Development of a Preference-based Goal Attainment Tool For a Balanced & Optimal Outcome

A Model-Based Decision-Making Approach

MSc. Construction Management and Engineering

Himanshu Patel

Development of a Preference-based Goal Attainment Tool For a Balanced & Optimal Outcome: A Model-Based Decision-Making Approach

Graduation thesis

University	Delft University of Technology
Faculty	Civil Engineering and Geosciences (CiTG)
Curriculum	MSc Construction Management and Engineering

Author

Name	Himanshu Patel
Student number	5620554

Graduation committee

Chairman, TU Delft	Dr. H. M. (Henk) Jonkers
1st supervisor, TU Delft	Dr.ir. Pieter van Gelder
2nd supervisor, TU Delft	Ir. Hans (J.P.G) Ramler
3rd supervisor,TU Delft	Dmitry Zhilyaev

In partial fulfilment of the Master of Science in **Construction Management and Engineering**.

December 23, 2023

Preface

The journey of this master's thesis has been a big learning curve in my academic career. One of such is being a researcher as this process taught me how to approach a problem in a structured manner and address it. I began this process with many unknowns and a confidence which I accumulated from past experiences and some luck as it does not took long to realize that. Although, at many times when I find it hard to make it through, I realized that, when you try enough, there is always some luck to guide you through. As, I was lucky enough to find such an interesting topic which not only allowed me to look at any process from the lens of systems engineering but also let me explore the area of people's involvement in such systems. I never realized when I had a shift from the goal of finishing this thesis to getting involved with the process and beginning my professional career to learn and contribute in this area.

For making it possible, I extend my heartfelt gratitude to my graduation committee for their unwavering support throughout this journey: Prof. dr. Henk Jonkers, Dr.ir. Pieter van Gelder, Ir.Hans Ramler, and Dmitry Zhilyaev. A special thanks to Dmitry, my direct contact, for his endless guidance and patience in answering all my queries, no matter how stupid they seemed. I'm also grateful to Mr. Tim Jonathan and other stakeholders of the Co-Creation Center project for their valuable contributions to my thesis through interviews and the provision of essential information. Additionally, I'd like to express my appreciation to Ms. Sandra Schuchmann for her diligent organization of appointments and booking of meeting rooms, not only for this thesis but for other requests as well.

In this often lonely journey, I've been fortunate to ride a rollercoaster of emotions, never truly alone thanks to the incredible people in my life. In those times and beyond, I can never forget the support of all my friends from CME, Hummus Delft, and my friends from back home in getting through every high and low. A heartfelt shoutout to my Thesis (mental) support group - we've walked this path together, and I couldn't be more grateful for your companionship. As change is the only constant in life, I am grateful to have these constants which stands strong.

Last but certainly not least, I extend my heartfelt thanks to my large and loving family for their support from across the globe.

Sincerely,

Himanshu Patel,
Delft, 27/11/2023

Bhagavad Gita, Chapter 2, Verse 47:

कर्मण्येवाधिकारस्ते मा फलेषु कदाचन ।
मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि ।। 47 ।।

Translation:

"You have a right to perform your prescribed duties, but you are not entitled to the fruits of your actions. Never consider yourself to be the cause of the results of your activities, nor be attached to inaction."

Explanation

This verse from the Bhagavad Gita emphasizes focusing on the process of action rather than its fruits. It comprises four core instructions:

1. **Do Your Duty, But Do Not Concern Yourself With the Results:** This principle teaches focusing on performing duties well without anxiety over the results.
2. **The Fruits of Your Actions Are Not for Your Enjoyment:** Actions should be performed as a service to society, rather than for personal enjoyment. The society can be family, community, country or the World.
3. **Give Up the Pride of Doership:** One should not harbor the ego of being the doer of actions, recognizing that the power to perform actions comes from a divine source.
4. **Do Not Be Attached to Inaction:** The Gita warns against avoiding action and asserts that inaction is not a solution to the complexities of life.

Executive Summary

In the Netherlands, the construction industry has seen a progressive shift towards more collaborative contract agreements aimed at involving more number of stakeholders early in the design process. These type of contracts are often employed in projects for better collaboration among stakeholder. Often, in the design process of a construction project, different parties like, clients, contractor, project manager, suppliers and government authorities, participate to find a solution which achieves not only its goals but also the goals of these stakeholders. Each project stakeholders come with their own set of needs, wishes and values that they want to achieve from the project. In the Design process, they conduct iterative meeting sessions for deciding project details. They often employ different techniques, such as, alliance contracts, lean tools, Building information Modelling (BIM), etc, to support them in making these decisions. However, these tools are typically used by single parties in the design process and thus fail to consider the needs, values, and perspectives of other stakeholders. Consequently, they tend to optimize for the priorities of one party while overlooking the interests of others. In essence, each party aims to maximize their own benefit, leading to challenges such as disagreements and misunderstandings between stakeholders.

To address these challenges, a tool is required that not only integrates various tools used by different stakeholders but also incorporates their priorities and preferences. In line with this, a new approach called as Preference-based Goal Attainment (PBGA), is introduced in this research. The approach addresses these problems by allowing all the stakeholders to integrating their interests, needs and values in this approach and generate an outcome which correctly reflected their position in the decision-making process.

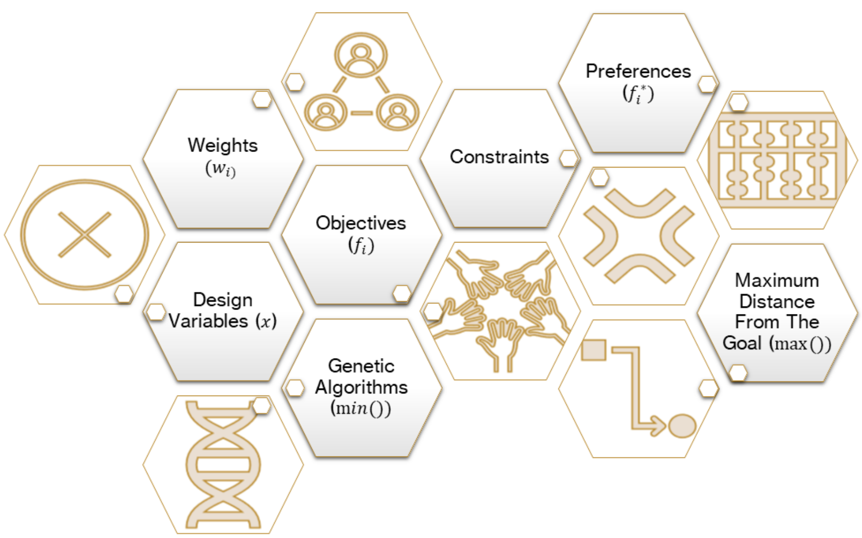


Figure 1: Components of PBGA

As shown in Figure 1, the PBGA has several components which are used to reflect the decision making process and find a balance outcome. To do that, PBGA employs two approaches: Multi-Objective Optimization Approach and weighted Goal-attainment approach. Consider pie-making as an analogy: the goals (satisfying hunger, budgeting costs, and ensuring health) act as the objective functions. The pie's attributes—such as size, ingredient ratios, and ingredient quality—serve as the design variables. To emphasize certain objectives, weights assign their relative importance. Constraints act like a recipe, filtering out infeasible options, ensuring the final pie meets all the pie-maker's requirements.

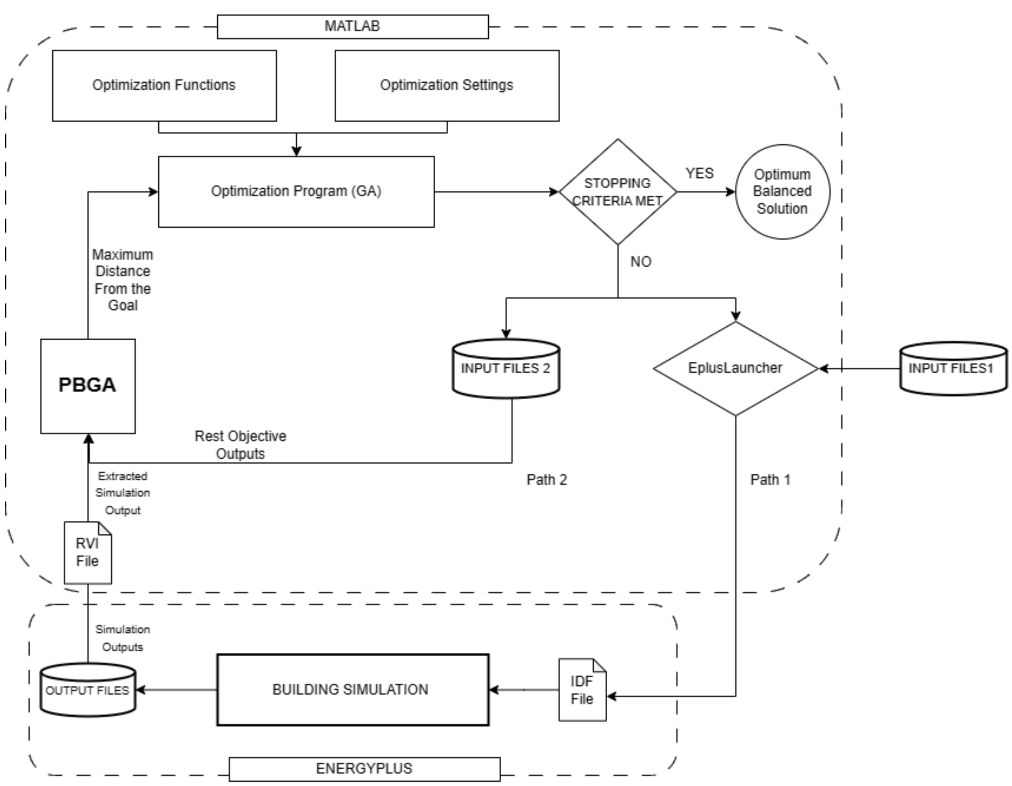
Incorporating a genetic algorithm into this process introduces a method inspired by natural selection. This algorithm begins with a population of potential pie recipes, iteratively evolving them through selection, crossover, and mutation. The fittest recipes, those meeting objectives most efficiently, are chosen to "reproduce," combining and refining attributes to explore the best possible pie solutions within defined constraints. By using all these components, the decision-making process is translated into a multi-objective optimization approach.

Further, the generation of the balanced outcome is carried out by using the weighted Goal-attainment approach. To refine the decision-making process further, each objective function is scaled according to stakeholders' preferences. For instance, in pie-making, preferences such as taste, cost, and healthiness are quantified on a uniform scale, allowing for a balanced assessment of each recipe. The algorithm then calculates the distance from these ideal preferences.

The equation Equation 1 presents the mathematical configuration of the approach.

$$\min_{z \in S} \left(\max_{i} w_i \left(100 - f_i^*(x)\right) \right) \tag{1}$$

Here, $f_i^*(x)$ represents the preference form of the i^{th} objective function, 100 represents the 'Goal' and w_i represents the weight of the corresponding objective function. By using the weighted Goal-attainment approach (as shown in Equation 1), the algorithm looks for a solution where the maximum deviation from any desired standard is to minimum. Through multiple iterations, the genetic algorithm sifts through and find improved solutions, ultimately converging on an optimal balance that aligns with the weighted objectives. This iterative optimization ensures that the final outcome represents the best compromise among all stakeholder preferences, embodying a balanced between all the objective, in pie's case, blend of taste, cost, and health.



Research Methodology

The research commences with identifying the aforementioned problems by conducting a background study withing the domains of 'design decision-making process', 'optimization-based approaches', 'stakeholders' perception', 'early stakeholder involvement'. Upon diving into these aspects, the research outlines its objectives and scope for this study. To implement the PBGA approach on a construction project, an existing building project was chosen as a case study. Further, the data required for constructing the model, which includes objectives, variables, and preferences is collected with the help of semi-structured interview with stakeholders. Further, the collected information was translated into computational form for implementation in the mathematical tool.

Figure 2: Methodology Framework

The procedural steps for constructing the model are as follows:

1. Identification of Objectives
2. Design Variables Selection
3. Objectives' Maxima and Minima Generation
4. Generation of Preference Curve
5. Weights Distribution
6. Generation of Optimum Balanced Design

Like any other computational model, this model operates by processing input data through defined objectives functions and design variables to generate output results as shown in the flowchart. The integration of these components was conducted in MATLAB® environment. The evaluation process of the tool is carried out by the method of validation and verification. As the validation process focused on establishing the practical applicability and legitimacy of the developed model, while the verification aims on internal correctness of the model.

Results & Evaluation

The results of the tool have been successfully validated by the stakeholders, which confirms that the results were acceptable to them in comparison to the current design. Furthermore, the tool have been able to create a balance between the objectives of stakeholders by generating trade-offs, and it reflect the concept of the PBGA approach. As seen in the Figure 3, preference score of objectives like thermal comfort and glare have improved significantly in the new design while in the current design it is more unbalanced.

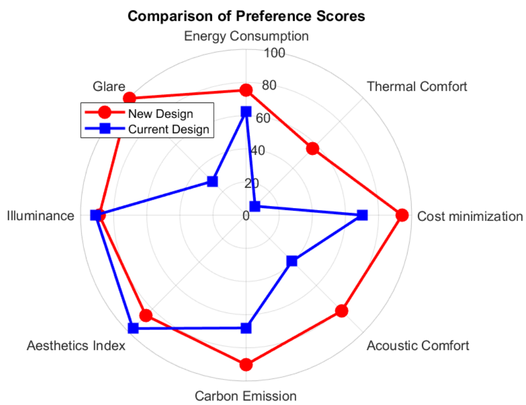


Figure 3: Preference scores for Current & New design

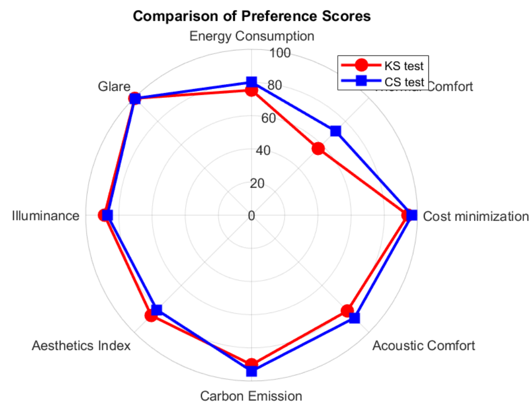


Figure 4: Preference scores for KS test and CS test

furthermore, as seen in the Figure 5, weighed distances of each objective from the goal are more balanced and equitable. For tool verification, a comparative analysis between KS and CS test, as shown in Figure 4 and Figure 6, draws the conclusion that the KS test, which represents the PBGA approach, is more likely to yield optimal design outcomes that truly reflect the stakeholders' weights and preferences. While the CS test might provide more technically optimal designs, it does not ensure that these designs align with stakeholders' preferences, as clearly demonstrated in this case study. Through detailed analysis, the effectiveness of the tool in reflecting stakeholder preferences has been critically assessed.

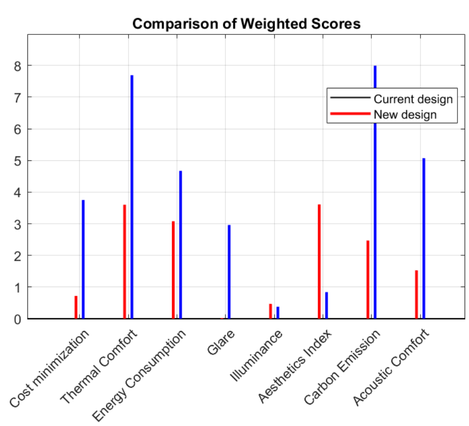


Figure 5: Weighted distances for Current & New design

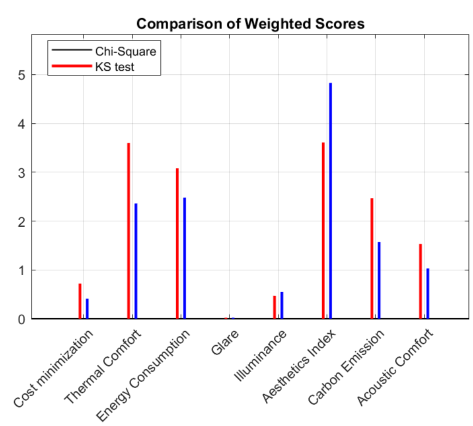


Figure 6: Weighted distances for KS test and CS test

Contents

List of Figures . . . xii
List of Tables . . . xiii
Nomenclature . . . xiv

1 Chapter 1: Introduction **1**
1 Background . . . 1
2 Problem Statement . . . 2
3 Research Objectives . . . 2
4 Research Scope . . . 3
5 Research Questions . . . 3
6 Thesis Relevance . . . 4
6.1 Theoretical Relevance . . . 4
6.2 Practical Relevance . . . 4

2 Chapter 2: Methodology **5**
1 Multi-Objective Optimization Problem (MOOP) . . . 5
1.1 Introduction . . . 6
1.2 Solution approaches . . . 8
1.3 Preference-based Goal Attainment Method . . . 10
1.4 Optimization Algorithms: . . . 11
2 Type of Study . . . 12
3 Data Collection and Interview Design . . . 13
4 Stakeholder Interviews . . . 14
5 Model Construction & Deriving Solutions . . . 15
6 Tool Evaluation . . . 17
6.1 Validation . . . 17
6.2 Verification . . . 19

3 Chapter 3: The Case Study: Co-Creation Center (CCC) **20**
1 Stakeholder Mapping & Interview Analysis . . . 20
2 Stakeholders' Needs & Expectations . . . 23
3 Objective Identification . . . 23
4 Design Variable Selection . . . 26
5 Problem Formulation . . . 27
5.1 Objectives Integration . . . 28
5.2 Integration of Design Variables . . . 35
5.3 Finding Maxima & Minima of the Objective Functions . . . 37
5.4 Generation of Preference curves . . . 37
5.5 Weights Distribution . . . 38
5.6 Generation of Balanced Optimum Design . . . 39

4 Chapter 4: Results & Evaluation **41**
1 Model Results and Interpretation . . . 41
2 Model Evaluation . . . 44
2.1 Stakeholders' Validation . . . 44
2.2 Tool Verification . . . 46

5 Chapter 5: Discussion **49**
1 Application of PBGA tool . . . 49
2 Assumption & limitations . . . 50
3 Future Directions . . . 51

6 Chapter 6: Conclusion **52**

References **55**

A Appendix A: Fanger's Comfort Model **61**

B Appendix B: MATLAB Code (Equal Wights Distribution) **62**

C Appendix C: Visual Comfort **73**

D Appendix D: Insulation Cost **74**

E Appendix E: Invitation Letter **76**

F Appendix F: Consent Form **77**

G Appendix F: Material EPDs **79**

H Appendix G: Preference Curves **81**

I Appendix H: Absorption Coefficients **83**

List of Figures

1 Components of PBGA . . . v
2 Methodology Framework . . . vii
3 Preference scores for Current & New design . . . viii
4 Preference scores for KS test and CS test . . . viii
5 Weighted distances for Current & New design . . . viii
6 Weighted distances for KS test and CS test . . . viii

2.1 Methodology Framework . . . 5
2.2 Pie making process . . . 6
2.3 Appetite vs. Pie Size . . . 7
2.4 Expense vs. Pie Size . . . 7
2.5 Pareto Front illustrating the trade-off between Appetite satisfaction and cost. . . . 8
2.6 Before and after the optimization by PBGA . . . 10
2.7 Preference Curve for Appetite . . . 11
2.8 Preference Curve for Cost . . . 11
2.9 Operations Research Framework . . . 12

3.1 The Co-Creation Center (*Si-X — Co-Creation Centre op The Greenvillage Delft*, 2023) . . . 20
3.2 Objective characteristics . . . 25
3.3 DesignBuilder Model . . . 28
3.4 Case Study: Block 1, Zone 1 . . . 28
3.5 Tool Framework . . . 30
3.6 Dimension Variables representation . . . 35
3.7 Thermal Comfort . . . 38
3.8 Visual Comfort . . . 38
3.9 Balanced Weights Scenario (BWS) Distribution . . . 39

4.2 Preference scores for BWS . . . 42
4.3 Weighted Distances for BWS . . . 42
4.1 Visual representation of obtained Obtained preferences scores . . . 43
4.4 Scenario: Owner . . . 44
4.5 Scenario: Climate Expert . . . 44
4.6 Scenario: Architect . . . 44
4.7 Scenario: User . . . 44
4.8 Design Process (from left to right) described by the Contractor . . . 45
4.9 Stakeholders' Satisfaction (weighted distances) for Current & New design . . . 46
4.10 Results for KS test . . . 47
4.11 Results for Chi square test . . . 47
4.12 Stakeholders' weighted distances from KS test & Chi Square test . . . 48

6.1 Solution Space diagram . . . 53

C.1 Visual Comfort settings in EnergyPlus Model . . . 73

D.1 Cost Estimation for different insulations . . . 75

G.1 Triple Glass Facade EPDs . . . 79
G.2 Gypsum PlasterBoard EPDs . . . 79
G.3 Names of the material from One Click LCA . . . 80

H.1 Project Cost . . . 81
H.2 Carbon Emission . . . 81
H.3 Aesthetic Index . . . 81
H.4 Acoustic Comfort . . . 81
H.5 Energy Consumption . . . 82
H.6 Thermal Comfort . . . 82
H.7 Glare . . . 82
H.8 Illuminance . . . 82

I.1 Absorption coefficient of wood wool panel . . . 83

List of Tables

2.1 Overview of open-ended questions 14
2.2 Model-Related Interview Questions Overview 14
2.3 Validation Round Interview Questions 18

3.1 Key Project Stakeholders Interviews 21
3.2 Client's Needs 23
3.3 Interview Outcomes 24
3.4 List of Final Objectives and Respective Data 26
3.5 Variables and their Bounds 27
3.6 Simulation Parameters (CONVERGE PROJECT) 29
3.7 EnergyPlus Configuration Parameters 30
3.8 Cost Overview 32
3.9 Variable definitions and equations for acoustics 33
3.10 CO2 Emissions Overview 34
3.11 Material Properties 37
3.12 Objective Bounds 37
3.13 Preferences for Each Objective 38
3.14 Unbalanced Weights for Different Scenarios 39

4.1 Results: BWS 41
4.2 Objective values for KS test vs CS test 47

Nomenclature

Abbreviation	Definition
AI	Aesthetics Index
API	Application Programming Interface
BVP	Best Value Procurement
BLAST	Building Loads Analysis and System Thermodynamics
CS	Chi-Square
DP	Design Process
ECE	Embodied Carbon Emission
ECI	Early Contractor Involvement
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene Insulation
MCDM	Multi-criteria Decision-Making
MOOP	Multi-objective Optimization Problem
PBGA	Preference-based Goal Attainment
CCC	Co-Creation Center
DGI	Daylight Glare Index
DOE-2	Department of Energy-2
GA	Genetic Algorithms
HVAC	Heating, Ventilation and Air Conditioning
IDF	Intermediate Data Format
KS	Kolmogorov-Smirnov
LCA	Life Cycle Assessment
lx	Horizontal Illuminance
PCMs	Phase Changing Materials
PFM	Preference Functional Modeling
PPD	Predicted Percentage Dissatisfied
PV	Photovoltaic
RT	Revebration Time
SSI	Semi-Structured Interview
XPS	Extruded Polystyrene Insulation

Chapter 1: Introduction

1 Background

In the Netherlands, the construction industry has seen a progressive shift towards more collaborative contract agreements aimed at involving more number of stakeholders early in the design process. This shift is adopted through range of contract forms, such as Integrated Contracts, Early Contractor Involvement (ECI), Alliance Contracts, Best Value Procurement (BVP), and other forms like construction team or commonly referred as 'Bouwteam' in Dutch construction industry (Lenferink, Tillema, & Arts, 2013; Wondimu, Klakegg, & Lædre, 2020; Reuer & Ariño, 2007; Storteboom, Wondimu, Lohne, & Lædre, 2017; Kluwer, 2021). These type of contracts are often employed in projects where the goal or objective is creating value for involved stakeholders(Storteboom et al., 2017; Beck, Ferasso, Storopoli, & Vigoda-Gadot, 2023). This involves projects which has goal of 'Better construction'. The term 'Better construction' includes domains such as, green, passive, sustainable, and smart construction (Lingegård, Havenvid, & Eriksson, 2021; Tian et al., 2018). The concept requires stakeholders integration in equitable manner where no stakeholder is 'left behind'. In addition, Todeschini, Cortimiglia, and De Medeiros (2020) point out that interaction between stakeholders is essential if environmental research is to be an effective tool for promoting the social transition to sustainability.

