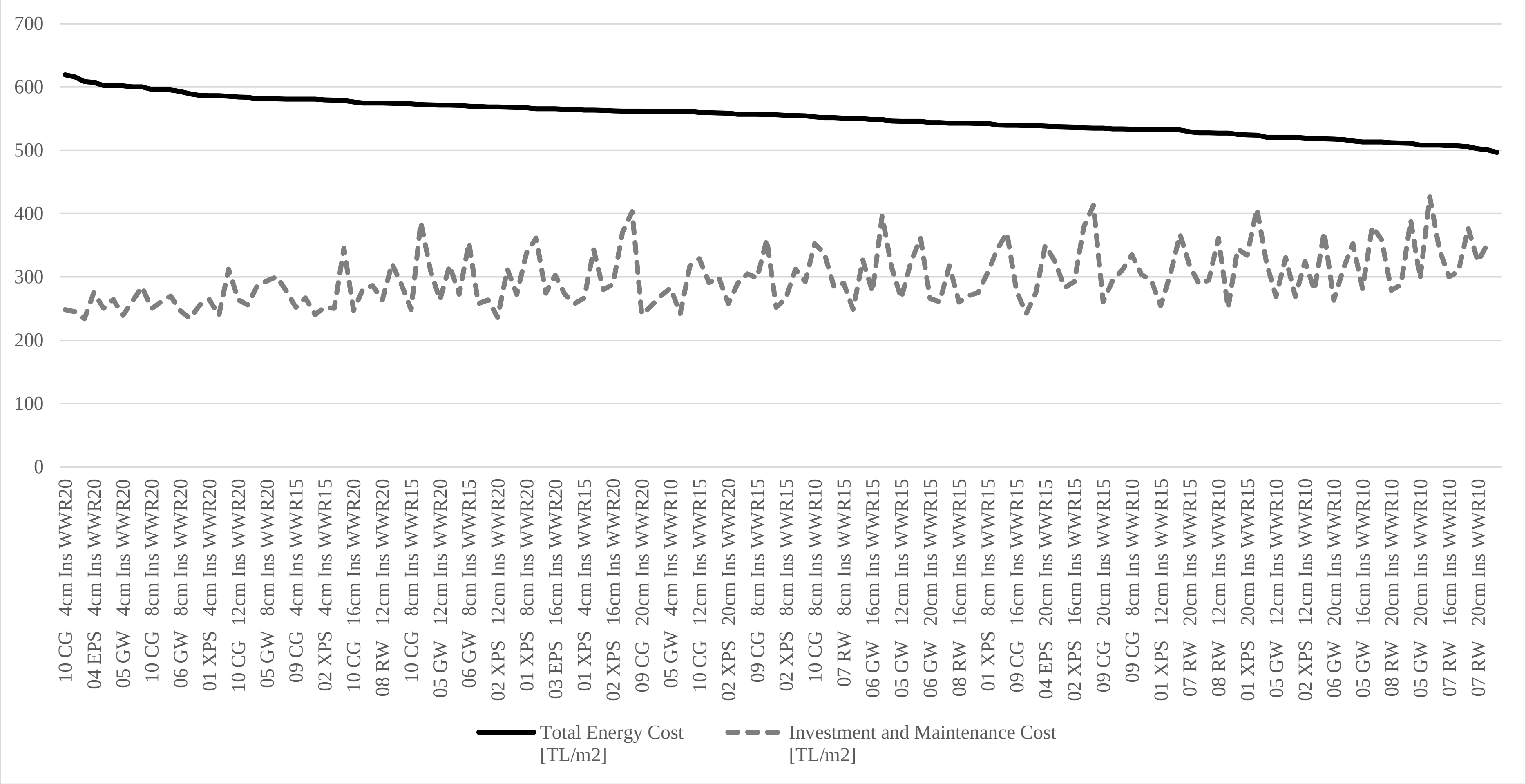

Figure 5.5 : Energy, investment and maintenance costs of 300 alternatives [TL/m^2]

5.3.3 Calculation of thermal comfort performance

Thermal comfort of alternatives are calculated in accordance with the methodology represented in section 4.3.3. Thermal comfort level is evaluated based on the adaptive comfort model defined in EN 15251: 2017.

In general, according to the results, thermal comfort level increases by increasing the thermal insulation material thickness and window to wall ration On the other hand, all scenarios provide a proper thermal comfort level so that the performance level does not vary between different insulation materials. Moreover, it is clear that, cases with no thermal insulation does not provide the thermal comfort unmet hours limit.

Detailed results of thermal comfort levels of 300 scenarios are given in Appendix D, Figure D.1 to Figure D.10. According to the results, thermal comfort unmet hours vary between 149.40 hr (10-CG, 4cm, 10%WWR) and 12.17 hr (01 XPS, 20cm, 20%WWR).

5.3.4 Calculation of environmental impact performance

Environmental impact values are calculated according to the methodology presented in section 4.3.4. Environmental impact is evaluated by the embodied carbon level and embodied energy levels of alternatives. Results of the calculation is presented in Figure 5.6 and Figure 5.7 for embodied carbon and embodied energy, respectively.

According to the results, it is clear that the most significant difference between the results of alternatives occur in environmental impact performance criteria.

.

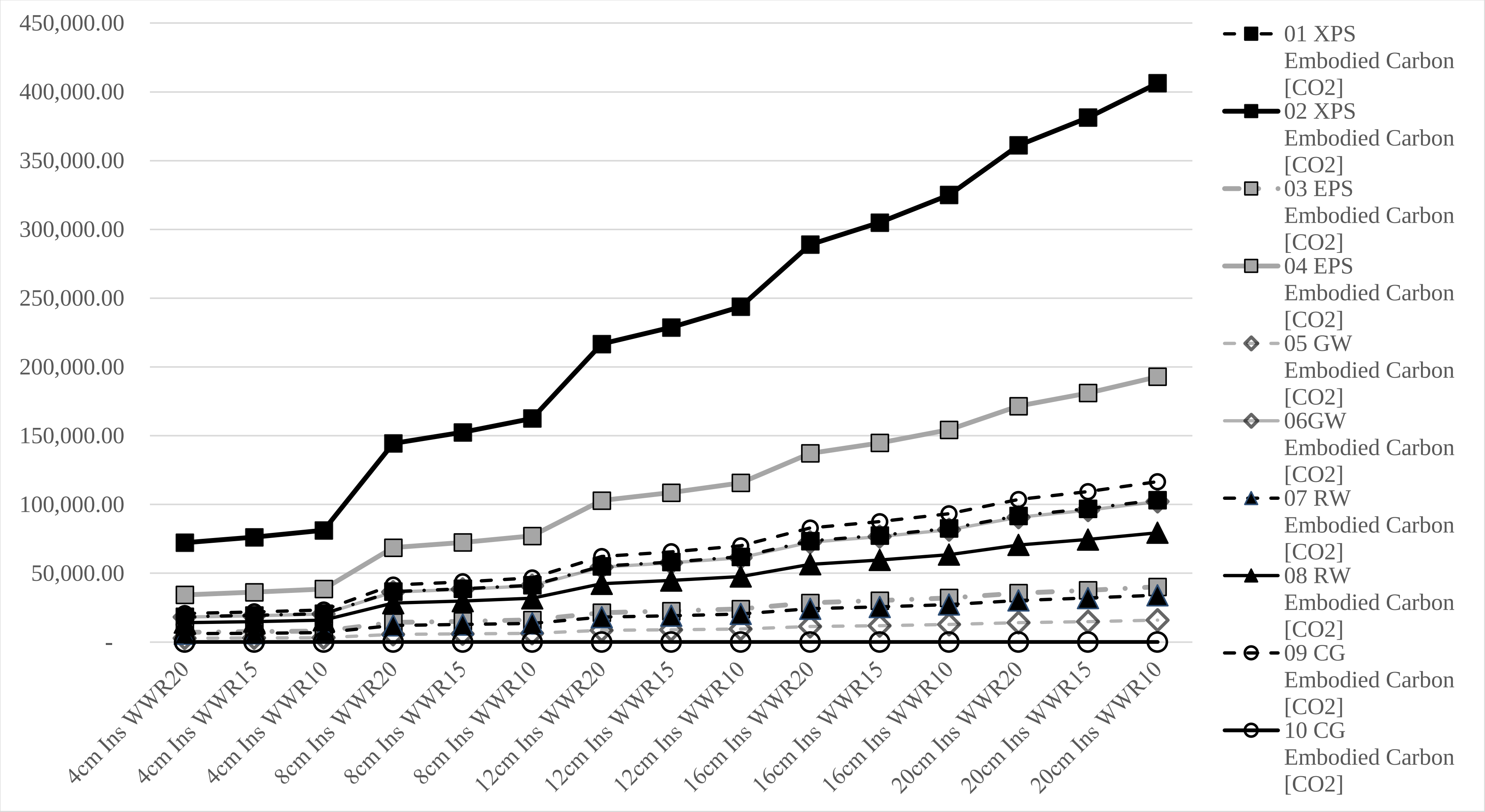

Figure 5.6 : Embodied carbon level of 300 alternatives [Mj]

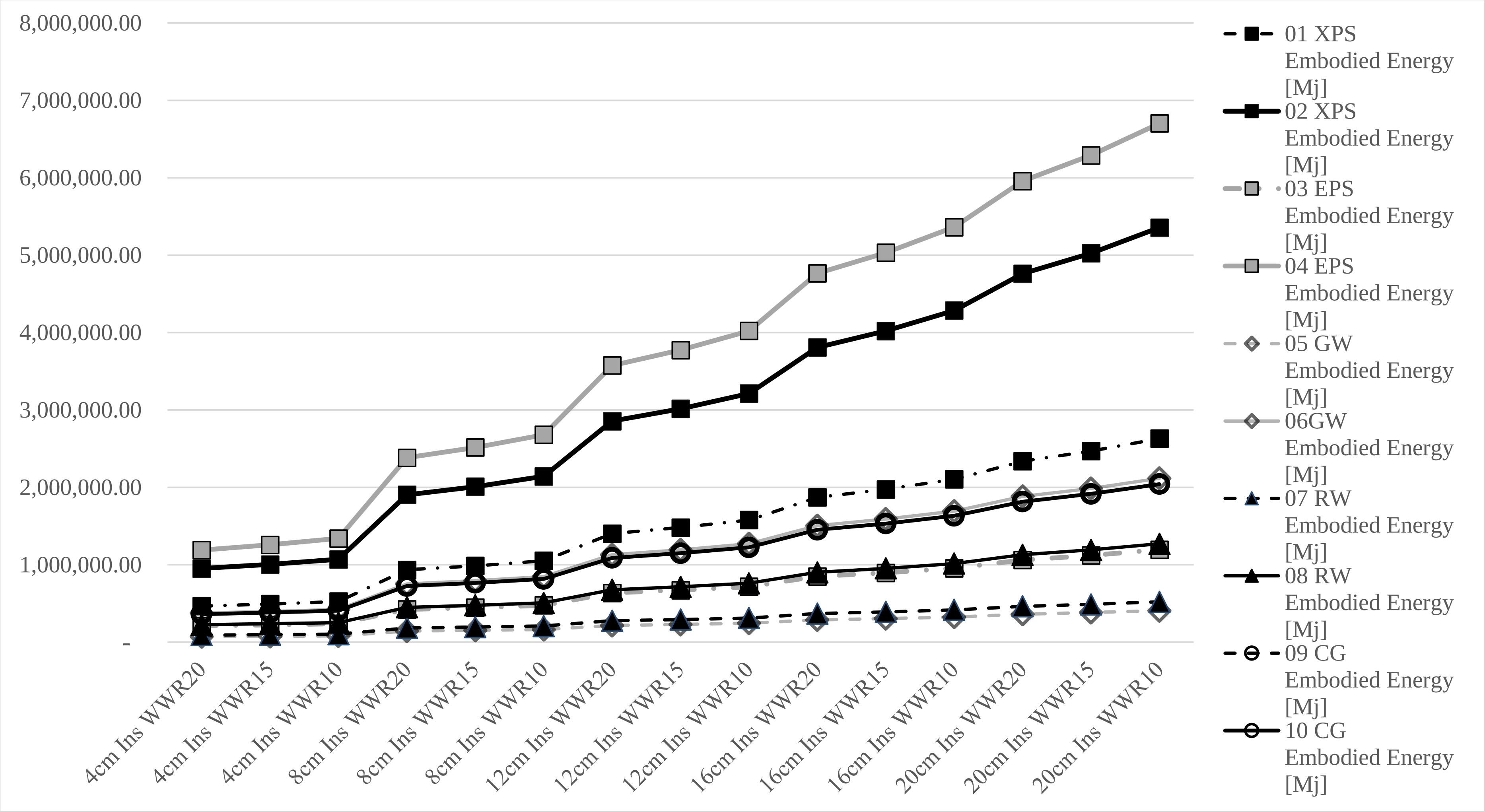

Figure 5.7 : Embodied energy level of 300 alternatives [Mj]

5.4 Implementation of the multiple criteria decision-making (MCDM) method

The implementation of the proposed MCDM consists of two methods as decision-making through equal weighting factors and decision making through calculated weighting factors through the prepared survey questions with AHP method.

Section 5.4.1 presents the results of the WSM and section 5.4.2 presents the results of the survey and AHP method.

5.4.1 Listing alternatives with energy and cost results

Figure 5.7 presents the primary energy use and life cycle cost results of 300 alternatives.

It is observed from the results presented in Figure 5.7 that, the alternatives are distributed meaningfully, which means that the parameterization created a decision space that is in accordance with the methodology.

In Figure 5.7, each material is represented with different symbol so that it is recognized that the lowest life cycle cost is represented with 04 EPS thermal insulation material and the highest life cycle cost is represented with 09 CG thermal insulation material.

From another point of view, the lowest primary energy use occurs with the application of 01 XPS thermal insulation material whereas the highest primary energy use occurs with the application of 10 CG thermal insulation material.

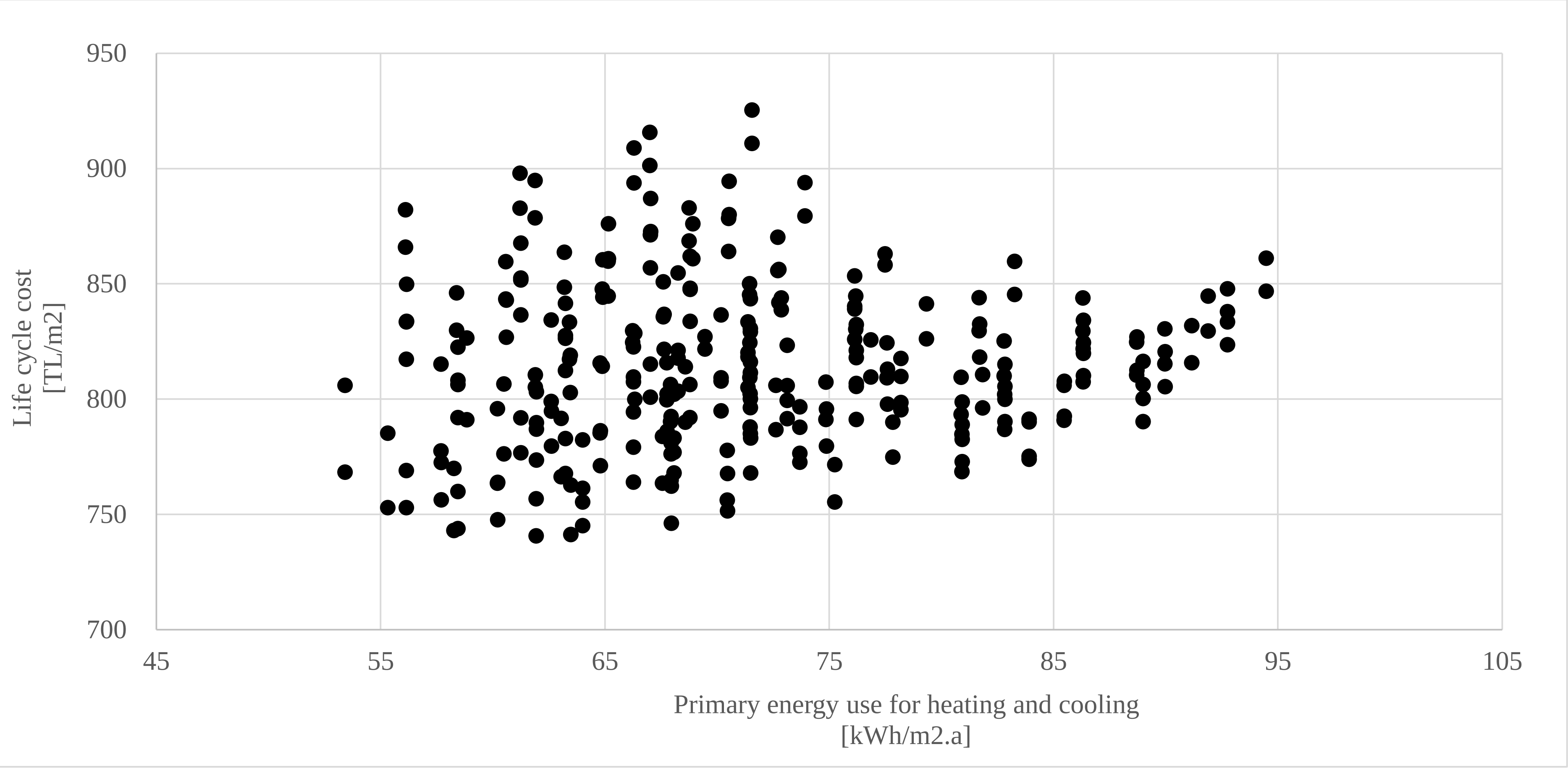

Figure 5.8 : Heating and cooling primary energy use and life cycle cost of 300 alternatives.

Energy and cost results are also given in Figures from 5.9 to 5.12, specified for different thermal insulation materials. According to the results, the range of EPS material alternatives in terms of life cycle cost [TL/m2] is between 740.67 and 826.92. Minimum primary energy use for heating and cooling is 56.14 kWh/m2.a and highest primary energy use is 88.71 kWh/m2.a.

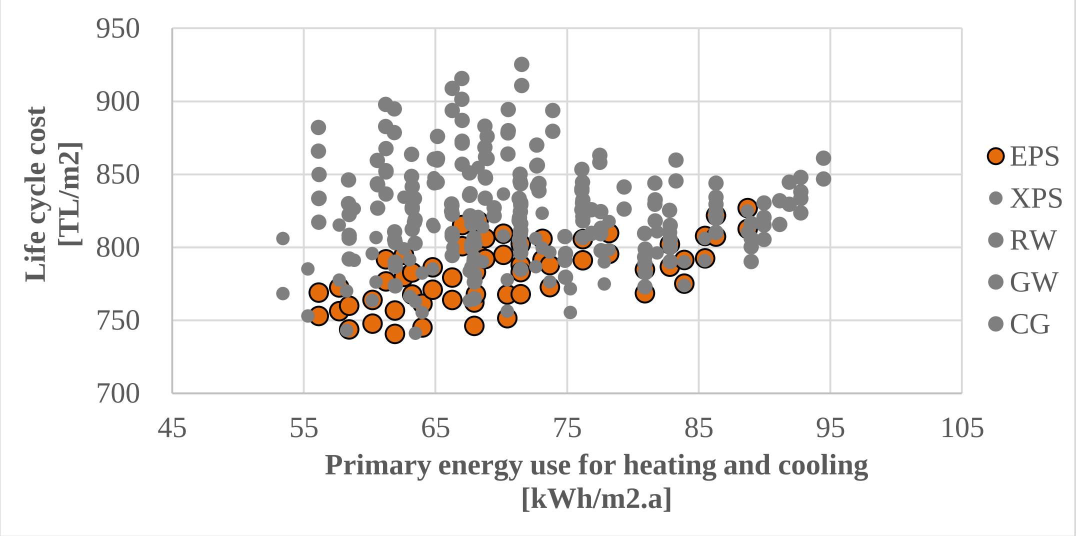

Figure 5.9 : Primary energy use for heating and cooling and life cycle cost of EPS thermal insulation material (60 alternatives highlighted).

XPS material alternatives show a variation between 741.23 TL/m2 and 854.70. TL/m2. Minimum primary energy use for heating and cooling is 53.41 kWh/m2.a and highest primary energy use is 88.71 kWh/m2.a.

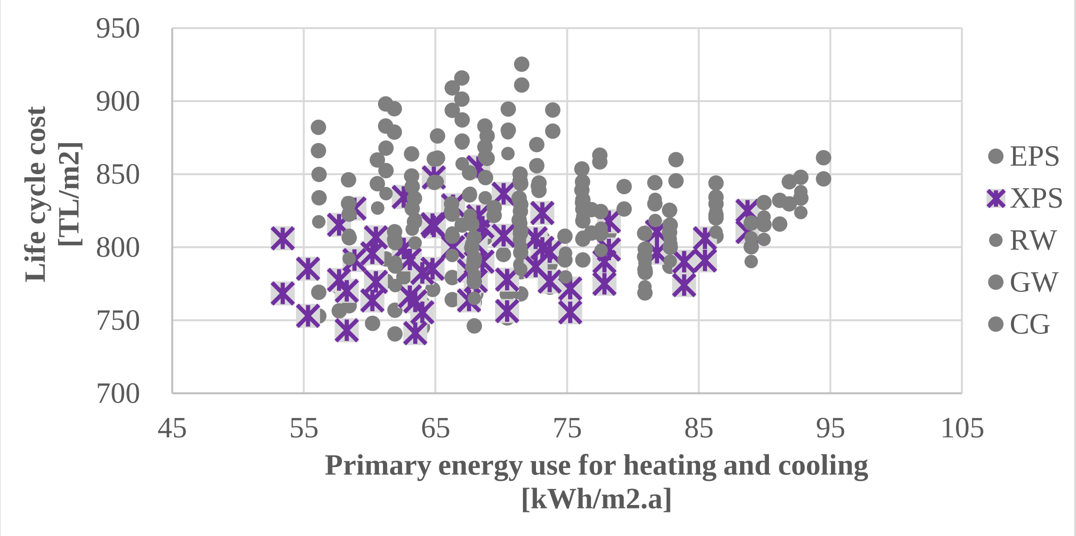

Figure 5.10 : Primary energy use for heating and cooling and life cycle cost of XPS thermal insulation material (60 alternatives highlighted).

Given in Figure 5.11, RW material alternatives show a variation between 764.85 TL/m2 and 880.05 TL/m2 for 30 years lifespan life cycle cost. Minimum primary energy use for heating and cooling is 56.15 kWh/m2.a and highest primary energy use is 92.76 kWh/m2.a.

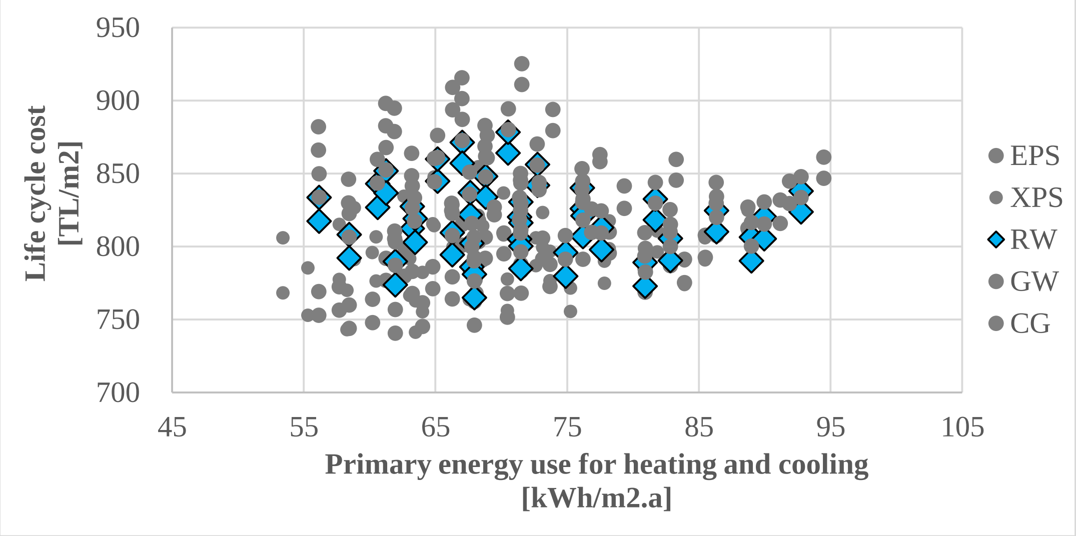

Figure 5.11 : Primary energy use for heating and cooling and life cycle cost of RW thermal insulation material (60 alternatives highlighted).

Given in Figure 5.12, GW material alternatives show a variation between 776.28 TL/m2 and 894.41 TL/m2 for 30 years lifespan life cycle cost. Minimum primary energy use for heating and cooling is 56.15 kWh/m2.a and highest primary energy use is 91.89 kWh/m2.a.

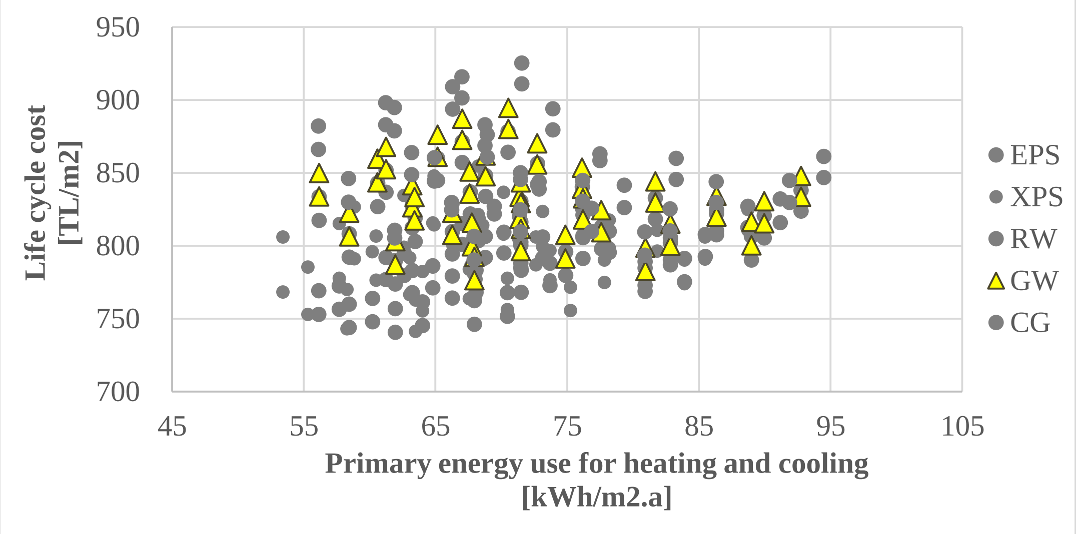

Figure 5.12 : Primary energy use for heating and cooling and life cycle cost of GW thermal insulation material (60 alternatives highlighted).

The range of CG material alternatives in terms of life cycle cost [TL/m2] is between 790.21 and 925.31. Minimum primary energy use for heating and cooling is 56.11 kWh/m2.a and highest primary energy use is 94.48 kWh/m2.a.

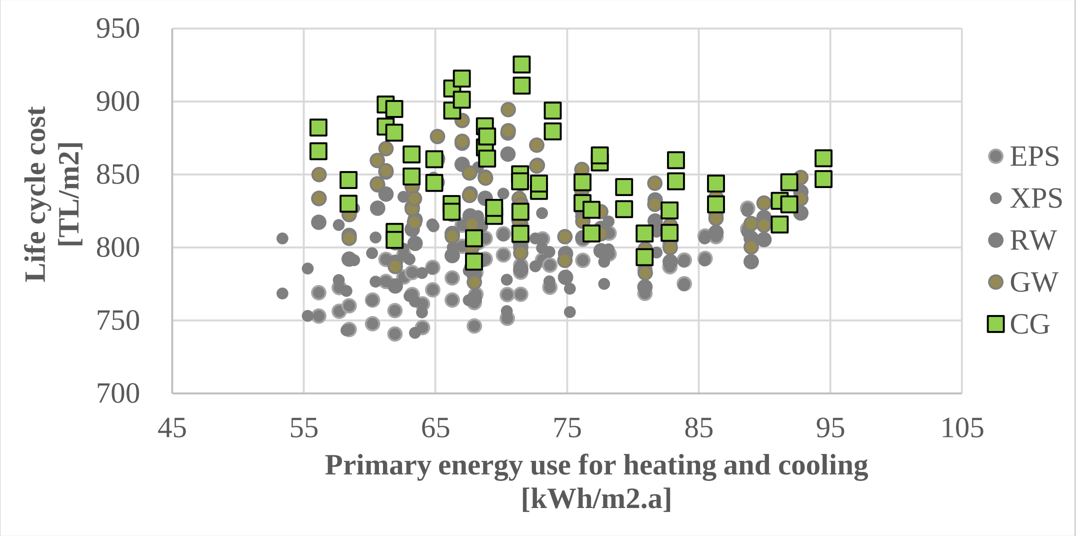

Figure 5.13 : Primary energy use for heating and cooling and life cycle cost of CG thermal insulation material (60 alternatives highlighted).