A Design process (DP) of a construction project involves stakeholders' participation in making series of decisions, ranging from site selection to selection of a better material. It all begins when a client or a customer engages other stakeholders to share his/her needs and visions. According to R Edward (2010); Vogwell (2003), project stakeholders encompass both individuals and organizations who play an active role in the project or whose interests may be influenced by the project's execution or completion. Project stakeholders defined by many scholars includes client, project management team, consultant and designing team, contractor, subcontractor, supplier, employees, local communities, funding bodies, and government authorities (Olander & Landin, 2005; Heravi, Coffey, & Trigunarsyah, 2015; J. Yang, Shen, Ho, Drew, & Xue, 2011). When participating in a project, stakeholders bring needs and wishes that they want to achieve from it. These individuals or groups are likely to be affected in some way by the project and thus want to have some say in how things turn out.

Stakeholders often employs interactive approach for developing sustainable and innovative outcome in the DP. Edelenbos and Klijn (2006) stated that these interactions allow stakeholders to communicate their values and wishes on the final design outcome. In the initial phases of the process, these needs are broadly defined, and during the course of this process they become specific and concrete. Therefore, in the early phase, the DP kicks-off by the objectives or goals of the project. Typically, stakeholders participate with different stakes and have different decision-making power. A stakeholder with higher power could influence the outcome of the DP which results in poor representation of less powerful stakeholder. Brouwer, Hiemstra, van Vugt, and Walters (2013) pointed out that if this power dynamics is not managed in more equitable manner, the DP will not be able to deliver sustainable and innovative solution which is the original aim of these processes. In addition, Koppenjan and Klijn (2004) state that this could lead a poor solution where one perception dominates other in a final solution.

Therefore, for an equitable solution, it is necessary for stakeholders to understand other stakeholders' needs and transparently communicate their needs in the interactive sessions of DP (Watson, Osborne-Brown, & Longhurst, 2002). However, with increasing number of stakeholders, the interactions or interactive sessions also increases, resulting in complexity in the DP. Complexity results in lack of transparency, negative perception, mostly because of lack of proper flow of information among stakeholders. This challenges lead these stakeholders to sought inherent interests to gain along with the collective goals of the project giving rise to conflicting interests (Bongo & Sy, 2023). Hence, it is important to have a positive perception among stakeholders with regards to their needs for avoiding decision with conflicting interests Olander and Landin (2005).

In order to tackle these challenges, different types of approaches and tools are utilized by project stakeholders. This not only includes different form of contract as mentioned above but also techniques like, lean tools, systems engineering, BIM, chain cooperation, risk allocation strategies, et cetera (Auteurs, 2013). With increasing accessibility of digital data, or big data, businesses across various sectors are recognizing the importance of adopting advanced digital tools to support decision-making activities (Marcher, Giusti, & Matt, 2020). The tools and techniques are adopted to provide stakeholders with information on various aspects where decision-making is critical and (Stanitsa, Hallett, & Jude, 2022; Eilon, Ackoff, Tanenbaum, & Holstein, 2023). However, poor involvement of stakeholders' needs and wishes in these tools inevitably results in poor decision-making. Hence, inequitable employment of these techniques supports informed decision-making within sub-processes resulting in unbalanced outcome. Subsequently, it fails to address the challenges which arise from power differences or satisfactions gaps among stakeholders. Hence, integration of such tools with multi-criteria decision-making (MCDM) methods approach provides a suitable alternative for better stakeholder involvement (Tan, Mills, Papadonikolaki, & Liu, 2021). This aligns with the concept of optimization-based approaches where each stakeholders' needs and wishes are included and an objective oriented outcome is finalized, which in this case, is to find a balanced or equitable solution.

After reviewing the decision-making process and stakeholder involvement in the previous paragraphs, it is evident that employing digital tools and techniques for such process requires better integration of needs and wishes of the stakeholders in DP. To address the challenges shown in the previous paragraphs, this thesis seeks to explore the possibilities of employing a novel approach, Preference-based Goal Attainment (PBGA), which is based on the foundation of Multi-objective Optimization (MOO) concepts. In order to make better decisions, the approach aims to find a design outcome with a balanced preferences among stakeholders. This may provide a better understanding of impacts of the stakeholders' decisions. Most approaches aim to find the optimum solution which often increases the satisfaction gap. Contrarily, this approach, in objective and transparent manner, finds a balanced solution in DP. Balanced outcome refers to minimizing the dissatisfaction of the most dissatisfied stakeholder as well as minimizing the satisfaction of the most satisfied stakeholder as shown in the Figure 2.6. In conflicting situations, it is unlike that all stakeholders expectations will be met (McManus, 2002). As a consequence, the balanced outcome will allow stakeholder in making informed decision which may avoid possible conflicting situations and lead to a commonly accepted design. In line with this, the following sections will outline the Problem statement, research objectives, scope and the research questions.

2 Problem Statement

As highlighted in the aforementioned section, with the involvement of multiple stakeholders, an increasing complexity remains an inherent problem for interactive approach in DP. One prevalent challenge encountered in various projects is the prioritization of individual gains by all stakeholders over the collective benefits of the entire system (Barough, Shoubi, & Skardi, 2012). In addition, the decisions made in this approach are based on subjective nature of the process. As a consequence, the impact on trade-off between objectives in the alternative choices in different decision choices cannot be quantified. Auteurs (2013) pointed out that each involved party seeks to maximize their own local gains which can result in sub-optimal performance on the project level. Such DP approaches results in conflicting interest, negative perceptions, trust deficit among the involved parties. Hence, **there is a problem lies in the current DP approaches and a better tools is required for handling these complexities and supporting decision-making to provide equitable solution.**

3 Research Objectives

Although performance-based optimization has been widely used in building design decision-making, the utilization of a preference-based optimization technique is a recent development (Robinson, 2021). In an early design process, the decisions are often made by using the available information in the most effective way. The goal attainment approach, also referred as min-max approach, aims to derive a balanced solution. The derived solution represents integration of weights in the optimization problem. However, it lacks to implement stakeholders' preferences in the DP. Therefore, this research aims to integrate preferences in the Goal Attainment approach resulting in Preference-based Goal Attainment (PBGA) approach.

While significant progress has been made in building design optimization research, Zhilyaev, Binnekamp, and Wolfert (2022) point out a crucial research gap regarding the inadequate consideration of stakeholders' involvement and group dynamics in the actual design process. Similarly, D. Yang, Wang, and Ji (2022) pointed out that limited research has been conducted on how stakeholders perceive and utilize optimization-based techniques as decision-making tools. Furthermore, understanding stakeholders' perception of tools like PBGA, which focuses on finding a more homogeneous and equalized solution, in building design projects is crucial for successful implementation. D. Yang et al. (2022) emphasizes that optimization results should serve as a "medium for reflection," guiding stakeholders in making informed design decisions rather than providing definitive design solutions. Moreover, the study examplify the integration of two areas : energy building simulation (using EnergyPlus) and tools for the management and design of research experiments (Gordillo, Ruiz, Stauffer, Dasen, & Bandera, 2020), in this case, MATLAB®.

4 Research Scope

In the quest to integrate the optimization-based approaches in real-world projects, each stage of the optimization-based approach could be an extensive topic of study. Therefore, it is essential to define the scope of this research

Each construction project contains the problem that this research aims to answer. However, this research is primarily focused on the early design stage of building projects. Early decisions made by the project stakeholders during the design phase can have far-reaching consequences, not only reducing the need for later adjustments but also minimizing total life-cycle costs (Attia, Hamdy, O'Brien, & Carlucci, 2013). The research focuses on developing, testing, and validating the PBGA tool in form of a priori optimization problem (discussed in section 1). The developing, testing and validating of this tool is carried out by a case study approach with a single case project. Therefore, implementation of the tool involves various aspects which are case specific. For instance, the process of collection objectives and the variables are specific to this case study. Furthermore, the methods and parameters employed in this study are designed to facilitate ease of use for stakeholders, particularly in terms of supplying the necessary inputs. This study aims to apply an optimization-based a priori approach on a real-life case study by integrating the preferences of the stakeholders by following the Preference Functional Modeling (PFM) theory (described in subsection 1.3). Overall, the tool aims to maximize the overall stakeholders' satisfaction by optimizing the quantitative objectives of the project. The developed tool can be applied to aid decision-making in other construction projects.

5 Research Questions

How can a tool, based on Preference-based goal-attainment approach, be created and implemented to find a 'balanced' solution in early design process of a construction project?

Which is elaborated further in Three sub-questions:

RQ1: What are the basic concepts of PBGA approach?
This question focuses on understanding the PBGA approach's foundational concepts. It involves a detailed literature review of the 'weighted goal-attainment' method, aiming to comprehend its fundamentals and the process of integrating preferences into this existing approach.

RQ2: What is the impact of implementing PBGA on the case design with balanced weights?
This inquiry examines the effects of applying the PBGA tool in a case study, specifically analyzing design changes when weights are balanced among stakeholders. It involves comparing the original building design with the modified version to assess the impact on design parameters and objective values, providing insights into the significance of stakeholder preferences in design outcomes.

RQ3: What is stakeholders' perspective on using PBGA tool in decision-making process?
This question seeks to understand stakeholders' views on the application of the PBGA tool in the decision-making process. It involves evaluating stakeholders' opinions on the tool's effectiveness and practical utility, based on their experiences in the design process of the selected case project.

6 Thesis Relevance

6.1 Theoretical Relevance

This thesis introduces PBGA (Preference-Based Goal Attainment), a unique approach in the realm of optimization techniques. Unlike traditional methods that aim for the best overall outcome or maximum satisfaction among key stakeholders, PBGA focuses on creating a balance among the diverse preferences of all stakeholders involved in a project. It achieves this by incorporating stakeholders' preferences into the Weighted Goal-Attainment method, as detailed in Chang's 2015 work (Chang, 2015). This integration occurs early in the process, following the principles of a priori articulation approaches. However, it's noteworthy that typical a priori approaches tend to favor solutions that meet the expectations and needs of specific decision-makers, often overlooking the interests of other stakeholders. In essence, based on input preferences, these methods usually produce solutions at the extremes of the solution space, leading to a significant disparity in stakeholder satisfaction. PBGA, in contrast, is designed to mitigate this issue by striving for a more equitable consideration of all stakeholders' preferences.

6.2 Practical Relevance

In addition to the mathematical foundation of the approach, the research aims to test the approach of a real-life case study and explore its real-life applications for decision-making in construction projects. Diverse tools are employed by different stakeholders to handle complexities and making informed decision (Auteurs, 2013). However, the lack of one system which allow stakeholder to communicate there wishes and needs in the DP results in these challenges: sub-optimal solution, conflicting situations, improper reflection of stakeholders' perception. The tool developed by employing PBGA approach will enables project stakeholders in integrating all interests into a sustainable common interest. In addition, it will not only allow stakeholders to prioritize their needs but also allow them to provide preferred condition for their respective needs. As a result, the technique will generate a balanced solution that will make sure that no stakeholder is "left behind" and is very dissatisfied with the outcome. Finally, this will allow decision-maker to make informed decision by being aware of the possible conflict situations and lead to a commonly-accepted solution.

Chapter 2: Methodology

Following the introduction of the Multi-Objective Optimization Problem and the solution techniques, this section elaborates on the approach and procedure that were devised for the development, implementation, and validation of the PBGA tool. The methodology framework illustrated in Figure 2.1 presents a structured approach to the multi-objective optimization problem. It commences with a background study, leads to data analysis through a case study approach, and culminates in tool evaluation after model construction. The framework emphasizes iterative stages such as objective identification, variable selection, and the generation of preference curves to ensure comprehensive solution development.

Figure 2.1: Methodology Framework

1 Multi-Objective Optimization Problem (MOOP)

As the approach plays an important role in this thesis, it is important to understand the concept and its components in detail. Therefore, this section introduces MOOP and its components.

1.1 Introduction

The utilization of an optimization-based approach in a decision-making process is done by defining the process as an optimization problem. The employment of optimization techniques to resolve multi-objective conflicting situations and value creation has gained traction over the past decade. The multi-objective optimization approach aids decision-makers in resolving multiple objectives that can often exhibit conflicts (Asha, Dey, Yodo, & Aragon, 2022). An optimization problem consists of the following components: objective functions, design variables, constraints. By varying these component or the values within them, a stakeholder can accumulate knowledge on various alternative decision choices. The goal of the 'value' or objective function is to systematically rank every viable option for the control variables (Hazelrigg, 1998). The decisions made in building projects will result in a final outcome which has certain quantitative characteristics like building performance or its architectural design. These characteristics are defined as objectives and variables as shown in the example Figure 2.2. The Objectives or needs of pie-makers, like hunger satisfaction, limiting the expenses, or eating healthy and the characteristics or variables of the pie, involves its size, ratio of different ingredients, quality of ingredients.

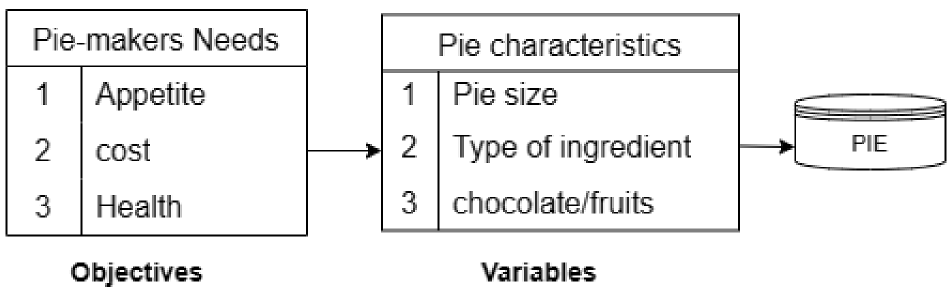


Figure 2.2: Pie making process

Furthermore, the differences in power of stakeholders are defined by relative weights which can be assigned to the preferred objectives of a respective stakeholder. However, solutions of an optimization problem are often in favor of stakeholders with higher weights.

An MOOP can be mathematically described as follows:

Minimize:

$$f(x) \tag{5.1a}$$

Subject to:

$$g_i(x) \geq 0; \quad i = 1, \ldots, m \tag{5.1b}$$

$$h_j(x) = 0; \quad j = 1, \ldots, p \tag{5.1c}$$

$$x'_k \leq x_k \leq x_{u_k}, \quad k = 1, \ldots, n \tag{5.1d}$$

Here:

x represents the design variables.

$f(x)$ is the objective function to be minimized.

$g_i(x)$ are inequality constraints.

$h_j(x)$ are equality constraints.

x_k represent specific values for the design variables.

x'_k represents the lower bound and x_{u_k} represents the upper bound for the k -th design variable.

This mathematical representation defines the objectives, constraints and variables of a MOOP, which are the key components of an optimization problem. Consider the previous example in Figure 2.2, making a pie, aiming to find the optimum pie that satisfies pie-makers needs, appetite, expense, and health. The challenge lies in achieving the right balance between these needs.

Mathematically, this trade-off can be framed as follows:

- Maximize:
  - Objective 1: Appetite
  - Objective 2: expense
  - Objective 3: Health

Subject to:

- Constraints related to the pie-making process, e.g., preparation time, available ingredients, dietary requirements.
- Constraints related to taste preferences, willingness to spend and health considerations.

The design variables, denoted by x_k, represent the range of choices such as the ratio of fruits to chocolate (x_1), the type of pie (x_2), and the size of the pie (x_3). The function $f(x)$ combines the objectives to maximize appetite, minimize cost, and optimize health, given the constraints $g_i(x)$ and $h_j(x)$. Figure 2.3 and Figure 2.4 show the linear representation of the objectives with one of the variables.

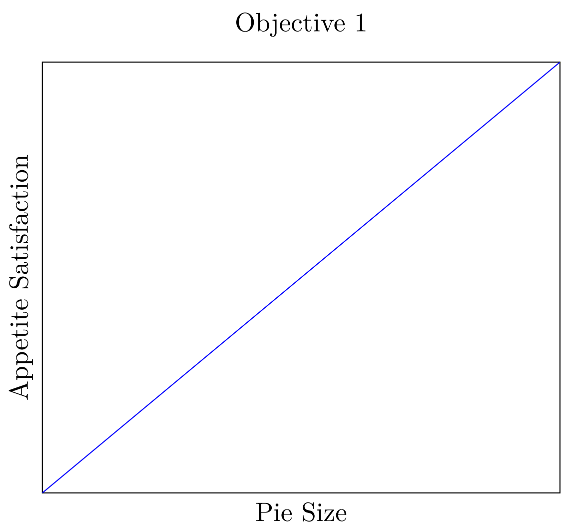


Figure 2.3: Appetite vs. Pie Size

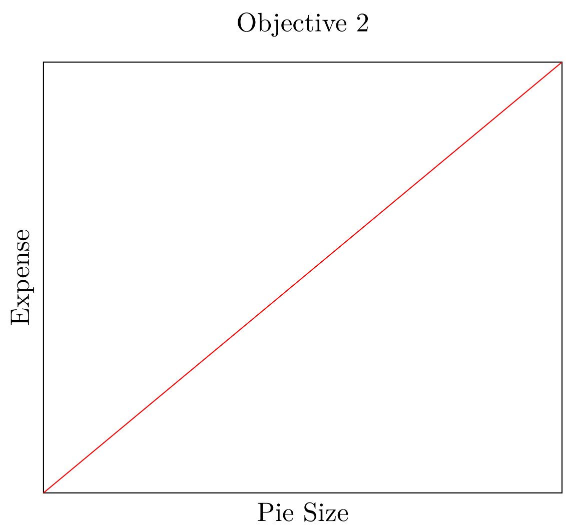


Figure 2.4: Expense vs. Pie Size

1.2 Solution approaches

Algorithms produce a large objective space (many possible outcomes) and a decision space (various possible values for design decision variables)(Zitzler, Laumanns, & Bleuler, 2004). The purpose of multi-objective optimization is to obtain a collection of solutions that are not dominated by any other solution, using an iterative approach. Finding an optimal solution that simultaneously minimizes or maximizes all objective functions is often unattainable due to the intrinsic conflicting nature of these objectives (Asha et al., 2022). In that case, finding a solution from a Pareto front is essential. The Pareto front refers to a set of solutions that are mutually non-dominated, meaning that no solution in the set is inferior to another in all objective functions (Akbari, Asadi, Besharati Givi, & Khodabandehlouie, 2014). By isolating only the non-dominant solutions, this methodology narrows the scope of alternative possibilities, thereby prioritizing those alternatives that yield optimal outcomes in alignment with the pre-defined objective function. In extant literature, these objectives commonly target optimal building performance (Islam, Jollands, Setunge, & Bhuiyan, 2015; Nguyen, Reiter, & Rigo, 2014; Robinson, 2021). This reduces the design space to the set of optimal trade-offs, which is the first step in selecting a suitable solution. By revisiting the above example, the Pareto front in Figure 2.5 provides a visual illustration of the trade-off between appetite and cost.

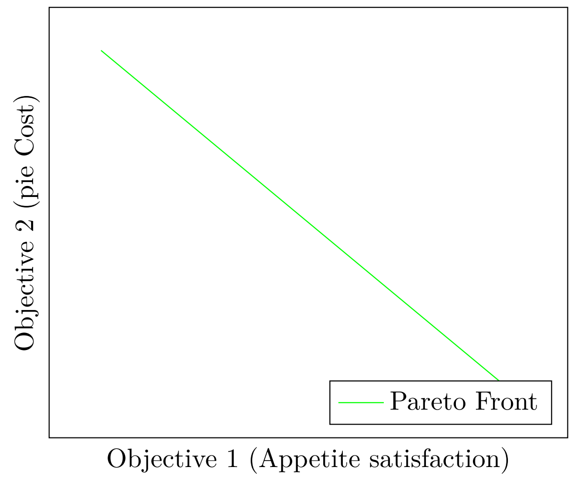


Figure 2.5: Pareto Front illustrating the trade-off between Appetite satisfaction and cost.

To better implement (translate) stakeholders' needs and desires in an optimization setup, another component, preferences or preference score, is employed. It is also defined as value in literature (Hazelrigg, 1998), where the purpose of value is to integrate such human factors in problem solvers. 'Human factor' here refers to preferences or value. To understand this, let's refer to the example Figure 2.2 of pie. Assuming there is a trade-off between objectives, an objective function refers to more food consumption for more appetite or prefer more chocolate over fruits. However, it does not provide their satisfactory conditions which that could result in a better trade-off between each consumer. For instance, if a consumer who favors chocolate desires 10 pieces of chocolate to fully enjoy the pie, it remains unclear how satisfied they would be if the number of chocolate pieces were reduced to 7, 8, or 9. In such cases, the preferences provide more information regarding other satisfactory conditions within the range of fully unsatisfied to fully satisfied. These conditions may create different satisfactory conditions within the range of needs, i.e., it may increase the number of possible solutions in the solution space.

In case of single objective problem, the incorporation of stakeholder's preferences into the optimization process should enable the identification, from the pool of optimal solutions, of the individual solution (or a specific region) that most effectively fulfills these preferences (Ferreira, Fonseca, & Gaspar-Cunha, 2007). However, in cases of multiple objectives, the solution often remain bias towards particular objective or preference. This is because of final resultant is sensitive towards the preferences and takes the extreme points of the solution space creating a large gap between stakeholders' satisfaction. for instance, it would result in a situation where pie is made of only chocolate or only fruits. Therefore, such outcomes of final design could have a negative impact on the DP. However, Robinson (2021) argues that preferred solution is subjective to stakeholders perspective thus a decision-making process could resemble a negotiating process, with trade-offs on mutually agreeable outcome.

In order to allow different objective functions to be optimized in a single model, it is important to normalize them to the same dimensions. The use of a preference scale for this normalization is one way to do that. Preference is a subjective, or psychological, feature rather than a physical characteristic of the things being valued. It can also be referred to as value or utility (Barzilai, 2010). By using preferences, the approach aims to integrate the qualitative requirements of the project's stakeholders with quantitative aspects of the project's outcomes, like building performance, cost, thermal comfort, etc.

Chang (2015) categorizes the methods to articulate the preferences of the decision-maker in 3 categories:

methods with a priori articulation of preferences, methods with a posteriori articulation of preferences, and methods with no articulation of preferences. Existing literature often utilizes the a posteriori method, where stakeholders identify the preferred solution from the set of solutions on the pareto front (Pereira, Oliver, Francisco, Cunha, & Gomes, 2022). The set of solutions presented on the pareto front does not contain the preferences of the stakeholders and is later added to the process of selsection. However, in a real-world DP, stakeholders often participate from the beginning, and their preferences can influence the direction of the project from its early stages (Zhilyaev et al., 2022). If these preferences are only considered at the end of the optimization process, it may lead to solutions that are technically optimal but not satisfactory to the stakeholders.

On the other hand, an a priori method reflects the real-world DP, as this approach integrates stakeholders' preferences and constraints from the early stages of the DP (Zhilyaev et al., 2022). This approach excludes solutions that do not satisfy the preferences of the stakeholders. However, the majority of a priori techniques have a common characteristic in that the optimal design solution they identify frequently demonstrates a pronounced bias towards the preferences or requirements of a particular stakeholder. A common example of this is the linear optimization approach. In such a case, it poses its own challenges, as it may favor certain stakeholders over others, even when their power and influence are equal. Deb and Sundar (2006) proposed a reference point approach based on an a priori method, where the aim was to identify a set of preferred Pareto-optimal solutions near the decision-maker's regions of interest. However, for this method, the decision-makers need to provide the location of the best solution on the Pareto front.

In order to obtain the design outcome based on stakeholder preferences, a priori preference articulation methods serve as navigational tools for complex decision landscapes. Among these, the *Weighted-sum Method* enables decision-makers to ascribe numerical weights to each objective, integrating them into a single objective function for optimization (Marler & Arora, 2010). However, this method may not find a Pareto optimal solution that is a balanced solution, where improvement of one objective requires degrading at least one other objective function (Xu, Lin, Tang, & Xie, 2004). In contrast, the *Lexicographic Method* takes a more ordinal approach. Objectives are ranked by their intrinsic importance, and each is subsequently solved in isolation while respecting constraints informed by the optimal solutions of higher-ranked objectives (Chang, 2015).