5.4.2 Determination of alternatives beyond cost optimal level

Listing of 300 alternatives with primary energy use and life cycle cost results are represented in Figure 5.14. The cost optimal level and cost optimal case are also marked in the Figure, in order to determine the threshold value.

The cost optimal case has 61.94 kWh/m2.a primary energy consumption for heating and cooling and 740.67 TL/m2 life cycle cost, with 12 cm “03 EPS” insulation application for 10% WWR.

The current requirement level has 83.91 kWh/m2.a primary energy consumption for heating and cooling and 773.93 TL/m2 life cycle cost, with 4 cm “02 XPS” insulation application for 10% WWR.

Within the 300 alternatives, 52 alternatives occur beyond the cost optimal level, and 164 alternatives occur within the acceptable range, which is determined in accordance with EPBD. Results of the alternatives beyond the cost optimal level are given in Appendix F, Table F.1. Determined alternatives represent each insulation material and application thickness between 8 cm and 20 cm.

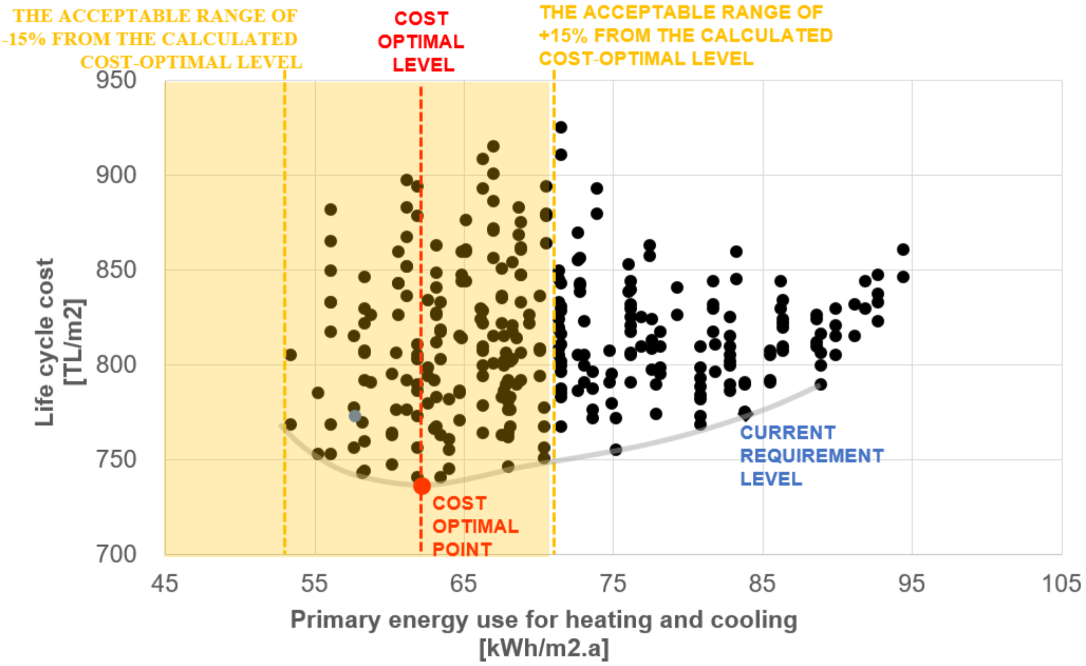

Figure 5.14 : Determination of alternatives beyond cost optimal level.

5.4.3 Listing the preferred alternatives with DM criteria values

According to the alternatives beyond the cost optimal level, listed in App F, primary energy use for heating and cooling of the alternatives vary between 53.41 kWh/m^2.a and 64.01 kWh/m^2.a, where the total primary energy use varies between 137.73 kWh/m2.a and 149.05 kWh/m2.a. In comparison with the cost optimal case, there occurs 16.6% energy reduction through the cases.

Investment cost of the cost optimal case is 218.52 TL/m2, which is the lowest value within 164 alternatives. So that, the cost optimal case is significant with both energy and cost performance.

When the alternatives are analyzed in terms of thermal comfort (unmet hours), XPS material with 16cm thickness and 15% WWR has the highest thermal performance level. It is significant that the cost optimal case has 23.33 hours of unmet thermal comfort which is the highest level for this criteria.

Environmental impact performance analysis show that, the highest performance is the cellular glass application with 20 m and 10% WWR, due to the materials environmental friendly attributes such as 0 embodied carbon.

It can be said that, the most significant difference between the alternatives occur within environmental impact criteria, through embodied carbon and embodied energy.

Additionally, the materials with better attributes are more dominant in comparison with the materials with lower attribute levels. This shows that, the materials with better attributes have a great impact on the cost optimal level, even if they have higher investment costs.

5.4.4 Normalization of energy, cost, thermal comfort and environmental impact performance values of alternatives

Performance values given in Table F.1 are normalized through the equation (4.3) explained in section 4.4.1.4. The results of the normalization are presented in Table F.2. Each performance criteria are normalized groupwise, within its value range.

5.4.5 Determination of the best alternatives through Equal Weights Method (EWM)

In this step, the normalized performance values are summed to obtain the EWM result of the alternatives. In this step, weighting of each criteria is considered as 0.25, obtaining the overall weighting as “1” by four criteria weights. EWM result and ranking of the alternatives are presented in the last two columns of Table F.2.

Best 10 alternatives are determined from Table F.2, based on the EWM result and ranking. The overall EWM result, ranking and the independent variables of the determined alternatives are given in Table 5.5 and 5.6.

According to Table 5.6, best 10 alternatives are represented by 01 EPS, 04 EPS, 01 XPS, 01 RW, 03 RW, 01 GW and 03 XPS thermal insulation material alternatives. Due to high investment costs, cellular glass thermal insulation material alternatives does not take place within the best alternatives. Moreover, based on the environmental impact criteria involvment, EPS material with low environmental impact(01 EPS and 04 EPS) take part within the best 10 alternatives, owing to the lower investment cost levels of EPS. Besides, XPS, RW and GW materials have 01 and 03 options corresponing to the low thermal conductivity and high cost low environmental impact for 01 and low cost and high environmental impact for 03 option. This result shows one of the maincontradiction between the environmental impact level and investment costs.

Best alternatives are signified in Figure 5.15, also showing the order of th ealternatives according to the overall EWM score. According tot Figure 5.15, best alternatives are generally beyond the cost optimal level and above the frontier line.

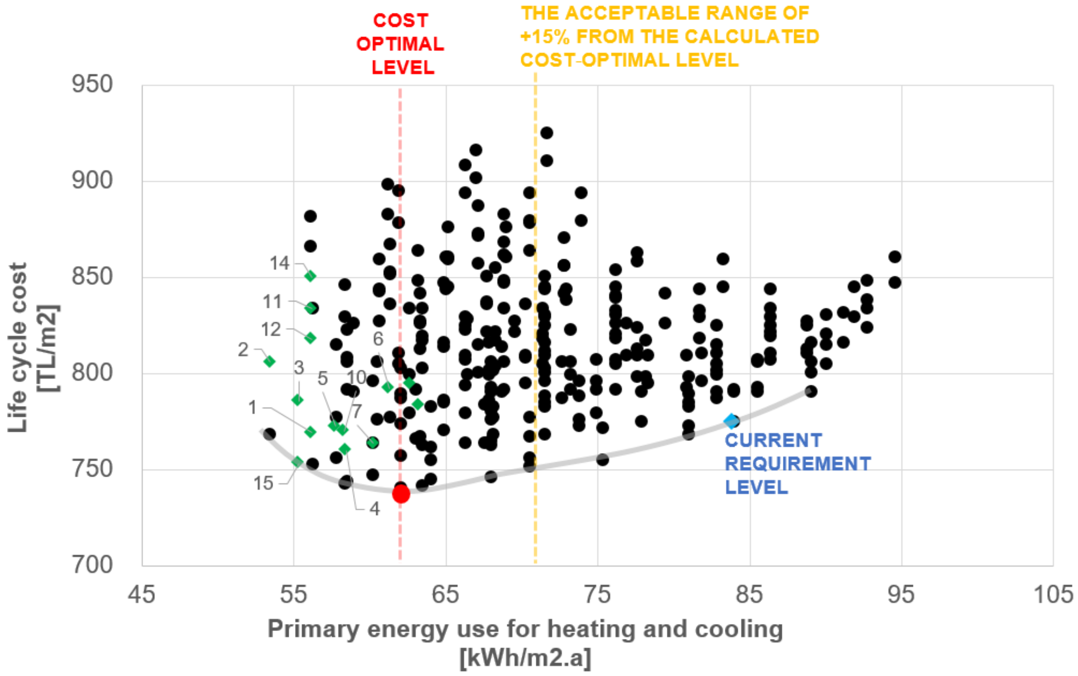

Figure 5.15 : Determination of the best alternatives through EWM.

Table 5.5 : Performance criteria values of the best alternatives (EWM).

	PEU for Heating and Cooling	Invest. Cost	Thermal Comfort	Embodied Carbon	Embodied Energy
Alternative Name	[kWh/m2]	[TL/m2]	[hr]	[kgCO2]	[Mj]
01 EPS 20cm Ins WWR10	56.143	259.149	13.830	40108.704	1195693.440
01 XPS 20cm Ins WWR10	53.408	307.260	8.830	103298.832	2632795.872
01 XPS 16cm Ins WWR10	55.314	282.670	12.670	82639.066	2106236.698
01 EPS 16cm Ins WWR10	58.442	245.250	19.000	32086.963	956554.752
04 EPS 20cm Ins WWR10	57.705	259.149	18.670	40108.704	1195693.440
01 EPS 20cm Ins WWR15	61.246	254.862	13.830	37634.452	1121932.720
04 EPS 16cm Ins WWR10	60.217	245.250	19.170	32086.963	956554.752
01 EPS 12cm Ins WWR10	61.940	234.558	20.830	24065.222	717416.064
01 EPS 16cm Ins WWR15	63.236	241.820	16.500	30107.562	897546.176
01 XPS 12cm Ins WWR10	58.267	261.287	19.000	61979.299	1579677.523
01 RW 20cm Ins WWR10	56.151	328.642	13.670	34054.560	522169.920
03 RW 20cm Ins WWR10	56.151	312.605	13.670	79460.640	1271370.240
04 EPS 20cm Ins WWR15	62.621	254.862	15.330	37634.452	1121932.720
01 GW 20cm Ins WWR10	56.155	339.334	13.670	15892.128	408654.720
03 XPS 16cm Ins WWR10	55.314	250.595	12.670	325107.533	4286333.952

Table 5.6 : EWM results and ranking of the best alternatives.

	Primary Energy Use for Heating and Cooling	Invest. Cost	Thermal Comfort	Embodied Carbon	Embodied Energy	**EWM Result and Ranking**	
Alternative Name	[kWh/m2]	[TL/m2]	[hr]	[kgCO2]	[Mj]		
01 EPS 20cm Ins WWR10	0.160	0.300	0.160	0.099	0.158	0.187087	**1**
01 XPS 20cm Ins WWR10	0.000	0.600	0.000	0.254	0.377	0.22896	**2**
01 XPS 16cm Ins WWR10	0.111	0.447	0.123	0.203	0.297	0.232833	**3**
01 EPS 16cm Ins WWR10	0.294	0.213	0.326	0.079	0.121	0.233407	**4**
04 EPS 20cm Ins WWR10	0.251	0.300	0.316	0.099	0.158	0.24871	**5**
01 EPS 20cm Ins WWR15	0.458	0.273	0.160	0.093	0.147	0.252735	**6**
04 EPS 16cm Ins WWR10	0.398	0.213	0.332	0.079	0.121	0.260687	**7**
01 EPS 12cm Ins WWR10	0.498	0.147	0.385	0.059	0.085	0.275446	**8**
01 EPS 16cm Ins WWR15	0.574	0.192	0.246	0.074	0.112	0.276255	**9**
01 XPS 12cm Ins WWR10	0.284	0.313	0.326	0.153	0.216	0.27696	**10**
01 RW 20cm Ins WWR10	0.160	0.733	0.155	0.084	0.055	0.279518	**11**
03 RW 20cm Ins WWR10	0.160	0.633	0.155	0.196	0.169	0.282801	**12**
04 EPS 20cm Ins WWR15	0.538	0.273	0.209	0.093	0.147	0.284827	**13**
01 GW 20cm Ins WWR10	0.160	0.800	0.155	0.039	0.037	0.288486	**14**
03 XPS 16cm Ins WWR10	0.111	0.247	0.123	0.800	0.630	0.299073	**15**

5.4.6 Determination of the best alternatives through Analytical Hierarchy Process (AHP) method

In this part of the study, weighting factor calculation results are represented with the survey design, application and result together with the AHP procedure application on survey results.

5.4.6.1 Survey questions

Survey questions are defined according to the principles defined in section 4.4.2.1. The questions are formed in four parts as demographic questions, questions for measuring the participants interest on the subject, questions for measuring the impact of decision maker on decisions, and questions for measuring the personal weighting factors of the participants given in the following subsections, respectively.

5.4.6.2 Part 1 – Demographic questions

There are three questions asked in the demographic part of the survey such as the profession of the participant, their educational level, and their position/employment status as given in Table A.1, A.2, and A.3 respectively.

5.4.6.3 Part 2 – Measuring the participants' (decision maker) interest on the subject

The questions for measuring the interest level of the decision makers / participants on the investigated subject are given in Table A.4 and Table A.5, below. It is asked to give personal answers to the questions within a likert scale from 1 to 5, about their personal interest on the subjects in building, envelope and material scales and attendance to the conferences, meetings, and activities related with the criteria subjects.

5.4.6.4 Part 3 – Measuring the impact of decision maker on decisions

Questions of this part, which aims to measure how the decision makers' decisions influence the design, are given in Table A.6 in Appendix A. It is asked to give personal answers to the questions within a likert scale from 1 to 5, about how often they take decisions on the issues of the social housing project in building, envelope and material scales.

5.4.6.5 Part 4 – Measuring the personal weighting factors of the participant

This part includes the main questions to be used in order to measure the weighting factors of the performance criteria based on the answers of the decision makers. Questions are presented in Table A.7 in Appendix A. It is asked to give personal answers to the questions within a likert scale from 1 to 5, about the importance of the criteria on the project in building, envelope and material scales.

5.4.6.6 Survey participants

In this part, survey participants are analyzed based on the answers of the survey questions.

The proficiency of the participants are as investors, architects, mechanical engineers, civil engineers, electrical engineers, and contractors representing the social housing project stakeholders. In sum, 10 decision makers take part in the project team, distributed according to their proficiency, education level and employment status as given in Table 5.7.

Table 5.7 : Decision makers of the project team according to their profession, education level and employment degree.

	Profession	**Education Level**	**Employement Degree**
DM 1	Civil Engineer	Bachelors Degree	Investor
DM 2	Architect	Masters Degree	Manager
DM 3	Other	Bachelors Degree	Manager
DM 4	Civil Engineer	Trade Technical	Contractor
DM 5	Other	Masters Degree	Contractor
DM 6	Electrical Engineer	Bachelors Degree	Designer
DM 7	Civil Engineer	Bachelors Degree	Designer
DM 8	Mechanical Engineer	Bachelors Degree	Designer
DM 9	Architect	Masters Degree	Designer
DM 10	Architect	Masters Degree	Designer

According to Table 5.7, project team includes one investor, two managers, two contractors and five designers. Designers are representing the electrical engineer, civil engineer, mechanical engineer and architects.

5.4.6.7 Survey results

In this part, decision makers' answers to the survey questions are presented in tables. Table 5.8 summarizes the answers to the questions given in Table A.4 as the personal interest of the decision makers on the subjects. Individual personal interests on the subject, as well as the overall average interest level of the team, are presented in the Table 5.8. According to the analysis, the overall average interest level varies between 3.02 and 3.3, which corresponds to a level between uncertain and interested. This shows the lack of interest of the project team on the subjects.

Table 5.8 : Results of interest of decision makers on the subject.

	Average Personal Interest (material scale)	Average Personal Interest (envelope scale)	Average Personal Interest (building scale)	Average Personal Interest
DM 1	3	3.33	3.33	3.22
DM 2	2.67	3.67	2.33	2.89
DM 3	3.67	3.67	3.67	3.67
DM 4	2.33	2.67	2.33	2.44
DM 5	3.67	3.67	4	3.78
DM 6	1.67	1	3.33	2
DM 7	4	4	4	4
DM 8	3.33	3	3.67	3.33
DM 9	3.67	3.67	4	3.78
DM 10	2.67	3.67	2.33	2.89
Overall Average Interest	3.07	3.24	3.3	3.2

Participant attendance frequency to the conferences, meetings and activities related with the subject are summarized in Table 5.9. According to the results, the level of attendance frequency is relatively lower where the overall decision frequency, given in Table 5.10, are higher than the personal interest levels and attendance to the activities, etc.

Table 5.9 : Results of attendance frequency to the conferences, meetings and activities related with the subject.

	Conference Attendance _ Financial	Conference Attendance _ Energy	Conference Attendance _ Environmental	Conference Attendance _ Comfort	Conference Attendance _ Average
DM 1	3	3	4	4	3.5
DM 2	1	3	3	3	2.5
DM 3	3	2	2	4	2.75
DM 4	2	1	1	1	1.25
DM 5	3	2	2	2	2.25
DM 6	1	3	3	3	2.5
DM 7	3	3	4	4	3.5
DM 8	1	3	3	3	2.5
DM 9	2	4	4	1	2.75
DM 10	1	3	3	3	2.5
Overall Average Attendance	2	2.7	2.9	2.8	2.6

Table 5.10 : Results of decision frequency of decision makers on the related subjects.

	Decision Frequency _ Cost	Decision Frequency _ Energy	Decision Frequency _ Thermal Comfort	Decision Frequency _ Environmental Impact	Average Personal Decision Frequency
DM 1	4.33	3	3	3	3.3325
DM 2	4.33	3	3	2.33	3.165
DM 3	5	4	4	3.33	4.0825
DM 4	5	2	2	2	2.75
DM 5	5	3	3	3	3.5
DM 6	2.67	3	1.33	1.33	2.0825
DM 7	4	5	4	4	4.25
DM 8	2.67	5	5	2	3.6675
DM 9	4	4	1	3	3
DM 10	4.67	2	3.67	2.67	3.2525
Overall Average Decision Frequency	4.167	3.4	3	2.666	3.30825

Table 5.11, 5.12, and 5.13 represent the weighting factor answers of decision makers at material, envelope, and building scales. These results are obtained by the answers of the decision makers to the questions in Able A.7. The answers of decision makers,

to be used for calculating the weighting factors of criteria, are for the evaluation of the alternatives in order to obtain the best alternatives within the 300 scenarios.

Table 5.11 : Weighting factor answers of decision makers (material scale).

	Material Selection	Material Cost	Material Thermal Conductance	Material Environmental Impact
DM 1	4	4	3	3
DM 2	4	4	3	3
DM 3	5	5	4	4
DM 4	5	5	3	2
DM 5	5	5	4	4
DM 6	4	4	4	4
DM 7	4	4	4	4
DM 8	4	3	5	4
DM 9	4	4	3	4
DM 10	5	5	3	2

Table 5.12 : Weighting factor answers of decision makers (envelope scale).

	Envelope Design	Envelope Cost	Envelope Thermal Performance	Envelope Environmental Impact
DM 1	4	5	2	3
DM 2	4	4	3	3
DM 3	5	5	3	4
DM 4	2	4	2	2
DM 5	5	4	3	4
DM 6	3	4	4	3
DM 7	4	3	4	3
DM 8	3	4	4	3
DM 9	4	4	2	3
DM 10	5	5	4	3

Table 5.13 : Weighting factor answers of decision makers (building scale).

	Building Design	Building Cost	Building Energy Performance	Building Environment. Impact	Building Thermal Comfort
DM 1	5	5	2	2	2
DM 2	4	4	3	3	2
DM 3	5	5	4	4	3
DM 4	4	5	3	2	1
DM 5	5	5	4	4	2
DM 6	4	4	5	4	3
DM 7	4	4	4	4	3
DM 8	4	4	5	4	4
DM 9	4	4	4	3	2
DM 10	5	5	3	2	2

5.4.6.8 Weighting factors

In this part, weighting factors are calculated according to the results of the decision makers to the answers given in Table A.7. Table 5.14 represents the average values of the weighting factors of decision makers in order to obtain one weighting factor for each criteria.

According to the results, weighting factors of each criteria is calculated as 4.33 for cost, 3.47 for energy, 3.23 for environmental impact, and 2.40 for thermal comfort. These values are obtained to be used in the AHP method. Then, the weighting factors are converted to a pairwise comparison matrix given in Table 5.15 and normalized weighting factors are calculated based on the methodology presented in section 4.4.2.4. Normalized weighting factors are given in Table 5.16 as 0.56 for cost, 0.19 for energy, 0.17 for environmental impact and 0.08 for thermal comfort.

Due to the number of criteria that occurs due to the material, envelope and building levels, it is laborious to obtain answers from the decision makers in AHP pairwise format. Thus, the survey questions are asked in a regular 1-5 likert scale where the AHP methodology uses 1-9 likert scale. Then, the obtained weighting factors are converted to a pairwise comparison, so that, each 0,5 difference between the weighting factors corresponds to one level of intensity of importance difference. Table 5.15 represents the application of AHP 1-9 likert scale to obtain the final weighting factors of the methodology.

Table 5.14 : Weighting factor answers of decision makers (average values).

	Selection And Design	Cost	Energy	Env. Impact	Thermal Comfort
DM 1	4.33	4.67	2.33	2.67	2.00
DM 2	4.00	4.00	3.00	3.00	2.00
DM 3	5.00	5.00	3.67	4.00	3.00
DM 4	3.67	4.67	2.67	2.00	1.00
DM 5	5.00	4.67	3.67	4.00	2.00
DM 6	3.67	4.00	4.33	3.67	3.00
DM 7	4.00	3.67	4.00	3.67	3.00
DM 8	3.67	3.67	4.67	3.67	4.00
DM 9	4.00	4.00	3.00	3.33	2.00
DM 10	5.00	5.00	3.33	2.33	2.00
Overall Average	4.23	**4.33**	**3.47**	**3.23**	**2.40**
Normalized Weights		**0.32**	**0.26**	**0.24**	**0.18**

Table 5.15 : Pairwise comparison matrix with intensity judgments.

	Cost	Energy	Env. Impact	Thermal Comfort
Cost	1	3	5	5
Energy	1/3	1	1	3
Environmental Impact	1/5	1	1	3
Thermal Comfort	1/5	1/3	1/3	1

Table 5.16 : Column addition of the pairwise comparison matrix.

	Cost	Energy	Env. Impact	Thermal Comfort
Cost	1.00	3.00	5.00	5.00
Energy	0.33	1.00	1.00	3.00
Environmental Impact	0.20	1.00	1.00	3.00
Thermal Comfort	0.20	0.33	0.33	1.00
Column Addition	**1.73**	**5.33**	**7.33**	**12.00**
Priority Vectors	**0.56**	**0.19**	**0.17**	**0.08**
Column Addition * PV	**0.97**	**1.02**	**1.26**	**0.92**

Table 5.17 : Normalized pairwise comparison matrix and priority vectors (PV).

	Cost	Energy	Env. Impact	Thermal Comfort	Sum of Weighting Factors	**Priority Vectors**
Cost	0.58	0.56	0.68	0.42	2.24	**0.56**
Energy	0.19	0.19	0.14	0.25	0.77	**0.19**
Environ. Impact	0.12	0.19	0.14	0.25	0.69	**0.17**
Thermal Comfort	0.12	0.06	0.05	0.08	0.31	**0.08**
Column Addition	1.00	1.00	1.00	1.00	4.00	**1.00**

In the following step, the CR is calculated step by step and the results are presented herewith. $\boldsymbol{\lambda}_{max}$ is calculated as 4.17 and used for calculation of CI.

$$\boldsymbol{\lambda}_{max} = 0.97 + 1.02 + 1.26 + 0.92 = 4.17$$

The, CI is calculated as equal to 0.06 and used for the calculation of CR. RI = 0.90 is used for the calculation of CR and finally, CR is calculated as 0.065.

$$CI = \frac{4.17-4}{4-1} = 0.06$$

$$CR = \frac{0.06}{0.90}$$

Results obtained from this step of the methodology are the priority vectors that are given in Table 5.17 and the CR. The values are then used in section 5.4.2.5, by multiplying the performance criteria value with the normalized weighting factors to obtain the score of the alternatives in order to obtain the best alternatives.

5.4.6.9 Calculation of the sum of normalized performance values through AHP weighting factors

In this part of the methodology, sum of normalized performance values are obtained by multiplying each normalized performance criteria value (given in Table F.2) with the normalized weighting factors (given in Table 5.18 and 5.19). Results are given in Table F.3 for the 164 alternatives that are beyond the cost optimal level or within the cost optimal range. Best 15 alternatives with AHP scores and ranking are given in Table 5.19.

When the AHP method is applied in order to assign the weighting factors for the performance criteria, obtained results are; 0.56 for cost, 0.19 for energy, 0.17 for environmental impact and 0.08 for thermal comfort, according to the survey answers of the sample participants.

When AHP method is applied, best 15 alternatives are represented by 01EPS, 02EPS, 03EPS, 04EPS, 03XPS thermal insulation materials. Due to high investment costs, cellular glass thermal insulation material alternatives does not take place within the best alternatives.

Moreover, based on the investment cost weighting factor, 16cm, 12cm and 8cm thickness application alternatives have a better score than the 20cm alternatives in general.

Similar with EWM results, WWR10 and WWR15 alternatives have better scores than WWR 20 alternatives. Thus, WWR 20 alternatives does not take place in the best 10 alternatives, either in EWM and AHP decision making.

Best alternatives are either beyond and behind the cost optimal level and close to the frontier line.

Table 5.18 : Performance criteria values of the best 10 alternatives (AHP).

Alternative Name	PEU for Heating and Cooling [kWh/m2]	Invest. Cost [TL/m2]	Thermal Comfort [hr]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]
01 EPS 16cm Ins WWR10	58.442	245.250	19.000	32086.963	956554.752
01 EPS 12cm Ins WWR10	61.940	234.558	20.830	24065.222	717416.064
03 EPS 12cm Ins WWR10	61.940	218.521	20.830	115785.504	4022978.688
01 EPS 20cm Ins WWR10	56.143	259.149	13.830	40108.704	1195693.440
04 EPS 16cm Ins WWR10	60.217	245.250	19.170	32086.963	956554.752
03 EPS 16cm Ins WWR10	58.442	229.213	19.000	154380.672	5363971.584
03 XPS 8cm Ins WWR10	63.476	221.729	23.330	162553.766	2143166.976
04 EPS 12cm Ins WWR10	64.010	234.558	23.330	24065.222	717416.064
01 EPS 16cm Ins WWR15	63.236	241.820	16.500	30107.562	897546.176
03 XPS 12cm Ins WWR10	58.267	234.558	19.000	243830.650	3214750.464
02 EPS 12cm Ins WWR10	64.010	218.521	23.330	115785.504	4022978.688
01 EPS 12cm Ins WWR15	66.271	231.788	22.670	22580.671	673159.632
04 EPS 20cm Ins WWR10	57.705	259.149	18.670	40108.704	1195693.440
02 EPS 16cm Ins WWR10	60.217	229.213	19.170	154380.672	5363971.584
03 EPS 12cm Ins WWR15	66.271	216.741	22.670	108642.852	3774806.544

Table 5.19 : AHP results and ranking of the best alternatives.

	PEU for Heating and Cooling	Invest. Cost	Thermal Comfort	Embodied Carbon	Embodied Energy	**AHP Result and Ranking**	
Alternative Name	[kWh/m2]	[TL/m2]	[hr]	[kgCO2]	[Mj]		
01 EPS 16cm Ins WWR10	0.294	0.213	0.326	0.079	0.121	0.218431	**1**
01 EPS 12cm Ins WWR10	0.498	0.147	0.385	0.059	0.085	0.219818	**2**
03 EPS 12cm Ins WWR10	0.498	0.047	0.385	0.285	0.590	0.225955	**3**
01 EPS 20cm Ins WWR10	0.160	0.300	0.160	0.099	0.158	0.232976	**4**
04 EPS 16cm Ins WWR10	0.398	0.213	0.332	0.079	0.121	0.238563	**5**
03 EPS 16cm Ins WWR10	0.294	0.113	0.326	0.380	0.795	0.24528	**6**
03 XPS 8cm Ins WWR10	0.588	0.067	0.465	0.400	0.303	0.245973	**7**
04 EPS 12cm Ins WWR10	0.619	0.147	0.465	0.059	0.085	0.249204	**8**
01 EPS 16cm Ins WWR15	0.574	0.192	0.246	0.074	0.112	0.252044	**9**
03 XPS 12cm Ins WWR10	0.284	0.147	0.326	0.600	0.466	0.252792	**10**
02 EPS 12cm Ins WWR10	0.619	0.047	0.465	0.285	0.590	0.255341	**11**
01 EPS 12cm Ins WWR15	0.751	0.129	0.444	0.056	0.078	0.262039	**12**
04 EPS 20cm Ins WWR10	0.251	0.300	0.316	0.099	0.158	0.262729	**13**
02 EPS 16cm Ins WWR10	0.398	0.113	0.332	0.380	0.795	0.265412	**14**
03 EPS 12cm Ins WWR15	0.751	0.036	0.444	0.267	0.552	0.267797	**15**

6. CONCLUSION

Estimation of building performance might be essential in building projects where the indicators of building performance are crucial. Housings, which are buildings such as apartments or units assigned for residence, are one of the main cases, since the amount of housing stock within the whole building stock has a great amount. As analyzed, urbanization and social housings has an important impact on the embodiment of ‘housings’. The requirements of social housings such as low investment costs for states and low operating costs for low-income group occupancies signify the importance of performance estimation for social housings. By the increase on the building energy consumption levels worldwide, thermal insulation materials became one of the key applications for building energy efficiency. When high performance building+

s are targeted, the thermal insulation materials become more significant, due to thicker applications of the material, so as with higher costs, higher environmental impacts. When high energy efficiency levels are targeted in building design, conflicts may occur on the high amount of investments causing high costs, high amount of material and technology use and related higher environmental impact levels.

This study proposes an approach on “performance based decision-making” in thermal insulation material selection for housing design. The proposed approach for performance based decision-making focuses on the social housing projects in Turkey, due to its’ representation of 10% of the housing stock. “High performance” is defined in this study with the performance indicators as energy, cost, thermal comfort, and environmental impact.

The analyses are done on a social housing archetype, considered as situated in temperate-dry climatic region of Turkey. Five thermal insulation materials, four different attribute concepts, five thickness variations, with three window to wall ratios are analyzed resulting with total 300 scenarios.

The methodology of the proposed approach has four main steps as given below:

- Determination of the archetype: Throughout the researches on the current social housing projects, it was observed that 4 apartment/floor plan scheme is one of the most common plan configuration within the whole social housings. Thus, in this study, an archetype which has a 4 apartment/floor plan scheme was designated.
- Parameterization with the designated independent variables: In this step of the methodology, the independent variables were determined for the parameterization. Independent variables represent the variation possibilities and opportunities in the design decision making. 5 thermal insulation materials with four different attribute concepts and 5 thickness variations and 3 window-to-wall ratios are combined and 300 alternatives are obtained to be evaluated in the decision making process.
- Calculation of the dependent variables: Dependent variables involved in the decision making process were determined as energy, cost, comfort and environmental impact and calculated for 300 alternatives.
- Multiple criteria decision-making: A multiple criteria decision making approach is proposed, as explained in section 4.4, in accordance with the EPBD requirements. Moreover, a survey to be applied to decision makers and AHP method is introduced in section 4.4.6 for determining the weighting factors for each performance criteria.

One of the most important and unique content of the proposed method is that, it enables the application of EPBD cost optimality method, while determining the best alternatives within the whole alternatives occurred by parameterization. Additionally, the adaptation of the method to social housings has a great importance due to the characteristics such as significant constraints on the project budget as well as the importance of considering the costs from the life cycle point of view in a social housing systems in order to evaluate the advantages of the investments on the expected low-cost operation of the building.

The key findings of the calculation of the dependent variables (performance criteria) are as below:

- Cases with no thermal insulation for WWR10%, WWR15% and WWR20% have primary energy use for heating and cooling as 127.35 kWh/m^2.a, 123.84

kWh/m^2.a, 123.03 kWh/m^2.a, respectively. Total primary energy use for heating and cooling varies between 94.48 kWh/m^2.a and 53.31 kWh/m^2.a for thermal insulation material applied alternatives. Results show that the application of thermal insulation material provides an energy efficiency between 24% and 57%, highlighting the importance of the thermal insulation material application.

- Life cycle cost of different thermal insulation material application alternatives vary between 745.18 TL/m^2 and 915 TL/m^2. On the other hand, the base case with no thermal insulation material has a LCC between 840 TL/m^2 and 860 TL/m^2. This shows that thermal insulation material has a great importance on decreasing the LCC, while decreasing the energy consumption levels.
- All alternatives' thermal comfort performance provides the requirement level, where the thermal comfort unmet hours vary between 149.40 hr (02 CG, 4cm, 10%WWR) and 12.17 hr (01 XPS, 20cm, 20%WWR).
- The most significant difference between the alternatives occur in environmental impact performance criteria, due to the different environmental attributes of 5 thermal insulation material options.

The analysis above shows that the performance criteria that are evaluated have an important impact on the alternatives and results. Thus, it is meaningful to include the four determined performance criteria (energy, cost, thermal comfort, and environmental impact) in the decision making process in order to select the best alternatives. In the next step, the decision making methodology is implemented in accordance with the flowchart given in Figure 4.5.

Highlights of the EPBD cost optimality implementation and the results are as below:

- Within the 300 alternatives, 164 alternatives occur beyond the cost optimal level, which is determined in accordance with EPBD.
- Determined alternatives represent each insulation material and application thickness between 8 cm and 20 cm.
- The cost optimal case has 61.94 kWh/m2.a primary energy consumption for heating and cooling and 740.67 TL/m2 life cycle cost, with 12 cm “03 EPS” insulation application for 10% WWR.

- The current requirement level has 83.91 kWh/m2.a primary energy consumption for heating and cooling and 773.93 TL/m2 life cycle cost, with 4 cm “02 XPS” insulation application for 10% WWR.
- Primary energy use for heating and cooling of the alternatives vary between 53.41 kWh/m^2.a and 64.01 kWh/m^2.a, where the total primary energy use varies between 137.73 kWh/m2.a and 149.05 kWh/m2.a
- In comparison with the cost optimal case, there occurs 16.6% energy reduction through the cases beyond the cost optimal level.

Then, EWM is applied on the determined 164 alternatives and significant results are obtained as follows:

- In order to apply the EWM, each criteria is considered to have 0.25 weighting factor.
- When EWM method is applied, best 15 alternatives are represented by 01 EPS, 04 EPS, 01 XPS, 01 RW, 03 RW, 01 GW and 03 XPS thermal insulation materials. Due to high investment costs, cellular glass thermal insulation material alternatives does not take place within the best alternatives.
- The best 15 alternatives are generally above the efficient frontier line and beyond the cost optimal level.
- Thermal insulation material thicknesses are around 16cm and 20cm.
- Only the 01 XPS material have the 12cm thickness application possibility.
- Since the four criteria have equal weighting factors, EPS material options represent the low environmental impact and high cost attribute scenarios, where the other material options are all low thermal conductivity, either with low and high environmental impact and costs.

Within the proposed approach, a survey is conducted to a focus project group, in order to obtain sample weighting factors for the performance criteria. Based on the results of the survey, weighting factors are calculated by AHP method. Survey answers are discussed as below:

- Survey is conducted to a sample group, in order to test the method and process.

- Sample group is composed of a housing project's stakeholders as investor, manager, designers and main contractors.
- Average personal interest of decision makers on the subject is 3.2, which is between uncertain and interested.
- Average value of attendance frequency to the conferences, meetings and activities is calculated as 2.6, which is between rarely and sometimes.
- Decision frequency of the decision makers on the related subject is 3.3 in overall average, which is between sometimes and often.
- Results show that, either the average and the individual values are in an acceptable range. However, it should be stated that, average values are not well satisfying.

The results of AHP implementation shows that:

- When the AHP method is applied in order to assign the weighting factors for the performance criteria, the obtained results are 0.56 for cost, 0.19 for energy, 0.17 for environmental impact and 0.08 for thermal comfort, according to the survey answers.
- The CR is calculated as 0.065, which shows that the results are consistence.
- The applied survey to the sample group showed that, differences between the weighting factors of the criteria may differ substantially.
- In this sample, cost criteria has the maximal weighting factor as 0.56, which is more than the half.

When the best alternatives are obtained through the weighting factors of AHP outputs, it is analyzed that:

- According to the results, the best 15 alternatives have changed significantly as, EPS alternatives are in the first orders instead of XPS. Moreover, based on the investment cost weighting factor, 12cm and 16cm thickness application alternatives have a better score than the 20cm alternatives in general.
- Moreover, based on the investment cost weighting factor, 12cm and 16cm thickness application alternatives have a better score than the 20cm alternatives in general.

- Significantly, 04 EPS material comes into prominence in AHP results, due to its low investment costs.
- Similar with EWM results, WWR10 and WWR15 alternatives have better scores than WWR 20 alternatives. Thus, WWR 20 alternatives does not take place in the best 15 alternatives, either in EWM and AHP decision making.
- Best alternatives are either beyond and behind the cost optimal level and close to the frontier line

Results show that a proper decision-making on selection of building thermal insulation materials, with different environmental and economic attributes, ensure higher performances for buildings. The proposed approach influences the selection of the best alternative which allows the personal preferences of the decision maker without digressing from the scope of EPBD.

Moreover, it is observed that the window to wall ratio has a significant effect on the results. Best alternatives of either EWM and AHP belong to the WWR of 10% and 15%. 20% window to wall ratio alternatives does not take part in the best alternatives. In the further studies, it should be analysed the overall façade with different window and glazing types in order to obtain higher performances and more accurate results.

In general, the construction market has a tendency to decrease the costs as much as possible to achieve high profits. In some cases, the targeted profit levels may prevent the benefits as environmental, thermal, etc. Thus, in a decision making approach, the weighting factors may be delimited to prevent the out of purpose results.

On the other hand, to promote the financial investments on sustainable design, reduction of prices on the construction market by offering alternatives or local products are urgent solutions to design higher performance buildings and increase the performance of existing building stock by retrofitting.

It is clear that the methodology used in multiple criteria decision-making and the weighting factors of the criteria are quite substantial and effective on the results of the decision. The study should be improved by assigning different weighting factors to decision-making criteria, in order to identify the deviations due to the different weighting factors. Thus, further studies should be conducted with different decision-making methods, and variation of the criteria and weighting factors should be analyzed. It is also contemplated that, a tool can be generated by using the proposed methodology, in order to have a quick analysis for further demands and design processes of different archetypes.

REFERENCES

Agenda21 (1992) retrieved from https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf

Akadiri P O, Olomolaiye P O, Chinyio E A. (2013). Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction 30*, 113-25.

Alanzi A, Seo D, Krarti M. (2009). Impact of building shape on thermal performance of office building in Kuwait. Energy Convers Manag. 50(3), 822-8.

Alwear H, Clements-Croome D J. (2010). Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and Environment 45*, 799-807.

Arens, E.A., Williams, P.B. (1997). The effect of wind on energy consumption in buildings. Energy and Buildings 1, 77-84.

Arroyo P, Tommelein I D, Ballard G, Rumsey P. (2016). Choosing by advantages: A case study for selecting an HVAC system for a net zero energy museum. *Energy and Buildings 111*, 26-36.

Arvidson, J.M., Sparks, L.L. & Guobang, C. (1983). *Tensile, Compressive, and Shear Properties of a 64-kg/m^3 Polyurethane Foam at Low Temperatures*. National Bureau of Standards, U.S. Department of Commerce.

Attia and Carlucci *Impact of Different Thermal Comfort Models on Zero Energy Residential Buildings in Hot Climate (PDF Download Available)*. Available from: https://www.researchgate.net/publication/277310999_Impact_of_Different_Thermal_Comfort_Models_on_Zero_Energy_Residential_Buildings_in_Hot_Climate [accessed Mar 05 2018].

Attia, S., Gratia, E., Herde, A., Hensen Jan L M, (2012). Simulation-based decision support tool for early stages of zero-energy building design. Energy and Buildings;49:2-15.

Aditya, L., Mahlia, T.M.I., Rismanchi, B., Ng, H.M., Hasan, M.H., Metselaar, H.S.C., Muraza, O., Aditiya, H.B. (2017). A review on insulation materials for energy conservation in buildings. Renewable and Sustainable Energy Reviews, 73,1352-1365. doi:10.1016/j.rser.2017.02.034.

Baker, D., Bridges, D., Hunter, R., Johnson, G., Krupa, J., Murphy J. and Sorenson, K. (2002). Guidebook to Decision Making Methods, WSRC-IM-2002-00002, Department of Energy, USA.

Behzadian M, Kazemzadeh R B, Albadvi A, Aghdasi M. (2010). PROMETHEE: A comprehensive literature review on methodologies and applications.' European Journal of Operational Research, 200, 198-215.

Behzadian M, Otaghsara S K, Yazdani M, Ignatius J. (2012). A state-of the-art survey of TOPSIS applications. Expert Systems with Applications, 39, 13051-69.

BEP (2009). Binalarda Enerji Performansı Yönetmeliği, 5 Aralık 2009 (revizyon: 1 Nisan 2010).

BEP-TR (2010). BEP-TR Bina Enerji Performansı Ulusal Hesaplama YöntemiNE Dair Tebliğ, Sayı: 27778, 7 Aralık 2010.

Biswas, K., Shrestha, S.S., Bhandari, M.S., Desjarlais, A.O. (2016). Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts. *Energy and Buildings, 112,* 256-269.

Blondeau, P. and Allard, F. (2002). Multicriteria analysis of ventilation in summer period. *Building and environment 37(2):* 165-176.

Braulio-Gonzola, M., Bovea, M.D. (2017). Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimization. *Energy and Buildings, 150,* 527-545.

Booth, A.T., Choudhary, R. (2013). Decision making under uncertainty in the retrofit analysis of the UK housing stock: Implications for the Green Deal. Energy and Buildings 64, 292-308.

Bozasky, D. (2010). The historical development of thermal insulation materials. Periodica Polytechnic, 41(2), 49-56.

Building Census (2000). Building Census 2000, State Institute of Statistics Prime Ministry, Republic of Turkey, ISBN 975-19-2819-2.

Burns, P.J. (1984). *Thickness Effect in Low- Density Insulation.* National Bureau of Standards, U.S. Department of Commerce.

Catalina T, Virgone J, Lordache V. (2011). Study on the impact of building form on the energy consumption. In: Proceedings of Building Simulation 2011: 12th Conference of International Performance Simulation Association, Sydney, 14-16 November. Romania: Technical University of Civil Engineering Bucharest.

Cinelli M, Coles S R, Kirwan K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators 46,* 138-48.

Directive (2002). Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings.

Directive (2010). Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the Energy Performance of Buildings (recast).

Demirboğa, R., Gül R. (2003). Thermal conductivity and compressive strength of expanded perlite aggregate concrete with mineral admixtures. *Energy and Buildings, 35,* 1155–1159.

Dombaycı, Ö. A., Gölcü, M., Pancar, Y. (2006). Optimization of insulation thickness for external walls using different energy-sources. *Applied Energy, 83,* 921-928.

Echenagucia T M, Capozzoli A, Cascone Y, Sassone M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy, 154,* 577–591.

Ekici, B.B., Gulten, A.A., Aksoy, U.T. (2012). A study on the optimum insulation thickness of various types of external walls with respect to different materials, fuels and climate zones in Turkey. *Applied Energy 92,* 211-217.

El-Darwish I, Gomaa M. (2017). Retrofitting strategy for building envelopes to achieve energy efficiency. *Alexandria Engineering Journal, 56,* 579–589.

Energy Plus (2015). Input Output Reference, The Encyclopedic Reference to EnergyPlus Input and Output. V8.3, 2015, Lawrence Berkeley National Laboratory, US.

EN 13501-1 (2007). *Fire classification of construction products and building elements—Part 1: Classification using data from reaction to fire tests.* European Committee for Standardization (EN 13501-1:2007).

EN 13790 (2008) Energy Performance of Buildings – Calculation of Energy Use for Space Heating and Cooling.

Faizi F, Noorani M, Ghaedi A, Mahdavinejad M. (2011). Design an optimum pattern of orientation in residential complexes by analyzing the level of energy consumption (case study: Maskan Mehr Complexes, Tehran, Iran). Procedia Eng. 21, 1179-87.

Fallahtafti R, Mahdavinejad M. (2015). Optimisation of building shape and orientation for better energy efficient architecture. Int J Energy Sect Manag. 9(4), 593-618.

Govindan K, Jepsen M B. (2016). ELECTRE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research, 250,* 1-29.

Harris, R. (1998) Introduction to Decision Making, Virtual Salt. http://www.virtualsalt.com/crebook5.htm

Hens, H. (2011). *Applied Building Physics. Boundary Conditions, Building Performance and Material Properties.* Germany, Wilhelm Ernst & Sohn.

Hens, H. (2012). *Performance Based Building Design 1. From Below Grade Construction to Cavity Walls.* Germany, Wilhelm Ernst & Sohn.

Hopfe CJ, Augenbroe GLM, Hensen, Jan LM. (2013). Multi-criteria decision making under uncertainty in building performance assessment. Building and Environment 69, 81-90.

Hsieh T-Y, Lu S-T, Tzeng G-H. (2004). Fuzzy MCDM approach for planning and design tenders selection in public office buildings. International Journal of Project Management 22, 573-84.

Huang J P, Poh K L, Ang B W. (1995). Decision analysis in energy and environmental modelling. *Energy 20, No. 9* :843-55.

Huang I B, Keisler J, Linkov I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of the Total Environment, 409,* 3578-94.

Humphreys, M.A.; Rijal, H.B.; Nicol, J.F. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. Build. Environ., 63, 40–55.

Hwang, C.L., Yoon, K. (1981). Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, New York.

Jato-Espino D, Castillo-Lopez E, Rodriguez-Hernandez J, Canteras-Jordana, JC. (2014). A review of application of multi-criteria decision making methods in construction. *Automation in Construction, 45,* 151-62.

Jelle, B.P. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities. *Energy and Buildings, 43,* 2549-2563.

Kaklauskas, A., Zavadskas, E.K., Raslanas, S., Givenicius, R., Komka, A., Malinauskas, P. (2006). Selection of low-e windows in retrofit of public buildings by applying multiple criteria method COPRAS: A Lithuanian case. *Energy and Buildings 38,* 454-462.

Karamanos, A, Hadiarakou, S, Papadopoulos, A.M. (2008). The impact of temperature and moisture on the thermal performance of stone wool. *Energy Build; 40,* 1402–1411.

Lapinskiene, V., Martinaitis, V. (2013). The Framework of an Optimization Model for Building Envelope. Procedia Engineering 57, 670-677.

Lee, J., Kim, J., Song, D., Kim, J., Jang, C. (2017). Impact of external insulation and internal thermal density upon energy consumption of buildings in a temperate climate with four distinct seasons. *Renewable and Sustainable Energy Reviews, 75,* 1081-1088.

Loken E. (2007). Use of multicriteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews, 11,* 1584-95.

Lucchi, E., Tabak, M., Troi, A. (2017). The “Cost Optimality” Approach for the Internal Insulation of Historic Buildings. *Energy Procedia, 133,* 412-423.

Machairas V, Tsangrassoulis A, Axarli K. (2014). Algorithms for optimization of building design: A review. *Renewable and Sustainable Energy Systems 31,* 101-12.

Mallory-Hill, S., Preiser, W.F.E., Watson, C. (2012). *Enhancing Building Performance.* UK, John Wiley & Sons.

Mardani A, Jusoh A, Zavadskas E K. (2015). Fuzzy multiple criteria decision-making techniques and applications – Two decades review from 1994 to 2014. *Expert Systems with Applications, 42*, 4126-48.

Mela K, Tiainen T, Heinisuo M, (2012). Comparative study of multiple criteria decision making methods for building design. *Advanced Engineering Informatics, 26*, 716-26.

Menyhart, K., Krarti, M. (2017). Potential energy savings from deployment of Dynamic Insulation Materials for US residential buildings. *Building and Environment, 114*, 203-218.

Mohsen, M.S., Akash, B.A. (2001). Some prospects of energy savings in buildings. *Energy Conversion and Management, 42,* 1307-1315.

Motuziene V, Rogoza A, Lapinskiene V, Vilutiene T. (2016). Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study. *Journal of Cleaner Production 112*, 532-41.

Nematchoua, M.K., Ricciardi, P., Reiter, S., Yvon, A. (2017). A comparative study on optimum insulation thickness of walls and energy savings in equatorial and tropical climate. *International Journal of Sustainable Built Environment, 6*, 170-182.

NEPA (1970). United States. National Environmental Policy Act. Approved January 1, 1970.

NIST Handbook 135 (1995). Life-Cycle Costing Manual for the Federal Energy Management Program, NIST Handbook 135, U.S. Department of Commerce.

Opricovic, S. (1998). Multicriteria Optimization of Civil Engineering Systems, Faculty of Civil Engineering, Belgrade 1998.

Opricovic, S., Tzeng, G–H. (2004). Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research; 156:445–55.

Özel, G., Açıkkalp, E., Görgün, B., Yamık, H., Caner, N. (2015). Optimum insulation thickness determination using the environmental and life cycle cost analyses based entransy approach. *Sustainable Energy Technologies and Assessment 11,* 87-91.

Özel, M. (2012). Cost analysis for optimum thickness and environment impacts of different insulation materials. Energy and Buildings, 49, 552-559.

Papadopoulos, A.M. (2008). State of the art in thermal insulation materials and aims for future developments State of the art in thermal insulation materials and aims for future developments. *Energy and Buildings; 37,* 77–86.

Pokehar S D, Ramachandran M. (2004). Application of multi-criteria decision making to sustainable energy planning – A review. Renewable and Sustainable Energy Reviews, 8, 365-81.

Rakhshan, K., Friess, W.A., Tajerzadeh, S. (2013). Evaluating the sustainability impact of improved building insulation: A case study in the Dubai residential built environment. *Building and Environment, 67,* 105-110.

Regulation (2012). Commission Delegated Regulation, No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements, Official Journal of the European Union; 2012.

Rey, E. (2004) ‘Office building retrofitting strategies: Multi-criteria approach of an architectural and technical issue’, Energy and Buildings 36, no 4, pp367–372.

Roulet, C.A.; Flourentzoua, F.; Labbena, H.H.; Santamouris, M.; Koronakib, I.; Dascalakib, E.; Richaletc, V. (2002). ORME: A multicriteria rating methodology for buildings. Build. Environ., 37, 579–586.

Russo R F S M., Camanho R. (2015). Criteria in AHP: a Systematic Review of Literature. Procedia Computer Science, 55, 1123-32.

Saaty, T. (1980). The analytic hierarchy process. New York: McGraw-Hill; 1980.

Saaty, R.W. (1987). The analytic hierarchy process – what it is and how it is used. Mathematical Modelling, Volume 9, Issue 3-5, 161-176.

Schiavoni, S., D’Alessandro, F., Bianchi, F., Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. *Renewable and Sustainable Energy Reviews, 62,* 988-1011.

Sea Directive (2001). Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment.

Shu H, Duanmu L, Zhang C, Zhu Y. (2010). Study on the decision-making of district cooling and heating systems by means of value engineering. *Renewable Energy 35,* 1929-39.

Simon, H.A. (1947). Administrative Behavior: A Study of Decision-Making Processes in Administrative Organizations, 1947.

Simon, H.A. (1993). Decision making: rational, nonrational, and irrational. Educ. Adm. Q. 29, 392–411 1993.

Simona, P.L., Spiru, P., Ion, I.V. (2017). Increasing the energy efficiency of buildings by thermal insulation. *Energy Procedia, 128,* 93-399.

Slovic, P., Fischhoff, B., and Lichtenstein, S. (1977) Behavioral decision theory. *Annual Review of Psychology , 28 (1),* 1–39.

Spanos I, Simons M, Holmes K. (2005). Cost savings by application of passive solar heating. Struct Surv 23(2): 111-30.

Spiegel, R. & Meadows, D. (2012). *Green Building Materials. A Guide to Product Selection and Specification.* Hoboken, New Jersey, John Wiley & Sons.

Stefano N M, Filho N C, Vergara L G L, Rocha R U G. (2015). COPRAS (Complex Proportional Assessment): State of the Art Research and its Applications. IEEE Latin America Transactions, 13, No. 12:3899-906.

Strantzali E, Aravossis K. (2016). Decision making in renewable energy investments: A review. Renewable and Sustainable Energy Reviews, 55, 885-98.

Tettey, U.Y.A., Dodoo, A., Gustavsson, L. (2014). Primary energy implications of different wall insulation materials for buildings in a cold climate. Energy Procedia, 61, 1204-1207.

Tettey, U.Y.A., Dodoo, A., Gustavsson, L. (2014). Effects of different insulation materials on primary energy and CO2 emissions of a multi-storey residential building. *Energy and Buildings, 82*, 369-377.

Tingley, D.D., Hathway, A., Davison, B., Allwood D. (2014). "The environmental impact of phenolic foam insulation boards", *Proceedings of the Institution of Civil Engineers , Paper 1400022,* 1-13.

Toydemir, N., Gürdal, E., Tanaçan, L. (2000). *Yapı Elemanı Tasarımında Malzeme.* İstanbul Teknik Üniversitesi Mimarlık Fakültesi, Temmuz 2000, İstanbul.

Turban, E., Aronson, J.E., Liang, TP., (2005). Decision Support Systems and Intelligent Systems, 7th edn. Pearson Prentice Hall, New Jersey 2005.

TS 825 (2008). Binalarda Isı Yalıtımı Kuralları Standardı, Mayıs 2008.

Ucar, A., Balo, F. (2009). Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey. Applied Energy 86, 730-736.

UNPF (2004). "*State of World Population"* United Nations Population Fund

Url-1 http://www.toki.gov.tr/en/housing-programs.html

Url-2 http://www.wiki-zero.com/index.php?q=aHR0cHM6Ly9lbi53aWtpcGVkaWEub3JnL3dpa2kvVGhlcm1hbF9pbnN1bGF0aW9u

Url-3https://www.icis.com/resources/news/2007/11/05/9076009/expandable-polystyrene-eps-production-and-manufacturing-process/

Url-4 http://www.toki.gov.tr/talep-satis-teslim/27

Vitruvius (1960). "De Architectura" - The Ten Books on Architecture, translated by Morgan, 1960.

Wang J-J, Jing Y-Y, Zhang C-F, Zhao J-H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making.' Renewable and Sustainable Energy Reviews, 13:2263-78.

Wang, Q., Poh, K L. (2014). A survey of integrated decision analysis in energy and environmental modelling. Energy, 77, 691-702.

Wang, W., Zmeureanu, R., Rivard, H. (2005). Applying multi-objective genetic algorithms in green building design optimization, Building and Environment;40:1512–25.

Wong, K.W.J., Li, H. (2008). Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems. Building and Environment 43(1), 108-125.

Woo J-H, Menassa C. Virtual Retrofit Model for aging commercial buildings in a smart grid environment. Energy and Buildings 2014;80:424-35.

Yeang, K. (2006). *EcoDesign : A manual for ecological design*. John Wiley & Sons.

Yılmaz, B. (2012). Türkiye için sürdürülebilir bina performans kriterleri ve bütünleşik tasarım yönetim modeli oluşturulması. İstanbul Teknik Üniversitesi, PhD Thesis.

Yılmaz, Y. (2017) *An approach for energy efficient retrofits evaluation of educational buildings through life cycle cost optimization in Turkey*. (PhD Thesis) İstanbul Technical University, Graduate School of Science Engineering and Technology, İstanbul.

Zavadskas, E.K., Antucheviciene, J., Saparauskas, J., Turskis, Z. (2013). Multi-criteria Assessment of Façades' Alternatives: Peculiarities of Ranking Methodology. Procedia Engineering 57, 107-112.

Zhang, G., Lu, J., Gao, Y. (2015). Multi-Level Decision Making, Models, Methods and Applications, 2015.

Zhou P, Ang B W, Poh K L. (2006). Decision analysis in energy and environmental modelling: An update. Energy 31, 2604-22.

APPENDICES

APPENDIX A: Survey questions

APPENDIX B: Heating and cooling primary energy uses for different thermal insulation material alternatives.