Yet, the *Goal-Attainment Method*, introduced by Gembicki and Haimes (1975), was presented to compute non-inferior index which represents a compromise or balanced solution is in an optimization problem. Mathematically, it is written as shown in the paper by Gembicki and Haimes (1975):

$$\text{Minimize: } z, \quad z, u \in D \tag{2.1}$$

$$\text{Subject to: } J_i(u) - w_i z \leq J_i^*, \quad i = 1, 2, ..., k \tag{2.2}$$

where $w_i > 0$, $J_i^* = 1, 2, ..., k$. Here, w_i and J_i^* are parameters and z is an unrestricted variable. The goal in this case is defined as J_i^*.

With the integration of weights on the Goal-attainment method, the *Weighted Goal-attainment Method*, also referred to as the *Weighted Tchebycheff Method*, offers a way to prioritize the objective functions. It seeks to minimize the function $u(z)$, representing the distance to an ideal point in the criterion space. This distance is the maximum distance of the objective from the ideal point. Mathematically, the problem is articulated as (Chang, 2015):

$$\text{Minimize } u(z) = \max_i \left\{ w_i \left[f_i(z) - f_i^0 \right] \right\} = \min_{z \in S} \left(\max_i w_i \left[f_i(z) - f_i^0 \right] \right) \tag{2.3}$$

The supplementary formulation involves λ which represents the distance from the goal:

$$\text{Minimize:} \lambda \tag{2.4}$$

$$\text{Subject to: } w_i(f_i(z) - f_i^0) \leq \lambda \leq 0, \quad \forall i \tag{2.5}$$

Here, w_i represents weights, f_i^0 refers to the Utopia Point which is the minimum value achieved by optimizing each objective individually without considering the other objectives. Lastly, $f_i(z)$ represents the objective function. Subsequently, the next section introduces the PBGA approach where preferences are centered on the Goal-Attainment Approach.

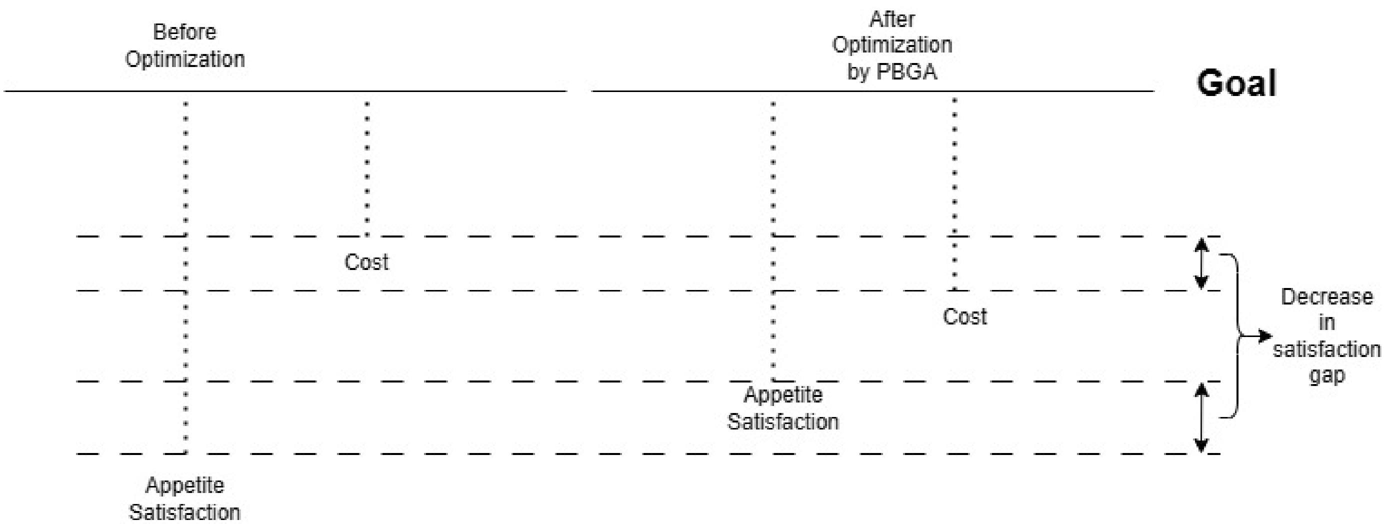


Figure 2.6: Before and after the optimization by PBGA

1.3 Preference-based Goal Attainment Method

As the name suggests, the PBGA method derive a solution based on the preferences of the stakeholders. In order to integrate preferences in an optimization problem, the method involves standardization of the objective functions on a dimensionless preference scale. In the context of aforementioned e.g., In a multi-objective optimization problem, the PBGA approach aims to decrease the satisfaction gap between stakeholder as shown in in the Figure 2.6.

In this research, preference function modeling (PFM) theory, developed by Barzilai (2010), is utilized for implementing the preferences in the optimization problem. The method for getting a preference scale for each objective using the PFM theory is described by Binnekamp (2010). In simpler terms, the PFM theory applies the mathematical operations of linear algebra and calculus by identifying the objective functions as vectors. This theory provides the basis for measuring preferences by creating a preference scale.

Another concept by Harrington (1965) creates a *desirability function* by translating the objectives into a scale-free "desirability" value between 0 and 1. A value closer to 1 is more desirable. Later, it combines all the desirability into a single objective dimension. However, the method requires high accuracy in defining the desirability function for a real-life process (Xu et al., 2004). On the other hand, Kim and Lin (1998) presents the concept of 'degree of satisfaction' based on the fuzzy optimization model. However, it defines membership functions with the aim of maximizing the degree of membership to the 'ideal solution' fuzzy set.

On the other hand, the PFM approach includes assigning a preference score of 0, which represents the least preferred value of the objective, and a preference score of 100, which represents the most preferred value of that particular objective function. Lastly, a minimum of one preferred value is assigned to the preferred intermediate preference score, i.e., between 0 and 100. This point provides the nature of the preference curve of a stakeholder for the corresponding objective.

Here, 'preferred value' refers to the desired outcomes of the stakeholders based on their identified needs. In the context of the Figure 2.2, the preference curves for appetite and cost are shown in the Figure 2.7 & Figure 2.8. In the depicted hypothetical graph for appetite, the curvature reflects that the preferences are non-linear in nature, with a preference score of 30 when half of the pie is consumed by that particular stakeholder. Likewise in the other graph, with a preference score of 70 when size is reduced to half. The stakeholders can choose any point on the curve to provide their preferences.

$$f_1^*(x) = p_1(f_1(x)), \quad f_2^*(x) = p_2(f_2(x)), \quad \ldots, \quad f_i^*(x) = p_i(f_i(x)) \tag{2.6}$$

Here, $f_i^*(x)$ presents objective functions in preference form. p_i for $i = 1, \ldots, n$ represents the preferences function of the i^{th} objective, and $f_i(x)$ are the objective functions.

Thus, the next step of involves preferences on the 'Weighted Goal Attainment' approach. mathematically, it is written as follows:

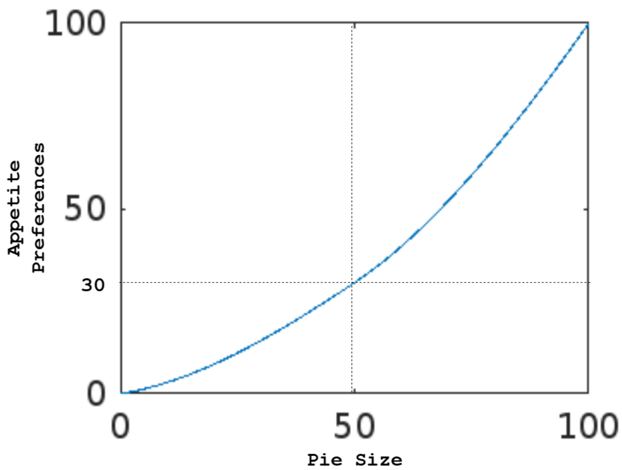


Figure 2.7: Preference Curve for Appetite

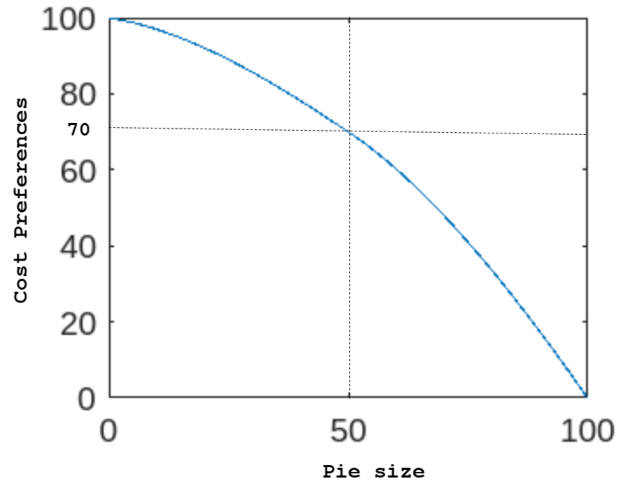


Figure 2.8: Preference Curve for Cost

$$\min_{z \in S} \left(\max_i w_i \lambda \right) \tag{2.7}$$

$$\lambda = \left(f_i^0 - f_i^*(x) \right), \text{ where } 0 \leq f_i^*(x), \leq 100 \tag{2.8}$$

Here, similar to the Equation 2.3, f_i^0 represents the Utopia point for the i^{th} objective function. $f_i^*(x)$ from the Equation 2.6 reflects the preferences of the i^{th} objective function, and w_i represents the weight of the corresponding objective function. λ, defined in Equation 2.4, represents the distance from the goals. In general, depending on the understanding of the stakeholders, the scale of the preference can be set to different numbers. In that case, the goal will always be equal to the upper limit of the preference scale, as it is the highest preferred score any objective can achieve.

In the PBGA, the preference scale ranges from 0 to 100, and the goal will always remain equal to 100. Hence, the distance from the goal, λ, also ranges from 0 to 100. Therefore, the aforementioned equation can be rewritten as follows:

$$\min_{z \in S} \left(\max_i w_i \left(100 - f_i^*(x)\right) \right) \tag{2.9}$$

$$\lambda = \left(100 - f_i^*(x)\right) \geq 0 \tag{2.10}$$

In a multi-objective PBGA optimization setup, each objective function is scaled on a preference scale using collected preferences from the respective stakeholder. Furthermore, the distance from the desired goal (λ) is obtained using Equation 2.10. Finally, as the Equation 2.9 explains, the maximum distance of the objective from the goal (inner bracket function) is minimized (outer bracket function). This process is carried out by optimization algorithms (in this case, genetic algorithms (GA), described in subsection 1.4). Through several iterations, the algorithm aims to find a solution that contains the optimum balanced solution.

1.4 Optimization Algorithms:

In building design simulations, the optimization problem often involves non-linear processes, multiple objectives, and a mix of variable types—continuous and discrete. These complexities are further compounded by diverse design variables like building orientation and material selection (Machairas, Tsangrassoulis, & Axarli, 2014). Given this multifaceted nature, genetic algorithms (GAs) offer a promising optimization strategy for this research. In addition, previous studies have shown that GA is robust on getting the optimal simulation (Wetter & Wright, 2004; Wright & Alajmi, 2016; Sahu, Bhattacharjee, & Kaushik, 2012).

A genetic algorithm is an optimization technique that imitates the process of natural evolution by allowing a population of candidate solutions, or "individuals," to converge on an optimal solution. Firstly, it creates a random population of individuals. The algorithm evaluates the viability of each individual based on the optimization problem's objective function. Through iterative processes known as "generations," the algorithm selects more suitable individuals to populate a new population, thereby increasing the likelihood of discovering optimal solutions (Goldberg & Kuo, 1987). When a predetermined number of generations are reached or a satisfactory fitness level is attained, the algorithm terminates.

2 Type of Study

Given that the objective of this research is to develop and implement a novel decision-making tool that inherently addresses operation-related challenges, the integration of qualitative and quantitative methods is essential. The primary objective of operations research (Figure 2.9) is to assist those in positions of authority in making optimal decisions by employing scientific methodology, strategies, and instruments to address system-related challenges (Haidar, 2015).

Figure 2.9: Operations Research Framework

Haidar (2015) mentioned the fundamental steps of operations research, which are tailored to align with the objectives of developing and implementing a preference-based goal attainment tool for optimizing building design decisions.

1. Problem Formulation
2. Model Construction
3. Deriving solutions from models
4. Stakeholder's Validation on the tool and on the 'balanced' design alternative

The research was conducted using a case-study approach. Case studies provide a comprehensive analysis of a specific project, encompassing its unique characteristics and incorporating real project data (Barlish & Sullivan, 2012). In addition, it seeks to comprehend the event under investigation and develop more general theories regarding the observed phenomenon (Quint ao, Andrade, & Almeida, 2020). As the approach has not been tested before, the relatively low complexity and confined boundaries of a building project will provide a better understanding of the tool's influence on its design decision-making process. The case study chosen is an existing building project with a diverse range of stakeholders, which allows for a study in a complex environment. In addition, this case also provides insights into achieving user satisfaction with the current design and functionality. These insights are gathered with the help of interviews with stakeholders and existing studies conducted on the building (described in section 4). Additionally, selecting an existing building allows for a comparative analysis between design generated through the tool and the current design. This comparative approach enables collection of relevant stakeholder feedback, aiding in the assessment of the tool's effectiveness in achieving an enhanced design.

The qualitative aspects of this research involve gathering stakeholder needs and expectations for the project, aiming to comprehend their objectives in the context of setting up the optimization problem. Further, it involves gathering insights regarding integration of decision-making tools, like PBGA, in the DP. Additionally, by conducting the interviews, the decision-making process that culminated in the current design is analyzed. On the other hand, quantitative aspects of this research encompass a two-fold approach. Firstly, data is collected from existing studies related to the building's performance (van den Engel et al., 2022; De Araujo Passos, Van Den Engel, Baldi, & De Schutter, 2023; Van Den Engel, Malin, Kodur Venkatesh, & Antonio De Araujo Passos, 2023). This data serves to inform the inclusion of relevant objectives in the optimization problem. Secondly, it serves to generate the design based on the gathered qualitative and supplementary quantitative data. Additionally, after generating optimized designs, validation interview round (described in subsection 6.1) will be set up with the stakeholders to measure the effectiveness of the tool in achieving a balanced and improved design.

This combined approach allows for a holistic investigation, leveraging the strengths of both qualitative and quantitative methods. The qualitative insights enrich the understanding of stakeholder perspectives and design decision-making processes, while the quantitative aspects provide the analytical foundation for optimizing designs and assessing the effectiveness of the proposed tool. As data plays a very crucial role in this research, the next section outlines the methodology for collecting relevant information.

3 Data Collection and Interview Design

To answer the main research question, the overall data collected serves the purpose of this research in the following ways:

1. Setting up the optimization problem.
2. Understanding the DP led to the current design of the building.
3. Gathering insights on the use of Optimization-based tools in DP.

The data collection research method serves to collect both quantitative and qualitative data. The first and foremost step in this research is to determine the expectations and requirements of the stakeholders involved with the chosen case study. The project stakeholders refer to the participants involved in the decision-making process of the DP of the chosen case project. The qualitative aspect of operational research involves data collection by conducting interviews with the project stakeholders. There are many methods of conducting the interview, ranging from fully structured to fully unstructured. For this case, the semi-structured interview (SSI) approach was employed, where the participant was questioned in an open fashion. The semi-structured interview is known to generally produce more precise and comprehensive data that is directly relevant to the phenomena being studied (Opdenakker, 2006). In definition, SSI's are a one-on-one conversational survey that uses a combination of open-ended and closed questions and frequently includes asking why or how to follow up (Adams, 2015). One-on-one SSI was set up with 7 participants out of a total of 9 participants. For the remaining 2 participants, due to personal circumstances, an alternative approach was adopted. Once the objectives of the stakeholders are identified by the qualitative approach, the next step is to collect the quantitative data, which serves as input in the construction of the model. This data is specifically related to the chosen objectives of this case study; hence, this step can vary for different objectives and/or for different projects. Table 3.6 in the provides a list of data collected from the quantitative approach. The next section outlines the interview set-up for this data collection process.

4 Stakeholder Interviews

Interviews with stakeholders are collected by various modes as shown in Table 3.1. In every interview mode, the interviewee is given an introduction to PBGA, along with an explanation of the project's specific objectives and the expected responsibilities of the stakeholder throughout project's duration. An interview was conducted in two phases. The initial phase focuses on collecting stakeholder opinions on the practical application and utility of optimization-based tools. Table 2.1 presents such questions related to specific objectives. In the subsequent phase, stakeholders are asked to define the relevant criteria applicable to them within the context of the CCC project, as shown in Table 2.2.

Steps	Interview Objectives	Questions
1	Stakeholder's role in design decision-making process	a. What was your role in the co-creation center Project? b. In which key design decision, you were part of? c. Which type of process was involved in making design decision? d. Which decisions were already made when you participated in the decision-making process?
2	Stakeholder's take on Tools like PBGA in decision-making process	a. Did you use digital tools in the design decision-making process? b. How do you see using decision-making tools in finalizing building design? c. In what way will the tool facilitate the decision-making process?

Table 2.1: Overview of open-ended questions

Table 2.2: Model-Related Interview Questions Overview

Steps	Interview Objectives	Interview Questions Overview
1	Defining Variables	a. Design adjustments for optimum solutions? b. Options for material choices? c. Crucial design elements/features for the project?
2	Stakeholder's Objectives	a. Expectations to optimize in this project? b. Important criteria for material choices?
3	Defining Preferences	a. Score of 100 for most desired outcome? b. Score of 0 for least desired outcome? c. Score between 0-100 for intermediate desired outcome?
4	Design Constraints	a. Constraints for objectives? b. Fixed design elements/features in decisions?

5 Model Construction & Deriving Solutions

In the previous section, data collection process was illustrated. This section describes research methodology for PBGA model construction. Like any other computational model, this model operates by processing input data through defined objectives functions, design variables, and other parameters to generate an output.

The procedural steps for constructing the model are as follows:

1. Identification of Objectives
2. Design Variables Selection
3. Objectives' Maxima and Minima Generation
4. Generation of Preference Curve
5. Weights Distribution
6. Generation of Optimum Balanced Design

Objectives Identification

As stakeholders' needs and expectations are ascertained from the interviews, the subsequent phase involves translation of this qualitative information into quantifiable objectives. In this regard, the term 'needs and expectations' refers to qualitative data that may or may not be quantifiable. Conversely, 'objectives,' as expounded upon in the preceding chapter, are quantifiable entities which will be subsequently employed in the formulation of an optimization problem.

For this case study, the methodology for this translation adheres to the following characteristics of this optimization component:

1. The selected objective should align with the stakeholder's expectations and requirements for the project.
2. The selected objective must be quantifiable.
3. The selected objective should exert a tangible influence on both the DP and the resulting design outcome.
4. The requisite data and/or models pertinent to the selected objective should be readily available for the construction of the model.

Design Variables Selection

The next step is to define the design variables of a project. Normally, In a real DP, the variables and the range of each variable are supplied by the stakeholders. In line with this, from discussion with the stakeholders about its design process, it was concluded that some building parameters were subject of discussion among them, like variables with critical design decisions. Hence, these variables were considered for further selection.

And, these variables are further chosen based on the following characteristics:

1. The necessary data and/or models relevant to the selected variable are either available.
2. The variable could influence one or more of the project's chosen objectives.
3. The variable is quantifiable.

For generating a feasible solution to an optimization problem, it is essential to specify the limits of each chosen variable. Typically, there are two primary limits of a design variable, which are called 'lower bound' and 'upper bound' in an optimization problem. Upon completion of this process, the variables and objectives to be incorporated into the model are identified. Given that these elements have the listed characteristics related to the availability of relevant models or data, the methodology for integrating diverse platforms, each corresponding to specific objectives, into MATLAB®, is described in the section 5.

Finding Maxima and Minima of the Objective Functions

Once the variables and their corresponding bounds have been established in the optimization problem, the next step is to identify the bounds of each objective function. This step is performed by optimizing each objective function of the MOOP individually. Therefore, for this step to perform, it is necessary to finalize all the variables and their respective bounds as changing them would result in different bounds of objective function. Given that certain objective functions are derived from EnergyPlus simulations, as depicted in Figure 3.5, these may entail longer computational times. To mitigate this, variables with no impact on a given objective function are omitted from its individual optimization setup. Each objective undergoes two simulations to ascertain its maximum and minimum values. These bounds are used as a basis for the next step, where preferences are defined on the range of objective function.

Generation of Preference curve

The concept of preferences collection is described in the aforementioned subsection 1.3. The PBGA framework is based on *a priori* approaches as the stakeholders' preferences are collected and integrated at this stage. The preferences of the stakeholders are generated based on the interviews conducted with them. Moreover, for the curve formation, Piecewise Cubic Hermite Interpolating Polynomial, referred as `pchip` function in MATLAB, is employed which processes the data collected into preference functions. The function has the ability to preserve the shape of the data while maintaining monotonicity. Apart from this, literature provides use of tools like, TETRA, to integrate stakeholders' preferences in an optimization problem (Arkesteijn & Binnekamp, 2014; A+BE | Architecture And The Built Environment, 2019; Binnekamp, 2010). TETRA is used to generate preference scale based on the PFM theory (Metrics, 2002). The approach provides a visual presentation of the stakeholders' preferences. However, In line with the objective of this research, the `pchip` function is more suitable as it is integrated into MATLAB and does not require any addition software to perform. This allows the model to be built on the same platform, creating simplicity for the stakeholders. Within MATLAB, there are different functions to generate such curves but `pchip` captures the preferences in correct manner. Other functions on MATLAB, like cubic splines or linear interpolation, are not chosen for this purpose as they do not capture the stakeholders' preferences in the right manner.

Mathematical representation:

Given $n+1$ data points $(x_0, y_0), (x_1, y_1), \ldots, (x_n, y_n)$, the pchip interpolant $P(x)$ is defined as:

$$P(x) = \begin{cases} P_0(x) & \text{for } x \in [x_0, x_1] \\ P_1(x) & \text{for } x \in [x_1, x_2] \\ \vdots & \\ P_{n-1}(x) & \text{for } x \in [x_{n-1}, x_n] \end{cases}$$

Each $P_i(x)$ is a cubic polynomial of the form:

$$P_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3$$

The coefficients a_i, b_i, c_i, d_i are determined such that $P(x)$ passes through the given data points and its first derivative is continuous across intervals.

Weights Distribution

The distribution of weights is done in a manner that summation of all the weights is 1.

$$\sum_{i=1}^{n} w_i = 1 \tag{2.11}$$

where w_i represents the weights for each objective.

Generation of Optimum Balanced Design

The optimization framework has been established, transitioning to the execution phase using the genetic algorithm (GA) in MATLAB. The process involves:

1. Calculating objective function values through designated computational models.
2. Deriving preference scores from these values.
3. Computing the value of λ for each objective (refer to Equation 2.10) and applying corresponding weights.
4. Utilizing MATLAB's `max` function to identify the largest of the weighted λ values.
5. Iteratively minimizing this maximal value to converge on the optimal solution.

This procedure aims to yield an optimal, balanced design, characterized by a set of variable values indicative of a near-optimal design solution within the solution space.

6 Tool Evaluation

In the preceding methodology section entailed systematic data collection, primarily through stakeholder interviews, to amass relevant project-specific information, followed by a framework for generating a balanced and optimum outcome. Subsequent to this, the current section focuses on evaluation of the tool and its generated outcome by interviewing the stakeholders listed in Table 3.1, aiming to assess its practical applicability. Stakeholders were invited for semi-structured interviews (Appendix E) to facilitate a comprehensive evaluation.

The evaluation of tools or models based on multi-objective optimization approaches are often carried out by the method of validation and verification(Zamanifar & Hartmann, 2020; Miller & Ziemiański, 2023; Algohary, Mahmoud, & Yehya, 2023). To employ one or both approaches in this research, it is essential to understand them in detail. Hence, the following subsections further elaborate on these methods of evaluation.

6.1 Validation

The definition of the validating a model is to establish its legitimacy as a suitable method for supporting design decision-making process (Oreskes, 1998). A model is said to be valid when it does not contain known or identifiable defects and is internally consistent (Oreskes, Shrader-Frechette, & Belitz, 1994). In this research, the validation process is focused on establishing the practical applicability and legitimacy of the developed model. This involves ensuring that the model not only adheres to theoretical expectations but also aligns with real-world scenarios and stakeholder needs. Moreover, the method of validation has been criticized if used for validating the actual results of the model as these results are dependent on the quality and quantity of the input data (Oreskes et al., 1994; Oreskes, 1998). Therefore, in this research, validation is employed for assessing how well the model can solve problems related to a real-life DP. In other words, stakeholder feedback is collected in understanding the practical effectiveness and relevance of model. This process is performed by conducting semi-structured interviews with key stakeholders. The interview process entailed an introduction of the PBGA methodology, correlating it with stakeholder-provided data in the initial interviews. This was followed by a comparative analysis contrasting the generated design outcome with the existing building design. This comparison emphasized discrepancies in design variables and objectives. An overview of the targeted open-ended questions used in this validation phase is detailed in Table 2.3.

As the research process relies solely on interviews with stakeholders from the case study project, several risks are identified:

- Diverse expertise among stakeholders leads to varied perceptions of the Decision Process (DP). For example, a project manager might focus on risk management, whereas a shading expert might assess tool compatibility with their systems.
- Stakeholders inexperienced in collaborative projects with shared interests or value-creation may lack insight into the practical application of the tool in such projects.

Category	Focus Area	Questions
Data Collection	Opinions on Collection of Needs and Preferences	1. What are your views on the collection of a) needs and b) preferences? 2. In your opinion, does the collected data accurately reflect the design process?
Generated Outcome	Evaluation of New Design	1. How satisfied are you with the new design of the building? 2. Do you consider the new design to be an improvement over the previous one?
Decision-making	Effectiveness in Decision-Making	1. Do you believe the tool aids in achieving balanced decision-making? 2. How do you think varying parameters and assessing their impact enhances building design decision-making? 3. Does the tool effectively provide information necessary for design decisions?
Effectiveness and Efficiency	Tool's Impact on Project Efficiency	1. Has the tool contributed to time savings in decision-making or design processes? 2. Can you comment on the accuracy and reliability of the data or results produced by the tool? 3. Could you provide an instance where the tool played a crucial role in resolving a complex project issue?
Impact and Feedback	Tool's Overall Impact and User Feedback	1. can the tool assist in improving team communication and collaboration? 2. Can the tool be used in assisting or identifying conflicting interests? 4. Overall, how satisfied are you with the tool, and what improvements would you suggest? 5. In what other ways this tool can aid decision-making in similar projects?
Future Use	Long-term Viability and Adaptability	1. Do you foresee this tool being beneficial for long-term use in future projects? 2. How adaptable do you find the tool with changes in project scope or objectives?

Table 2.3: Validation Round Interview Questions

- Stakeholders' subjective viewpoints could introduce bias in evaluating the tool's effectiveness, as noted by Robinson et al. (Robinson, 2021).
- Limited expertise in certain aspects of the tool among stakeholders may hinder a comprehensive understanding of its functionalities and applications and could result in feedback of compromised quality.

6.2 Verification

Unlike validation, verification focuses on the internal correctness of the model, ensuring the output accurately represents the developed mathematical relationships among parameters (Oreskes et al., 1994). A model is said to be verified if its reliability has been demonstrated and it can be used for making decisions (Oreskes et al., 1994). The model generates results based on closed mathematical components such as genetic algorithms. These are subjected to verification through sensitivity analysis of the model. This research limits its scope to nominal range sensitivity analysis, examining the impact of variations in a single input parameter, such as weights, on the model's outcomes, while other parameters remain constant (Christopher Frey & Patil, 2002). To ascertain the model's validity and analyze the results, goodness-of-fit tests are employed. These include the Kolmogorov-Smirnov (KS) test, which in this context, aligns with the PBGA approach by focusing on the maximum weighted distance from the goal as shown below as 'Distance for KS', and this distance is further minimized as shown in Equation 3.15.

$$\text{Distance for KS} = \max\Big(w_{\text{EC}}\lambda_{\text{EC}}, w_{\text{TC}}\lambda_{\text{TC}}, w_{\text{AC}}\lambda_{\text{AC}}, w_{\text{CM}}\lambda_{\text{CM}}, w_{\text{I}}\lambda_{\text{I}}, w_{\text{G}}\lambda_{\text{G}}, w_{\text{AI}}\lambda_{\text{AI}}, w_{\text{CE}}\lambda_{\text{CE}}\Big)$$

And, the equation for KS test can be formulated as:

$$\text{KS test} = \min_{w,\lambda \in S} (\text{Distance for KS}) \tag{2.12}$$

While, the Chi-square test evaluates the summation of squares of weighted distances across all objectives as shown in the Equation 2.13 and this value is further minimized using by GA as shown in Equation 2.14.

$$\begin{aligned}\text{Distance for Chi-square} = \Big(&(w_{\text{EC}} \cdot \lambda_{\text{EC}})^2 + (w_{\text{TC}} \cdot \lambda_{\text{TC}})^2 + \\ &(w_{\text{AC}} \cdot \lambda_{\text{AC}})^2 + (w_{\text{CM}} \cdot \lambda_{\text{CM}})^2 + \\ &(w_{\text{I}} \cdot \lambda_{\text{I}})^2 + (w_{\text{G}} \cdot \lambda_{\text{G}})^2 + \\ &(w_{\text{AI}} \cdot \lambda_{\text{AI}})^2 + (w_{\text{CE}} \cdot \lambda_{\text{CE}})^2\Big);\end{aligned} \tag{2.13}$$

$$\text{Chi-square test} = \min_{w,\lambda \in S} (\text{Distance for Chi-square}) \tag{2.14}$$

where λ is the array the distances of the preferences of each objective from the goal functions, defined as $\lambda = 100 - \text{Objective\_m}$. And, S is the feasible set defined as $0 \leq w_i \leq 1$ for all i and $\lambda_{\min} \leq \lambda_i \leq \lambda_{\max}$ for all i.

Here, EC stands for Energy Consumption, TC for Thermal Comfort, AC for Acoustic Comfort, CM for Cost Minimization, I for Illuminance, G for Glare, AI for Aesthetic Index, and CE for Carbon Emission.

This chapter commences by presenting an overview of MOOP and its various solution strategies. It then delves into a fundamental explanation of the PBGA method. The chapter proceeds to outline the methodology adopted for this research, beginning with the initial phase of data collection from the case project. Subsequently, it elaborates on the subsequent stage, which involves integrating this data into a mathematical model framed around MOOP. The final section of this chapter is dedicated to discussing the approach for evaluating the effectiveness of the tool developed. The subsequent chapter 3 will offer an in-depth analysis of the selected case study and articulate the problem formulation for that specific case.

Chapter 3: The Case Study: Co-Creation Center (CCC)

In 2018, TU Delft's Green Village foundation launched the Co-Creation Centre (CCC) project, targeting the development of a near-zero-energy building. Located in TU Delft's Green Village, the CCC (Figure 3.1) functions as both a collaborative space and a research center. It houses a versatile conference room suitable for events such as conferences, seminars, and meetings. The building incorporates several innovative sustainability features, including a climate tower with Phase Changing Materials (PCMs) and Venetian blinds for temperature regulation, triple-glazed paneling in its structure and façade, and the use of recycled concrete in its foundation.

Figure 3.1: The Co-Creation Center (*Si-X — Co-Creation Centre op The Greenvillage Delft*, 2023)

This chapter proceeds to outline the identification of stakeholder needs and expectations, followed by a detailed exposition of the process for determining objectives and variables, and concludes with the problem formulation.

1 Stakeholder Mapping & Interview Analysis

To implement a tool for Decision-making in DP, it is important to gather information about the original DP of the CCC. This allows to formulate the optimization problem. Thus, this section presents the process of the current decision-making process of the CCC project. This DP engages multiple stakeholders with diverse backgrounds. This include the project manager representing the client, contractors, architects, glass experts, shading specialists, and researchers. Table 3.1 provides a comprehensive list of the stakeholders responsible for decision-making within the project.

Table 3.1: Key Project Stakeholders Interviews

Sr. No.	Stakeholder	1st Round Interview	2nd Round Interview
1	Project Manager 1 (Client)	One-on-one	One-on-one
2	Project Manager 2 (Client)	One-on-one	Online
3	Structural Project Manager	One-on-one	-
4	Researcher for Thermal Comfort	One-on-one	-
5	Building Shades Expert	Online	Online
6	Architect	Email	-
7	Contractor	Email	One-on-one
8	Glass Expert	One-on-one	One-on-one
9	Climate Tower Expert	One-on-one	-

Each interviewed stakeholder occupies a critical role in the project's DP. To gain insights into the project's stakeholders' needs and expectations, the initial phase of the research involved conducting interviews with these stakeholders. The two objectives of this phase are depicted in the section 4. Following provide a comprehensive summary of stakeholders take in response to the related questions:

Interview Objective 1: Stakeholder's role in design decision-making process

At the beginning of this project, TU Delft, as a key stakeholder, which is the client, laid down its basic requirements.

> "The Co-creation Center at the Green Village will be a central research and meeting place site, uniquely combining research on sustainable themes, inspiration for the general public, and co-creation." —Client

The Green Village is an organization on the TU Delft campus that acts as a field lab for sustainable innovation in the urban environment. The facility allows researchers, students, companies and various other organizations to conduct studies in collaboration with one another. The building has a sizable inflow of researchers and students with the purpose of conducting research in different domains (van den Engel et al., 2022; De Araujo Passos, Van Den Engel, et al., 2023; Van Den Engel et al., 2023; De Araujo Passos, Ceha, Baldi, & De Schutter, 2023). Due to the nature of the facility, the majority of the projects frequently rely on funding from the involved research. Similarly, various ongoing research studies were part of the CCC project. They aim to study different aspects of the building, like the strength of the glass structure, recycled concrete in the foundation, and the facade. Therefore, it can be concluded that, apart from internal stakeholders, a range of external parties were involved in the decision-making process, which in one way or another, mainly with the project's budget, had an impact on the building's DP.

> "For project development, we usually have the funding for a certain type of research, like research on structural elements." —Project Manager 1

The main goal, as described by project manager 2, was to make an event center that can be used to organize and host events and workshops to address the hurdles that prevent innovation from scaling up. For that, the idea was developed that the building should reflect the main goal, which is to facilitate innovation in an open environment. In line with this, the second goal was to construct a building with a diverse range of innovations within it. To realize these goals, the project participants employed a 'construction team', commonly referred to as 'bouwteam' in the Dutch construction industry, where participants worked on their own jobs in coordination and contributed to the tasks of fellow participants by providing advice when possible (Kluwer, 2021). The process involved 'very high numbers of iterations', as described by the interviewee, before coming to the final design. This includes the project manager, researchers, architect, contractor, structural project manager, and climate engineers. In line with the goal of boosting innovations, the process primarily focused on how to bring innovation to the table.

> "To trigger innovation, we posed "how can" questions to each stakeholder respective to their field."
> -Project Manager 2

> " One goal was to learn what kind of process, collaboration and starting points are required to be able to make innovation possible in practice'' —Architect

> "Innovation, in comparison to other objectives, was a special item''-Structural Project Manager

Hence, it can be inferred that, at this stage, innovation as an objective had the highest weight among the rest. Therefore, the criteria played a pivotal role in influencing several crucial decisions pertaining to the architecture of the building. The selection of glass as both the structural and facade material for the structure is a notable aspect. The aforementioned choice was undertaken with the aim of achieving the objectives outlined in the research and development (as shown in Table 3.2). In addition, the information regarding the project conveys that, due to the uniqueness of the project, several building constraints were lowered to create a flexible environment for innovation.

> " Given the experimental nature of the structure, there was a degree of flexibility in adhering to the building code, as long as the deviations were deemed acceptable in terms of providing comfort and could be effectively managed within the framework of construction safety and fire safety.''—Client

> "We decided to go for thermal comfort class C, which is the minimum comfort criteria. So, we will allow little discomfort in the building"— Project Manager 1

Hence, it can be inferred that the prioritization of needs such as user satisfaction and the facilitation of events and workshops (one need) were assigned lesser weights in comparison to the objective of establishing a building for 'research & development' purposes (another need). However, like every construction project, this project also involved three inherent objectives, commonly referred to as the iron triangle: the project's cost, time and quality, which are interrelated to each other (Pollack, Helm, & Adler, 2018). Therefore, concerns and questions regarding the cost and feasibility of these innovations and their impact on the three pillars of the iron triangle were also part of the DP. The interviews and project-related documents provided some early design needs that were later excluded from the project plan. This includes the ability to host two programs simultaneously and a fully glass structure; former was excluded due to design-related issues like degradation in acoustic comfort and latter was due to exceeding cost.

Hence, At this stage of the process it can be concluded that objectives pertaining to the budget and user comfort

Interview Objective 2: Stakeholder's take on Tools in decision-making process

Like any other construction project, the stakeholders in the CCC project were involved in the iterative DP, which resulted in its current design. Different parties have employed different tools for making informed decisions and for design optimization. Parties often use tools to optimize for one or more objectives of the building design to make better choices of materials and systems. However, the stakeholders' pointed out that they did not use a tool to understand the trade-off between project objectives.

> " We made calculations of the performance of the systems that we could implement. It was the question of level of performance to control the solar heat gain rejection and the interaction with the glass" —Shading Expert

> "Energy efficiency and level of comfort (visual) were quite critical for this building"—Shading Expert

> "I make decisions based on my personal experience and intuition, commonly referred to as gut feeling." —Glass Expert

Interviewees have shown agreement with the problems that this thesis aims to address, which are conflicting interests and the project's complexity. Typically, stakeholders' tend to focus more on delivering the project with their values, views and principles in the back of their minds. However, interviewees also conveyed that such behavior often results in conflicts with other stakeholders. For instance, a contractor would not want to compromise the promise of their values, like structural strength or smooth project execution, while this may have implications for the aesthetic or flexibility of the building. Another case could be where consistency in the building's color may have more importance than its other configurations, like visual comfort. In such cases, interviewees indicated that they often participate in iterative discussion rounds to find similar grounds to agree upon.

> "We used to have iterative design discussions where (names of the participants) interacted and made decisions for design finalization"—Project Manager 2

A decision that is finalized through interactive decision-making techniques does not necessarily guarantee all stakeholder satisfaction in the process. In such a collaboration technique, stakeholders can easily experience misunderstandings and conflicts due to various reasons, like miscommunication (Søderberg & Romani, 2017), and negative perception. This section analyzes the initial phase of the interview and summarizes the process of making the decision about the existing building. In addition, it not only sheds light on the goals or needs of stakeholders but also provides information regarding their consideration of building components, which is useful for selecting relevant design variables in this project.

2 Stakeholders' Needs & Expectations

This section elucidates the data acquired for model construction. The collated information is subsequently translated into quantifiable objectives that underpin the construction of the mathematical model.

The client delineated the project's needs by formulating design Requirements, which was provided by the Green Village Organization. These needs are bifurcated into two main categories (deduced from Table 3.2):

- needs pertaining to the building's usage.
- needs related to research and development.

Table 3.2: Client's Needs

Building Use	Research and Development
Energy Consumption	Thermal Comfort
Double Program Event Accommodation	Visual Comfort
Carbon Emission	Glass Structure
Circularity	Climate System
Acoustic Comfort	
Flexibility in Space Use	

An overview of the needs and expectations retrieved from the interviews with the stakeholders is provided in Table 3.3.

3 Objective Identification

Following the identification of stakeholders' needs and expectations, the next step involves translating this information into quantifiable objectives. In this context, 'needs and expectations' refer to qualitative information, which may or may not be quantifiable. However, 'objectives', as described in the above chapter, can be quantified and will later be used to set up an optimization problem. For this case study, the following characteristics, as shown in Figure 3.2, of the objectives were employed for translating the needs:

- The chosen objective should serve the purpose of Stakeholder's expectations and requirements from the project.
- The chosen objective is quantifiable.
- The chosen objective has an impact on the DP and the design outcome.
- The required data and/or model related to the chosen objective is available for model construction.

Table 3.3: Interview Outcomes

Stakeholders	Needs & Expectations
Client	1. Research on Sustainable Themes 2. Flexibility in Space 3. Circularity 4. Minimizing Project Cost
Structural Project Manager	1. Project Learning 2. Public Relation 3. Innovation Realization
Shading and Acoustic Supplier	1. Optimum Solution for Solar Heat Gain Control & Glare Prevention
Contractor	1. Minimizing Project's Duration 2. Minimizing Project's Cost 3. Flexibility and Adaptability 4. Aesthetics 5. Sustainability
Climate Expert	1. Passive Climate System
Researchers	1. Thermal Comfort 2. Visual Comfort
Architect	1. Project Learning for Realizing Innovation 2. Collaboration Strategies for Innovation

The chosen objective should have an impact on the design process and the design outcome: The identified stakeholders in this project have emphasized the importance of objectives such as project learning and public relations as major priorities. According to the stakeholders' statements during the interview, the primary goal is to promote collaboration as a means to aid the achievement of heightened creativity and to determine suitable processes and methodologies for developing innovative approaches. However, one may argue that both project-based learning and public relations can be categorized as lagging objectives, as their evaluation often takes place after the end of the respective projects. This evaluation serves to gauge the project's efficacy and the extent of its influence on stakeholders (Vandersleen & Dodia, 2010). It stands to reason that these objectives do not impact the design process. Hence, these objectives are not involved in the optimization problem.

The chosen objective should be quantifiable. For seamless integration into the optimization matrix, objectives demand quantification. The following provides an analysis of this characteristic of the remaining needs.

Flexibility in Space Utilization: This requirement was identified during an interview conducted with Project Manager 1. This stakeholder defines flexibility as the blending of various elements. One primary consideration relates to the utilization of space for the purpose of event organization, specifically emphasizing the need for a flexible building plan. Additionally, it pertains to the adaptability of the building's floor, namely the requirement for detachable flooring to facilitate research and maintenance activities. The purpose of the project also encompasses the consideration of the adaptability of the building component to effectively cater to the requirements of researchers. Therefore, this particular need does not meet the criteria for the optimization issue.

Sustainable Theme Research: Based on the client's list of requirements, this need was identified. The investigation of sustainable themes is a qualitative imperative, as it does not yield additional insights into measurable requirements within the given data. Therefore, this particular need does not meet the criteria for the optimization problem.

Realization of Innovation: The project's primary purpose is to foster innovation, which has garnered interest from numerous stakeholders with varying degrees of involvement. The structure of the building incorporates various new features, such as a glass facade and the utilization of PCMs for climate management. To incorporate this particular purpose into the optimization problem, it is imperative to comprehend the influence of this target on the architectural design of the building as well as its interplay with the remaining

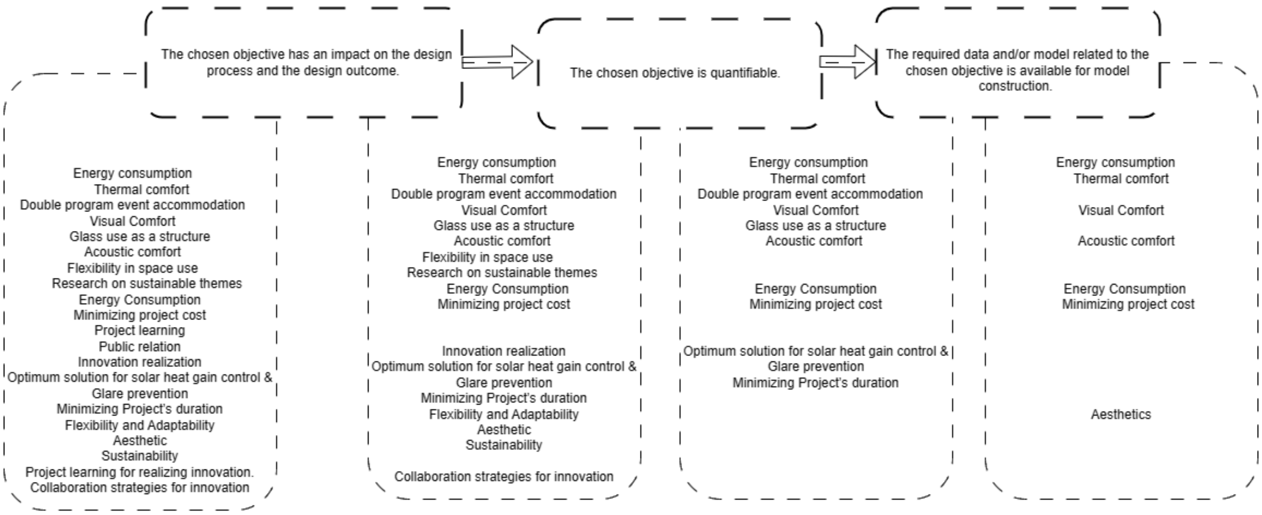


Figure 3.2: Objective characteristics

objectives. The identification of appropriate metrics for assessing innovation enables a deeper understanding of its essence, facilitates the enhancement of performance, and cultivates an environment conducive to fostering innovation (Ponta, Puliga, & Manzini, 2021). Innovation is commonly associated with development, industry leadership, long-term sustainability, and employee engagement. However, astute executives recognize that innovation also entails expenses and potential hazards that necessitate proactive anticipation and management (Bremen, 2023). The determination of the impact of innovation on objectives such as project length requires additional data, such as early cost predictions, as simply comparing it to existing market solutions is insufficient for scaling innovation. One could posit that the necessity of an initial investment is a prerequisite for innovation, hence establishing an inverse relationship between the frequency of innovation and the expense associated with the project.

Collaboration tactics for innovation. This need was discovered through an interview with the project's architect. The objective of the architect is to ascertain the necessary collaborative process and initial considerations that facilitate the practical realization of innovation. This requirement can be classified as qualitative since it does not offer any measurable data. Therefore, this particular need does not meet the criteria for the optimization problem.

Flexibility and Adaptability: The identification of the need was facilitated through email correspondence with the main contractor involved in the project. As per the contractor's statement, the co-creation center should possess the capability to accommodate various forms of co-creation activities and adapt to changing requirements over time. The design should facilitate convenient modification of furniture, equipment, and spatial configurations in order to adapt to evolving needs. Due to the lack of a thorough justification or quantification of this demand from the project participants, it is a non-tangible objective. Therefore, this particular need does not meet the criteria for the optimization issue.

Aesthetics: The aesthetic value of a structure includes the sum of its parts, including but not limited to its form, size, texture, color, balance, unity, movement, emphasis, contrast, symmetry, proportion, space, alignment, pattern, decoration, culture, and context (Ashikhmina & Ashikhmina, 2023). According to the contractor, the Co-creation Center should have an appealing and inspiring aesthetic design. It should create a welcoming and comfortable atmosphere that encourages creativity and innovation. The use of natural light, vibrant colors, and visually pleasing elements can contribute to a positive ambiance. Due to a lack of communication with the architect, the characteristics of aesthetics in the context of CCC have not been established. However, the conducted interview with other stakeholders showed that aesthetics played an important role with regards to the dimensions of height, overhang, color and the overall glass-to-window ratio. Hence, a relative function is assumed, including these characteristics of the building.

Required data and/or model related to the chosen objective is available for model construc-

tion.

Double program event accommodation: This requirement was discovered based on the list of requirements provided by the client. The aforementioned criteria in Dutch can be translated into English as follows: "The building must be able to accommodate a double-program event at the same time. Even if research occupies one part, the other part will have to be available.'. This objective does not qualify for this case study because the necessary model to examine its structural feasibility is not included.

Glass as structural support: no relevant model to study structure feasibility is provided. Hence, this requirement does not qualify for the optimization problem.

Optimum solution for solar heat gain control & Glare prevention: During the interview with the Building Shades Expert, this need was identified. There is no relevant model for studying solar heat gain control and glare prevention. Consequently, this requirement is ineligible for the optimization challenge.

Project's Duration: This requirement is identified through email communication with the project's primary contractor. No relevant example is provided to investigate this requirement. Consequently, this requirement is ineligible for the optimization challenge.

Upon reviewing all the needs of the stakeholders, the list of final objectives which contains the aforementioned three properties are exhibited in Table 3.4.

Table 3.4: List of Final Objectives and Respective Data

Objectives	**DATA**
Thermal Comfort	EnergyPlus
Minimizing cost	BouwKosten.nl & Project data
Aesthetics	Assumptions
Energy consumption	EnergyPlus
Carbon emission	One Click LCA
Acoustic Comfort	Publicly available data
Visual comfort	EnergyPlus

4 Design Variable Selection

Decision-makers frequently encounter situations that require the careful selection of materials, a decision that has a profound impact on both the project's objectives and the overall structural integrity of the building. For example, when choosing a wall material, it is important to look closely at the different properties that come with each option. These properties can affect a number of project goals, such as thermal comfort and cost-effectiveness. Input variables play a critical role in shaping the architectural design and are thus integral to the decision-making process aimed at achieving optimal design solutions. The process is operationalized through the strategic manipulation of these input variables.