APPENDIX C: Life cycle cost for different thermal insulation material alternatives.

APPENDIX D: Thermal comfort results for different thermal insulation material alternatives.

APPENDIX E: Environmental impact performance of different thermal insulation material alternatives.

APPENDIX F: Performance criteria values, normalized values and EWM and AHP scores of alternatives.

APPENDIX A: Survey questions

Table A.1 : Survey questions, Part 1 – Demographic questions: profession.

Profession	
Electrical Engineer	☐
Civil Engineer	☐
Mechanical Engineer	☐
Architect	☐
Other (please note):	....

Table A.2 : Survey questions, Part 1 – Demographic questions: educational level.

Educational level	
High school graduate, diploma or the equivalent	☐
Trade/technical/vocational training	☐
Bachelor’s degree	☐
Associate degree	☐
Master’s degree	☐
Doctorate degree	☐
Other (please note):	....

Table A.3 : Survey questions, Part 1 – Demographic questions: employment status/position.

Employment status/position	
Please note:	....

Table A.4 : Survey questions, Part 2 – Personal interest on the subjects.

	1 (Strongly not interested)	**2 (Not interested)**	**3 (Uncertain)**	**4 (Interested)**	**5 (Strongly interested)**
MATERIAL SCALE					
Cost of building material	☐	☐	☐	☐	☐
Thermal transmittance of building material	☐	☐	☐	☐	☐
Environmental impact of building material	☐	☐	☐	☐	☐
BUILDING ENVELOPE SCALE					
Cost of building envelope	☐	☐	☐	☐	☐
Thermal transmittance of building envelope	☐	☐	☐	☐	☐
Environmental impact of building envelope	☐	☐	☐	☐	☐
BUILDING SCALE					
Investemnt cost in buildings	☐	☐	☐	☐	☐
Energy consumption in buildings	☐	☐	☐	☐	☐
Environmental impact of buildings	☐	☐	☐	☐	☐

Table A.5 : Survey questions, Part 2 – Attendance to the conferences, meetings and activities related with the subjects.

	1 (Never)	**2 (Rarely)**	**3 (Sometimes)**	**4 (Often)**	**5 (Always)**
Building finance, etc.	☐	☐	☐	☐	☐
Building energy performance	☐	☐	☐	☐	☐
Building environmental impact	☐	☐	☐	☐	☐
Building thermal comfort	☐	☐	☐	☐	☐

Table A.6 : Survey questions, Part 3 – How often do you decide on the following issues in housing projects that are being carried out by you?

	1 (Never)	2 (Rarely)	3 (Sometimes)	4 (Often)	5 (Always)
MATERIAL SCALE					
Selection of building material	☐	☐	☐	☐	☐
Cost of building material	☐	☐	☐	☐	☐
Thermal performance of the building material	☐	☐	☐	☐	☐
Environmental impact of building material	☐	☐	☐	☐	☐
BUILDING ENVELOPE SCALE					
Building envelope design	☐	☐	☐	☐	☐
Cost of building envelope	☐	☐	☐	☐	☐
Thermal performance of the building envelope	☐	☐	☐	☐	☐
Environmental impact of building envelope	☐	☐	☐	☐	☐
BUILDING SCALE					
Building design	☐	☐	☐	☐	☐
Cost of building	☐	☐	☐	☐	☐
Energy performance of the building	☐	☐	☐	☐	☐
Environmental impact of building	☐	☐	☐	☐	☐
Thermal comfort of building	☐	☐	☐	☐	☐

Table A.7 : Survey questions, Part 4 -

	1 (Not important)	2 (Less important)	3 (Uncertain)	4 (İmportant)	5 (Very important)
MATERIAL SCALE					
Selection of building material	☐	☐	☐	☐	☐
Cost of building material	☐	☐	☐	☐	☐
Thermal comfort of building material	☐	☐	☐	☐	☐
Environmental impact of building material	☐	☐	☐	☐	☐
BUILDING ENVELOPE SCALE					
Building envelope design	☐	☐	☐	☐	☐
Cost of building envelope	☐	☐	☐	☐	☐
Thermal comfort of building envelope	☐	☐	☐	☐	☐
Environmental impact of building envelope	☐	☐	☐	☐	☐
BUILDING SCALE					
Building design	☐	☐	☐	☐	☐
Building investment cost	☐	☐	☐	☐	☐
Building energy performance	☐	☐	☐	☐	☐
Building environmental impact	☐	☐	☐	☐	☐
Building thermal comfort	☐	☐	☐	☐	☐

APPENDIX B : Heating and cooling primary energy uses for different thermal insulation material alternatives

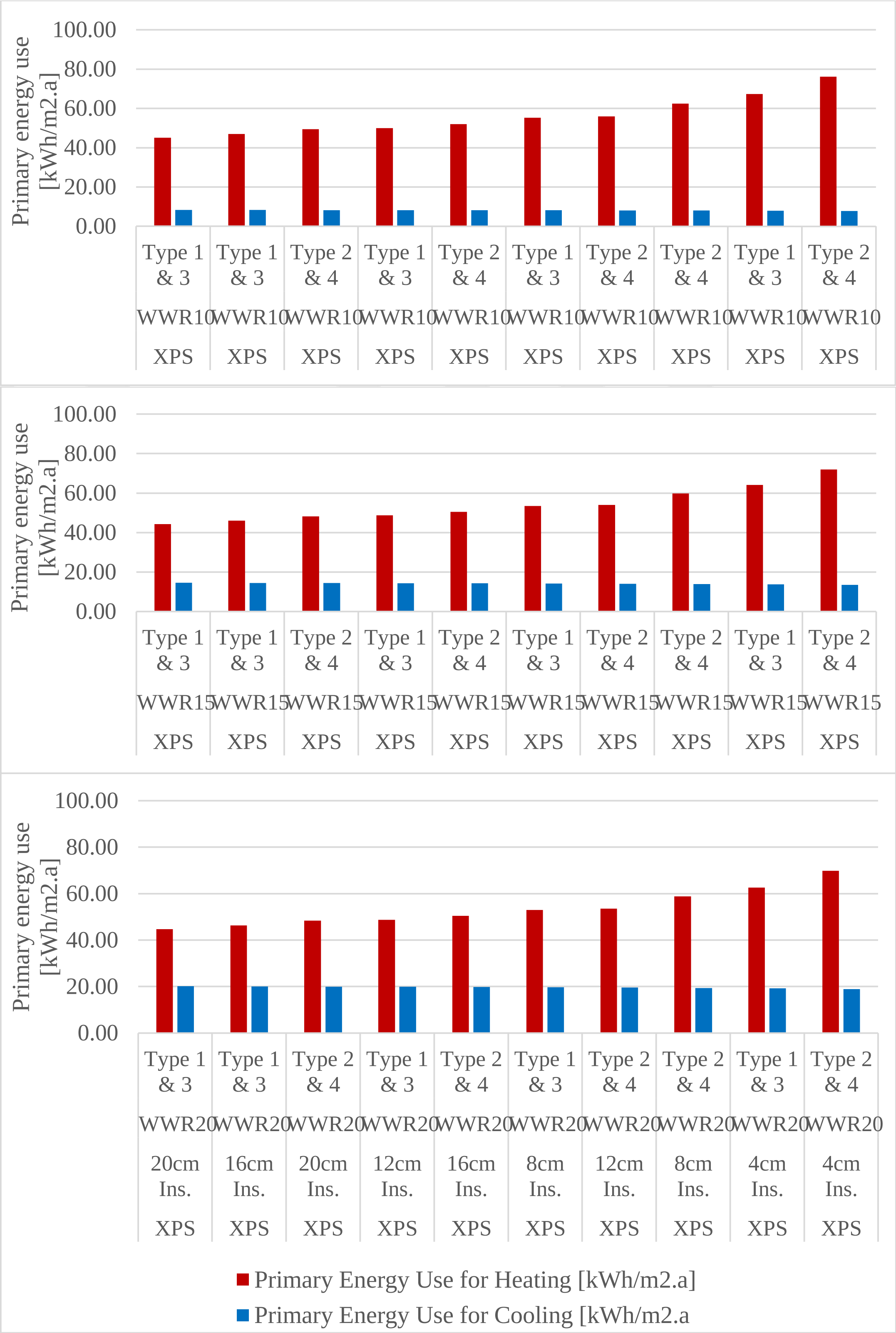

Figure B.1 : Heating and cooling energy uses for XPS thermal insulation material (60 alternatives).

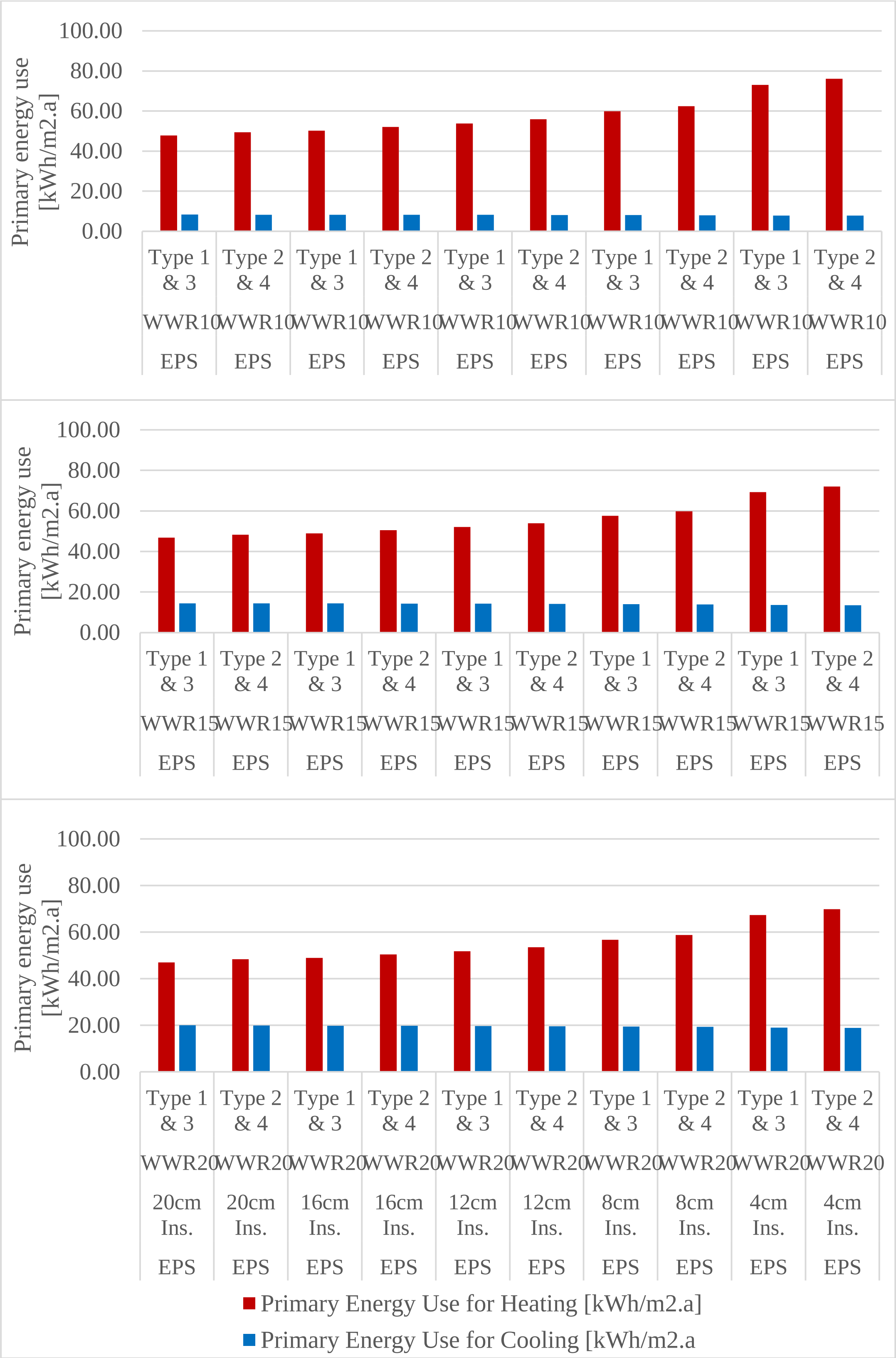

Figure B.2 : Heating and cooling energy uses for EPS thermal insulation material (60 alternatives).

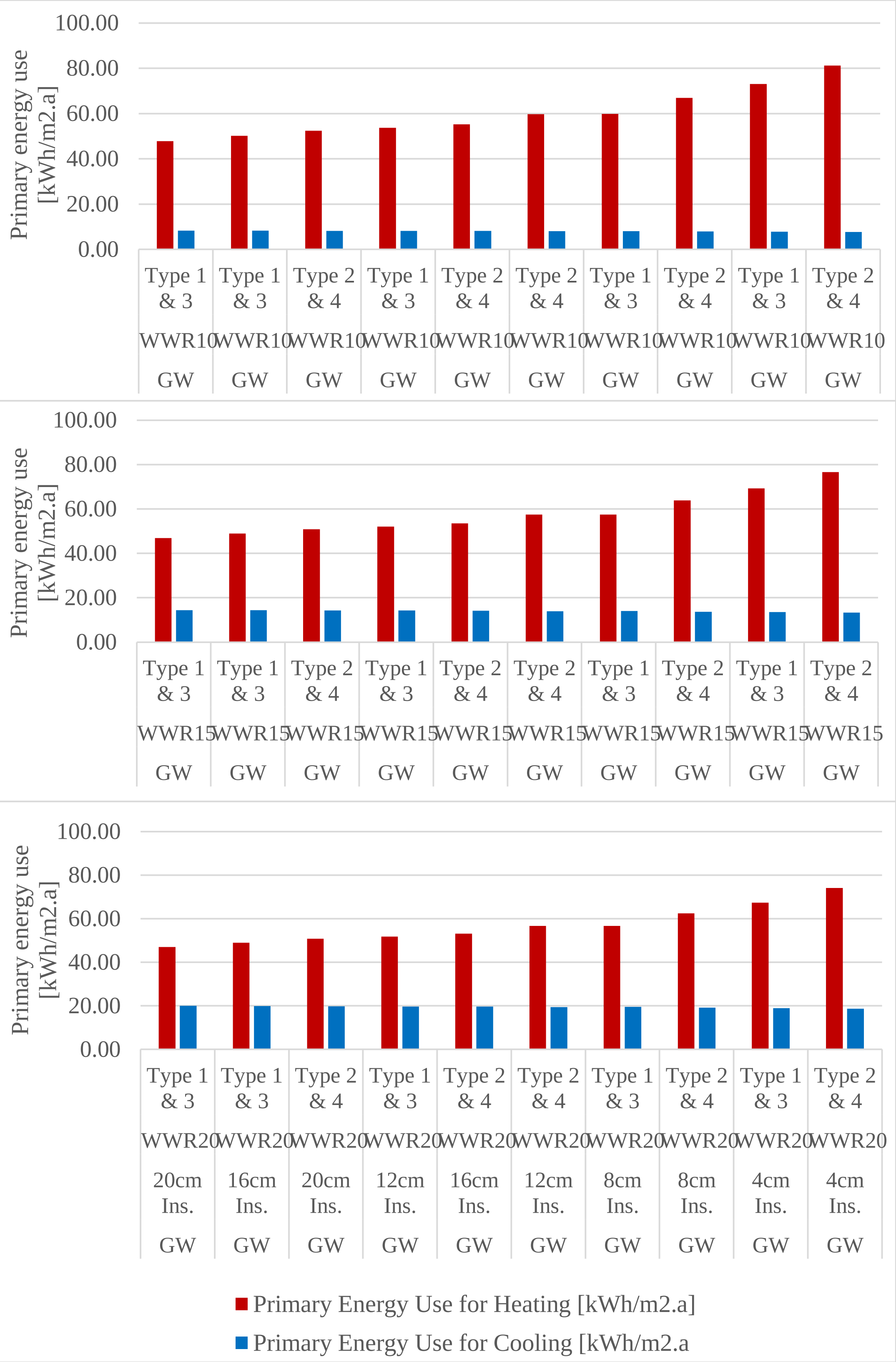

Figure B.3 : Heating and cooling energy uses for GW thermal insulation material (60 alternatives).

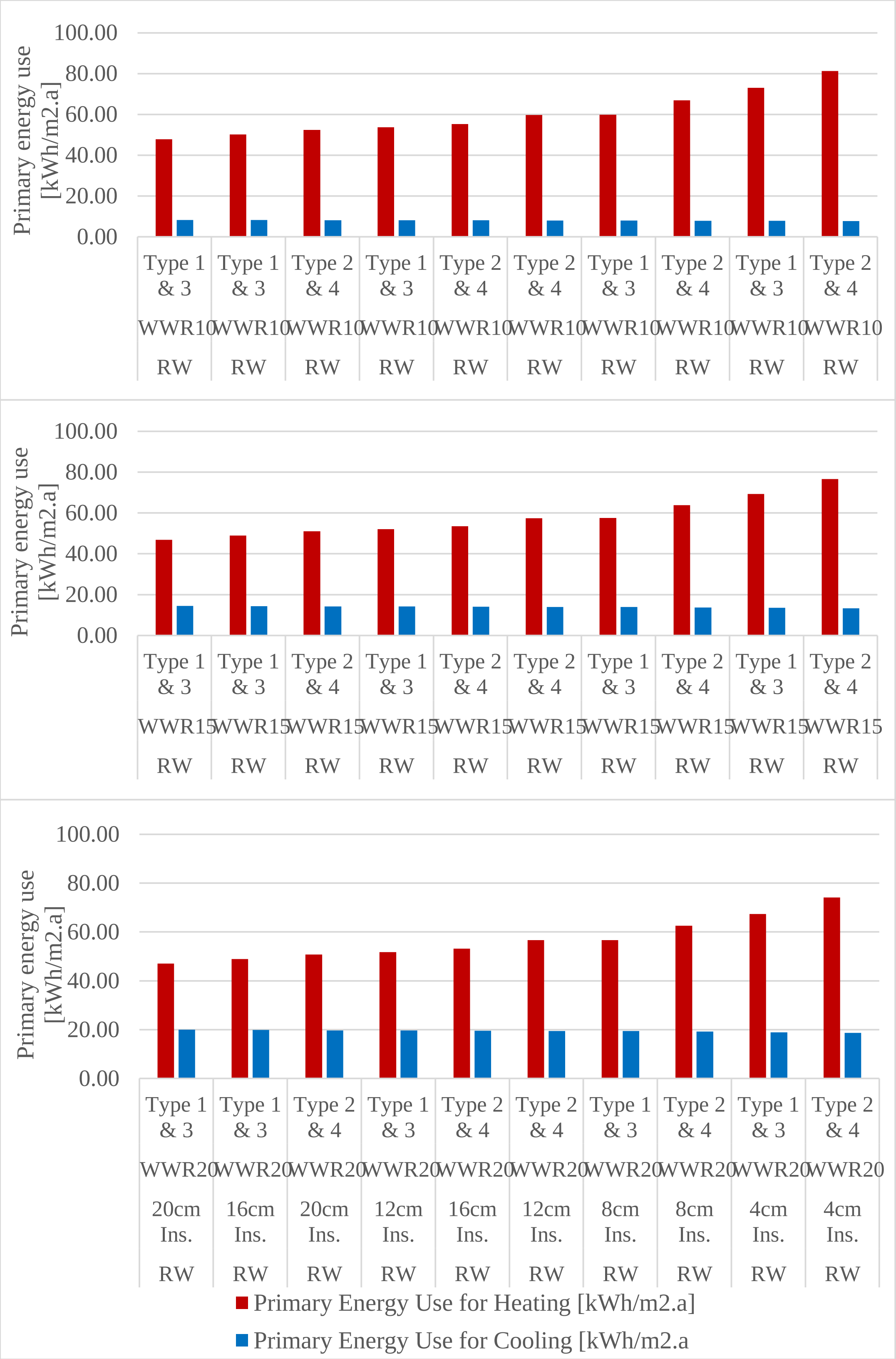

Figure B.4 : Heating and cooling energy uses for RW thermal insulation material (60 alternatives).

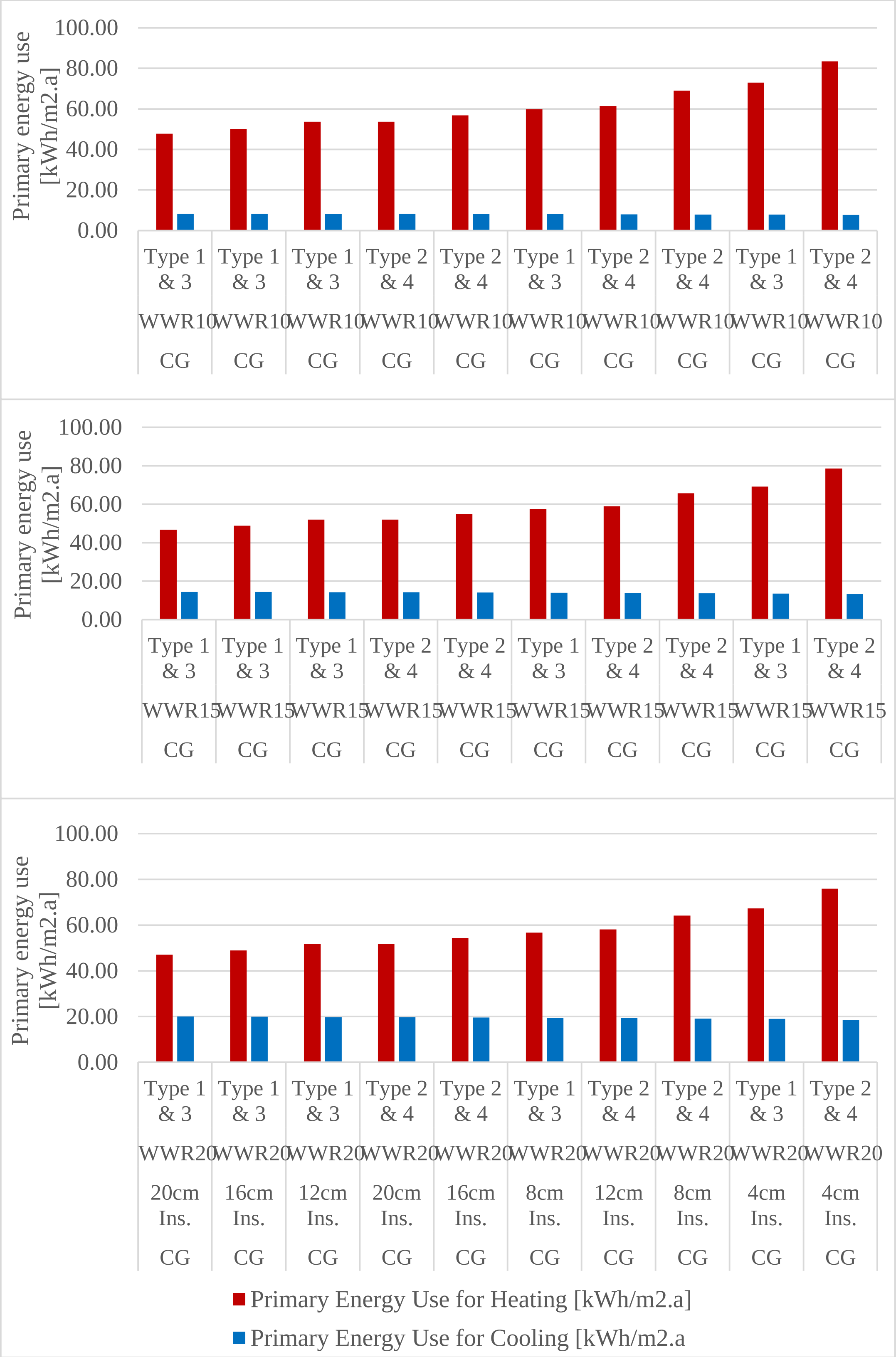

Figure B.5 : Heating and cooling energy uses for CG thermal insulation material (60 alternatives).

APPENDIX C : Life cycle cost for different thermal insulation material alternatives.

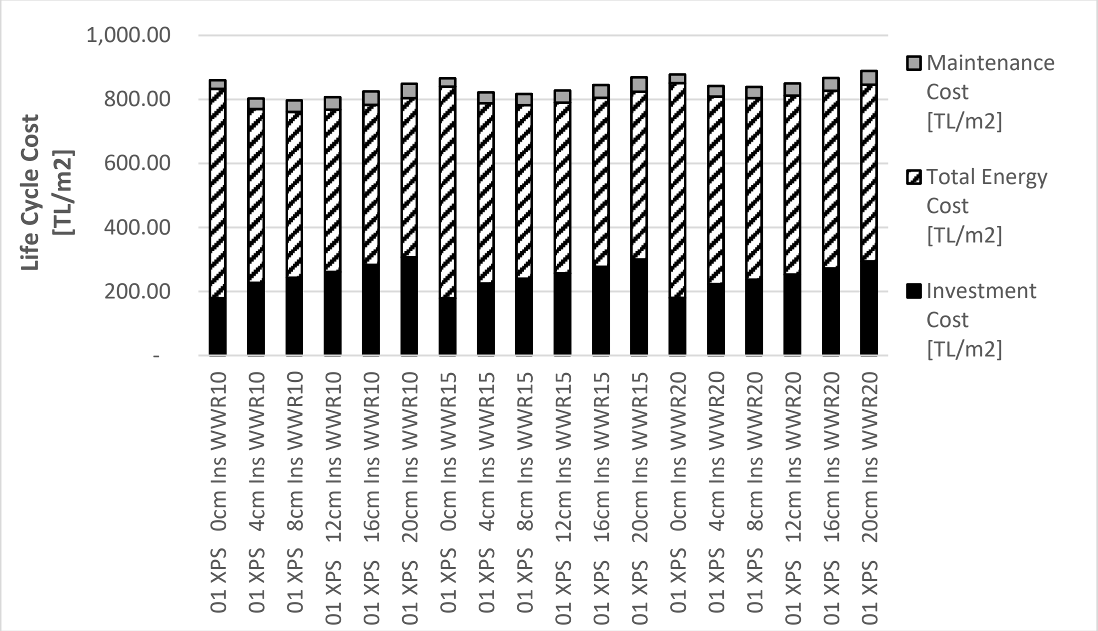

Figure C.1 : Life cycle cost for 01 and 04 XPS thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

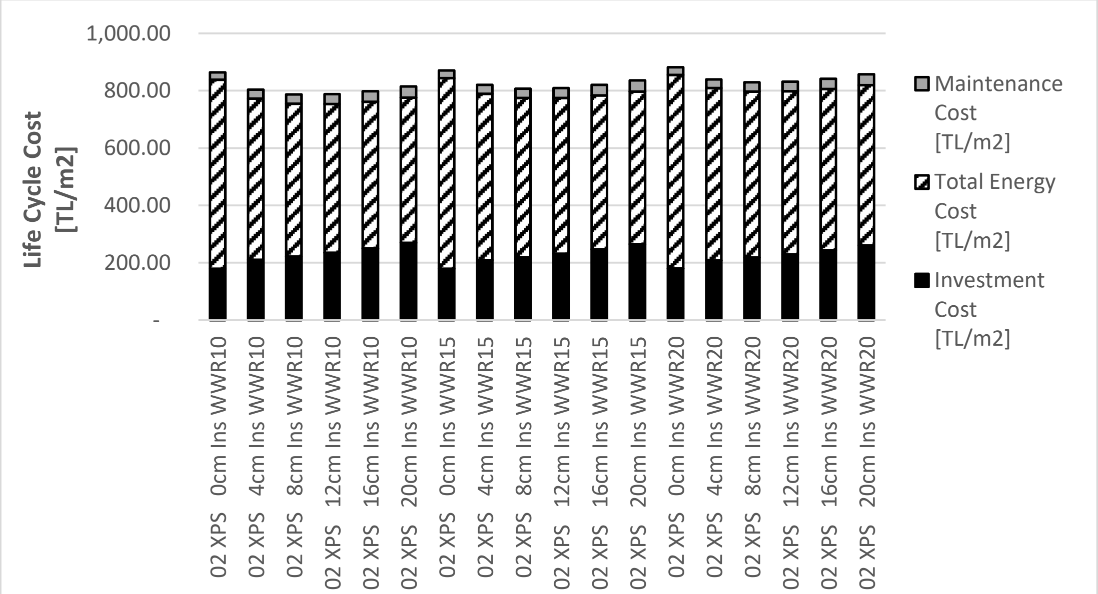

Figure C.2 : Life cycle cost for 02 and 03 XPS thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