In the optimization problem being examined, the design variables can be classified into two distinct categories: continuous and discrete. Continuous variables provide a wide range of design options inside the solution space, but discretizing these factors limits the number of feasible alternatives that may be assessed in order to get an optimal solution (Binnekamp, 2010). However, in real-life situations, the feasibility of the problem depends on various factors, such as cost, labor, availability, etc. For instance, an uncommonly used dimension of a material that is derived for the optimum design may cause problems related to its availability in the market or its customization cost. Significantly, the variables employed in this study are independent and exhibit a static nature, indicating that they do not depend on other aspects, such as time. The selection process of the final design variables was driven by different factors, like stakeholder interviews, conducted studies, and curiosity about the impact. During the interview sessions, stakeholders often present a set of design-related components, which were the topic of discussion in the DP of the CCC.

> "In the original design, we had 3 wall glass and 1 wall non-glass to facilitate different domain of research like, types of facade, insulation material, cladding, interior wall, in the end we solved it by having the surface pavilion next to it." —Project Manager 1

Table 3.5: Variables and their Bounds

Variable Name	Units	Lower Bound	Upper Bound
Window-wall ratio	–	0.01	0.99
Interior Surface Properties	–	0.01	0.99
Overhang Width	m	0.01	3
Building Height	m	-2	2.5
Roof Insulation Thickness	m	0.040	0.200
Floor Insulation Thickness	m	0.060	0.200
Wall Insulation Thickness	m	0.030	0.200
Insulation Type	–	Three Types	

> "The glass size was variable, at the beginning we considered to be 7.2 meter." —Project Manager 1

Apart from that, a study conducted on CCC by van den Engel et al. (2022) shows that reducing the proportion of glass in a building would not only lead to lower heating and cooling demand but also lower the investment and maintenance costs and result in better visual comfort. Additionally, it conveys that a brighter selection of colors would result in less use of lighting in the building. Hence, variables such as window-to-wall ratio and interior surface properties are chosen by curiosity based on their impact on the trade-off process. Therefore, this study aims to generate a balanced solution and analyze the components of the decision-making process rather than understand the impact of these design variables on such building properties. The list of chosen design variables and respective minimum and maximum bounds is shown in Table 3.5.

The determination of the range for design variables is influenced by multiple factors. For variables such as Window-wall ratio, interior surface properties, overhang width, and building height, estimates were obtained through responses to open-ended questions, as indicated in Table 2.2. Some of these variable ranges serve as preliminary design decisions that may be adjusted prior to finalizing the design. For example, the building's initial height was set at 7.2 meters but was later modified to 5.2 meters. The boundaries for the remaining variables are assumed to offer a suitable sample space, facilitating the interaction between variables and objectives. In addition to the selected design variables, elements such as sun protection shades and acoustic wall panels are subject to variation due to changes in the building's dimensions. These variations, in turn, would influence the identified objectives.

The chapter until this section concludes the process of collection and selection of objectives and variables, respectively. In the next section 5, the description and assumption about the employed model and its compatibility, followed by the integration of objectives and design variables, are provided.

5 Problem Formulation

The simulation model employed for the Co-Creation Center (CCC) project originates from the TU Delft CONVERGE project (`www.thegreenvillage.org/project/converge/`) and serves as a case study for this research. The model, depicted in Figure 3.3, utilizes the DesignBuilder software and has been provided by a researcher affiliated with the CONVERGE project. In 2018, the Green Village Foundation, in association with TU Delft, commenced the CCC project. The edifice was intended to function as both an event venue and a research facility and is situated within the Green Village sector of the TU Delft campus.

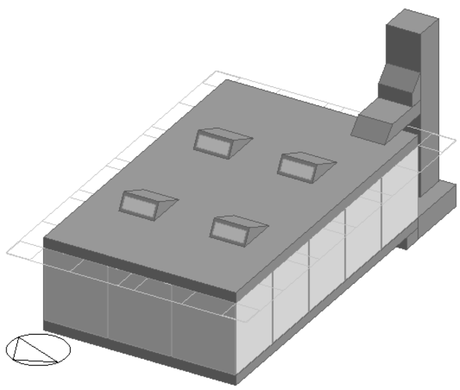


Figure 3.3: DesignBuilder Model

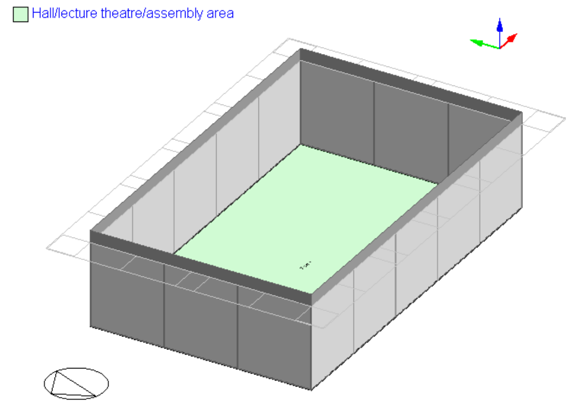


Figure 3.4: Case Study: Block 1, Zone 1

The DesignBuilder model depicted in Figure 3.3 is segmented into 11 distinct blocks that together form the complete model. This study, however, focuses solely on Block 1, which constitutes the primary section of the model, as illustrated in Figure 3.4. The simulation spans a temporal period commencing on January 1st and concluding on December 31st. Geographically, the site is situated at latitude 52.3N and longitude 4.77E. The time zone is denoted by the numerical value '1' while the elevation is registered at -4 meters, indicating a sub-sea-level altitude. The weather file employed for the simulation is sourced from EnergyPlus and is specific to the Netherlands (NLD_Amsterdam_IWEC-epw). The floor area encompassed by the model measures 318 m^2. Table 3.6 enumerates several other parameters employed in the DesignBuilder simulation model.

In addition to the DesignBuilder model, other requisite data for setting up the objectives and performing the optimization is collected from various project participants. This includes documents that outline the client's project needs. It should be noted that some of the data used in this research is confidential. Utmost care has been taken to preserve privacy and comply with ethical guidelines. Due to the sensitive nature of this data and in adherence to confidentiality agreements (Non-Disclosure agreement), explicit details regarding the data source, structure, or specific contents will not be disclosed in this report.

5.1 Objectives Integration

As one of the key components of the optimization problem, defining the objective functions clearly becomes an essential for formulating a problem. To incorporate the objectives listed in Table 3.4 into the optimization problem, this section describes the process on integration of objectives in the optimization framework, in this case MATLAB®.

As one of the key components of the optimization problem, defining the objective functions clearly becomes essential for formulating a problem. To incorporate the objectives listed in Table 3.4 into the optimization problem, this section describes the process of integrating objectives into the optimization framework, in this case, MATLAB®.

As listed in the aforementioned Table 3.4, EnergyPlus simulation platform enables calculations for 3 out of 7 objectives in this study. DesignBuilder provides a platform to analyze EnergyPlus results and, most importantly, to manage and edit simulations conducted within the EnergyPlus software. DesignBuilder is a powerful tool that enables users to create digital models of buildings and simulate their energy use, thermal comfort, HVAC systems, lighting, and other aspects to evaluate their energy efficiency and environmental impact (*DesignBuilder Software Ltd - About Us*, n.d.). During and after the CCC project, assessments for many of the aforementioned needs are conducted in this software. For this project, DesignBuilder does not allow direct paths to co-simulate with MATLAB®, therefore, it can only be used to retrieve the intermediate data format files. EnergyPlus, on the other hand, provides a building energy simulation program to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings (Crawley, Lawrie, Pedersen, & Winkelmann, 2000). The calculations of EnergyPlus are reliable and fast, as they are based on the venerable DOE-2 and BLAST algorithms (Yuan et al., 2022).

Table 3.6: Simulation Parameters (CONVERGE PROJECT)

Category	Parameter	Value
Construction	Glass: U-value	0.531
	Glass: g-value	0.54
	Glass: LT-value	0.72
	Window-frame	Aluminum with thermal break
	Fixed blinds (overhang) width	1.786 m
	Distance between overhang and glass	0 m
	Roof U-value	0.15 W/m^{2}K
	Floor U-value (on the ground)	0.20 W/m^{2}K
	Blinds	Low reflective blinds; block direct solar beams; closed at inside temperature $>$ 23C, opened at $\leq$ 20C; no glare control
Occupancy	Occupancy	240 persons
	Occupancy time	10:00 – 22:00 on workdays
	Metabolism	People standing/walking; clo-value: 1 in winter, 0.5 in summer; total heat production per person: 140 W (sensible and latent heat)
	Heating, Cooling & Ventilation	Only during occupancy time
Heating	Heating capacity	13 kW
	Heating set-point	20C; setback: 20C
	Maximum supply temperature	35C
Cooling	Cooling capacity	35 kW (20 kW from persons, 10 kW from solar, 5 kW from other sources)
	Cooling set-point	26C; setback: 27C
	Minimum supply temperature	18C
Ventilation	Heat recovery	93%
	Mechanical ventilation ACH	3.65 (7 l/s or 25 m^3/h per person during occupancy time - minimum level)
	Extra ventilation ACH	7.3 (14 l/s or 50 m^3/h per person) when indoor temperature $>$ 27C
	Infiltration rate	0.3 m^3/hm^2 at 4 Pa (24/7)
	Underfloor air distribution interior	
Lighting	Normalized power density	1.065 W/100 lux
	Target illuminance	300 lux
	Default display lighting density	7 W/m^2
Weather File	Weather-file	Energy Plus weather-file for the Netherlands (NLD Amsterdam.062400_IWEC-epw)

The software calculates the result values by reading the text-based Intermediate Data Format (IDF) file and generates results in a text-based file. However, it lacks capabilities for managing and editing simulations and for analyzing the outcomes those simulations provide (Gordillo et al., 2020). The conducted literature does not provide any way to integrate MATLAB® and DesignBuilder. Therefore, the study adopts an application programming interface (API), made and presented by Gordillo et al. (2020), which serves to merge energy building simulation (using EnergyPlus) and MATLAB® to perform optimization. For the purpose of simulation, the retrievable *.idf-file from the DesignBuilder model was supported for EnergyPlus version 9.4.0.

The API is compatible with the MATLAB® environment and provides the capability to modify the simulation file before the initiation of each experiment. The Alongside the `*.idf` file, the API's configuration mandates the specification of a weather file, a `*.rvi` file, an installed version of the EnergyPlus software, an output directory, and specified tags, as delineated in the subsequent example figure (refer to Table 3.7).The `EplusLauncher` program scans `*.idf` files, which contain text-based data. During this scanning process, the program identifies specific tags, also referred to as identifiers, within these files. These identifiers are subsequently substituted with different variables.

Table 3.7: EnergyPlus Configuration Parameters

Parameter	Description
InputFile	Path to the IDF file (e.g., 'idfmodeltry2.idf') located in the specified folder.
WeatherFile	Path to the weather file (e.g., 'weather.epw') located in the specified folder.
RviFile	Path to the RVI file (e.g., 'model.rvi') located in the specified folder.
EnergyPlusFolder	Path to the EnergyPlus installation (e.g., 'C:9-4-0').
OutputFolder	Path to the output folder (e.g., 'OutputJob') where the results will be saved.
Tags	Tags to be replaced in the IDF file for specific configurations (e.g., '@@thermal@@;, '@@visible@@', etc.).

Subsequent to each simulation, the Epluslauncher inputs a set of variables chosen by the algorithm in the `*.idf` file as denoted by 'Path 1' in Figure 3.5. Subsequently, pertinent outputs will be extracted via a `.rvi` file in `.csv` format, which will then be further processed using MATLAB's `csvread/readtable` functions. Final, the outputs will be integrated in the PBGA approach in MATLAB as shown in Figure 3.5.

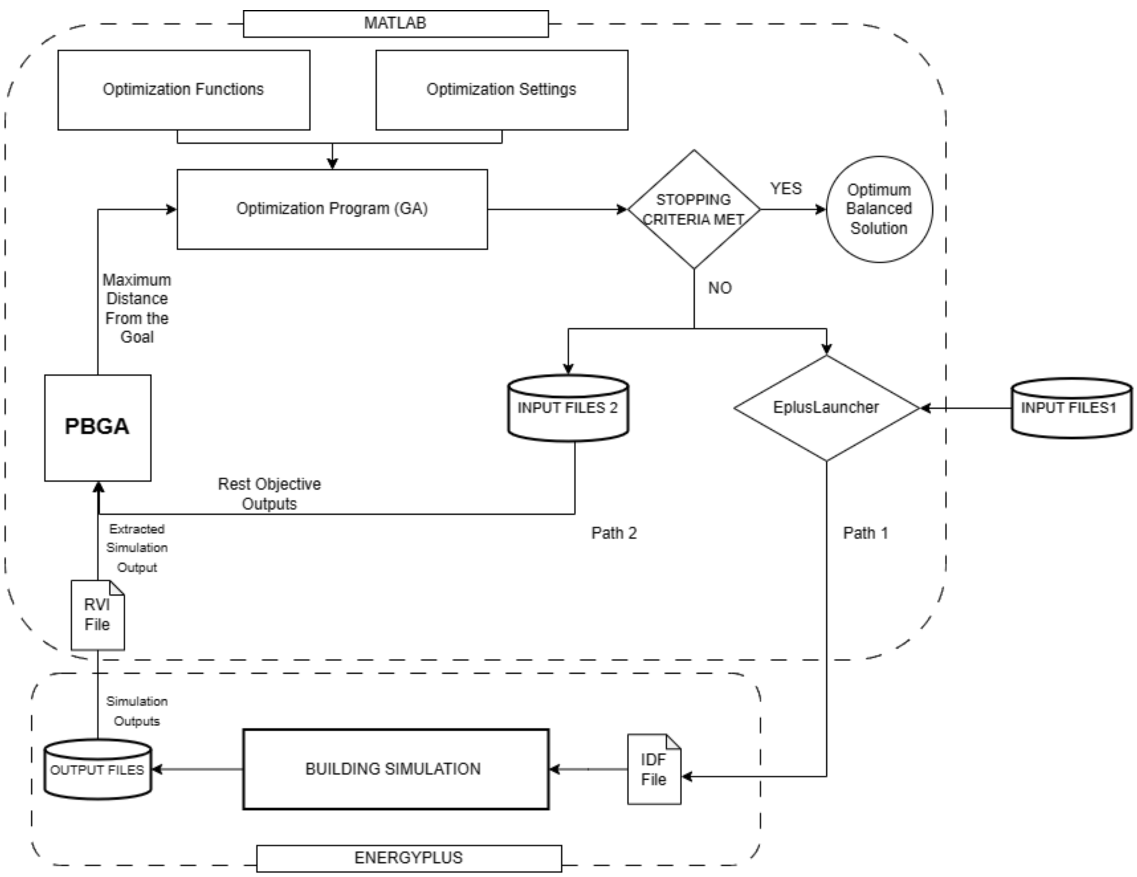


Figure 3.5: Tool Framework

Following elaborate the chosen models for respective objectives constitutes in EnergyPlus in detail:

- **Thermal Comfort:** EnergyPlus offers a spectrum of metrics for evaluating thermal comfort. This includes the KSU Two-Node Model, the Adaptive Comfort Model Based on ASHRAE Standard 55-2010, Adaptive Comfort Model Based on European Standard EN15251-2007, and Fanger Comfort

Model. Among these, the Predicted Percentage Dissatisfied (PPD) index, devised by Fanger (1970) in 1970, is employed to compute thermal comfort for this study. The index is considered suitable for this study for its relatively ease of comprehension for stakeholders, allowing them to readily understand its background and input their preferences. This index quantitatively assesses the fraction of occupants who are thermally unsatisfied, be it due to excessive warmth or cold. PPD essentially reflects the percentage of occupants expected to experience discomfort (Guenther & Guenther, 2023). Theoretically, PPD values range from 0 to 100, where 0 signifies complete satisfaction with the room's thermal conditions, and conversely, 100 represents complete dissatisfaction. In the current scenario, the PPD value is obtained from the `eplusout.csv` file generated in the output directory using MATLAB®'s `readtable` function. This process serves the role of objective function for this particular objective.

- **Energy Consumption:** Evaluating energy consumption in buildings is complex, requiring a nuanced understanding of the interactions between the structure, HVAC systems, and external climate, along with effective mathematical models for accurate characterization (Fumo, Mago, & Luck, 2010). The cumulative energy consumption in this case encompasses the heating, cooling, and lighting expenditures of the building. The building is powered by an electricity grid in conjunction with partial energy generation from its photovoltaic (PV) panels. For this case study, the EnergyPlus model does include the energy production by the PV panel. Analogous to thermal comfort, the total energy consumption value is harvested from the `eplustbl.csv` file in the output directory, utilizing the `readtable` function in MATLAB®. The energy consumption is extracted in the unit of `KWh`, and this process serves as the objective function for caliberating a building's energy consumption.

- **Visual Comfort:** EnergyPlus primarily calculates two metrics: Daylight Glare Index (DGI) and Horizontal Illuminance (lx). The software employs the Split-flux method for these calculations, accounting for factors like shading geometry, solar radiation vectors, and reference point orientation (DoE, 2009). The method of glare is defined as the incidence of inordinate light intensity within the visual field, leading to either discomfort or reduced visual clarity (I, 2020). However, Tabadkani, Tsangrassoulis, Roetzel, and Li (2020) pointed out that the DGI metric functions accurately only under conditions of uniform lighting, and its accuracy is compromised when subjected to direct sunlight or non-uniform light sources within the field of view. In terms of the rational aspect of visual comfort, glare metrics play an important role as they involve the conditions and subjective responses of the occupants locally. On the other hand, illuminance is the measure of light level at a specific point on a surface, calculated as the ratio between the incoming light and the area around that point (Tabadkani et al., 2020).

This concludes the list of objectives which are computed by EnergyPlus. Next, the rest of the objectives are computed within MATLAB environment.

Following enlist the details regarding the objective which are computed within MATLAB, denoted as Path 2 in Figure 3.5:

- **Minimizing Cost:** Owing to discrepancies and issues of confidentiality, the cost data pertinent to the project under consideration is approximated from the publicly accessible database `Bouwkosten.nl`, which furnishes cost information for construction and infrastructure projects in the Netherlands. In the present model, only the material costs are considered for optimization objectives. Expenditures related to transportation, labor, and material customization are explicitly excluded from the cost-optimization scope of this study. The unit cost details of the variable materials are delineated in Table 3.8.

  To perform an optimization with cost minimization as one of the objectives, the objective function for the cost is formulated based on the change in material volume and material type due to the input variables. The code added in MATLAB® aims to compute the alteration in the cost of several elements in the modeled project. Specifically, it focuses on the materials subjected to facade windows, walls, acoustic panels on the walls, insulation on the floor, wall, and roof, and finally the overhangs. For each element, the code considers material costs and dimensions to arrive at an overall project cost. The structure of the code can be broken down as follows:

  - **Defining terms of the cost inputs:**
    - `Gprice` represents the cost per square meter of glass.

Table 3.8: Cost Overview

Material	Unit	Cost/unit
Triple façade glass	m^2	600
Concrete Block	m^2	1.34
Brickwork	piece	0.09178
Gypsum Plasterboard	Kg	0.63
Aluminium (overhang)	m^2	75.75
XPS insulation	m^3	426.5
PIR insulation	m^3	1098.89
PIR insulation	m^3	185.625
Wall Acoustic Panel	m^2	20.4
Venetian Blinds	m^2	88.91

  * `Concrete_block`, `Brickwork_outer`, `Gypsum_Plaster`, `Wall_acousticpanel`, and `Blinds_cost` denote the respective costs per unit area, per piece, or per kilogram of various construction materials.
  * `Gypsum_Plaster_Thickness` and `Gypsum_Plaster_Density` are utilized to calculate the required amount of gypsum plaster.
  * Variable d and `overhang_length` serve to compute the total overhang area (`overhang_area`).
  * `Cost_overhang` calculates the cost associated with the overhang area.
  * `FinsulThckness_cost`, `RinsulThcknessXPS_cost`, `RinsulThcknessEPS_cost`, `RinsulThcknessPIR_cost`, and `Winsulthckness_cost` are used to calculate the cost of insulation based on thickness.
  * `Cost_other` represents other costs not categorized.
  * `Cost_Objective` is the sum of `Cost_other` and `Cost_escalation` for subsequent optimization.

- **Objective function for cost:**
  * `Cost_Objective` is the summation of the cost of varying elements and the cost of unchanged elements. Due to confidentiality and discrepancies in the obtained data, the cost of unchanged elements is an approximation estimation which is equal to 633177.62 euros. This value serves the purpose of ease of understanding the impact of preferences on the cost objective.

$$C = C_{\text{glass}} + C_{\text{wall}} + C_{\text{overhang}} + C_{\text{insulation}} + C_{\text{Blinds}} + C_{\text{unchanged material}} \tag{3.1}$$

Where each component is defined as:

$$C_{\text{glass}} = (S1 + S2 + S3 + S4) \times \text{Gprice} \tag{3.2}$$

$$\begin{aligned} C_{\text{wall}} = SWall \times \Big(&\text{Concrete\_block} + \text{Winsulthckness\_cost} \\ &+ \frac{\text{Brickwork\_outer}}{0.21} \\ &+ \text{Gypsum\_Plaster\_Thickness} \times \text{Gypsum\_Plaster} \times \text{Gypsum\_Plaster\_Density} \\ &+ \text{Wall\_acousticpanel}\Big) \end{aligned} \tag{3.3}$$

$$C_{\text{overhang}} = \text{Cost\_overhang} \tag{3.4}$$

$$C_{\text{Floor and roof insulation}} = SFnR \times \text{FinsulThckness\_cost} + SFnR \times \text{cost} \tag{3.5}$$

$$C_{\text{Blinds}} = (S1 + S2 + S3 + S4) \times \text{Blinds\_cost} \tag{3.6}$$

$$C_{\text{unchanged material}} = \text{Cost\_other} \tag{3.7}$$

Where:

Symbol	Meaning
$S1, S2, S3, S4$	Surface area of windows on respective walls
$Gprice$	Unit price of glass
$SWall$	Surface area of the project wall on Wall 1
$Concrete\_block$	Cost per m^2 of Concrete Block
$Winsulthckness\_cost$	Cost per m^2 of wall insulation
$Brickwork\_outer$	Cost per piece of 0.21m thick Brick in the wall
$Gypsum\_Plaster\_Thickness$	Thickness of Gypsum Plaster in m
$Gypsum\_Plaster$	Cost per kg of Gypsum Plaster
$Gypsum\_Plaster\_Density$	Density of Gypsum Plaster in kg/m^3
$Wall\_acousticpanel$	Cost per m^2 of acoustic panel
$Cost\_overhang$	Overhang costs
$FinsulThckness\_cost$	Cost per m^2 of floor insulation
$SFnR$	Surface area of Floor and Roof
$cost$	Cost per m^2 of roof insulation
$Blinds\_cost$	Cost per m^2 of blinds
$Cost\_other$	Cost of unchanged building parameters

The costs data for different types of insulations used in the roof, floor and wall are provided in Figure D.1.

- **Acoustic Comfort:** Acoustic comfort in a building is primarily determined by the reverberation time within its closed environment (Ciaburro & Iannace, 2021). In this study, the reverberation time, denoted as $RT60$, is computed using Sabine's equation. The reverberation time is influenced by the volume of the room and the cumulative amount of sound absorbed by all its internal surfaces (Sabine & Egan, 1994). Table 3.9 presents the average absorption coefficients for the room's interior surfaces, calculated at frequencies of 125, 250, 500, 1000, and 2000 Hz.

$$T60 = 0.161 \times \frac{V}{\sum_{i=1}^{N} \alpha_i \times S_i} \tag{3.8}$$

Where:

- $T60$ is the time (in seconds) for a sound to decay by 60 dB.
- 0.161 is a constant (s/m).
- V represents the volume of the room in m^3.
- α_i is the i-th sound absorption coefficient.
- S_i is the i-th surface area in m^2 with an absorption coefficient of α_i.

Symbol	Description	Average absorption coefficient
a_{IS}	Wood wool acoustic panel	0.62
a_1, a_2, a_3, a_4	triple glazed glass	0.066
a_{ceiling}	Ceiling elements	0.3660
a_{Floor}	Floor elements	0.4860

Table 3.9: Variable definitions and equations for acoustics

The wood wool employed over the project wall is 25mm thick and is subjected to vary with varying dimensions of the project wall. The α value of wood wool are attached in Figure I.1. Further, the α for the ceiling and floor are obtained from the research by Hamida and Ding (2021) on the co-creation centre.