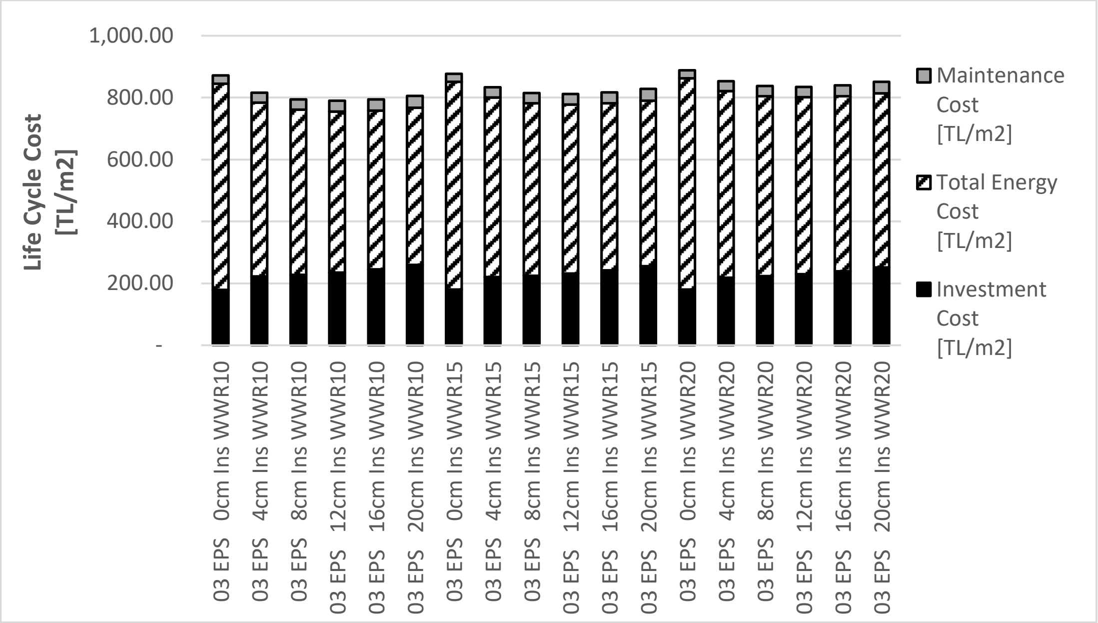

Figure C.3 : Life cycle cost for 01 and 04 EPS thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

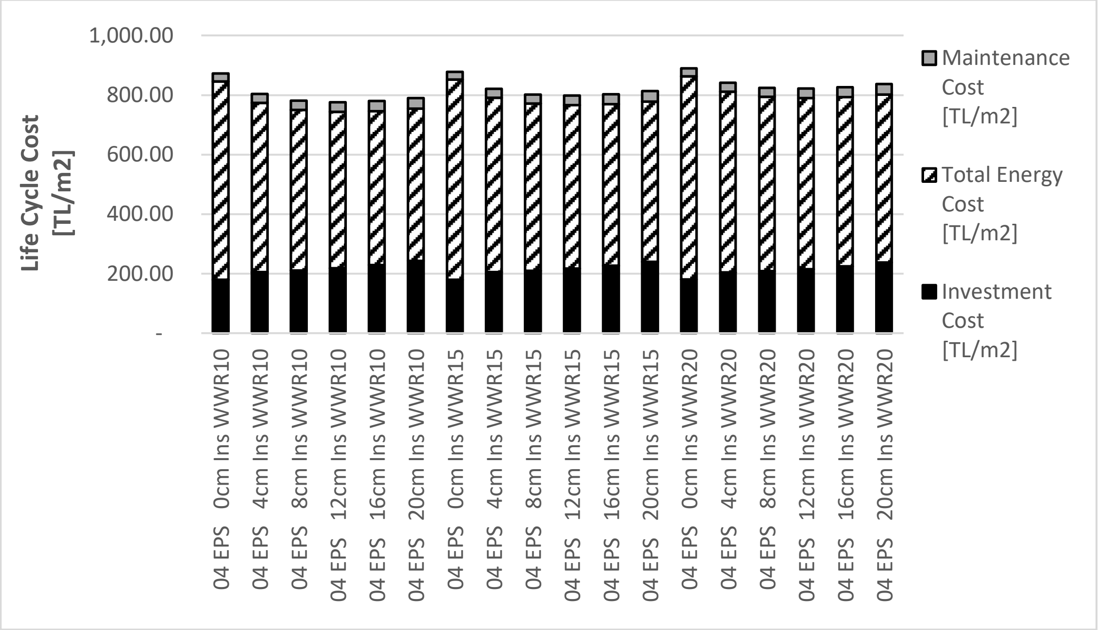

Figure C.4 : Life cycle cost for 02 and 03 EPS thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

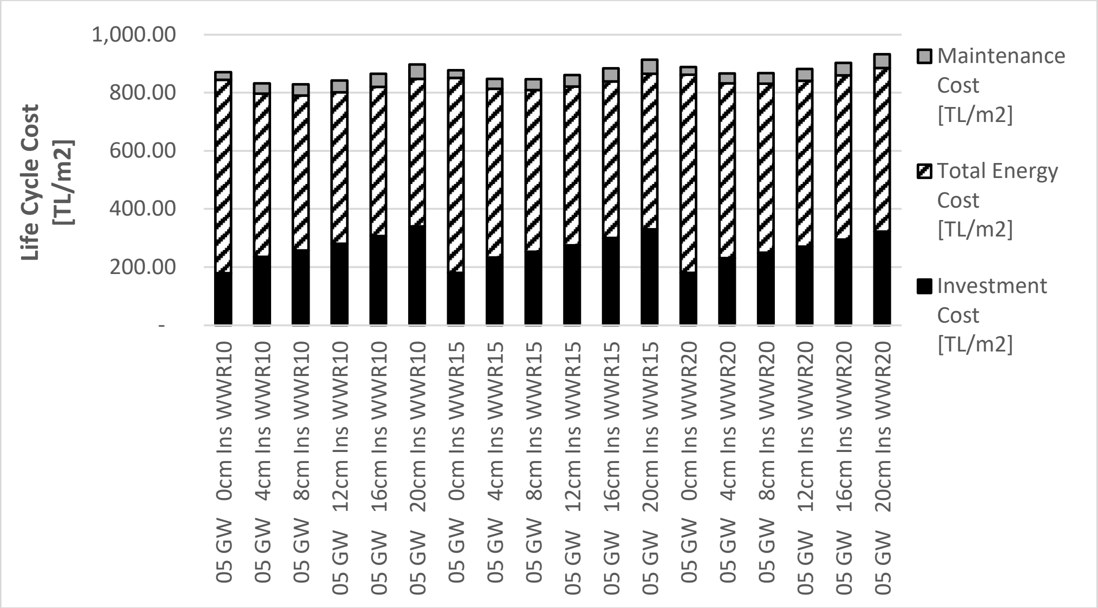

Figure C.5 : Life cycle cost for 01 and 04 GW thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

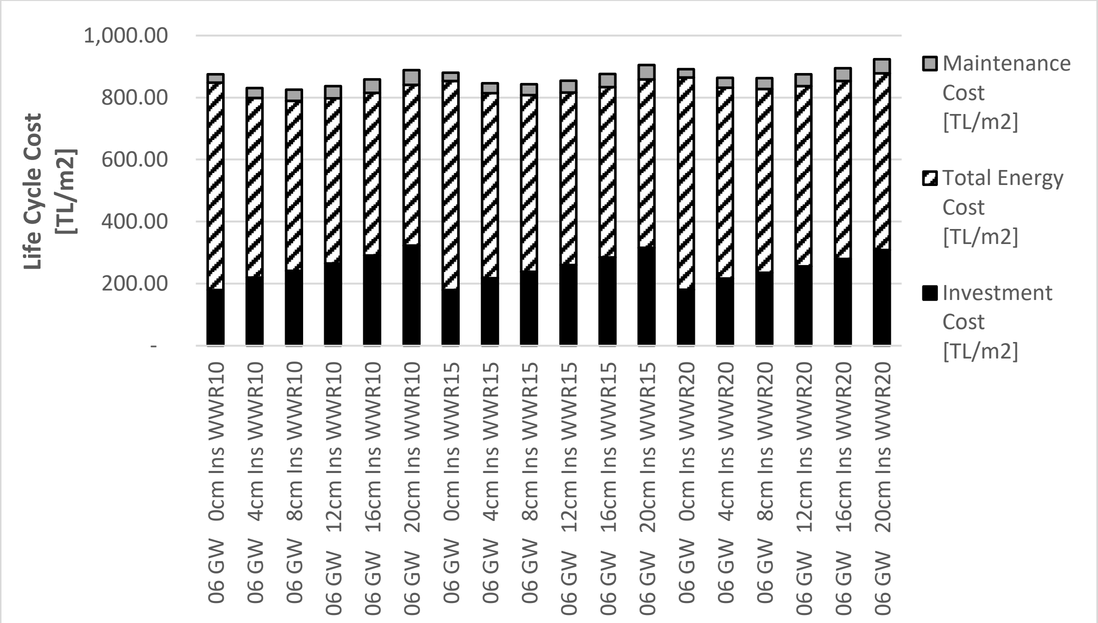

Figure C.6 : Life cycle cost for 02 and 03 GW thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

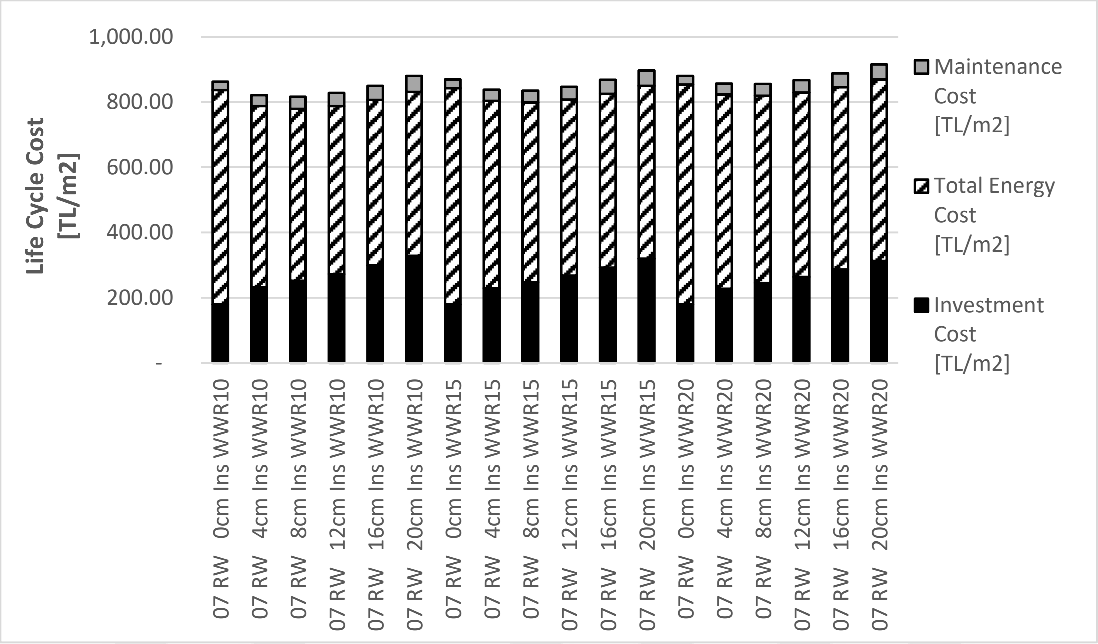

Figure C.7 : Life cycle cost for 01 and 04 RW thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

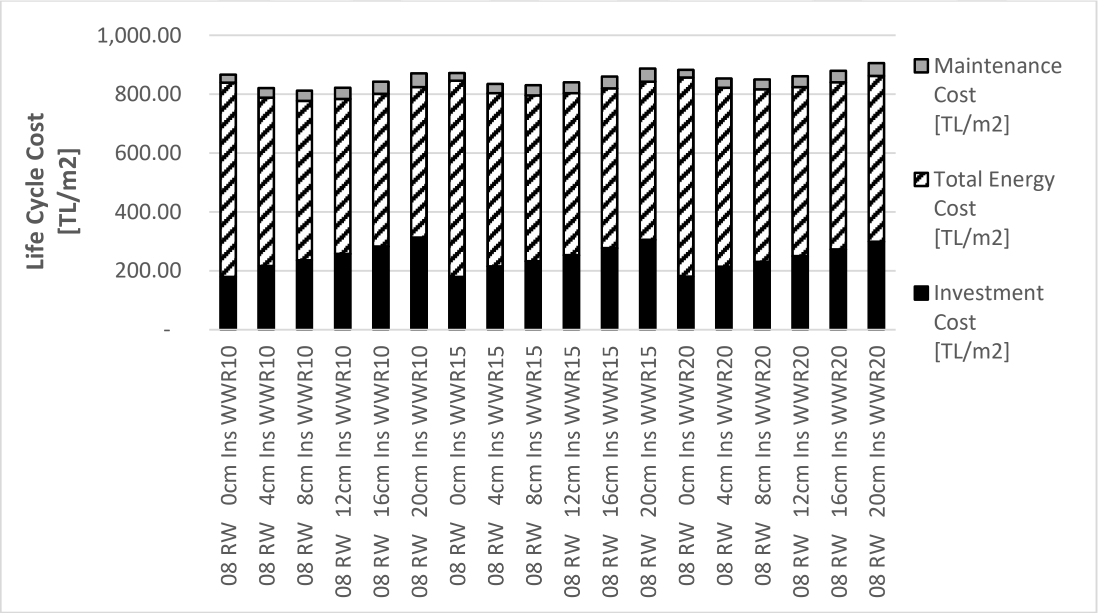

Figure C.8 : Life cycle cost for 02 and 03 RW thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

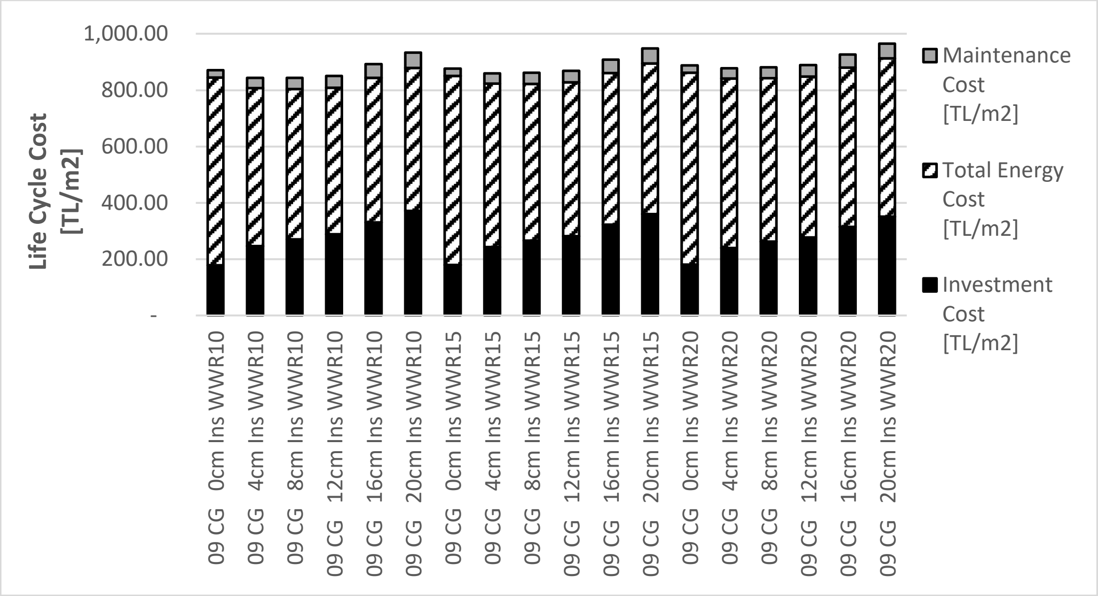

Figure C.9 : Life cycle cost for 01 and 04 CG thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

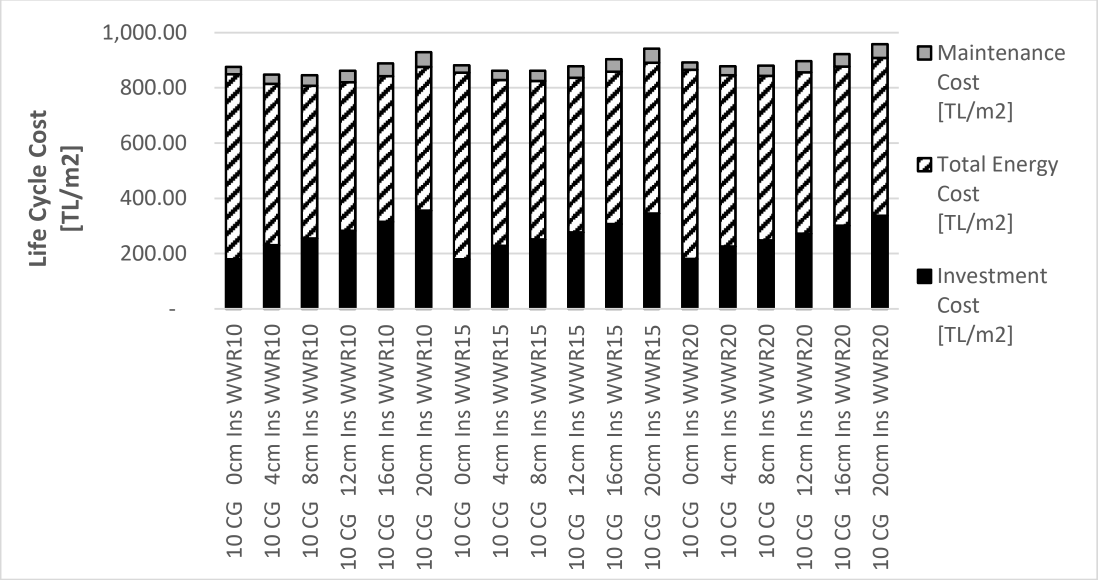

Figure C.10 : Life cycle cost for 02 and 03 CG thermal insulation material alternatives (30 alternatives + 3 no insulation scenarios).

APPENDIX D : Thermal comfort results for different thermal insulation material alternatives.

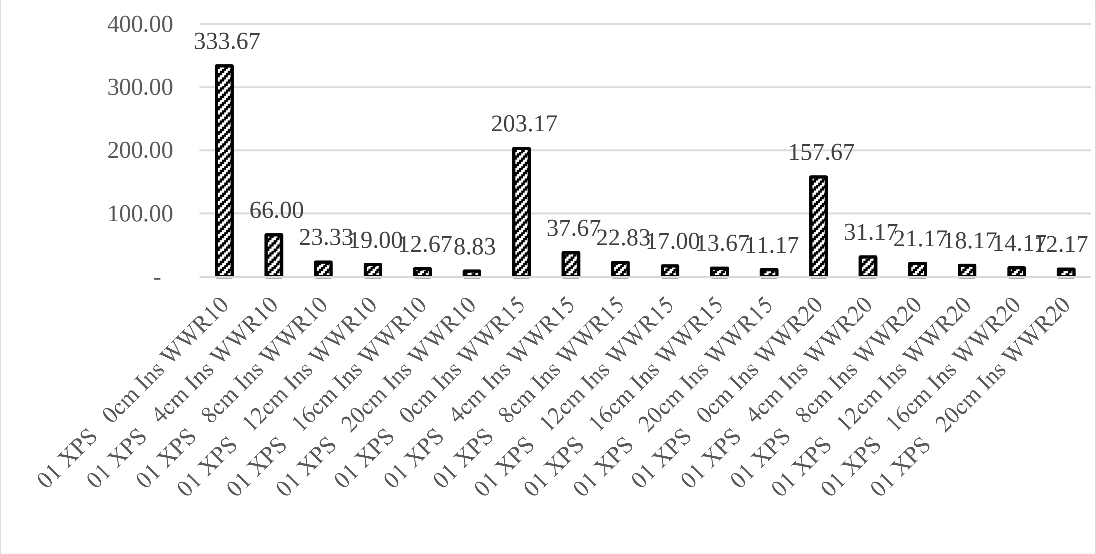

Figure D.1 : Thermal comfort results for 01 and 03 XPS thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

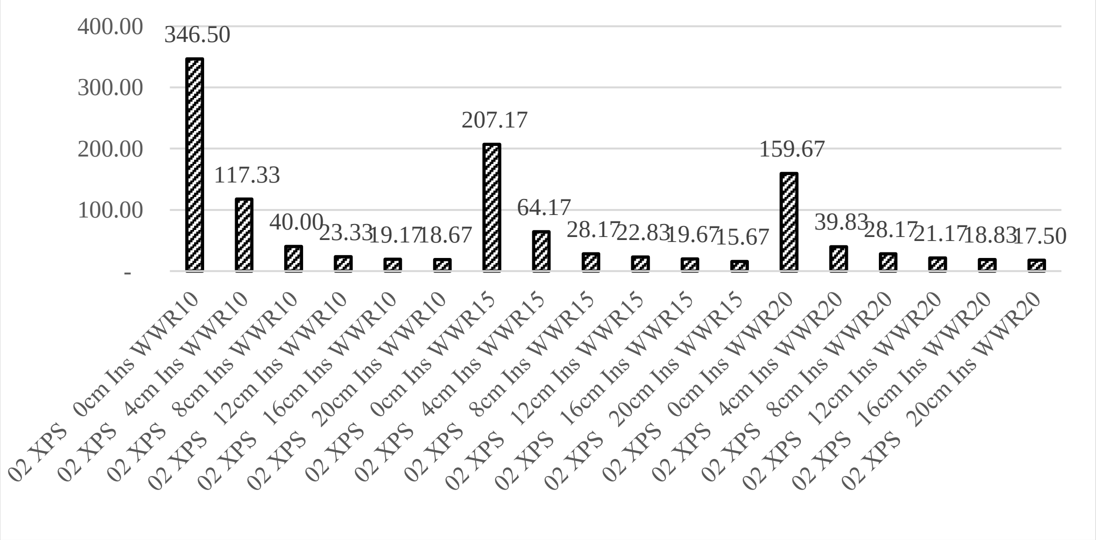

Figure D.2 : Thermal comfort results for 02 and 04 XPS thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

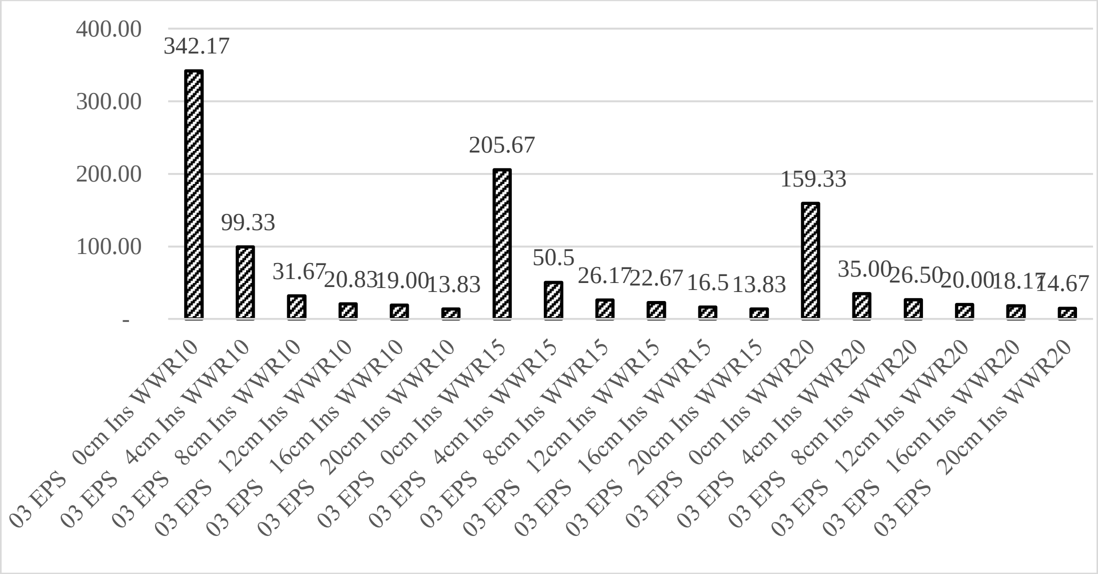

Figure D.3 : Thermal comfort results for 01 and 03 EPS thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

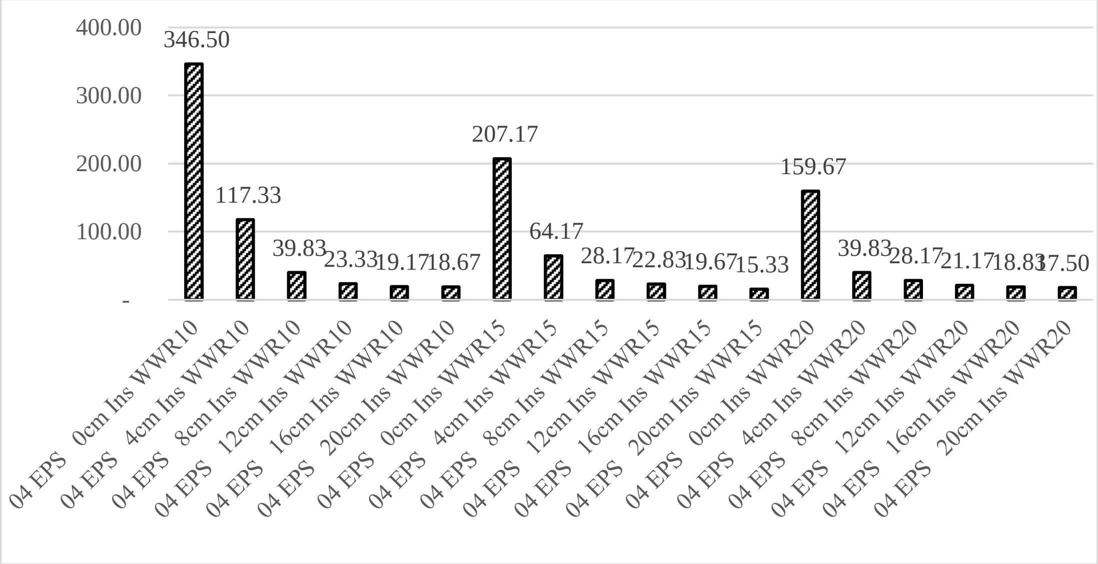

Figure D.4 : Thermal comfort results for 02 and 04 EPS thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

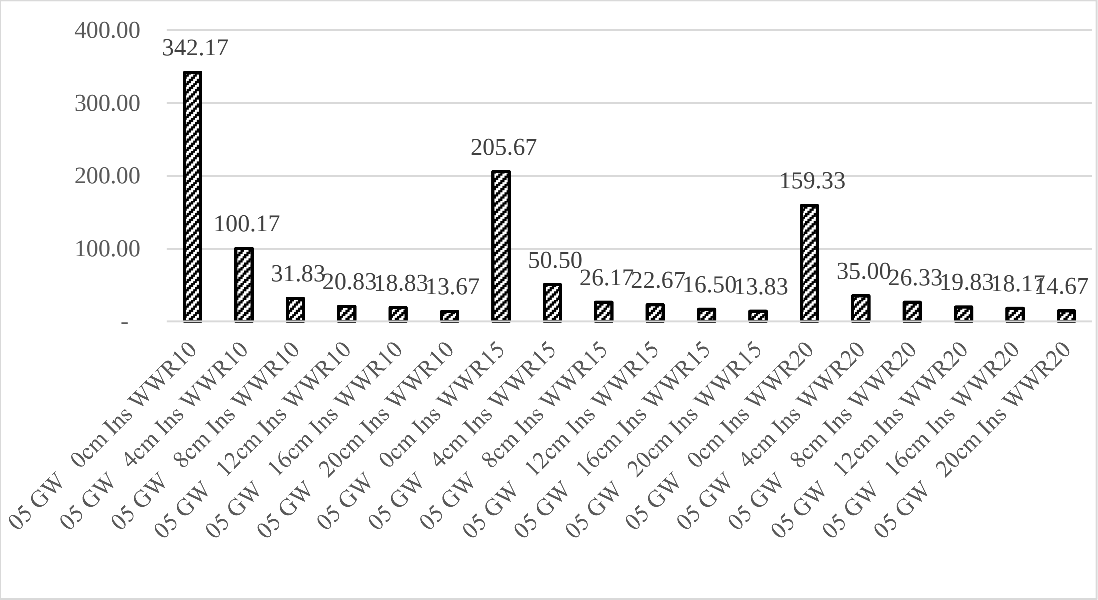

Figure D.5 : Thermal comfort results for 01 and 03 GW thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