- **Aesthetics Index (AI):** AI is based on three different aspects: the window-to-wall ratio, the overhang width, and the change in building height. These three factors are combined linearly using specific weights to obtain the final aesthetic index A. The weights indicate the significance of each factor in determining the overall aesthetic appeal of the building.

  The Aesthetic Index A is computed as:

  $$A = w_1 \times A_1 + w_2 \times A_2 + w_3 \times A_3$$

  It is assumed that these factors and their respective weights are adequate to quantify the aesthetic elements contributing to the overall comfort and visual appeal of the building or room.

- **Embodied Carbon Emissions (ECE):** This study employs One Click LCA software to collect the Environmental Product Declaration (EPD) data for computing the CO_2 emissions for the building elements. The software holds multiple certifications and complies with standards like LEED and BREEAM for LCA (Bounds, 2023). The data includes the emissions of the materials' product stage which encompasses raw material supply, transportation, and Manufacturing. Thereby, it does not include the later stage of materials' life cycle. EPDs of some of the materials, as available in the software, can be found in the Appendix G. Further, the full names of material adopted from One Click LCA are listed in Figure G.3.

Table 3.10: CO2 Emissions Overview

Material	**(kg CO2e/Unit)**	**CO2 Emission (kg CO2e/m2)**
Triple façade glass	m^2	70
Concrete Block	m^3	67.715
Brickwork	m^3	113
Gypsum Plasterboard	Kg	0.2
Aluminium (overhang)	m^2	7.5
XPS Insulation	m^3	69.6
PIR Insulation	m^3	278.5
EPS Insulation	m^3	103.1
Acoustic Panel	m^2	5.49
Venetian Blinds	m^2	132

  - **Defining terms of the CO2 inputs:**
    * `G_ece` represents the CO2 emissions per square meter of insulating glass unit with laminated glass and argon cavity filament.
    * `Concrete_ece`, `Brickwork_ece`, `PlasterBoard_ece`, `Overhang_ece`, `Roof_ece`, `Acoustic_panel_ece`, and `Blinds_ece` denote the CO2 emissions in kg CO2e/m2 for various construction materials.
  - **Objective function for CO2 emissions:**

  $$\text{ece\_Change} = ECE_{\text{glass}} + ECE_{\text{wall}} + ECE_{\text{overhang}} + ECE_{\text{insulation}} + ECE_{\text{Blinds}} \tag{3.9}$$

  Where each component is defined as:

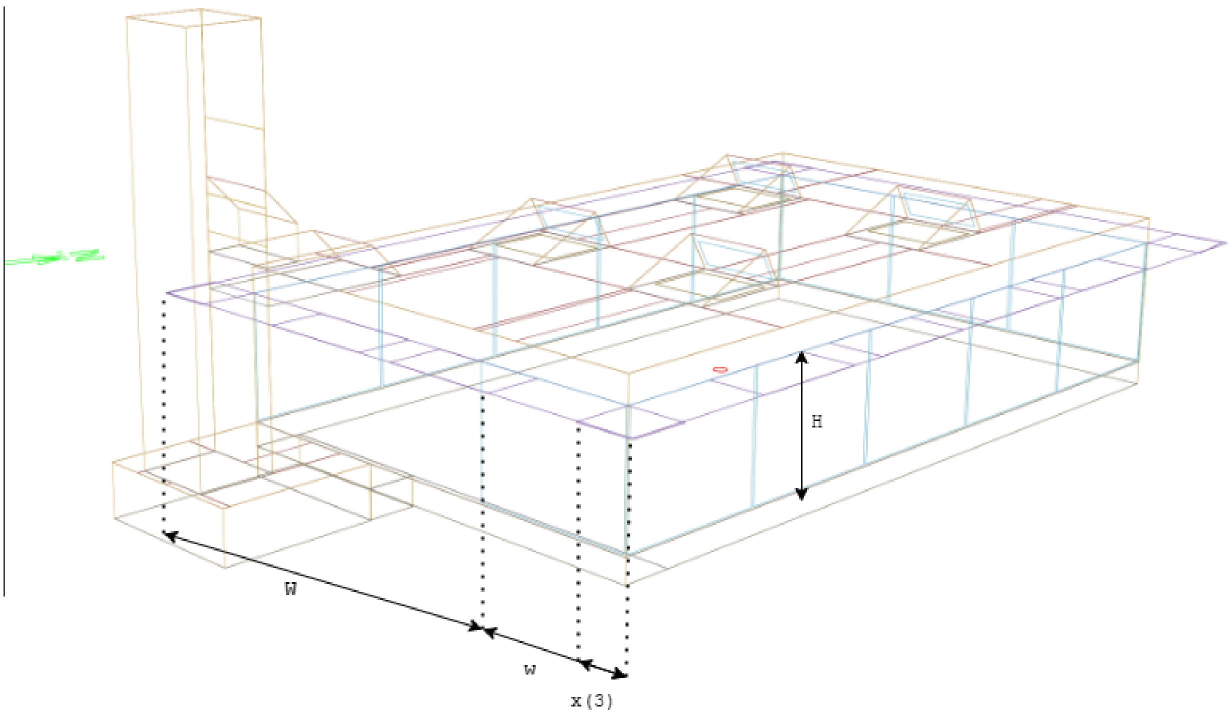


Figure 3.6: Dimension Variables representation

$$ECE_{\text{glass}} = (S1 + S2 + S3 + S4) \times G\_ece \tag{3.10}$$

$$ECE_{\text{wall}} = SWall \times \Big(Concrete\_ece + Brickwork\_ece + PlasterBoard\_ece + Winsul\_ece + Acoustic\_panel\_ece\Big) \tag{3.11}$$

$$ECE_{\text{overhang}} = \text{Overhang\_ece} \times \text{overhang\_area} \tag{3.12}$$

$$ECE_{\text{Insulation}} = Finsul\_ece \times SFnR + Roof\_ece \times SFnR \tag{3.13}$$

$$ECE_{\text{Blinds}} = (S1 + S2 + S3 + S4) \times Blinds\_ece \tag{3.14}$$

where: (Due to similarities with the calculations of cost objective, terms pertaining to surface areas are referred in Equation 5.1.)

The section provides detailed explanation for each objective function included in this study. The next section underlines the details related to the design variables employed in this study.

5.2 Integration of Design Variables

The data retrieved for this study includes the building's model in a rectangular shape, maintaining constant floor and roof areas. As described above, the EplusLauncher's 'tags' feature provides an avenue to modify the EnergyPlus `*.idf.file`, offering a wide range of possible variables. These variables encompass different material types, each having diverse properties like roughness, thickness, conductivity, density, specific heat, thermal emittance, solar absorptance, and visible absorptance. Furthermore, several other components can be introduced as potential design variables, allowing this study to incorporate different dimensions of the building components.

For this case study, the following variables are defined:

- $x(1)$ - Represents the window-to-wall ratio of the south-west side of the building. In the `*.idf.file`, this variable is implemented using 'tags' that control the coordinates of the surface 'Block1:Zone1_Wall_2_0_0_0_0_2_Win'. The tags '@@WX@@' and '@@WY@@' are employed in the file to adjust the window's coordinates, particularly varying its width without altering the building's height. As shown in Figure 3.6, the `W` and `w` represents the varying width of the wall and window respectively. This continuous variable ranges between 0.01 and 0.99.

- $x(2)$ - Refers to internal surface properties such as thermal emittance, solar absorptance, and visible absorptance of the roof and floor's inner exposed material. The associated tags are '@@thermal@@', '@@solar@@', and '@@visible@@'. All these properties, discrete in nature, range from 0 to 1.

- $x(3)$ - A continuous variable defining the overhang's width, ranging between 1 to 2 meters. The width of the overhang ($x(3)$) of one of the sides of the building is shown in the Figure 3.6. The tags to vary this dimension are given as '@@O1X1@@', '@@O1Y1@@',, '@@O1X2@@', '@@O1Y2@@','@@O2X1@@', '@@O2Y1@@', '@@O2X2@@', '@@O2Y2@@', '@@O3X1@@', '@@O3Y1@@', '@@O3X2@@', '@@O3Y2@@','@@O4X1@@', '@@O4Y1@@', '@@O4X2@@', '@@O4Y2@@', '@@O5X1@@', '@@O5Y1@@', '@@O5X2@@', '@@O5Y2@@', '@@O6X1@@', '@@O6Y1@@', '@@O6X2@@', '@@O6Y2@@','@@O7X1@@', '@@O7Y1@@', '@@O7X2@@', '@@O7Y2@@','@@O8X1@@', '@@O8Y1@@', '@@O8X2@@', '@@O8Y2@@', '@@O9X2@@', '@@O9Y2@@','@@O11X1@@', '@@O11Y1@@', '@@O12X2@@', '@@O12Y2@@', '@@O16X1@@','@@O16Y1@@'.

- $x(4)$ - Defines the building's height change and is represented in MATLAB® as x(4). This continuous variable can adjust the building's current height of 5.2 meters by -2 to +2.5 meters. the height of the building is shown as `H` in Figure 3.6 which is 5.2 meters in the existing model. Tags for this variable include '@@H1@@', '@@H2@@','@@H3@@', '@@H4@@', '@@H5@@', '@@H6@@', '@@H7@@','@@H8@@', '@@H9@@', '@@H10@@', '@@H11@@', '@@H12@@', '@@H13@@', '@@H14@@', '@@H15@@', '@@H16@@', '@@H17@@', '@@H18@@', '@@H19@@', '@@H20@@', '@@H21@@', '@@H22@@', '@@H23@@', '@@H24@@', '@@H25@@','@@H26@@'.

- $x(5)$, $x(6)$, and $x(7)$ - The thicknesses of insulations' used in the roof, floor, and wall respectively. Specifically,

  - $x(5)$ ranges from 40 to 200 mm,
  - $x(6)$ ranges from 60 to 200 mm, and
  - $x(7)$ ranges from 30 to 200 mm.

  These variables are discrete in nature. The tags used for these variables in the EnergyPlus `*.idf` file are denoted as `@@RFInsulThickness@@`, `@@FloorInsulThickness@@`, and `@@WallInsulThickness@@` respectively.

- The last variable, pertaining to the type of roof insulation, is defined as $x(8)$ and is also discrete in nature. This variable can take three types of roof insulation:

  1. Extruded Polystyrene Insulation (XPS),
  2. PTR rigid foam Insulation
  3. Expanded Polystyrene Insulation (EPS)

  All three types of insulation have varying insulation thicknesses derived from variable $x(5)$, classifying them as mutually dependent. Table 3.11 presents the material properties of these insulation.

This section concludes the design variables used for this research. The section 4 enlist the variables and their respective bounds.

Table 3.11: Material Properties

Material properties	**XPS**	**PTR**	**EPS**
Thickness (mm)	$x(5)$	$x(5)$	$x(5)$
Conductivity (w/m-K)	0.034	0.023	0.033
Density (kg/m3)	35	40	35
Specific Heat (J/kg K)	1400	1400	1131
Thermal Emittance	0.9	0.9	0.9
Solar Absorptance	0.6	0.6	0.6
Visible Absorptance	0.6	0.6	0.6

5.3 Finding Maxima & Minima of the Objective Functions

The process of identifying the range—specifically, the maxima and minima—of each objective function necessitates the optimization of each objective individually, subject to the variables delineated in the preceding chapter. Within this context, the term 'minima' is employed to indicate the point at which stakeholder satisfaction reaches its lowest level, whereas the 'maxima' denotes the point that is most favored by stakeholders. The range within which each objective function operates is cataloged in Table 3.12.

Table 3.12: Objective Bounds

Objectives	Unit	**Minima**	**Maxima**
Thermal Comfort	-	92.38	81.07
Cost minimization	Euros	1055236.07	7766270.00
Energy Consumption	KWh	28186.72	20793.33
Visual Comfort (Illuminance)	lx	250.17	5096.96
Visual Comfort (Glare)	DGI	16.68	8.41
Acoustic Comfort	Seconds	1.42	0.65
Aesthetics Indox	-	0.05	1.00
Embodied Carbon emission	Kg CO2e	138820.02	42223.01

5.4 Generation of Preference curves

To construct a preference curve for each objective, at least three desired preference scores are needed. In that case, two of these points correspond to the maximum and minimum bounds, while the third point represents the intermediate desired outcome of the objective functions. For instance, Figure 3.7 illustrates a preference curve based on a three-point configuration, the scores for which are detailed in Table 3.13. Alternatively, Figure 3.8 presents a more nuanced five-point preference curve that incorporates three intermediate points; these scores are likewise enumerated in Table 3.13. Appendix H includes the plots of all the preference curves for this study.

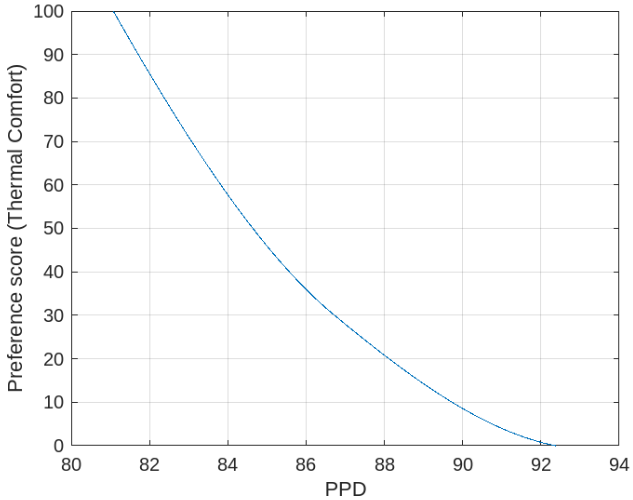


Figure 3.7: Thermal Comfort

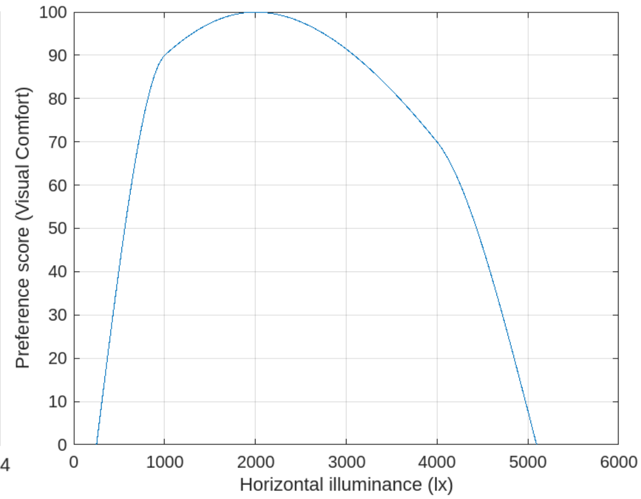


Figure 3.8: Visual Comfort

Table 3.13: Preferences for Each Objective

Objective	Bound	Value	Preference scores
Thermal Comfort	Maxima	81.07340707	100
	Intermediate	86.72652748	30
	Minima	92.37964989	0
Energy Consumption	Maxima	20793.33	100
	Intermediate	26000	40
	Minima	28186.72	0
Acoustic Comfort	Maxima	0.648030313	100
	Intermediate	1.033359039	40
	Minima	1.418687765	0
Cost Minimization	Maxima	766270	100
	Intermediate	916020	30
	Minima	1055236.07	0
Visual Comfort (Glare)	Maxima	7.8866	100
	Intermediate	12.665	80
	Minima	16.926	0
Visual Comfort (Illuminance)	Maxima	250.17	0
	Int1	1000	90
	Int2	2000	100
	Int3	4000	70
	Minima	5096.96	0
Aesthetics Index	Maxima	0.9980	100
	Intermediate	0.3218	80
	Minima	0.0535	0
Embodied Carbon Emission	Maxima	42223.01	100
	Intermediate	84447	70
	Minima	138820.02	0

5.5 Weights Distribution

The weights distribution among the objectives can be used to represent the prioritise of the objectives pertaining to respective stakeholders as shown in Figure 3.9. In this scenario, the weights among stakeholders and their prioritization of respective objective functions are kept equal. Hence, the overall weights for each objective will be determined by how many objectives that particular stakeholder has (as shown in Figure 3.9). Contrarily, these weights can also be used to define stakeholders' power in the decision-making process as shown in Table 3.14 where each row represents different scenario which single stakeholder holding all the power.

Mathematical, the summation of all weights is equal to 1 as shown below:

$$w_{\text{Energy consumption}} + w_{\text{Thermal comfort}} + w_{\text{Acoustic Comfort}} + w_{\text{Cost minimization}} + w_{\text{Illuminance}} + w_{\text{Glare}} + w_{\text{Aesthetic Index}} + w_{\text{Carbon Emission}} = 1$$

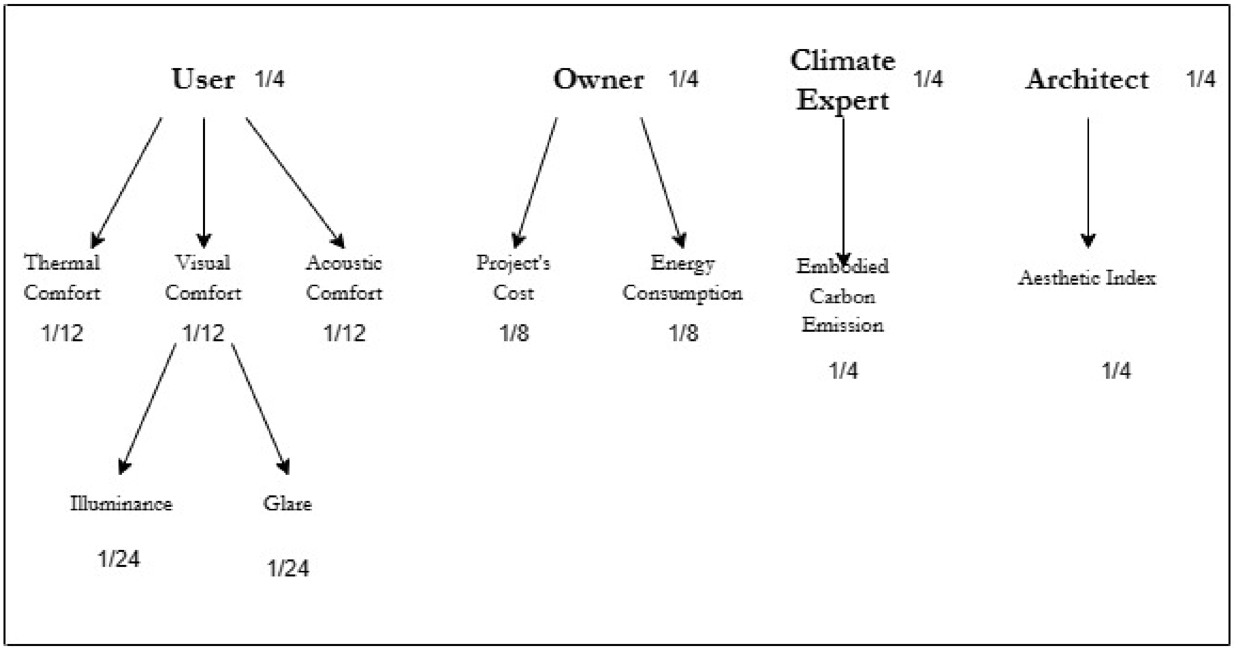


Figure 3.9: Balanced Weights Scenario (BWS) Distribution

Objectives	**User**	**Owner**	**Climate Expert**	**Architect**
Cost minimization	0	1/2	0	0
Thermal Comfort	1/3	0	0	0
Energy Consumption	0	1/2	0	0
Glare	1/6	0	0	0
Illuminance	1/6	0	0	0
Aesthetics Index	0	0	0	1
Carbon Emission	0	0	1	0
Acoustic Comfort	1/3	0	0	0

Table 3.14: Unbalanced Weights for Different Scenarios

5.6 Generation of Balanced Optimum Design

In this study phase, the Genetic Algorithm (GA) is employed to generate an optimal design alternative for the building. The term "optimal" is used to denote a near-optimal solution, as GA aims for the most optimal outcome but acknowledges the potential for better solutions through further parameter optimization. Multiple simulations are essential for a robust conclusion.

For the implementation of the GA, specific numerical parameters are configured using the `optimoptions` function. These include a `PopulationSize` of 60, `MaxGenerations` set to 70, `MaxStallGenerations` at 10, and `EliteCount` configured as 6. These parameters guide the GA's search through the design space, thereby influencing the quality and characteristics of the resulting near-optimal solution.

In MATLAB, GA aims to minimize any function assigned to it. Therefore, The fitness function Opt is defined which aims to find the maximum distance (λ) from the goal (100). Hence, Opt is defined as:

$$\text{Opt} = \max\Big(w_{\text{EC}}\lambda_{\text{EC}}, w_{\text{TC}}\lambda_{\text{TC}}, w_{\text{AC}}\lambda_{\text{AC}}, w_{\text{CM}}\lambda_{\text{CM}}, w_{\text{I}}\lambda_{\text{I}}, \\ w_{\text{G}}\lambda_{\text{G}}, w_{\text{AI}}\lambda_{\text{AI}}, w_{\text{CE}}\lambda_{\text{CE}}\Big)$$

And, The optimization problem can be formulated as:

$$\min_{w,\lambda \in S} (\text{Opt}) \tag{3.15}$$

where λ is the array the distances of the preferences of each objective from the goal functions, defined as $\lambda = 100 - \text{Objective\_m}$. And, S is the feasible set defined as $0 \leq w_i \leq 1$ for all i and $\lambda_{\min} \leq \lambda_i \leq \lambda_{\max}$ for all i.

Here, EC stands for Energy Consumption, TC for Thermal Comfort, AC for Acoustic Comfort, CM for Cost Minimization, I for Illuminance, G for Glare, AI for Aesthetic Index, and CE for Carbon Emission.

Chapter 4: Results & Evaluation

1 Model Results and Interpretation

The design parameters and the optimal value of the fitness function obtained from the input parameters employed in section 5 took approximately 22h on computer with Windows 10 system (Intel(R) Core(TM), 2.50GHz CPU). In this case, the results obtained are shown in the Table 4.1. The obtained design from GA shown consistent value of fitness function for 5 consecutive `generations`.

Table 4.1: Results: BWS

	Components	Unit	Current design	Generated design
Objectives	Cost minimization	Euro	9.16E+05	8.18E+05
	Thermal Comfort	PPD	9.02E+01	8.41E+01
	Energy Consumption	KWh	2.44E+04	2.34E+04
	Glare	DGI	1.57E+01	8.48E+00
	Illuminance	lx	1.05E+03	3.16E+03
	Aesthetics Index	-	4.31E-01	3.53E-01
	Carbon Emission	Kg Co2e	8.44E+04	5.82E+04
	Acoustic Comfort	Seconds	1.04E+00	7.53E-01
	-	Weights (w_i)	$w_i * \lambda_i$	$w_i * \lambda_i$
Weighted Distances of Preferences from goal ($w_i * \lambda_i$)	Cost minimization	1/8	3.75	0.72
	Thermal Comfort	1/12	7.69	3.6
	Energy Consumption	1/8	4.67	3.08
	Glare	1/24	2.96	0.02
	Illuminance	1/24	0.38	0.47
	Aesthetics Index	1/4	0.84	4.54
	Carbon Emission	1/4	7.99	2.26
	Acoustic Comfort	1/12	5.07	1.53
	Maximum distance	-	7.99	4.54
Variables	Window-wall ratio	-	0.99	.99
	Interior Surface Properties	-	0.97	0.01
	Overhang Width	m	1.78	1.01
	Building Height factor	m	0	-1.79
	Roof Insulation Thickness	m	0.20	0.19
	Roof Insulation Thickness	m	0.16	0.06
	Wall Insulation Thickness	m	0.08	0.19
	Roof Insulation Type	m	XPS	EPS

As mentioned in the subsection 1.3, the balanced design generated by PBGA comes from the trade-off among stakeholders' objectives. The values, which show an increment in the weighted distances, are an easy way to identify these trade-offs. Hence, in this case, Glare has realized an increment in the DGI value; however, as shown in the Table 3.13, a preference score of 80 was assigned to the DGI value of 12.665. which implies that this trade-off is realized without large implication on the glare objective as it has a near-highest satisfactory preference score as shown in the Figure H.7. In Figure 4.1, the obtained preferences score of each objective are represented as green cross. It can be observe from these graphs that all the preference score in this case are generated above the intermediate point provided by the stakeholders. Each plot can be distinguished by comparing the units of respective objective function from the Table 4.1.