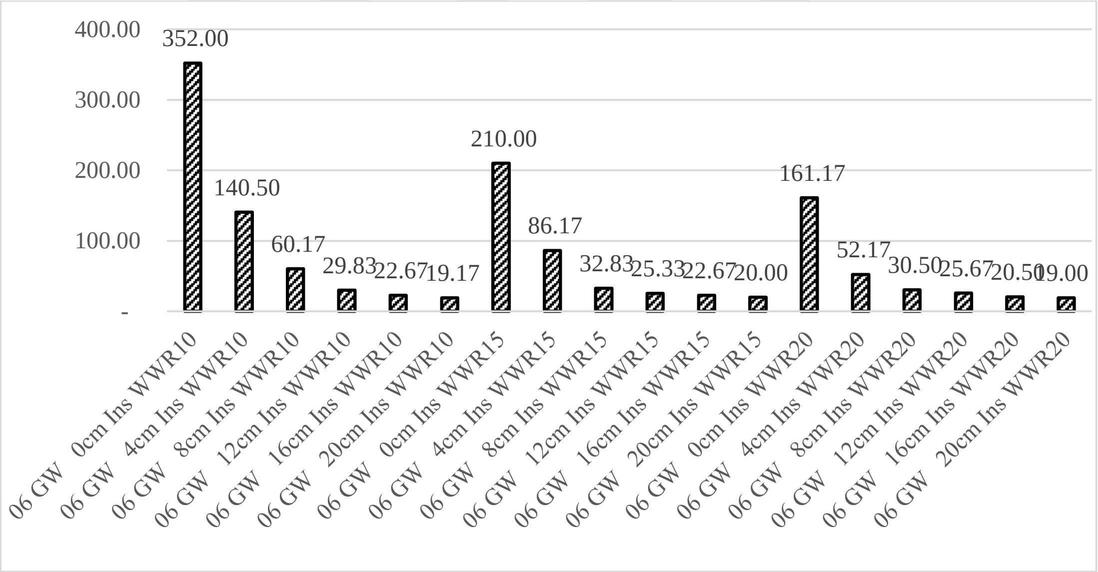

Figure D.6 : Thermal comfort results for 02 and 04 GW thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

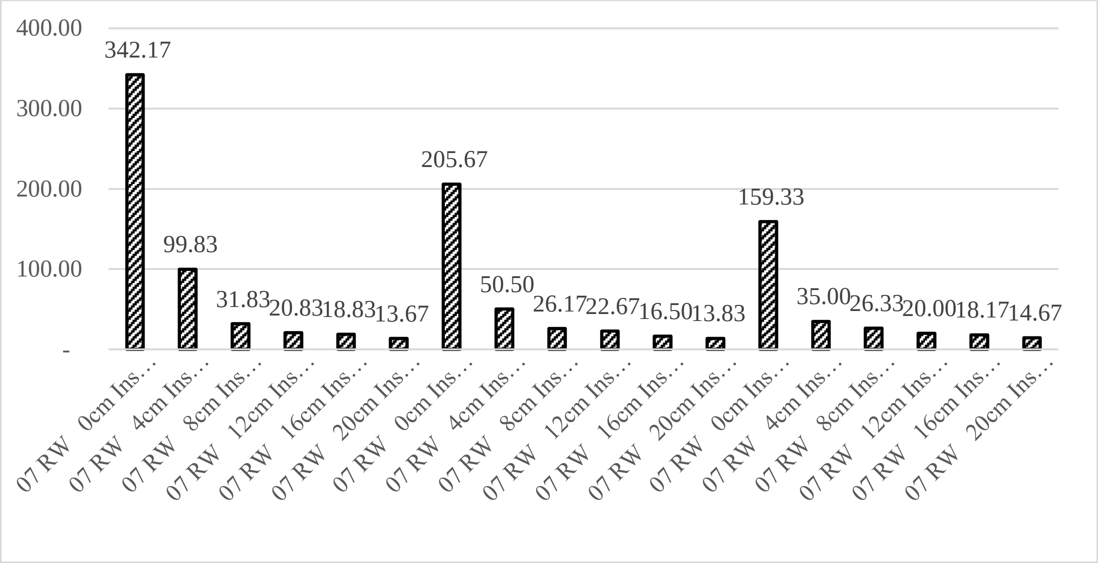

Figure D.7 : Thermal comfort results for 01 and 03 RW thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

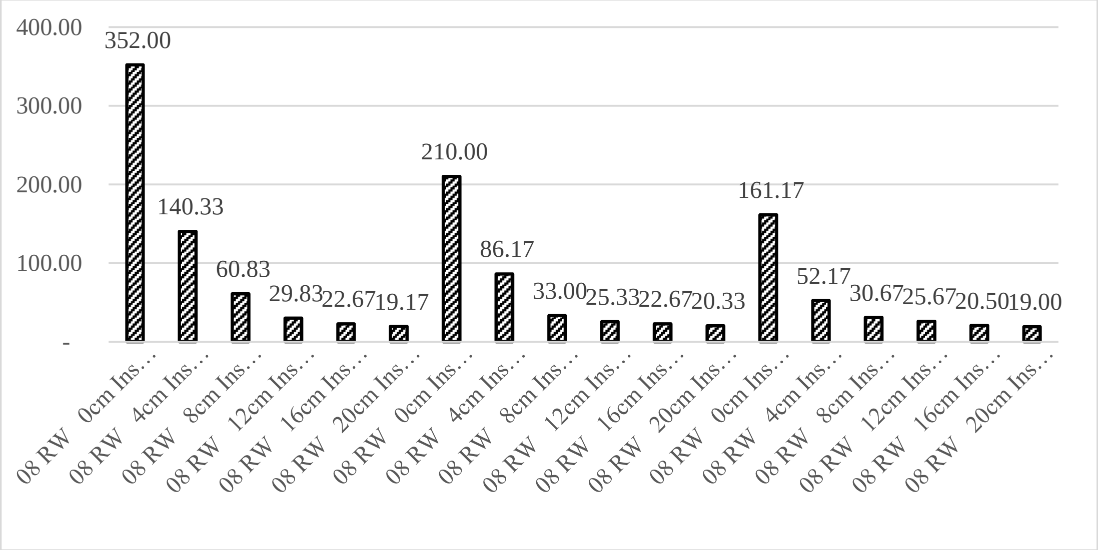

Figure D.8 : Thermal comfort results for 02 and 04 RW thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

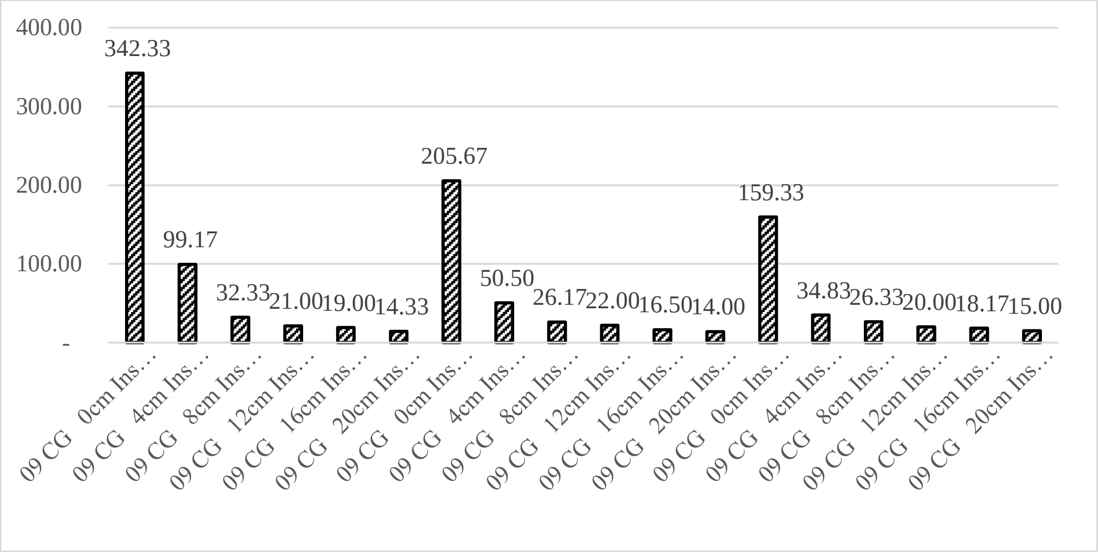

Figure D.9 : Thermal comfort results for 01 and 03 CG thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) (30 alternatives + 3 no insulation scenarios).

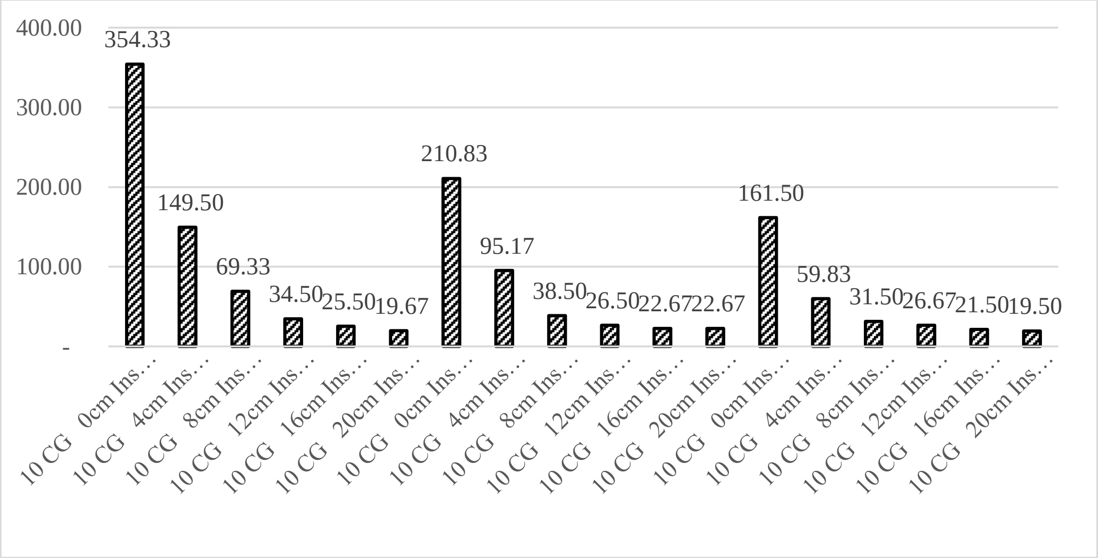

Figure D.10 : Thermal comfort results for 02 and 04 CG thermal insulation material alternatives (Adaptive Comfort Method – EN 15251 Categort III – unmet hours [hr]) .

APPENDIX E : Environmental impact performance of different thermal insulation material alternatives.

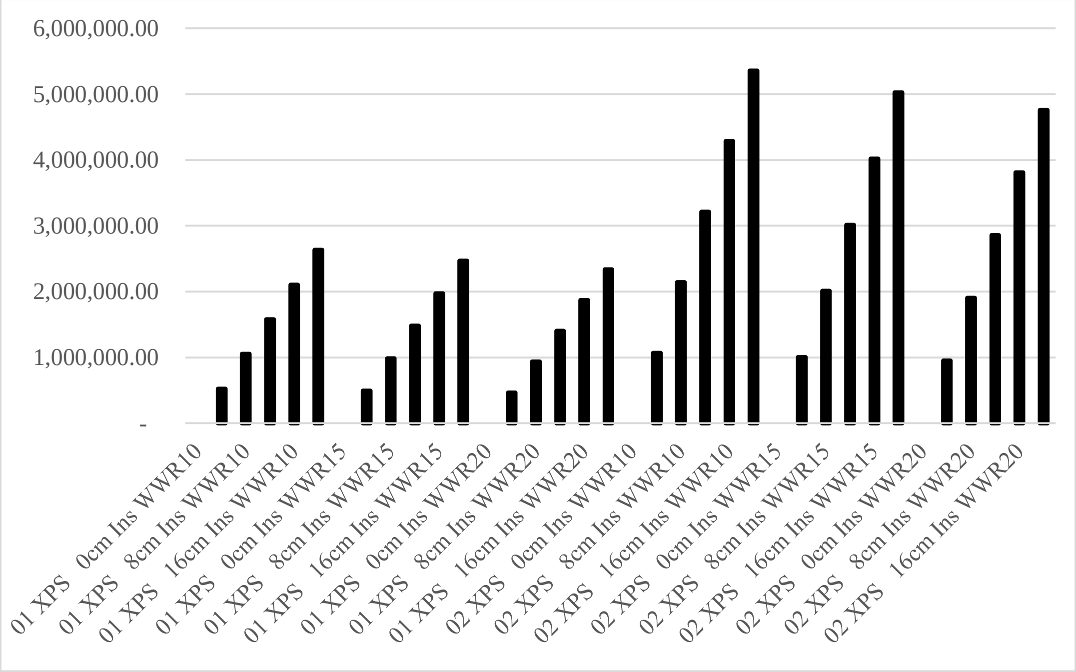

Figure E.1 : Embodied Carbon [kgCO2] environmental impact performance of XPS thermal insulation material alternatives.

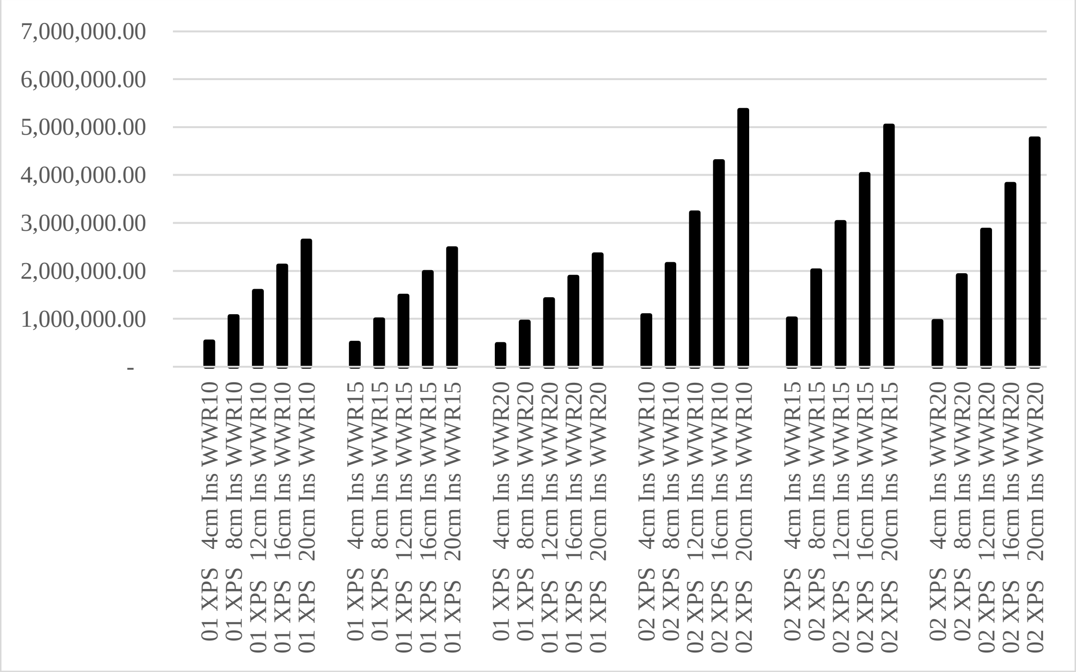

Figure E.2 : Embodied Energy [Mj] environmental impact performance of XPS thermal insulation material alternatives.

*01 XPS = O4 XPS, 02 XPS = 03 XPS in terms of environmental impact attributes.

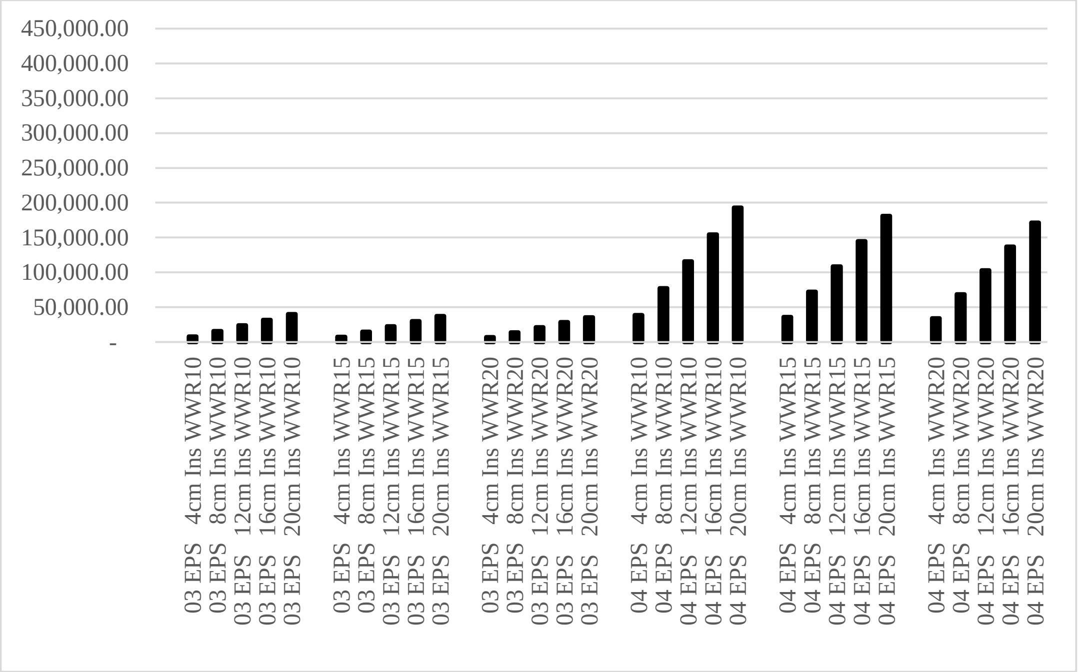

Figure E.3 : Embodied Carbon [kgCO2] environmental impact performance of EPS thermal insulation material alternatives.

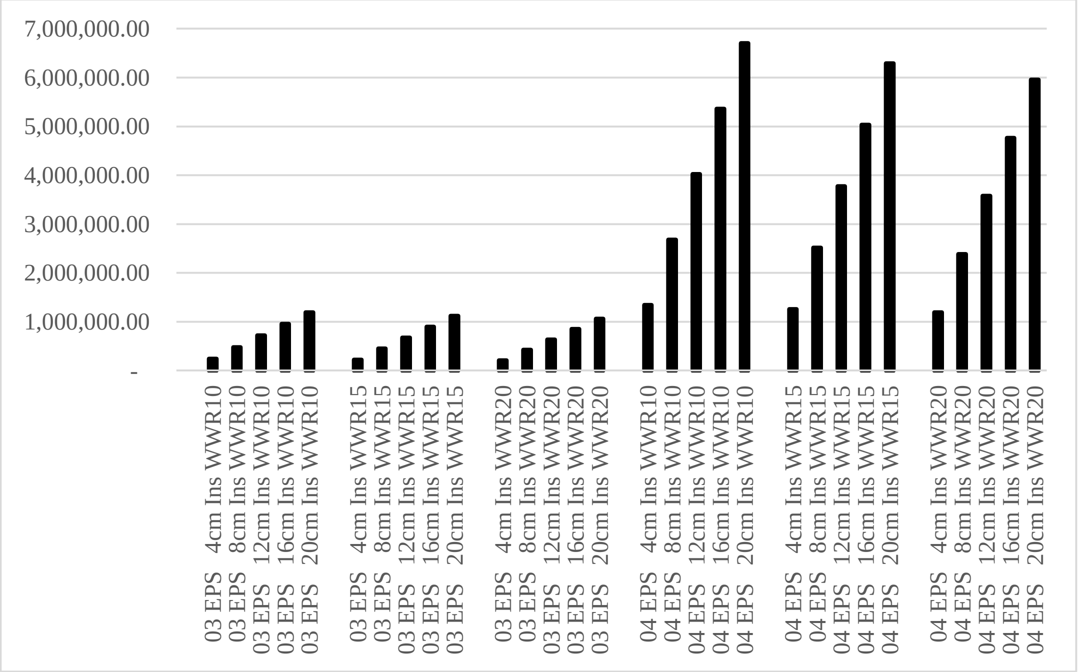

Figure E.4 : Embodied Energy [Mj] environmental impact performance of EPS thermal insulation material alternatives.

*01 EPS = O4 EPS, 02 EPS = 03 EPS in terms of environmental impact attributes.

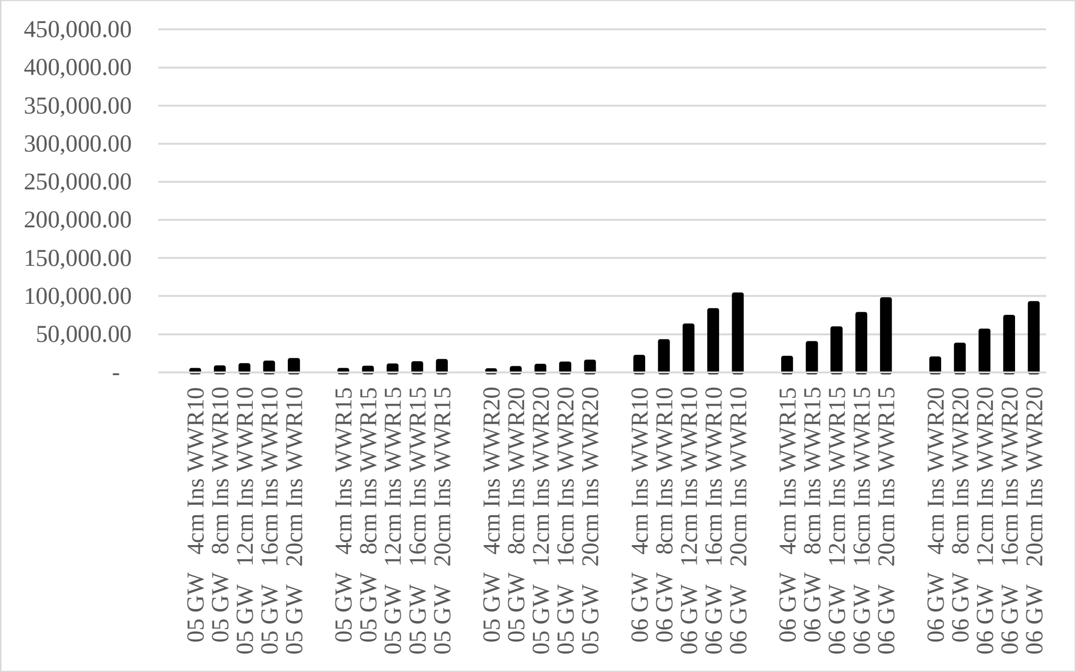

Figure E.5 : Embodied Carbon [kgCO2] environmental impact performance of GW thermal insulation material alternatives.

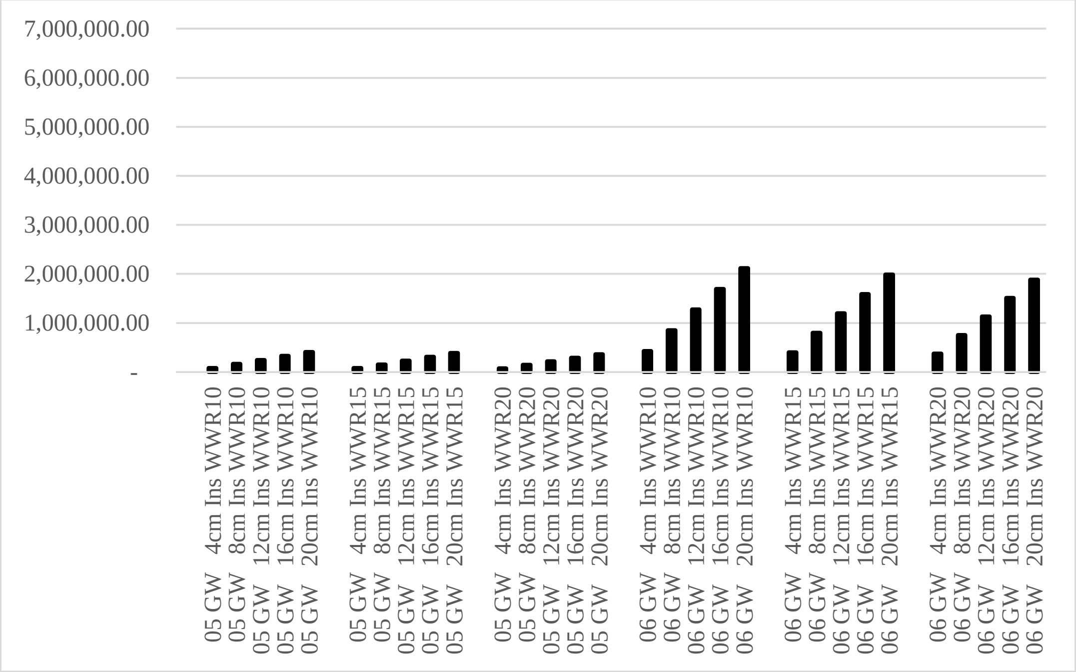

Figure E.6 : Embodied Energy [Mj] environmental impact performance of GW thermal insulation material alternatives.

*01 GW = O4 GW, 02 GW = 03 GW in terms of environmental impact attributes.

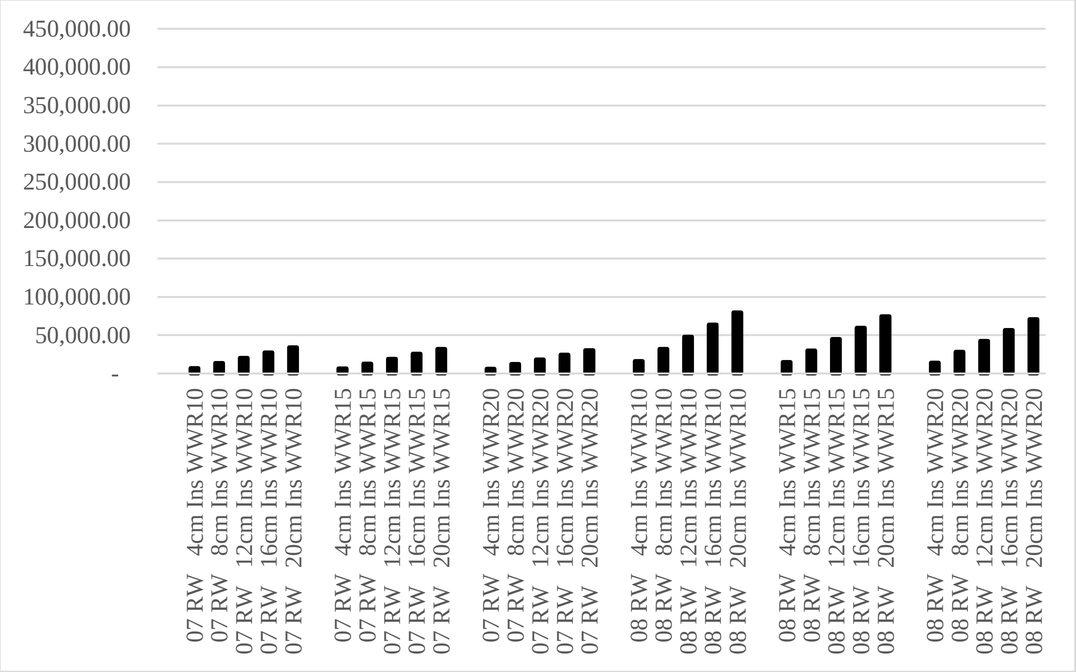

Figure E.7 : Embodied Carbon [kgCO2] environmental impact performance of RW thermal insulation material alternatives.

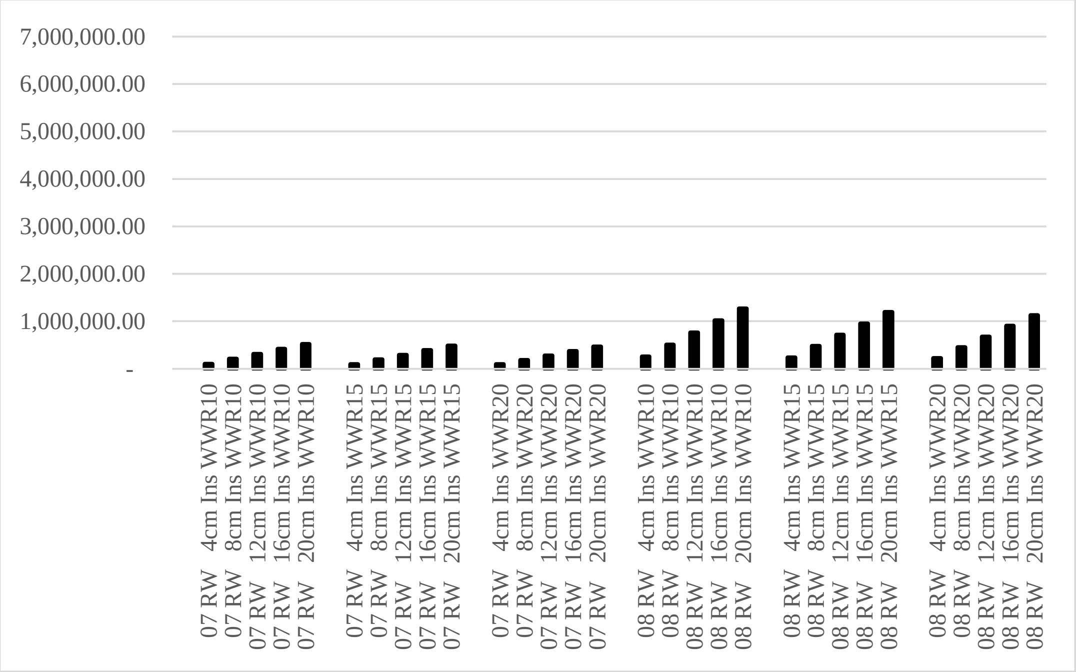

Figure E.8 : Embodied Energy [Mj] environmental impact performance of RW thermal insulation material alternatives.

*01 RW = O4 RW, 02 RW = 03 RW in terms of environmental impact attributes.

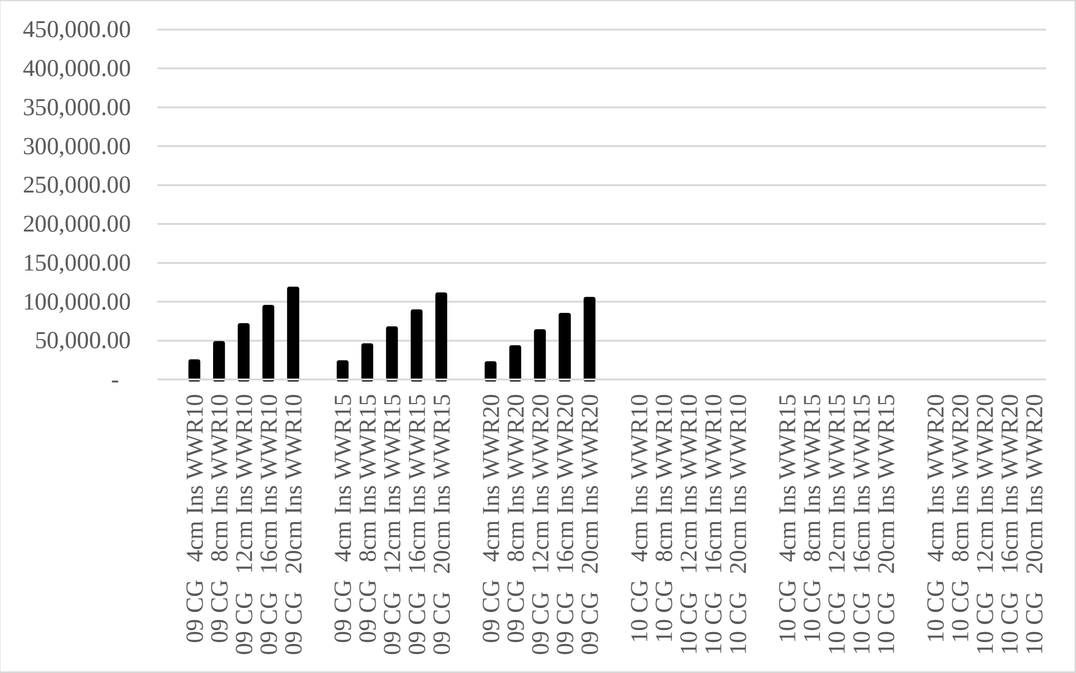

Figure E.9 : Embodied Carbon [kgCO2] environmental impact performance of CG thermal insulation material alternatives.

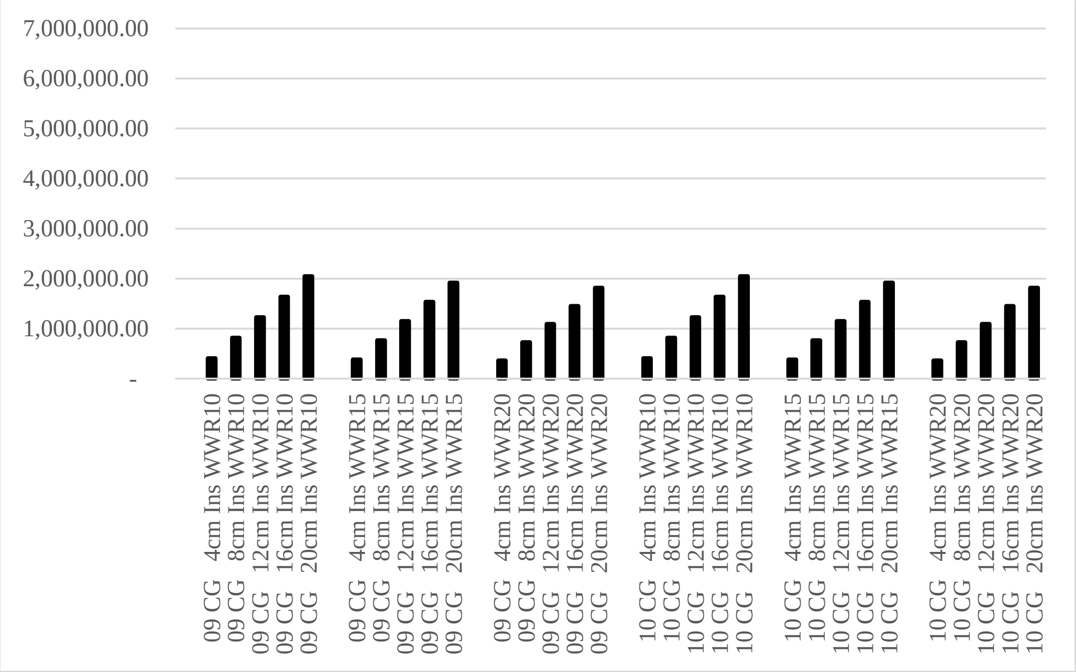

Figure E.10 : Embodied Energy [Mj] environmental impact performance of CG thermal insulation material alternatives.

*01 CG = O4 CG, 02 CG = 03 CG in terms of environmental impact attributes.

APPENDIX F : Performance criteria values, normalized values and EWM and AHP scores of alternatives.

Table F.1 : Alternatives beyond cost optimal level.

	PERFORMANCE INDICATORS AND LEVELS				
	CRITERIA 1	CRITERIA 2	CRITERIA 3		CRITERIA 4
	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
01 EPS 12cm Ins WWR10	234.558	61.940	24065.222	717416.064	20.830
01 EPS 16cm Ins WWR10	245.250	58.442	32086.963	956554.752	19.000
03 EPS 12cm Ins WWR10	218.521	61.940	115785.504	4022978.688	20.830
03 XPS 8cm Ins WWR10	221.729	63.476	162553.766	2143166.976	23.330
04 EPS 16cm Ins WWR10	245.250	60.217	32086.963	956554.752	19.170
04 EPS 12cm Ins WWR10	234.558	64.010	24065.222	717416.064	23.330
03 EPS 8cm Ins WWR10	211.037	67.964	77190.336	2681985.792	31.670
01 EPS 20cm Ins WWR10	259.149	56.143	40108.704	1195693.440	13.830
03 EPS 16cm Ins WWR10	229.213	58.442	154380.672	5363971.584	19.000
02 EPS 12cm Ins WWR10	218.521	64.010	115785.504	4022978.688	23.330
03 XPS 12cm Ins WWR10	234.558	58.267	243830.650	3214750.464	19.000
01 EPS 12cm Ins WWR15	231.788	66.271	22580.671	673159.632	22.670
01 EPS 8cm Ins WWR10	227.074	67.964	16043.482	478277.376	31.670
01 EPS 16cm Ins WWR15	241.820	63.236	30107.562	897546.176	16.500
03 EPS 12cm Ins WWR15	216.741	66.271	108642.852	3774806.544	22.670
04 EPS 20cm Ins WWR10	259.149	57.705	40108.704	1195693.440	18.670
02 EPS 16cm Ins WWR10	229.213	60.217	154380.672	5363971.584	19.170
02 EPS 8cm Ins WWR10	211.037	70.462	77190.336	2681985.792	39.830

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
03 XPS 8cm Ins WWR15	219.750	67.567	152526.043	2010957.888	22.830
01 XPS 8cm Ins WWR10	243.111	63.476	41319.533	1053118.349	23.330
04 EPS 12cm Ins WWR15	231.788	68.087	22580.671	673159.632	22.830
04 EPS 16cm Ins WWR15	241.820	64.796	30107.562	897546.176	19.670
02 EPS 12cm Ins WWR15	216.741	68.087	108642.852	3774806.544	22.830
03 EPS 16cm Ins WWR15	226.772	63.236	144857.136	5033075.392	16.500
04 EPS 8cm Ins WWR10	227.074	70.462	16043.482	478277.376	39.830
01 EPS 20cm Ins WWR15	254.862	61.246	37634.452	1121932.720	13.830
01 XPS 12cm Ins WWR10	261.287	58.267	61979.299	1579677.523	19.000
03 RW 8cm Ins WWR10	235.628	67.952	31784.256	508548.096	31.830
03 XPS 12cm Ins WWR15	231.788	63.049	228789.065	3016436.832	17.000
03 EPS 20cm Ins WWR10	243.111	56.143	192975.840	6704964.480	13.830
03 RW 12cm Ins WWR10	257.010	61.945	47676.384	762822.144	20.830
04 EPS 20cm Ins WWR15	254.862	62.621	37634.452	1121932.720	15.330
02 EPS 16cm Ins WWR15	226.772	64.796	144857.136	5033075.392	19.670
01 XPS 8cm Ins WWR15	239.814	67.567	38770.586	988152.894	22.830
03 XPS 16cm Ins WWR10	250.595	55.314	325107.533	4286333.952	12.670
01 EPS 16cm Ins WWR20	239.070	68.787	28520.106	850222.016	18.170
02 EPS 20cm Ins WWR10	243.111	57.705	192975.840	6704964.480	18.670
03 GW 8cm Ins WWR10	240.973	67.954	40865.472	847580.160	31.830
02 XPS 12cm Ins WWR10	234.558	64.005	243830.650	3214750.464	23.330
02 XPS 8cm Ins WWR10	221.729	70.456	162553.766	2143166.976	40.000
01 XPS 12cm Ins WWR15	256.868	63.049	58155.880	1482229.342	17.000

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
04 EPS 16cm Ins WWR20	239.070	70.183	28520.106	850222.016	18.830
03 EPS 20cm Ins WWR15	239.814	61.246	181071.420	6291344.240	13.830
03 RW 12cm Ins WWR15	252.855	66.276	44735.292	715764.672	22.670
03 EPS 16cm Ins WWR20	224.815	68.787	137219.376	4767700.672	18.170
03 GW 12cm Ins WWR10	264.494	61.947	61298.208	1271370.240	20.830
01 RW 8cm Ins WWR10	251.665	67.952	13621.824	208867.968	31.830
01 EPS 20cm Ins WWR20	251.423	67.030	35650.132	1062777.520	14.670
01 XPS 16cm Ins WWR10	282.670	55.314	82639.066	2106236.698	12.670
03 XPS 12cm Ins WWR20	229.567	68.590	216725.897	2857391.712	18.170
03 XPS 16cm Ins WWR15	246.836	60.493	305052.086	4021915.776	13.670
01 RW 12cm Ins WWR10	273.047	61.945	20432.736	313301.952	20.830
02 EPS 20cm Ins WWR15	239.814	62.621	181071.420	6291344.240	15.330
02 XPS 12cm Ins WWR15	231.788	68.078	228789.065	3016436.832	22.830
02 EPS 16cm Ins WWR20	224.815	70.183	137219.376	4767700.672	18.830
04 EPS 20cm Ins WWR20	251.423	68.263	35650.132	1062777.520	17.500
04 XPS 12cm Ins WWR10	261.287	64.005	61979.299	1579677.523	23.330
03 CG 8cm Ins WWR10	254.872	67.928	0.000	817309.440	32.330
01 GW 8cm Ins WWR10	257.010	67.954	6356.851	163461.888	31.830
04 XPS 8cm Ins WWR10	243.111	70.456	41319.533	1053118.349	40.000
03 RW 16cm Ins WWR10	282.670	58.444	63568.512	1017096.192	18.830
02 XPS 16cm Ins WWR10	250.595	60.207	325107.533	4286333.952	19.170
03 GW 12cm Ins WWR15	259.877	66.278	57516.804	1192941.120	22.670
02 RW 12cm Ins WWR10	257.010	67.769	47676.384	762822.144	29.830

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
01 GW 12cm Ins WWR10	280.531	61.947	9535.277	245192.832	20.830
01 XPS 12cm Ins WWR20	253.324	68.590	55089.544	1404077.086	18.170
01 XPS 16cm Ins WWR15	276.932	60.493	77541.173	1976305.789	13.670
01 RW 12cm Ins WWR15	267.903	66.276	19172.268	293974.776	22.670
03 EPS 20cm Ins WWR20	237.169	67.030	171524.220	5959625.840	14.670
04 XPS 12cm Ins WWR15	256.868	68.078	58155.880	1482229.342	22.830
03 XPS 20cm Ins WWR10	269.840	53.408	406384.416	5357917.440	8.830
03 CG 12cm Ins WWR10	282.670	61.896	0.000	1225964.160	21.000
03 RW 16cm Ins WWR15	276.932	63.243	59647.056	954352.896	16.500
03 XPS 16cm Ins WWR20	243.821	66.335	288967.862	3809855.616	14.170
02 XPS 16cm Ins WWR15	246.836	64.789	305052.086	4021915.776	19.670
02 EPS 20cm Ins WWR20	237.169	68.263	171524.220	5959625.840	17.500
04 XPS 16cm Ins WWR10	282.670	60.207	82639.066	2106236.698	19.170
01 GW 12cm Ins WWR15	274.925	66.278	8947.058	230067.216	22.670
01 RW 16cm Ins WWR10	298.707	58.444	27243.648	417735.936	18.830
03 GW 16cm Ins WWR10	291.223	58.447	81730.944	1695160.320	18.830
02 GW 12cm Ins WWR10	264.494	67.761	61298.208	1271370.240	29.830
04 RW 12cm Ins WWR10	273.047	67.769	20432.736	313301.952	29.830
03 CG 12cm Ins WWR15	276.932	66.234	0.000	1150336.080	22.000
02 RW 16cm Ins WWR10	282.670	63.462	63568.512	1017096.192	22.670
01 XPS 20cm Ins WWR10	307.260	53.408	103298.832	2632795.872	8.830
03 XPS 20cm Ins WWR15	264.893	58.846	381315.108	5027394.720	11.170
01 CG 8cm Ins WWR10	270.909	67.928	46616.909	817309.440	32.330

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
01 CG 12cm Ins WWR10	288.015	61.896	69925.363	1225964.160	21.000
01 XPS 16cm Ins WWR20	272.330	66.335	73452.725	1872102.781	14.170
04 XPS 16cm Ins WWR15	276.932	64.789	77541.173	1976305.789	19.670
01 GW 16cm Ins WWR10	307.260	58.447	12713.702	326923.776	18.830
01 RW 16cm Ins WWR15	291.979	63.243	25563.024	391966.368	16.500
03 GW 16cm Ins WWR15	284.957	63.245	76689.072	1590588.160	16.500
02 XPS 20cm Ins WWR10	269.840	57.691	406384.416	5357917.440	18.670
03 RW 16cm Ins WWR20	272.330	68.797	56502.096	904033.536	18.170
04 GW 12cm Ins WWR10	280.531	67.761	9535.277	245192.832	29.830
02 XPS 16cm Ins WWR20	243.821	70.177	288967.862	3809855.616	18.830
02 RW 16cm Ins WWR15	276.932	67.642	59647.056	954352.896	22.670
03 RW 20cm Ins WWR10	312.605	56.151	79460.640	1271370.240	13.670
01 CG 12cm Ins WWR15	281.947	66.234	65611.762	1150336.080	22.000
01 XPS 20cm Ins WWR15	300.005	58.846	96926.466	2470382.236	11.170
01 GW 16cm Ins WWR15	300.005	63.245	11929.411	306756.288	16.500
04 RW 16cm Ins WWR10	298.707	63.462	27243.648	417735.936	22.670
02 GW 16cm Ins WWR10	291.223	63.416	81730.944	1695160.320	22.670
02 XPS 20cm Ins WWR15	264.893	62.609	381315.108	5027394.720	15.670
03 XPS 20cm Ins WWR20	260.926	64.885	361209.828	4762319.520	12.170
03 CG 16cm Ins WWR10	314.744	58.392	0.000	1634618.880	19.000
04 XPS 20cm Ins WWR10	307.260	57.691	103298.832	2632795.872	18.670
04 XPS 16cm Ins WWR20	272.330	70.177	73452.725	1872102.781	18.830
01 RW 16cm Ins WWR20	286.584	68.797	24215.184	371299.488	18.170

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
03 RW 20cm Ins WWR15	305.021	61.251	74558.820	1192941.120	13.830
03 GW 16cm Ins WWR20	279.932	68.799	72645.552	1506722.560	18.170
02 CG 12cm Ins WWR10	282.670	69.460	0.000	1225964.160	34.500
04 RW 16cm Ins WWR15	291.979	67.642	25563.024	391966.368	22.670
02 GW 16cm Ins WWR15	284.957	67.602	76689.072	1590588.160	22.670
01 RW 20cm Ins WWR10	328.642	56.151	34054.560	522169.920	13.670
04 GW 16cm Ins WWR10	307.260	63.416	12713.702	326923.776	22.670
03 CG 16cm Ins WWR15	307.027	63.196	0.000	1533781.440	16.500
04 XPS 20cm Ins WWR15	300.005	62.609	96926.466	2470382.236	15.670
01 XPS 20cm Ins WWR20	294.186	64.885	91815.906	2340128.476	12.170
01 GW 16cm Ins WWR20	294.186	68.799	11300.419	290582.208	18.170
02 RW 20cm Ins WWR10	312.605	60.604	79460.640	1271370.240	19.170
03 GW 20cm Ins WWR10	323.297	56.155	102163.680	2118950.400	13.670
04 GW 16cm Ins WWR15	300.005	67.602	11929.411	306756.288	22.670
02 XPS 20cm Ins WWR20	260.926	68.256	361209.828	4762319.520	17.500
01 RW 20cm Ins WWR15	320.068	61.251	31953.780	489957.960	13.830
04 CG 12cm Ins WWR10	288.015	69.460	69925.363	1225964.160	34.500
01 GW 20cm Ins WWR10	339.334	56.155	15892.128	408654.720	13.670
03 RW 20cm Ins WWR20	298.938	67.033	70627.620	1130041.920	14.670
02 RW 20cm Ins WWR15	305.021	65.149	74558.820	1192941.120	20.330
03 GW 20cm Ins WWR15	315.053	61.253	95861.340	1988235.200	13.830
03 CG 16cm Ins WWR20	300.838	68.755	0.000	1452911.040	18.170
04 XPS 20cm Ins WWR20	294.186	68.256	91815.906	2340128.476	17.500

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
04 RW 20cm Ins WWR10	328.642	60.604	34054.560	522169.920	19.170
01 GW 20cm Ins WWR15	330.100	61.253	14911.764	383445.360	13.830
02 CG 16cm Ins WWR10	314.744	64.911	0.000	1634618.880	25.500
01 CG 16cm Ins WWR10	330.781	58.392	93233.818	1634618.880	19.000
01 RW 20cm Ins WWR20	313.192	67.033	30268.980	464124.360	14.670
02 GW 20cm Ins WWR10	323.297	60.586	102163.680	2118950.400	19.170
04 RW 20cm Ins WWR15	320.068	65.149	31953.780	489957.960	20.330
02 RW 20cm Ins WWR20	298.938	70.517	70627.620	1130041.920	19.000
02 CG 16cm Ins WWR15	307.027	68.923	0.000	1533781.440	22.670
03 GW 20cm Ins WWR20	308.441	67.034	90806.940	1883403.200	14.670
01 CG 16cm Ins WWR15	322.075	63.196	87482.349	1533781.440	16.500
04 GW 20cm Ins WWR10	339.334	60.586	15892.128	408654.720	19.170
02 GW 20cm Ins WWR15	315.053	65.154	95861.340	1988235.200	20.000
01 GW 20cm Ins WWR20	322.695	67.034	14125.524	363227.760	14.670
04 GW 20cm Ins WWR15	330.100	65.154	14911.764	383445.360	20.000
04 RW 20cm Ins WWR20	313.192	70.517	30268.980	464124.360	19.000
03 CG 20cm Ins WWR10	355.371	56.113	0.000	2043273.600	14.330
01 CG 16cm Ins WWR20	315.093	68.755	82869.741	1452911.040	18.170
02 GW 20cm Ins WWR20	308.441	70.533	90806.940	1883403.200	19.000
03 CG 20cm Ins WWR15	345.148	61.219	0.000	1917226.800	14.000
04 GW 20cm Ins WWR20	322.695	70.533	14125.524	363227.760	19.000
04 CG 16cm Ins WWR10	330.781	64.911	93233.818	1634618.880	25.500
04 CG 16cm Ins WWR15	322.075	68.923	87482.349	1533781.440	22.670

Table F.1 (continued) : Alternatives beyond cost optimal level.

	Investment Cost [TL/m2]	Primary Energy Use for Heating and Cooling [kWh/m2]	Embodied Carbon [kgCO2]	Embodied Energy [Mj]	Thermal Comfort (Category III - Unmet) [hr]
03 CG 20cm Ins WWR20	336.949	67.007	0.000	1816138.800	15.000
02 CG 20cm Ins WWR10	355.371	61.885	0.000	2043273.600	19.670
02 CG 20cm Ins WWR15	345.148	66.293	0.000	1917226.800	22.670
01 CG 20cm Ins WWR10	371.408	56.113	116542.272	2043273.600	14.330
01 CG 20cm Ins WWR15	360.196	61.219	109352.936	1917226.800	14.000
01 CG 20cm Ins WWR20	351.204	67.007	103587.176	1816138.800	15.000
04 CG 20cm Ins WWR10	371.408	61.885	116542.272	2043273.600	19.670
04 CG 20cm Ins WWR15	360.196	66.293	109352.936	1917226.800	22.670

Table F.2 : Normalized performance values of alternatives.

	NORMALIZED PERFORMANCE LEVELS				
	CRITERIA 1	CRITERIA 2	CRITERIA 3		CRITERIA 4
	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
01 EPS 12cm Ins WWR10	0.147	0.498	0.059	0.085	0.385
01 EPS 16cm Ins WWR10	0.213	0.294	0.079	0.121	0.326
03 EPS 12cm Ins WWR10	0.047	0.498	0.285	0.590	0.385
03 XPS 8cm Ins WWR10	0.067	0.588	0.400	0.303	0.465
04 EPS 16cm Ins WWR10	0.213	0.398	0.079	0.121	0.332
04 EPS 12cm Ins WWR10	0.147	0.619	0.059	0.085	0.465
03 EPS 8cm Ins WWR10	0.000	0.850	0.190	0.385	0.733
01 EPS 20cm Ins WWR10	0.300	0.160	0.099	0.158	0.160
03 EPS 16cm Ins WWR10	0.113	0.294	0.380	0.795	0.326
02 EPS 12cm Ins WWR10	0.047	0.619	0.285	0.590	0.465
03 XPS 12cm Ins WWR10	0.147	0.284	0.600	0.466	0.326
01 EPS 12cm Ins WWR15	0.129	0.751	0.056	0.078	0.444
01 EPS 8cm Ins WWR10	0.100	0.850	0.039	0.048	0.733
01 EPS 16cm Ins WWR15	0.192	0.574	0.074	0.112	0.246
03 EPS 12cm Ins WWR15	0.036	0.751	0.267	0.552	0.444
04 EPS 20cm Ins WWR10	0.300	0.251	0.099	0.158	0.316
02 EPS 16cm Ins WWR10	0.113	0.398	0.380	0.795	0.332
02 EPS 8cm Ins WWR10	0.000	0.996	0.190	0.385	0.995
03 XPS 8cm Ins WWR15	0.054	0.827	0.375	0.282	0.449
01 XPS 8cm Ins WWR10	0.200	0.588	0.102	0.136	0.465
04 EPS 12cm Ins WWR15	0.129	0.857	0.056	0.078	0.449
04 EPS 16cm Ins WWR15	0.192	0.665	0.074	0.112	0.348

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
02 EPS 12cm Ins WWR15	0.036	0.857	0.267	0.552	0.449
03 EPS 16cm Ins WWR15	0.098	0.574	0.356	0.744	0.246
04 EPS 8cm Ins WWR10	0.100	0.996	0.039	0.048	0.995
01 EPS 20cm Ins WWR15	0.273	0.458	0.093	0.147	0.160
01 XPS 12cm Ins WWR10	0.313	0.284	0.153	0.216	0.326
03 RW 8cm Ins WWR10	0.153	0.849	0.078	0.053	0.738
03 XPS 12cm Ins WWR15	0.129	0.563	0.563	0.436	0.262
03 EPS 20cm Ins WWR10	0.200	0.160	0.475	1.000	0.160
03 RW 12cm Ins WWR10	0.287	0.498	0.117	0.092	0.385
04 EPS 20cm Ins WWR15	0.273	0.538	0.093	0.147	0.209
02 EPS 16cm Ins WWR15	0.098	0.665	0.356	0.744	0.348
01 XPS 8cm Ins WWR15	0.179	0.827	0.095	0.126	0.449
03 XPS 16cm Ins WWR10	0.247	0.111	0.800	0.630	0.123
01 EPS 16cm Ins WWR20	0.175	0.898	0.070	0.105	0.300
02 EPS 20cm Ins WWR10	0.200	0.251	0.475	1.000	0.316
03 GW 8cm Ins WWR10	0.187	0.849	0.101	0.105	0.738
02 XPS 12cm Ins WWR10	0.147	0.619	0.600	0.466	0.465
02 XPS 8cm Ins WWR10	0.067	0.995	0.400	0.303	1.000
01 XPS 12cm Ins WWR15	0.286	0.563	0.143	0.202	0.262
04 EPS 16cm Ins WWR20	0.175	0.980	0.070	0.105	0.321
03 EPS 20cm Ins WWR15	0.179	0.458	0.446	0.937	0.160
03 RW 12cm Ins WWR15	0.261	0.751	0.110	0.084	0.444
03 EPS 16cm Ins WWR20	0.086	0.898	0.338	0.704	0.300

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
03 GW 12cm Ins WWR10	0.333	0.499	0.151	0.169	0.385
01 RW 8cm Ins WWR10	0.253	0.849	0.034	0.007	0.738
01 EPS 20cm Ins WWR20	0.252	0.795	0.088	0.137	0.187
01 XPS 16cm Ins WWR10	0.447	0.111	0.203	0.297	0.123
03 XPS 12cm Ins WWR20	0.116	0.887	0.533	0.412	0.300
03 XPS 16cm Ins WWR15	0.223	0.414	0.751	0.590	0.155
01 RW 12cm Ins WWR10	0.387	0.498	0.050	0.023	0.385
02 EPS 20cm Ins WWR15	0.179	0.538	0.446	0.937	0.209
02 XPS 12cm Ins WWR15	0.129	0.857	0.563	0.436	0.449
02 EPS 16cm Ins WWR20	0.086	0.980	0.338	0.704	0.321
04 EPS 20cm Ins WWR20	0.252	0.867	0.088	0.137	0.278
04 XPS 12cm Ins WWR10	0.313	0.619	0.153	0.216	0.465
03 CG 8cm Ins WWR10	0.273	0.848	0.000	0.100	0.754
01 GW 8cm Ins WWR10	0.287	0.849	0.016	0.000	0.738
04 XPS 8cm Ins WWR10	0.200	0.995	0.102	0.136	1.000
03 RW 16cm Ins WWR10	0.447	0.294	0.156	0.130	0.321
02 XPS 16cm Ins WWR10	0.247	0.397	0.800	0.630	0.332
03 GW 12cm Ins WWR15	0.305	0.751	0.142	0.157	0.444
02 RW 12cm Ins WWR10	0.287	0.839	0.117	0.092	0.674
01 GW 12cm Ins WWR10	0.433	0.499	0.023	0.012	0.385
01 XPS 12cm Ins WWR20	0.264	0.887	0.136	0.190	0.300
01 XPS 16cm Ins WWR15	0.411	0.414	0.191	0.277	0.155
01 RW 12cm Ins WWR15	0.355	0.751	0.047	0.020	0.444