As detailed in Table 4.1, the 'Maximum Distance' row quantifies the furthest objective distance in relation to its weight. Within the present design, energy consumption exhibits the largest weighted distance at 7.69. In contrast, in the new design, the largest weighted distance takes precedence with a value of 4.54. As described in Figure 2.6, the method seeks to equalize satisfaction among stakeholders by drawing the most distant objective closer to the goal while also pushing the objectives closer to the goal further away. The resulting design reduces the satisfaction disparity by 3 points.

Let's contemplate the real numbers: the new design results in a cost reduction of roughly 81.5 thousand euros. Given the simplicity of this computation, the reductions can be attributed to changes in the building height and overhang width. This observation is mirrored in the carbon emission objective. Notably, for both designs, the PPD values, indicative of thermal comfort, surpass the acceptable range. This discrepancy suggests potential anomalies in the employed model, further corroborated by Table 3.12, which highlights a narrow objective range between 81 and 92.4. As objective preferences fall within this range, the solution inevitably lies therein. A comparative analysis between the current and new PPD values indicates an improvement in thermal comfort of roughly 54 % in the new design. However, without multiple simulations, identifying the cause of this improvement is challenging. Objectives such as energy consumption and acoustic comfort also show enhanced values in the new design.

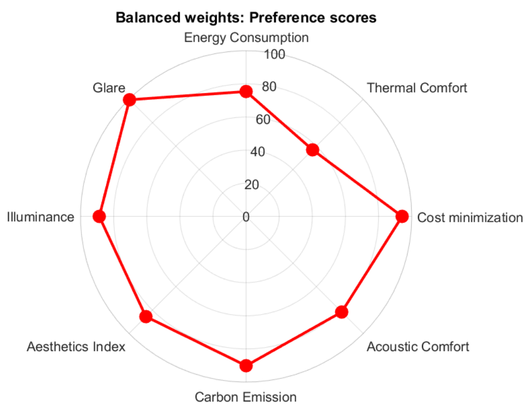


Figure 4.2: Preference scores for BWS

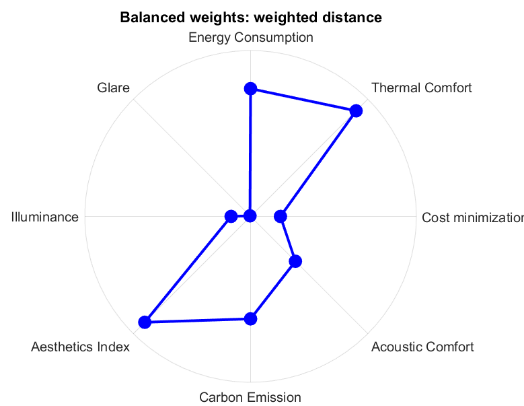


Figure 4.3: Weighted Distances for BWS

As highlighted in subsection 1.3, the design produced by PBGA reflects the balance of stakeholder objectives. A clear method to identify these trade-offs is by observing changes in weighted distances. In this context, there's an observed increase in the DGI value for glare. As shown in Table 3.13, a DGI value of 12.665 was given a preference score of 80. This suggests that the trade-off doesn't have a big effect on the glare objective, which is also supported by the fact that it has a high satisfaction score in Figure H.7. This phenomenon can be understood by not only comparing the preferences but also their weighted distances, as they are used for optimization purposes. By comparing the preferences' scores on each objective in Figure 4.2 their corresponding weighted distances in Figure 4.3, the basis of the results generated by the method becomes more clear. For instance, the maximum weighted distance, which is farthest from the goal and fundamentally captured by the PBGA method to minimize, is thermal comfort and the obtained preference score for this objective is the least among others.

In order to find the extreme points of the solution space of this optimization problem, the weights distribution described in Table 3.14 is employed. The results for each of these scenarios are presented in Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7.

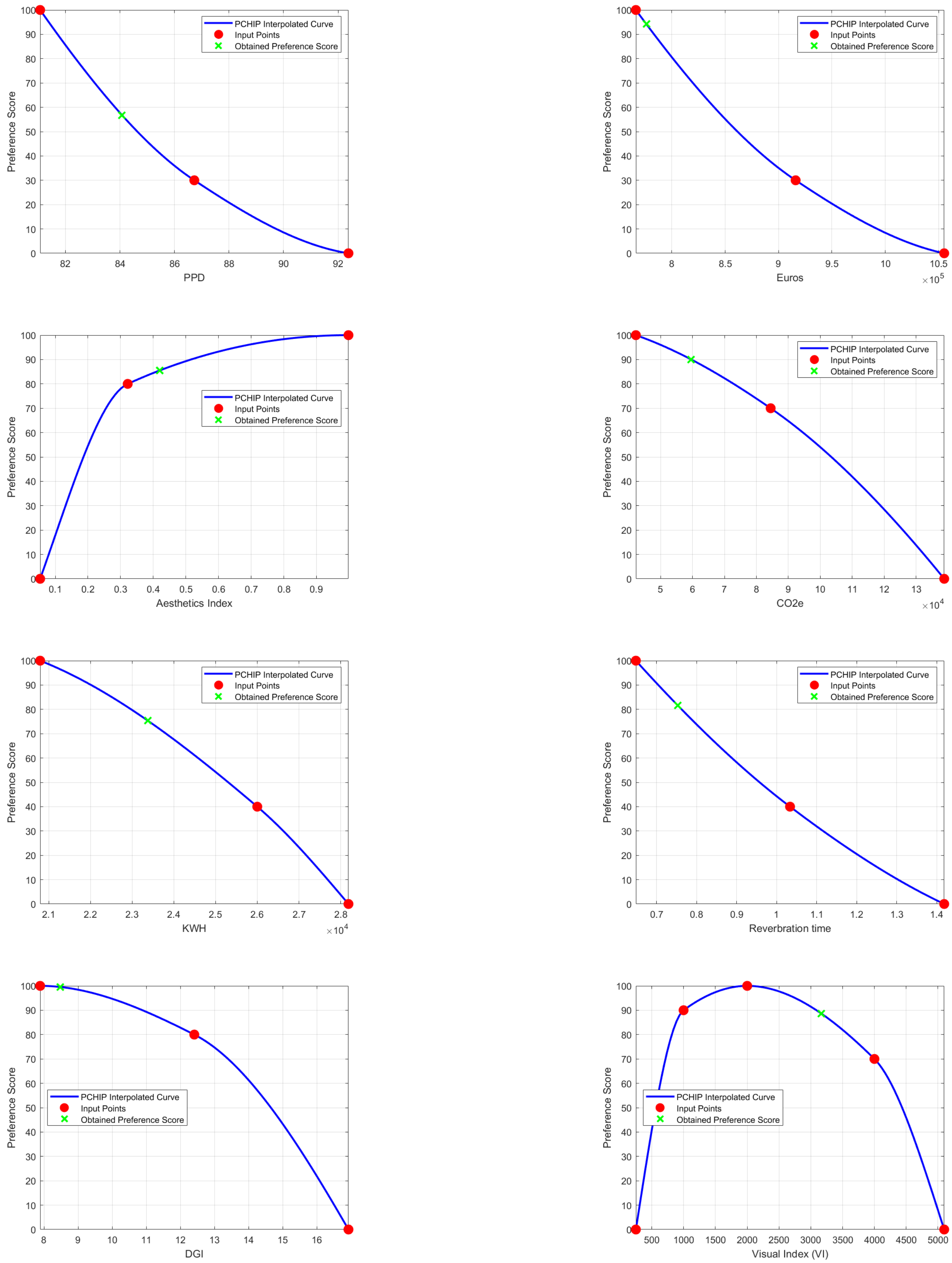


Figure 4.1: Visual representation of obtained Obtained preferences scores

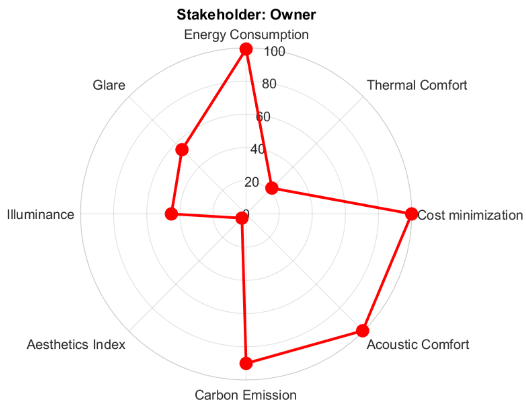


Figure 4.4: Scenario: Owner

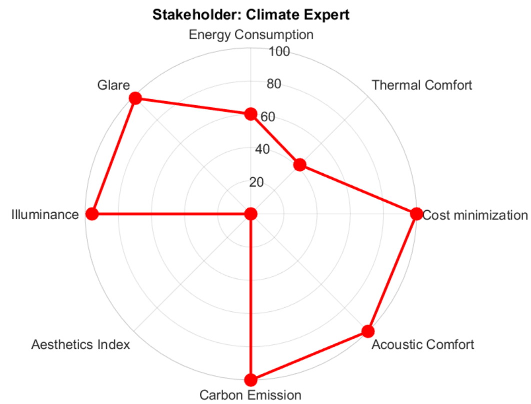


Figure 4.5: Scenario: Climate Expert

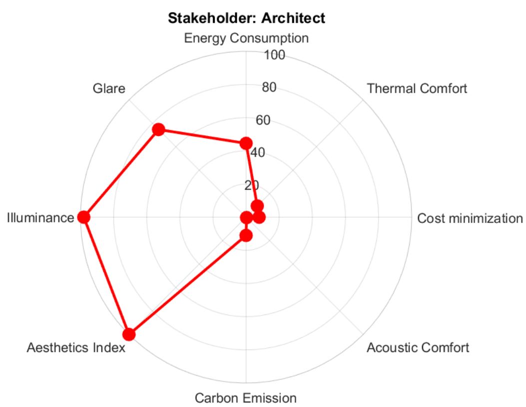


Figure 4.6: Scenario: Architect

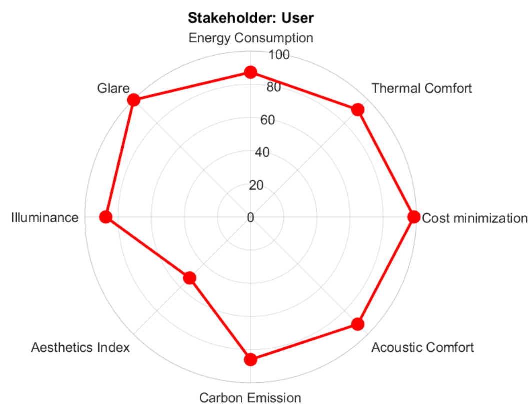


Figure 4.7: Scenario: User

2 Model Evaluation

This section evaluates the approach, the model, and its generated results. To do that, it provides an overview of the stakeholders' validation round, followed by verification of the results. The process of verification and validation of a model is a continuous process where reviewers jointly work to assure that the model represents the real-world process (Carson, 2002). Therefore, no model is said to be 100 percent verified and validated (Carson, 2002; Kleijnen, 1995). However, the scope of this research is limited to validating the model with the project stakeholders. In line with this, the methodology for the validation and verification processes is described in subsection 6.1 and subsection 6.2 respectively.

2.1 Stakeholders' Validation

The validation process, as described by Carson (2002), requires the reviewers who possess knowledge of the real systems to jointly work to review the model. The interviews with the stakeholders were conducted to validate the results and gather insights on the applicability of the tool developed based on the PBGA approach. The results of the tool have been successfully validated by the stakeholders, which means that the results were acceptable to them. For the next part of the interviews, stakeholders were asked open-ended questions presented in the Table 2.3 starting from the process of collecting such data in the real-world DP to the impact of such tools in the decision-making process.

Reflecting on the practical application of the tool in the DP, stakeholders shared varied insights. Project Manager 1 shed light on the tool's ability to determine both objective values and design variable values but noted a lack of clarity regarding the influence of these variables on objectives and which elements are most impactful. They observed that projects typically involve a combination of standard and project-specific variables and suggested that this standardized use of variables could allow stakeholders to incorporate the tool in an easier manner. The Project Manager also highlighted that variables identified at the beginning could have an impact on the design of the building. Hence, it could be considered a potential design variable.

Nonetheless, they recognized the difficulty in gathering stakeholder preferences at the early DP stages due to the abstract nature of such inputs. Corroborating this viewpoint, Project Manager 2 commented on the challenges of acquiring quantifiable data in the initial stages, proposing a more generalized approach to collecting preferences, like setting individual goals and acceptable minimum standards for each party. He also emphasized that there is an increasing need to incorporate parameters like circularity and sustainability from the beginning of the project. However, due to a lack of information and the uncertain nature of such objectives, it becomes difficult for them to quantify or justify the adoption of measures they undertook for the implementation of such parameters. Hence, by constantly monitoring the impact of adopting such measures on other model parameters, like objectives, variables and the overall DP, the tool can contribute to mitigating these unknown factors and allowing stakeholders to make informed decisions.

> "The discussion among stakeholders regarding the choice of preferences and weights could enable stakeholders to create insight within the team to transparently understand each others choices and it could start the co-creation process" —Project Manager 2

On the other hand, the glass expert expressed concerns regarding the potential lack of transparency in the bounds of variables provided by stakeholders, which might limit the achievement of optimal outcomes. In line with this, they emphasized the need to have a wide range of expertise and experience for stakeholders to provide suitable inputs for design variables. They suggested that assigning weights to the objectives could be facilitated through interactive sessions, where the impact on objectives can be analyzed and priorities can be established based on collective agreement.

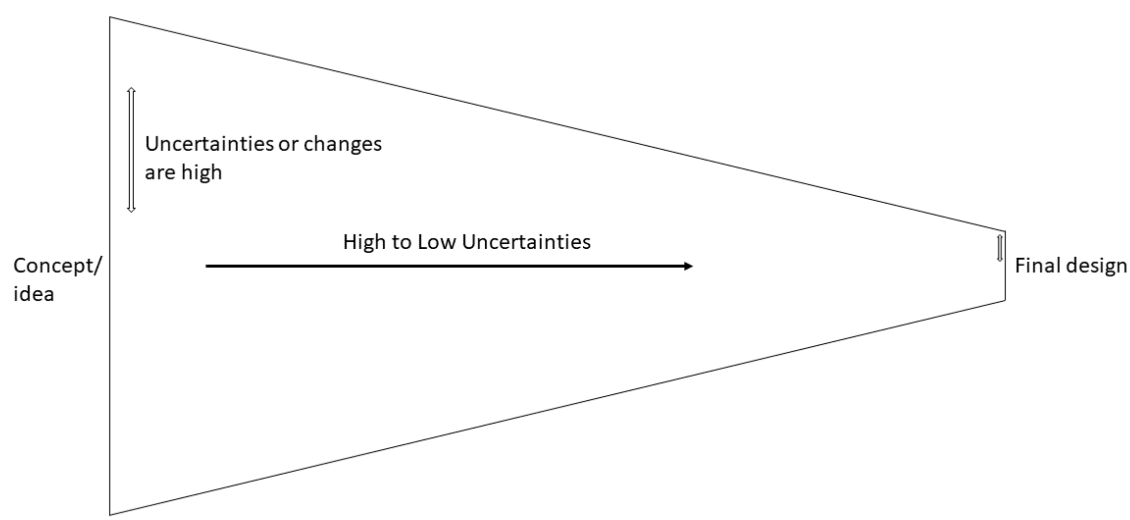


Figure 4.8: Design Process (from left to right) described by the Contractor

Further, the contractors emphasized the value of the tool in enhancing stakeholder communication during these sessions, helping in finding balanced solutions. The tool can improve this communication by visualizing the levels of satisfaction and the impact of conflicting interests. However, they raised questions about who bears the responsibility for the tool's application in real-life projects, highlighting the challenge of gathering comprehensive data from all stakeholders for its effective integration throughout the DP.

> " The person or team responsible must collect the data from all the stakeholders for incorporating in the tool and keep updating it" —Contractor

In addition, the contractors described the DP as a learning process, as shown in Figure 4.8 which initiates with a wide range of unknowns and uncertainties, converging to finalize the design with very little room for uncertainties. Echoing this, the contractor highlights the need to incorporate these parameters into the tool to better reflect the process. Moreover, they emphasized the tool's ability to easily incorporate any changes in the process pertaining to any component of the tool. As retrieving information is the key for this tool to work, they highlighted that information from repetitive projects, like social housing, could be used to make a better and optimal design for such similar projects.

In the case study, the research aimed to achieve a balanced design through the involvement of four key stakeholders: the user, owner, climate expert, and architect. However, participation in the validation process was constrained due to the unavailability of most stakeholders. Consequently, the validation of the results was primarily conducted with the client's involvement. For this purpose, the client was presented with data regarding the achieved values of each objective and design variable. The client's feedback indicated that the outcomes were both acceptable and in alignment with the needs of the stakeholder, leading to successful validation from the client's perspective. In this stakeholders' validation round, each stakeholder provided insights and arguments regarding its real-world applicability.

2.2 Tool Verification

According to Thacker et al. (2004), a model implementation is verified to correspond precisely with the developer's conceptual description of the model and the model's solution. The results shown in the aforementioned section 1 provide an indication that the tools developed in this thesis have been able to create a balance between the objectives by creating trade-offs between them, and they correctly reflect the fundamental concept of the PBGA approach. It can also be concluded by comparing the changes in weighted distances of the stakeholders' satisfaction with the current and new designs from Figure 4.9. For instance, carbon emissions in the new design have a maximum distance of approximately 8 units from the goal, followed by thermal comfort, while other objectives, such as illumination, are highly satisfied. However, in the new design, the maximum distance from the goal is less than 4, which indicates that the satisfaction gap has been significantly lowered. The term 'weighted distance' refers to '$w_i * \lambda_i$'as defined in the Equation 2.9 which is the distance a particular objective's preferences form from the goal. Hence, in the new design, the stakeholders' involvement is more balanced and equitable. The values shown in Figure 4.9 and in Figure 4.12 represent the weighted distances (shown in the Table 4.1) of the objectives and the weights used from the Figure 3.9.

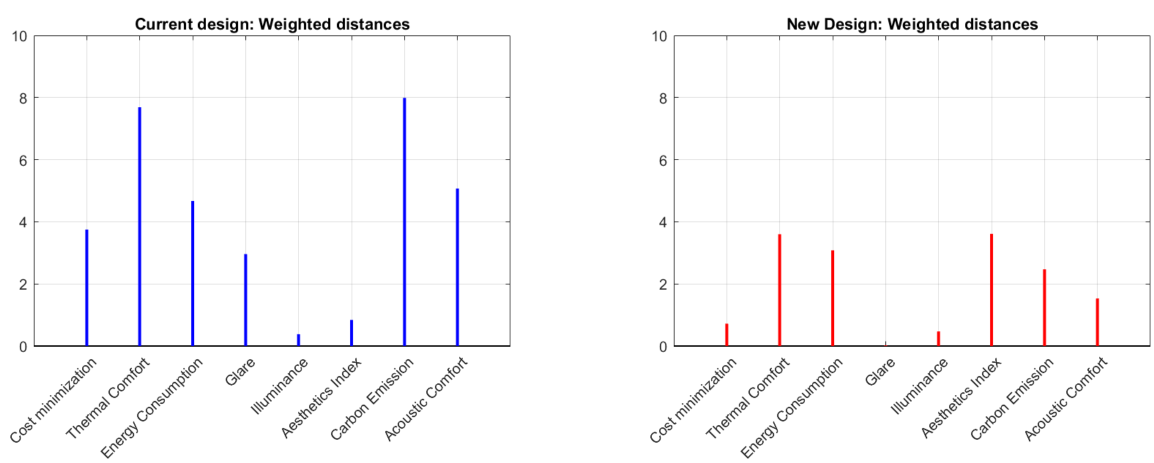


Figure 4.9: Stakeholders' Satisfaction (weighted distances) for Current & New design

Further, verification of simulation tools, as defined by previous studies (Kleijnen, 1995; Thacker et al., 2004), involves ensuring that no programming errors occur during simulation. The tool in question was developed in MATLAB, utilizing the built-in Global Optimization toolbox. This toolbox is well-documented, offering a variety of options for conducting optimization tasks. The entire code for the balanced design project is included in the supplementary material, referenced as Appendix B. Essential data and information needed for the code to function properly without generating errors are available on a GitHub repository, the details of which are also provided in Appendix B. Upon performing the simulation, the tool does not generate any errors.

Moreover, this research employs the current design of the building as a base case for comparison with the new design outcomes. For further verification of the tool, the study adopts the Kolmogorov-Smirnov (KS) test and the Chi-square (CS) test, where the simulations are performed for these two scenarios. The first scenario focuses on finding the solution where the maximum weighted distance from the goal is minimum, which is shown in Equation 3.15, while the second scenario identifies the solution with the minimum of the summation of squares of weighted distances across all objectives, as shown in Equation 2.14. The weights and preferences employed for both scenarios are displayed in Figure 3.9 and Table 3.13.

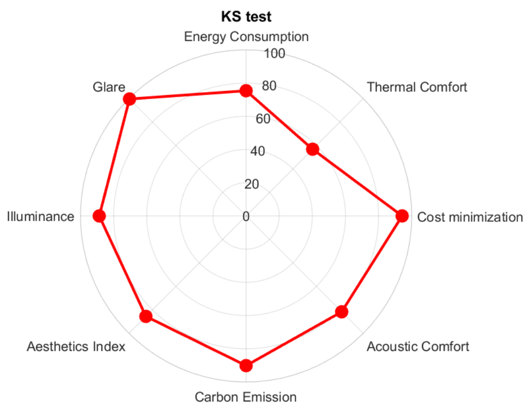


Figure 4.10: Results for KS test

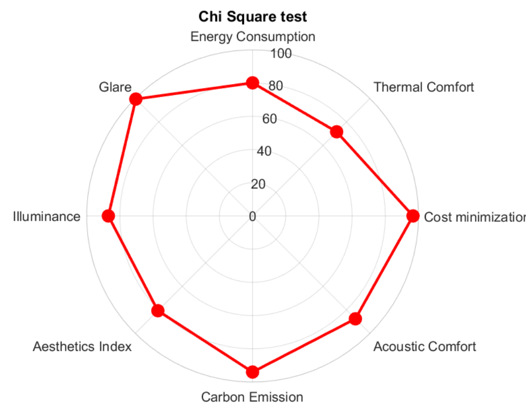


Figure 4.11: Results for Chi square test

Table 4.2: Objective values for KS test vs CS test

	Components	Unit	CS test	KS test
Objectives	Cost minimization	Euro	8.02E+05	8.18E+05
	Thermal Comfort	PPD	8.30E+01	8.41E+01
	Energy Consumption	KWh	2.30E+04	2.34E+04
	Glare	DGI	8.52E+00	8.48E+00
	Illuminance	lx	3.26E+03	3.16E+03
	Aesthetics Index	-	3.33E-01	3.53E-01
	Carbon Emission	Kg Co2e	5.39E+04	5.82E+04
	Acoustic Comfort	Seconds	7.18E-01	7.53E-01

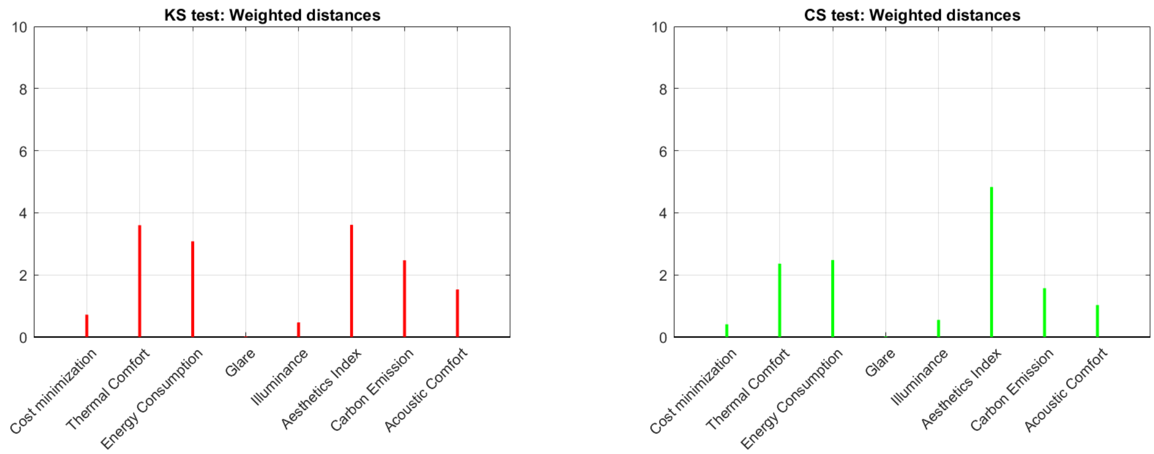


Figure 4.12: Stakeholders' weighted distances from KS test & Chi Square test

Analyzing the spider graphs in Figure 4.10 and Figure 4.11, it can be inferred that overall objective preference scores are higher in the results generated by the CS test than in the KS test. Especially, the score of thermal comfort has improved in the CS test, indicating that it leads to a better design outcome than the KS test. However, this outcome is better if the goal is to generate a solution where all the objectives are improved regardless of their assigned weights and preferences. Consequently, the CS test's results may not accurately mirror the stakeholders' prioritization of objectives. While the outcomes might be optimal, they do not necessarily align with the satisfaction levels of all stakeholders. For instance, in the results from the Figure 4.12 (right side), the architect who has the objective of aesthetics index emerges as having significantly high dissatisfaction in comparison to the stakeholder. On the other hand, according to findings from the KS test, as shown in Figure 4.12 (left side), the maximum weighted distance (Aesthetic Index and Thermal comfort) is lower than 4 units. The comparison also shows an increment in the weighted distances of other objectives, fundamentally representing the trade-offs between these objectives. Hence, the KS test's results exhibit a more balanced approach compared to the CS test. This difference stems from the KS test's incorporation of individual stakeholder weights and preferences, leading to a more balanced outcome. In contrast, the CS test considers the collective weights of all stakeholders, de-emphasizing the importance of individual stakeholder preferences. This approach, due to its reliance on the summation of weighted squares of collective objectives (as indicated in Equation 2.13), focuses solely on the overall project value. It strives for solutions where stakeholder satisfaction is highly unbalanced, despite the equal weights assigned to each stakeholder (as depicted in Figure 3.9) in both tests and the current design.