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
03 EPS 20cm Ins WWR20	0.163	0.795	0.422	0.886	0.187
04 XPS 12cm Ins WWR15	0.286	0.857	0.143	0.202	0.449
03 XPS 20cm Ins WWR10	0.367	0.000	1.000	0.794	0.000
03 CG 12cm Ins WWR10	0.447	0.496	0.000	0.162	0.390
03 RW 16cm Ins WWR15	0.411	0.574	0.147	0.121	0.246
03 XPS 16cm Ins WWR20	0.204	0.755	0.711	0.557	0.171
02 XPS 16cm Ins WWR15	0.223	0.665	0.751	0.590	0.348
02 EPS 20cm Ins WWR20	0.163	0.867	0.422	0.886	0.278
04 XPS 16cm Ins WWR10	0.447	0.397	0.203	0.297	0.332
01 GW 12cm Ins WWR15	0.398	0.751	0.022	0.010	0.444
01 RW 16cm Ins WWR10	0.547	0.294	0.067	0.039	0.321
03 GW 16cm Ins WWR10	0.500	0.294	0.201	0.234	0.321
02 GW 12cm Ins WWR10	0.333	0.838	0.151	0.169	0.674
04 RW 12cm Ins WWR10	0.387	0.839	0.050	0.023	0.674
03 CG 12cm Ins WWR15	0.411	0.749	0.000	0.151	0.423
02 RW 16cm Ins WWR10	0.447	0.587	0.156	0.130	0.444
01 XPS 20cm Ins WWR10	0.600	0.000	0.254	0.377	0.000
03 XPS 20cm Ins WWR15	0.336	0.318	0.938	0.744	0.075
01 CG 8cm Ins WWR10	0.373	0.848	0.115	0.100	0.754
01 CG 12cm Ins WWR10	0.480	0.496	0.172	0.162	0.390
01 XPS 16cm Ins WWR20	0.382	0.755	0.181	0.261	0.171
04 XPS 16cm Ins WWR15	0.411	0.665	0.191	0.277	0.348
01 GW 16cm Ins WWR10	0.600	0.294	0.031	0.025	0.321

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
01 RW 16cm Ins WWR15	0.505	0.574	0.063	0.035	0.246
03 GW 16cm Ins WWR15	0.461	0.574	0.189	0.218	0.246
02 XPS 20cm Ins WWR10	0.367	0.250	1.000	0.794	0.316
03 RW 16cm Ins WWR20	0.382	0.899	0.139	0.113	0.300
04 GW 12cm Ins WWR10	0.433	0.838	0.023	0.012	0.674
02 XPS 16cm Ins WWR20	0.204	0.979	0.711	0.557	0.321
02 RW 16cm Ins WWR15	0.411	0.831	0.147	0.121	0.444
03 RW 20cm Ins WWR10	0.633	0.160	0.196	0.169	0.155
01 CG 12cm Ins WWR15	0.442	0.749	0.161	0.151	0.423
01 XPS 20cm Ins WWR15	0.555	0.318	0.239	0.353	0.075
01 GW 16cm Ins WWR15	0.555	0.574	0.029	0.022	0.246
04 RW 16cm Ins WWR10	0.547	0.587	0.067	0.039	0.444
02 GW 16cm Ins WWR10	0.500	0.584	0.201	0.234	0.444
02 XPS 20cm Ins WWR15	0.336	0.537	0.938	0.744	0.219
03 XPS 20cm Ins WWR20	0.311	0.670	0.889	0.703	0.107
03 CG 16cm Ins WWR10	0.647	0.291	0.000	0.225	0.326
04 XPS 20cm Ins WWR10	0.600	0.250	0.254	0.377	0.316
04 XPS 16cm Ins WWR20	0.382	0.979	0.181	0.261	0.321
01 RW 16cm Ins WWR20	0.471	0.899	0.060	0.032	0.300
03 RW 20cm Ins WWR15	0.586	0.458	0.183	0.157	0.160
03 GW 16cm Ins WWR20	0.430	0.899	0.179	0.205	0.300
02 CG 12cm Ins WWR10	0.447	0.937	0.000	0.162	0.824
04 RW 16cm Ins WWR15	0.505	0.831	0.063	0.035	0.444

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
02 GW 16cm Ins WWR15	0.461	0.829	0.189	0.218	0.444
01 RW 20cm Ins WWR10	0.733	0.160	0.084	0.055	0.155
04 GW 16cm Ins WWR10	0.600	0.584	0.031	0.025	0.444
03 CG 16cm Ins WWR15	0.599	0.572	0.000	0.209	0.246
04 XPS 20cm Ins WWR15	0.555	0.537	0.239	0.353	0.219
01 XPS 20cm Ins WWR20	0.518	0.670	0.226	0.333	0.107
01 GW 16cm Ins WWR20	0.518	0.899	0.028	0.019	0.300
02 RW 20cm Ins WWR10	0.633	0.420	0.196	0.169	0.332
03 GW 20cm Ins WWR10	0.700	0.160	0.251	0.299	0.155
04 GW 16cm Ins WWR15	0.555	0.829	0.029	0.022	0.444
02 XPS 20cm Ins WWR20	0.311	0.867	0.889	0.703	0.278
01 RW 20cm Ins WWR15	0.680	0.458	0.079	0.050	0.160
04 CG 12cm Ins WWR10	0.480	0.937	0.172	0.162	0.824
01 GW 20cm Ins WWR10	0.800	0.160	0.039	0.037	0.155
03 RW 20cm Ins WWR20	0.548	0.796	0.174	0.148	0.187
02 RW 20cm Ins WWR15	0.586	0.686	0.183	0.157	0.369
03 GW 20cm Ins WWR15	0.649	0.458	0.236	0.279	0.160
03 CG 16cm Ins WWR20	0.560	0.896	0.000	0.197	0.300
04 XPS 20cm Ins WWR20	0.518	0.867	0.226	0.333	0.278
04 RW 20cm Ins WWR10	0.733	0.420	0.084	0.055	0.332
01 GW 20cm Ins WWR15	0.742	0.458	0.037	0.034	0.160
02 CG 16cm Ins WWR10	0.647	0.672	0.000	0.225	0.535
01 CG 16cm Ins WWR10	0.747	0.291	0.229	0.225	0.326

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
01 RW 20cm Ins WWR20	0.637	0.796	0.074	0.046	0.187
02 GW 20cm Ins WWR10	0.700	0.419	0.251	0.299	0.332
04 RW 20cm Ins WWR15	0.680	0.686	0.079	0.050	0.369
02 RW 20cm Ins WWR20	0.548	0.999	0.174	0.148	0.326
02 CG 16cm Ins WWR15	0.599	0.906	0.000	0.209	0.444
03 GW 20cm Ins WWR20	0.607	0.796	0.223	0.263	0.187
01 CG 16cm Ins WWR15	0.692	0.572	0.215	0.209	0.246
04 GW 20cm Ins WWR10	0.800	0.419	0.039	0.037	0.332
02 GW 20cm Ins WWR15	0.649	0.686	0.236	0.279	0.358
01 GW 20cm Ins WWR20	0.696	0.796	0.035	0.031	0.187
04 GW 20cm Ins WWR15	0.742	0.686	0.037	0.034	0.358
04 RW 20cm Ins WWR20	0.637	0.999	0.074	0.046	0.326
03 CG 20cm Ins WWR10	0.900	0.158	0.000	0.287	0.176
01 CG 16cm Ins WWR20	0.649	0.896	0.204	0.197	0.300
02 GW 20cm Ins WWR20	0.607	1.000	0.223	0.263	0.326
03 CG 20cm Ins WWR15	0.836	0.456	0.000	0.268	0.166
04 GW 20cm Ins WWR20	0.696	1.000	0.035	0.031	0.326
04 CG 16cm Ins WWR10	0.747	0.672	0.229	0.225	0.535
04 CG 16cm Ins WWR15	0.692	0.906	0.215	0.209	0.444
03 CG 20cm Ins WWR20	0.785	0.794	0.000	0.253	0.198
02 CG 20cm Ins WWR10	0.900	0.495	0.000	0.287	0.348
02 CG 20cm Ins WWR15	0.836	0.752	0.000	0.268	0.444
01 CG 20cm Ins WWR10	1.000	0.158	0.287	0.287	0.176

Table F.2 (continued) : Normalized performance values of alternatives.

	Investment Cost	Primary Energy Use for Heating and Cooling	Embodied Carbon	Embodied Energy	Thermal Comfort (Category III - Unmet)
01 CG 20cm Ins WWR15	0.930	0.456	0.269	0.268	0.166
01 CG 20cm Ins WWR20	0.874	0.794	0.255	0.253	0.198
04 CG 20cm Ins WWR10	1.000	0.495	0.287	0.287	0.348
04 CG 20cm Ins WWR15	0.930	0.752	0.269	0.268	0.444

Table F.3 : EWM and AHP scores of alternatives

Order of alternatives based on EWM score	EWM Score	Order of alternatives based on AHPO score	AHP Score
01 EPS 12cm Ins WWR10	0.192	01 EPS 16cm Ins WWR10	0.390
01 EPS 16cm Ins WWR10	0.195	01 EPS 12cm Ins WWR10	0.358
03 EPS 12cm Ins WWR10	0.198	03 EPS 12cm Ins WWR10	0.324
03 XPS 8cm Ins WWR10	0.212	01 EPS 20cm Ins WWR10	0.291
04 EPS 16cm Ins WWR10	0.215	04 EPS 16cm Ins WWR10	0.653
04 EPS 12cm Ins WWR10	0.216	03 EPS 16cm Ins WWR10	0.573
03 EPS 8cm Ins WWR10	0.216	03 XPS 8cm Ins WWR10	0.233
01 EPS 20cm Ins WWR10	0.221	04 EPS 12cm Ins WWR10	0.281
03 EPS 16cm Ins WWR10	0.222	01 EPS 16cm Ins WWR15	0.465
02 EPS 12cm Ins WWR10	0.222	03 XPS 12cm Ins WWR10	0.429
03 XPS 12cm Ins WWR10	0.229	02 EPS 12cm Ins WWR10	0.497
01 EPS 12cm Ins WWR15	0.230	01 EPS 12cm Ins WWR15	0.482
01 EPS 8cm Ins WWR10	0.231	04 EPS 20cm Ins WWR10	0.431
01 EPS 16cm Ins WWR15	0.234	02 EPS 16cm Ins WWR10	0.462
03 EPS 12cm Ins WWR15	0.236	03 EPS 12cm Ins WWR15	0.310
04 EPS 20cm Ins WWR10	0.240	03 EPS 8cm Ins WWR10	0.263
02 EPS 16cm Ins WWR10	0.242	01 EPS 20cm Ins WWR15	0.287
02 EPS 8cm Ins WWR10	0.246	03 EPS 16cm Ins WWR15	0.253
03 XPS 8cm Ins WWR15	0.247	04 EPS 16cm Ins WWR15	0.538
01 XPS 8cm Ins WWR10	0.248	03 XPS 8cm Ins WWR15	0.463
04 EPS 12cm Ins WWR15	0.250	03 EPS 20cm Ins WWR10	0.218
04 EPS 16cm Ins WWR15	0.252	01 XPS 8cm Ins WWR10	0.245
02 EPS 12cm Ins WWR15	0.256	04 EPS 12cm Ins WWR15	0.397
03 EPS 16cm Ins WWR15	0.260	01 EPS 8cm Ins WWR10	0.356
04 EPS 8cm Ins WWR10	0.261	03 XPS 12cm Ins WWR15	0.422
01 EPS 20cm Ins WWR15	0.262	01 XPS 12cm Ins WWR10	0.399
01 XPS 12cm Ins WWR10	0.263	02 EPS 12cm Ins WWR15	0.427
03 RW 8cm Ins WWR10	0.264	03 XPS 16cm Ins WWR10	0.397
03 XPS 12cm Ins WWR15	0.266	04 EPS 20cm Ins WWR15	0.362
03 EPS 20cm Ins WWR10	0.269	02 EPS 16cm Ins WWR15	0.395
03 RW 12cm Ins WWR10	0.276	03 RW 12cm Ins WWR10	0.265
04 EPS 20cm Ins WWR15	0.277	01 EPS 16cm Ins WWR20	0.239
02 EPS 16cm Ins WWR15	0.278	02 EPS 20cm Ins WWR10	0.361
01 XPS 8cm Ins WWR15	0.280	01 XPS 8cm Ins WWR15	0.330
03 XPS 16cm Ins WWR10	0.282	01 XPS 12cm Ins WWR15	0.545
01 EPS 16cm Ins WWR20	0.286	03 RW 8cm Ins WWR10	0.561
02 EPS 20cm Ins WWR10	0.288	02 EPS 8cm Ins WWR10	0.492
03 GW 8cm Ins WWR10	0.289	03 EPS 20cm Ins WWR15	0.529
02 XPS 12cm Ins WWR10	0.294	01 XPS 16cm Ins WWR10	0.666
02 XPS 8cm Ins WWR10	0.294	04 EPS 16cm Ins WWR20	0.591
01 XPS 12cm Ins WWR15	0.298	01 EPS 20cm Ins WWR20	0.273
04 EPS 16cm Ins WWR20	0.301	02 XPS 12cm Ins WWR10	0.318

Table F.3 (continued) : EWM and AHP scores of alternatives.

Order of alternatives based on EWM score	EWM Score	Order of alternatives based on AHPO score	AHP Score
03 EPS 20cm Ins WWR15	0.306	03 XPS 16cm Ins WWR15	0.492
03 RW 12cm Ins WWR15	0.309	03 EPS 16cm Ins WWR20	0.457
03 EPS 16cm Ins WWR20	0.310	04 EPS 8cm Ins WWR10	0.522
03 GW 12cm Ins WWR10	0.312	02 EPS 20cm Ins WWR15	0.507
01 RW 8cm Ins WWR10	0.313	03 XPS 12cm Ins WWR20	0.423
01 EPS 20cm Ins WWR20	0.313	03 GW 12cm Ins WWR10	0.389
01 XPS 16cm Ins WWR10	0.315	03 RW 12cm Ins WWR15	0.650
03 XPS 12cm Ins WWR20	0.316	03 GW 8cm Ins WWR10	0.731
03 XPS 16cm Ins WWR15	0.319	04 EPS 20cm Ins WWR20	0.220
01 RW 12cm Ins WWR10	0.321	01 RW 12cm Ins WWR10	0.226
02 EPS 20cm Ins WWR15	0.322	02 EPS 16cm Ins WWR20	0.348
02 XPS 12cm Ins WWR15	0.324	03 RW 16cm Ins WWR10	0.304
02 EPS 16cm Ins WWR20	0.325	02 XPS 12cm Ins WWR15	0.371
04 EPS 20cm Ins WWR20	0.327	03 XPS 20cm Ins WWR10	0.339
04 XPS 12cm Ins WWR10	0.328	01 XPS 16cm Ins WWR15	0.451
03 CG 8cm Ins WWR10	0.329	04 XPS 12cm Ins WWR10	0.481
01 GW 8cm Ins WWR10	0.329	02 XPS 16cm Ins WWR10	0.337
04 XPS 8cm Ins WWR10	0.329	01 RW 8cm Ins WWR10	0.292
03 RW 16cm Ins WWR10	0.333	02 XPS 8cm Ins WWR10	0.317
02 XPS 16cm Ins WWR10	0.338	01 XPS 12cm Ins WWR20	0.285
03 GW 12cm Ins WWR15	0.342	03 EPS 20cm Ins WWR20	0.552
02 RW 12cm Ins WWR10	0.343	01 GW 12cm Ins WWR10	0.481
01 GW 12cm Ins WWR10	0.344	03 GW 12cm Ins WWR15	0.252
01 XPS 12cm Ins WWR20	0.346	03 XPS 16cm Ins WWR20	0.277
01 XPS 16cm Ins WWR15	0.350	03 RW 16cm Ins WWR15	0.420
01 RW 12cm Ins WWR15	0.351	01 GW 8cm Ins WWR10	0.382
03 EPS 20cm Ins WWR20	0.355	01 RW 12cm Ins WWR15	0.444
04 XPS 12cm Ins WWR15	0.356	03 CG 8cm Ins WWR10	0.422
03 XPS 20cm Ins WWR10	0.358	04 XPS 12cm Ins WWR15	0.281
03 CG 12cm Ins WWR10	0.361	03 CG 12cm Ins WWR10	0.246
03 RW 16cm Ins WWR15	0.364	02 EPS 20cm Ins WWR20	0.464
03 XPS 16cm Ins WWR20	0.367	01 XPS 20cm Ins WWR10	0.487
02 XPS 16cm Ins WWR15	0.368	02 RW 12cm Ins WWR10	0.422
02 EPS 20cm Ins WWR20	0.369	02 XPS 16cm Ins WWR15	0.462
04 XPS 16cm Ins WWR10	0.371	04 XPS 16cm Ins WWR10	0.328
01 GW 12cm Ins WWR15	0.372	01 RW 16cm Ins WWR10	0.362
01 RW 16cm Ins WWR10	0.374	03 XPS 20cm Ins WWR15	0.255
03 GW 16cm Ins WWR10	0.375	03 GW 16cm Ins WWR10	0.249
02 GW 12cm Ins WWR10	0.379	04 XPS 8cm Ins WWR10	0.474
04 RW 12cm Ins WWR10	0.387	01 GW 12cm Ins WWR15	0.445
03 CG 12cm Ins WWR15	0.389	01 XPS 16cm Ins WWR20	0.393

Table F.3 (continued) : EWM and AHP scores of alternatives.

Order of alternatives based on EWM score	EWM Score	Order of alternatives based on AHPO score	AHP Score
02 RW 16cm Ins WWR10	0.390	03 CG 12cm Ins WWR15	0.424
01 XPS 20cm Ins WWR10	0.390	01 RW 16cm Ins WWR15	0.303
03 XPS 20cm Ins WWR15	0.392	03 GW 16cm Ins WWR15	0.277
01 CG 8cm Ins WWR10	0.394	02 RW 16cm Ins WWR10	0.552
01 CG 12cm Ins WWR10	0.395	01 GW 16cm Ins WWR10	0.627
01 XPS 16cm Ins WWR20	0.396	01 CG 12cm Ins WWR10	0.517
04 XPS 16cm Ins WWR15	0.399	04 XPS 16cm Ins WWR15	0.551
01 GW 16cm Ins WWR10	0.399	02 GW 12cm Ins WWR10	0.566
01 RW 16cm Ins WWR15	0.402	01 XPS 20cm Ins WWR15	0.581
03 GW 16cm Ins WWR15	0.404	03 RW 20cm Ins WWR10	0.450
02 XPS 20cm Ins WWR10	0.408	03 RW 16cm Ins WWR20	0.419
03 RW 16cm Ins WWR20	0.409	02 XPS 20cm Ins WWR10	0.409
04 GW 12cm Ins WWR10	0.410	02 XPS 16cm Ins WWR20	0.379
02 XPS 16cm Ins WWR20	0.411	04 RW 12cm Ins WWR10	0.262
02 RW 16cm Ins WWR15	0.414	01 GW 16cm Ins WWR15	0.268
03 RW 20cm Ins WWR10	0.417	03 XPS 20cm Ins WWR20	0.383
01 CG 12cm Ins WWR15	0.420	02 RW 16cm Ins WWR15	0.341
01 XPS 20cm Ins WWR15	0.422	01 CG 8cm Ins WWR10	0.404
01 GW 16cm Ins WWR15	0.426	01 CG 12cm Ins WWR15	0.374
04 RW 16cm Ins WWR10	0.430	02 XPS 20cm Ins WWR15	0.670
02 GW 16cm Ins WWR10	0.432	03 RW 20cm Ins WWR15	0.745
02 XPS 20cm Ins WWR15	0.435	04 GW 12cm Ins WWR10	0.699
03 XPS 20cm Ins WWR20	0.438	04 RW 16cm Ins WWR10	0.628
03 CG 16cm Ins WWR10	0.439	04 XPS 20cm Ins WWR10	0.326
04 XPS 20cm Ins WWR10	0.440	03 CG 16cm Ins WWR10	0.369
04 XPS 16cm Ins WWR20	0.440	04 XPS 16cm Ins WWR20	0.533
01 RW 16cm Ins WWR20	0.445	02 GW 16cm Ins WWR10	0.500
03 RW 20cm Ins WWR15	0.445	01 RW 20cm Ins WWR10	0.562
03 GW 16cm Ins WWR20	0.446	01 RW 16cm Ins WWR20	0.548
02 CG 12cm Ins WWR10	0.449	03 GW 16cm Ins WWR20	0.312
04 RW 16cm Ins WWR15	0.452	01 XPS 20cm Ins WWR20	0.279
02 GW 16cm Ins WWR15	0.454	04 XPS 20cm Ins WWR15	0.486
01 RW 20cm Ins WWR10	0.454	03 CG 16cm Ins WWR15	0.508
04 GW 16cm Ins WWR10	0.455	03 GW 20cm Ins WWR10	0.446
03 CG 16cm Ins WWR15	0.464	04 RW 16cm Ins WWR15	0.484
04 XPS 20cm Ins WWR15	0.465	02 GW 16cm Ins WWR15	0.427
01 XPS 20cm Ins WWR20	0.466	04 GW 16cm Ins WWR10	0.459
01 GW 16cm Ins WWR20	0.468	01 GW 16cm Ins WWR20	0.392
02 RW 20cm Ins WWR10	0.468	01 RW 20cm Ins WWR15	0.436
03 GW 20cm Ins WWR10	0.470	02 RW 20cm Ins WWR10	0.449
04 GW 16cm Ins WWR15	0.476	02 XPS 20cm Ins WWR20	0.383

Table F.3 (continued) : EWM and AHP scores of alternatives.

Order of alternatives based on EWM score	EWM Score	Order of alternatives based on AHPO score	AHP Score
02 XPS 20cm Ins WWR20	0.476	01 GW 20cm Ins WWR10	0.366
01 RW 20cm Ins WWR15	0.480	03 RW 20cm Ins WWR20	0.317
04 CG 12cm Ins WWR10	0.482	03 GW 20cm Ins WWR15	0.382
01 GW 20cm Ins WWR10	0.486	02 CG 12cm Ins WWR10	0.342
03 RW 20cm Ins WWR20	0.487	04 GW 16cm Ins WWR15	0.284
02 RW 20cm Ins WWR15	0.490	02 RW 20cm Ins WWR15	0.269
03 GW 20cm Ins WWR15	0.495	01 GW 20cm Ins WWR15	0.356
03 CG 16cm Ins WWR20	0.503	03 CG 16cm Ins WWR20	0.388
04 XPS 20cm Ins WWR20	0.505	04 XPS 20cm Ins WWR20	0.288
04 RW 20cm Ins WWR10	0.505	04 RW 20cm Ins WWR10	0.283
01 GW 20cm Ins WWR15	0.510	01 RW 20cm Ins WWR20	0.497
02 CG 16cm Ins WWR10	0.513	01 CG 16cm Ins WWR10	0.525
01 CG 16cm Ins WWR10	0.515	04 CG 12cm Ins WWR10	0.390
01 RW 20cm Ins WWR20	0.520	02 GW 20cm Ins WWR10	0.347
02 GW 20cm Ins WWR10	0.521	03 GW 20cm Ins WWR20	0.368
04 RW 20cm Ins WWR15	0.525	02 RW 20cm Ins WWR20	0.337
02 RW 20cm Ins WWR20	0.527	04 RW 20cm Ins WWR15	0.592
02 CG 16cm Ins WWR15	0.529	02 CG 16cm Ins WWR10	0.525
03 GW 20cm Ins WWR20	0.534	01 CG 16cm Ins WWR15	0.307
01 CG 16cm Ins WWR15	0.534	02 CG 16cm Ins WWR15	0.331
04 GW 20cm Ins WWR10	0.537	04 GW 20cm Ins WWR10	0.466
02 GW 20cm Ins WWR15	0.540	01 GW 20cm Ins WWR20	0.430
01 GW 20cm Ins WWR20	0.548	02 GW 20cm Ins WWR15	0.489
04 GW 20cm Ins WWR15	0.555	03 CG 20cm Ins WWR10	0.468
04 RW 20cm Ins WWR20	0.559	04 GW 20cm Ins WWR15	0.561
03 CG 20cm Ins WWR10	0.560	04 RW 20cm Ins WWR20	0.631
01 CG 16cm Ins WWR20	0.570	03 CG 20cm Ins WWR15	0.508
02 GW 20cm Ins WWR20	0.574	01 CG 16cm Ins WWR20	0.541
03 CG 20cm Ins WWR15	0.579	02 GW 20cm Ins WWR20	0.434
04 GW 20cm Ins WWR20	0.588	04 GW 20cm Ins WWR20	0.463
04 CG 16cm Ins WWR10	0.589	04 CG 16cm Ins WWR10	0.348
04 CG 16cm Ins WWR15	0.600	03 CG 20cm Ins WWR20	0.325
03 CG 20cm Ins WWR20	0.614	04 CG 16cm Ins WWR15	0.366
02 CG 20cm Ins WWR10	0.625	02 CG 20cm Ins WWR10	0.401
02 CG 20cm Ins WWR15	0.638	01 CG 20cm Ins WWR10	0.318
01 CG 20cm Ins WWR10	0.640	01 CG 20cm Ins WWR15	0.332
01 CG 20cm Ins WWR15	0.654	02 CG 20cm Ins WWR15	0.550
01 CG 20cm Ins WWR20	0.685	01 CG 20cm Ins WWR20	0.583
04 CG 20cm Ins WWR10	0.706	04 CG 20cm Ins WWR10	0.598
04 CG 20cm Ins WWR15	0.713	04 CG 20cm Ins WWR15	0.612

CURRICULUM VITAE

Name Surname : Burcu Çiğdem YILMAZ

Place and Date of Birth : Şişli, 1985

E-Mail : burcucigdemc@gmail.com

EDUCATION

- **B.Sc.** : 2008, Yıldız Technical University, Faculty of Architecture
- **M.Sc.** : 2010, Istanbul Technical University, Graduate School of Science Engineering and Technology, Building Physic MSc Program

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2016 - 2018 Bahçeşehir University – Part time lecturer
- 2015 – 2016 Ministry of Science, Industry and Technology – Research and Development Project – “An Integrated Building Element forThermal, Visual and Solar Control on Windows” – Project Owner
- 2015 – 2016 Ministry of Science, Industry and Technology – Research and Development Project – “Solar Wall System as an Industrial ” – Project Partner
- 2009 - 2012 EKOMİM Ecological Consultancy

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Yılmaz, B.Ç.,** Özgünler, S.A., 2018. Yüksek Performanslı Bina Tasarımında Isı Yalıtım Malzemesi Seçimi İçin Bir Yaklaşım.. *Tesisat Mühendisliği Dergisi*,165.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- Yılmaz, Y., **Çelik, B.**, Oral, G., 2013. Energy Efficiency Improvement and Life Cycle Cost Evaluation of a Detached House through a Passive Solar Refurbishment Series. CLIMA 2013 Energy Efficient, Smart and Healthy Buildings, June 15-18, Prag, Czech Republic.
- Günaydin, G., **Çelik, B.**, Manioğlu, G., Oral, G. 2013. Evaluation of Traditional Architecture within the Context of Climate Balanced Design Parameters: the Case of Gaziantep. VIII. International Sinan Symposium, April 25-26, Edirne, Turkey.
- **Çelik, B.**, Yılmaz, Z., Corgnati, S. 2011. Parametric Sensitivity Analysis of Buildings for Heating and Cooling Energy Demand Leading Energy Performance Certification. VI. Mediterranean Congress of Air Conditioning CLIMAMED, June 2-3, Madrid, Spain.
- **Çelik, B.**, Yilmaz, Z., Corgnati, S. 2011. Konut Binaları Enerji Sertifikasyonunda Isıtma ve Soğutma Enerji İhtiyacının Bina Parametrelerine Duyarlılık Analizi: BEP-TR Hesaplama Metodolojisi ile Değerlendirme. X. Ulusal Tesisat Mühendisliği Kongresi, April 13- 16, İzmir, Turkey.
- Bayraktar, M., **Çelik, B.**, Yılmaz, Z. 2010. Energy Performance and Comfort Level Evaluation of an Office Building in Istanbul through Facade Design and Lighting Control. X. Rehva World Congress CLIMA 2010, May 9-12, Antalya, Turkey.
- **Çelik, B.** 2010. Assumptions on The Boundry Conditions for Energy Certification of Existing Buildings: Influence of the Building Parameters on Energy Class (Master thesis). İstanbul Technical University, Graduate School of Science Engineering and Technology.