Hence, this analysis draws the conclusion that the KS test, which represents the PBGA approach, is more likely to yield optimal design outcomes that truly reflect the stakeholders' weights and preferences. While the CS test might provide more technically optimal designs, it does not ensure that these designs align with stakeholders' preferences, as clearly demonstrated in this case study.

In conclusion, this chapter has presented a comprehensive evaluation of the tool and its results, highlighting how different testing approaches influence stakeholder satisfaction and balance in design outcomes. Through detailed analysis, the effectiveness of the tool in reflecting stakeholder preferences has been critically assessed. Moving forward, the next chapter will delve into a discussion of these findings, exploring their implications and drawing connections to broader theoretical and practical contexts in the field.

Chapter 5: Discussion

This chapter transitions from the empirical findings of the tool evaluation to an in-depth discussion. It focuses on real-world applications, aiming to extract meaningful insights and implications. The discussion also addresses potential limitations and considers future directions for research and practice in the field.

1 Application of PBGA tool

To effectively implement the PBGA model, it's essential to gather the necessary data for setting up the optimization problem. In practical design processes, this data can be obtained through various means, such as interactive rounds with stakeholders. Utilizing strategies like game theory can enhance this analysis, as it encourages stakeholders to participate actively, share information, and make decisions (Waycaster et al., 2015). Moreover, effective communication among stakeholders, crucial for the project's success, hinges on sharing accurate and relevant information (Terje Karlsen, Græe, & Jensvold Massaoud, 2008). One approach to foster better communication is to use stakeholders' preferences as a discussion medium, enhancing information transparency. For example, when a stakeholder expresses specific preferences for an objective, these can be transparently evaluated in light of their intended goals. This method promotes the exchange of pertinent information for problem-solving.

However, the success of such processes relies heavily on trust among stakeholders. They must be willing to allow others to share accurate information and influence their decisions (Carnevale & Wechsler, 1992). Factors that build this trust include common goals, integrity, and clear communication. One critical factor, the alignment of common goals, can be bolstered by identifying shared objectives among stakeholders, leading to balanced design solutions.

Our analysis of stakeholder interviews and information revealed that while stakeholders often participate with common goals, such as project learning and innovation, their focus on individual sub-processes frequently leads to sub-optimal outcomes. This is partly due to a lack of understanding of how their system-specific design decisions impact the broader project or other systems. Hence, PBGA tool can be useful in such cases, not only as a platform for integration of these systems but also enables stakeholders to input their preferences and assign weights.

Ease of use is a hallmark of the PBGA tool. It permits the integration of new objectives or variables at any point, making it adaptable for stakeholders throughout the DP. This adaptability enables stakeholders to comprehend the ramifications of design alterations. Unlike some approaches, like desirability function, that convert objectives into single desirability function, PBGA allows to keep the objectives and their preferences singular. This feature encourages stakeholders to understand the impact of each objective, enabling them to make informed decisions.

To provide preferences, stakeholders have the flexibility to denote as many preference points as they deem fit for a specific objective. However, it's crucial for stakeholders to recognize the intention behind the collection of preferences. Inaccurate or incomplete information about objectives can skew design results. Thus, transparency in articulating needs is paramount, as any omissions can lead to unsatisfactory results. The tool standardizes objectives on a preference scale ranging from 0 to 100. Notably, the GA tends to struggle with functions that have consistent preference scores for multiple points. In such situations, the tool might identify a local optima, neglecting a potentially superior solution – the global optima. This nuance implies that non-convex preferences often yield better results.

Shifting focus to the design process, the so-called 'iron triangle' analogy suggests that parameters like cost, duration, and quality are interdependent. A change in one directly influences the others. This interdependence can be visualized as a polygon, where each objective is a vertex. Adjusting the significance of one objective invariably impacts other vertices of the polygon. However, it's essential to acknowledge that certain stakeholder needs may be omitted due to constraints such as computational challenges or compatibility issues. Hence, the tool cannot always provide an accurate depiction of the ripple effect one objective might have on others. Furthermore, the chosen evaluation methodology for this thesis focuses on practical application and stakeholder feedback, rather than broad validation involving diverse expert opinions. To truly gauge impact, objectives need to possess quantifiable traits, which isn't always feasible. Yet, the optimization perspective offers a lens to observe these impacts via design variables.

Since this research is conducted on a simplified case, this section outlines the inherent limitations of the model used in this research. While the model offers significant insights into DP, it is important to recognize its constraints and the potential impact on the study's findings.

2 Assumption & limitations

This thesis adopts a novel method, PBGA, to implement on a a project executed from 2018 to 2019, with research commencing in May 2023. For successful implementation of the tool, the data related to stakeholders' needs, preferences and prioritise is required to identify from the parties involved. For that purpose, initial interviews with stakeholders occurred in June and July 2023. The significant time gap between the project's completion and these interviews might affect the reliability of information gathered, as stakeholders, despite receiving question lists prior to the interview, may struggle to accurately recall project details. In line with this, The obtained data pertaining to stakeholders' preferences related to the respective needs could be influenced by their current understanding with regards to building's current performance. This raises concerns about the certainty and precision of the data for this study. Moreover, as detailed in Table 3.1, interviews were conducted using three methods: one-on-one sessions, online meetings via Microsoft Teams, and emails. The varied interview modes introduce risks, especially online and email communication, which may hinder accurate information exchange due to potential communication barriers.

The data utilized in this model, which aims to achieve the objectives outlined in Table 3.4, is sourced from multiple origins. Firstly, a significant portion of the data, particularly the EnergyPlus model central to several objectives, was sourced from the CONVERGE project. Consequently, this research inherits any assumptions made in the CONVERGE study, as noted in the source documentation. The input data, detailed in Table 3.6, was provided by a researcher from the CONVERGE project and has been validated by the data provider. However, it's important to note that the model does not encompass data related to critical building aspects such as foundations and structural components. This omission restricts the research's ability to address certain key objectives related to these aspects, as elaborated in section 3. This limitation in data scope may impact the comprehensiveness and applicability of the model's findings in contexts where such building aspects are crucial.

Secondly, due to confidentiality in the information for project's cost, The information for this objective is sourced from the 'BOUWKOSTEN' public database, focusing solely on material costs and excluding other expenses. This approach, while streamlined, doesn't account for additional project costs like labor and logistics, potentially limiting the study's applicability to real-world project budgeting. Furthermore, In addition, many materials used in the co-creation center are employed for research purposes and hence are not available in the aforementioned database. This necessitates the use of approximate materials with assumed similar properties and costs, adding a layer of assumption to the analysis. Additionally, the project's unique aspects, such as lower stakeholder participation fees and specific research funding, influence its cost structure. These factors, along with the project's specialized requirements, make it challenging to accurately determine the overall project costs. In order to represent the overall cost of the project, an estimation was created from the available data for the material which remain constant in the project.

Lastly, the data for determining embodied carbon emission are obtained from One Click LCA The data includes the emissions of the materials' product stage which encompasses raw material supply, transportation, and Manufacturing. Thereby, it does not include the later stage of materials' life cycle. In addition, for the materials which were not found in the database, closest possible materials were selected. The data from the project owners does not provide any specific details on material used for the project construction and therefore CO2 emissions of the material which are constant are not included in this research.

After the data collection, the research integrated the objectives & variables in the optimization problem. Starting with the initial process of translating stakeholder needs and wishes into the form of an objective function (as shown in section 3), many stakeholder needs did not qualify for inclusion in the tool. Consequently, stakeholders might encounter difficulties conveying their needs strictly in the form of measurable quantities. To mitigate this, the PBGA approach necessitates stakeholders to adopt a quantitative mindset, converting their needs into measurable objectives and design variables. in order to quantify the architect's needs and desires, an objective is constructed based on the interview with other stakeholders of the project and therefore it does not reflect the needs and preferences of the stakeholder. With each objective comes its computational approach which is used to determine its value for different set of design variables.

The generation of outcomes in Optimization are computationally extensive. In this research, there are 8 design variables and 7 objective function and the computational time for running 90 generations with the initial population size of 60 was approximately 22h on computer with Windows 10 system (Intel(R) Core(TM), 2.50GHz CPU), 12 GB RAM. With increasing number of variables, this time may increase.However, this time can be decreased by limiting the solution space by introduction constraints in the problem. The computational time mainly depends on how fast the models related to particular objective can compute their values. As in this case, the objectives values were determined by EnergyPlus were taking more time than other objective. Hence, this computational time depends on externally computing model for these objectives.

3 Future Directions

The PBGA-based tool, being an emergent innovation, offers considerable potential in its respective domains. For its validation and to ensure fidelity to real-world scenarios, empirical testing in a live construction project is imperative. Such application will facilitate an in-depth understanding of data acquisition, integration efficacy, and the design's iterative impact throughout the project lifecycle.

Future research and development trajectories for this tool include:

1. Enhanced User-Friendly Interface: Prioritize the development of an intuitive interface for stakeholders with limited technical knowledge, simplifying interaction with the tool's components.

2. Expert Validation: Obtain feedback and validation from experts in optimization-based decision-making to refine the tool's functionality and relevance.

3. Sensitivity Analysis Through Scenario Testing: Conduct tests with various scenarios to analyze the tool's sensitivity, focusing on altering elements like preferences and weights for real-world application insights.

4. Optimization of Solution Space and Software Performance: Implement strategies to constrain the solution space and enhance software performance, aiming to reduce computational time for real-time decision-making suitability.

5. Explaining Variable Changes in Relation to Objectives: Enhance the tool to provide clear insights on how changes in design variables impact specific objectives, addressing the current lack of explanations.

6. Application in Decision-Making Processes: Utilize the tool in actual decision-making settings to collect data on conflict resolution and balanced outcome achievement, assessing its real-world effectiveness.

Chapter 6: Conclusion

The research commences with identifying the problems in DP by conducting a background study withing the domains of ‘design decision-making process’, ‘optimization-based approaches’, ‘stakeholders’ perception’, ‘early stakeholder involvement’. It was identified that with increasing number of stakeholders, the interactions or interactive sessions also increases, resulting in complexity in the DP. Complexity results in lack of transparency, negative perception, mostly because of lack of proper flow of information among stakeholders. To address these challenges, this research presents a novel approach, Preference-based Goal Attainment, which aim to find a solution which correctly integrates not only stakeholders’ needs wishes but also prioritise and preferences. The approach addresses these problems by allowing all the stakeholders to integrating their interests, needs and values to generate an outcome where these parameters are reflected in the design outcome.

The research uses a case-study methodology, focusing on an existing building project with diverse stakeholders. The PBGA tool was implemented on the design process of this case project. Stakeholders’ needs and wishes were translated in form of quantifiable objectives and variables. Further, the generated results are evaluated on assessing the tool’s practical applicability through stakeholder interviews, validation, and verification methods.

The results obtained from this study aims to answer sub-research question as follows:

RQ1: What are the basic concepts of PBGA approach?

The PBGA approach innovatively integrates stakeholders’ preferences into the decision-making framework of the Weighted Goal-attainment Method. This integration commences with the transformation of objectives into a preference-based format, essential for translating abstract goals into quantifiable measures. This transformation hinges on the crucial step of identifying the range of each objective function, subsequently mapping these onto a preference scale. PBGA incorporates Preference Function Modelling (PFM) theory to create a preference scale. the PFM theory applies the mathematical operations in correct form to remove any discrepancies in aggregation of preferences. Such scaling allows for further assignment of preference scores, where the the highest value on the preference scale is naturally the most desired value for that particular objective. Once the objectives are translated in the form preferences, the methodology aligns with the conventional Weighted Goal-attainment Method. Further, the satisfaction gap for each objective is measured by subtracting its preference score from the highest score, identifying the most significant gaps in goal attainment. The approach then seeks to minimize this gap, finding a set of design variables that achieve the best trade-off among objectives. The definition of ’best’ is guided by the preferences and weights of the objectives. In this approach, a solution with the smallest gap for the farthest objective is sought, acknowledging that this may lead to other objectives being further from their goals. This trade-off ensures a balanced solution, and as PBGA is applied in multi-objective optimization, it not only seeks balance but also optimality as shown in Figure 6.1. Therefore, while there might be more balanced solutions, they may not be optimal.

The core of PBGA lies in its mathematical formulation, which standardizes objective functions on a dimensionless preference scale. This allows for a more balanced and compromise-based solution, as demonstrated by equations such as

$$\min_{z\in S}\left(\max_{i} w_i\left(100 - f_i^*(x)\right)\right) \tag{6.1}$$

Here, $f_i^*(x)$ represents the preference form of the i^{th} objective function, 100 represents the ‘Goal’ and w_i represents the weight of the corresponding objective function.

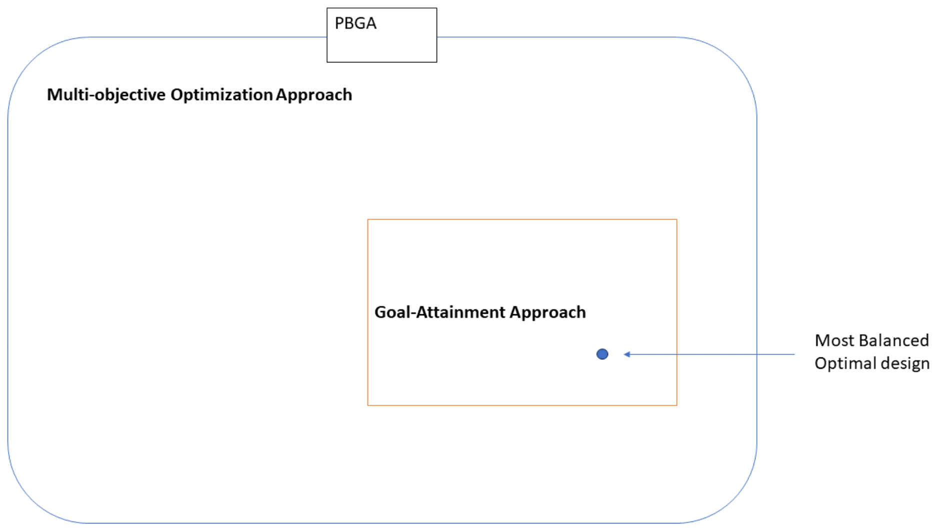


Figure 6.1: Solution Space diagram

The PBGA approach not only offers a mathematically rigorous method for optimization but also provides a practical framework for correctly incorporating stakeholder preferences and weights, making it a valuable tool in complex decision-making scenarios.

RQ2: What is the impact of implementing PBGA on the case design?

The design driven by PBGA showcases a balance achieved among stakeholders compared to the current design as shown in Figure 4.9. The dimensions of the resultant design of the building have changed from the current design. this includes the height of the building, size of the overhang. The insulation thicknesses and type also found to be different from the current design. This changes occurred in order to find a balance between optimal and their importance. Furthermore, the comparative analysis drawn from the verification by KS and CS test provide better insights on how the method impact the objectives in both scenarios. As, in the KS test, The balanced was created by generating a trade-off between Architect and other 3 stakeholders as seen by comparing the outcomes of Figure 4.12 with the current design scenario. However, the Chi-square test focused on generating a optimal outcome discarding the prospects of balancing the approach.

In the existing design, energy consumption is the most divergent objective, whereas cost minimization is prioritized in the new design. The strategy adopted seeks a harmonized stakeholder satisfaction, adjusting the objective distances in relation to the primary goal. The new design results in approximately €81.5 thousand cost savings, attributable to the altered building dimensions. This trend is paralleled in the carbon emission objective.

Notably, the PPD values, indicative of thermal comfort, remain beyond the desired range in both the current and new designs, suggesting a need for model refinement. However, the new design demonstrates a 54% improvement in thermal comfort. Improvements are also observed in energy consumption and acoustic comfort in the new design.

RQ3: What is stakeholders' perspective on using PBGA tool in decision-making process?

Stakeholders of the CCC project underwent a recurrent Decision Process (DP) that culminated in its existing design. Various tools were utilized by different parties to make informed decisions and for design optimization, primarily focusing on individual project objectives, such as selecting suitable materials or systems. As the tool developed in this approach integrates all individual systems together, the stakeholders have highlighted it importance in the decision-making process. Stakeholders have highlighted that finding an optimal solution has been in practice for quite some time but as the design process is not only about finding an optimal solution, these tools have been poorly employed for making design decisions.On the other hand, stakeholders like the Project Managers of the chosen case project has appreciate the tool's ability to integrate not only their needs and wishes but also their prioritise and preferences. However, they also pointed out the need for more clarity in understanding how these variables impact overall objectives. A common theme among their concerns is the difficulty of integrating stakeholder preferences because of its abstraction in the early stages. The Glass Expert, on the other hand, raises concerns about the potential lack of transparency in the variables provided by stakeholders, potentially hindering optimal outcomes. They advocate for a broad range of expertise in setting design variables and propose interactive sessions for better objective prioritization.

Contractors value the tool for enhancing communication among stakeholders, particularly in visualizing the impact of conflicting interests and achieving balanced solutions. However, they question the responsibility for the tool's application and stress the challenge of gathering comprehensive data for effective integration. They also describe the DP as a learning process, highlighting the importance of flexibility and adaptability in the tool to accommodate changes and uncertainties. Overall, while recognizing the tool's potential in aiding decision-making, stakeholders also highlight significant challenges such as clarity, transparency, and responsibility, suggesting improvements like standardization and early incorporation of sustainability considerations.On one hand, stakeholders acknowledge the challenges addressed by this thesis, notably, conflicting interests and project intricacies. On the other hand, they pointed out various factors play role while making important decisions, such as intuition, trust, inter-stakeholder relations. Hence, such tools could support decision-making process while its real-life application required further exploration.

Lastly, the answer to the main research question is briefed as follows:

> **How can a tool, based on Preference-based goal-attainment approach, be created and implemented to find a 'balanced' solution in early design process of a construction project?**

To create a PBGA tool, the first step is to identify the needs and wishes of the stakeholders. Based on this information, the next step involves conversion of these factors in quantifiable component of the tool. These components are Objective functions, variables, preferences, weights, and constraints. A balanced design can be obtained by changing the design variables to a condition which increases balance among stakeholders' satisfaction. To realize this, the preferences are integrated within the Goal Attainment method which aims to minimize the maximum factor of any problem. In this case, it is used to minimize the maximum weighted preference score of corresponding objective from the most preferred condition. By conducting this approach on the design process of the Co-Creation Centre, a balanced design is generated.

In concluding this thesis, it's evident that the three sub-research questions and the main research question have been comprehensively addressed, revealing significant insights into the use of tool based on systems engineering in decision-making processes. The exploration and application of the PBGA tool in the context of the Co-Creation Centre have demonstrated its effectiveness in balancing stakeholder needs and preferences, thereby offering a novel approach to informed decision-making. This study not only contributes to the field of design optimization but also paves the way for future research in integrating stakeholder-centric methods in design processes. The findings of this thesis underscore the importance of multi-faceted, inclusive approaches in design and decision-making, emphasizing the potential of computational tools in achieving balanced and optimized design outcomes. With this, the research journey embarked upon in this thesis reaches its conclusion, leaving a foundation for further exploration and development in the domain of model-based decision-making and stakeholder engagement.

References

A+BE | Architecture And The Built Environment. (2019, December). A+BE | Architecture and the Built Environment, No. 12 (2019): Corporate Real Estate Alignment. Retrieved 2023-11-10, from https://journals.open.tudelft.nl/abe/issue/view/729 (Publisher: A+BE | Architecture and the Built Environment) doi: 10.7480/ABE.2019.12

Adams, W. C. (2015, August). Conducting Semi-Structured Interviews. In K. E. Newcomer, H. P. Hatry, & J. S. Wholey (Eds.), *Handbook of Practical Program Evaluation* (1st ed., pp. 492–505). Wiley. Retrieved 2023-10-15, from https://onlinelibrary.wiley.com/doi/10.1002/9781119171386.ch19 doi: 10.1002/9781119171386.ch19

Akbari, M., Asadi, P., Besharati Givi, M., & Khodabandehlouie, G. (2014). Artificial neural network and optimization. *Advances in Friction-Stir Welding and Processing*, 543–599. (Publisher: Elsevier)

Algohary, S. A., Mahmoud, A., & Yehya, M. (2023, October). Multi-Objective Decision-Making Tool for Envelope Energy Retrofitting Measures of Gated Community Housing in Egypt. *Designs*, *7*(6), 123. Retrieved 2023-11-22, from https://www.mdpi.com/2411-9660/7/6/123 doi: 10.3390/designs7060123

Arkesteijn, M. H., & Binnekamp, R. (2014). Real Estate Portfolio Decision Making. In A. V. Gheorghe, M. Masera, & P. F. Katina (Eds.), *Infranomics* (Vol. 24, pp. 89–99). Cham: Springer International Publishing. Retrieved 2023-11-10, from https://link.springer.com/10.1007/978-3-319-02493-6_7 (Series Title: Topics in Safety, Risk, Reliability and Quality) doi: 10.1007/978-3-319-02493-6_7

Asha, L. N., Dey, A., Yodo, N., & Aragon, L. G. (2022). Optimization Approaches for Multiple Conflicting Objectives in Sustainable Green Supply Chain Management. *Sustainability*, *14*(19). Retrieved from https://www.mdpi.com/2071-1050/14/19/12790 doi: 10.3390/su141912790

Ashikhmina, S., & Ashikhmina, S. (2023, March). *Aesthetics in architecture – how beauty and design are inspiring each other - BRE Group*. Retrieved from https://bregroup.com/insights/aesthetics-in-architecture-how-beauty-and-design-are-inspiring-each-other/

Attia, S., Hamdy, M., O'Brien, W., & Carlucci, S. (2013, May). Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy and Buildings*, *60*, 110–124. (Publisher: Elsevier BV)

Auteurs, V. E. O. (2013, October). *het-is-tijd-voor-een-ander-systeem*. Retrieved from https://www.cobouw.nl/78331/het-is-tijd-voor-een-ander-systeem

Barlish, K., & Sullivan, K. (2012, July). How to measure the benefits of BIM — A case study approach. *Automation in Construction*, *24*, 149–159. (Publisher: Elsevier BV)

Barough, A. S., Shoubi, M. V., & Skardi, M. J. E. (2012, October). Application of Game Theory Approach in Solving the Construction Project Conflicts. *Procedia - Social and Behavioral Sciences*, *58*, 1586–1593. (Publisher: Elsevier BV)

Barzilai, J. (2010). Preference Function Modelling: The Mathematical Foundations of Decision Theory. *International Series in Operations Research & Management Science*, 57–86. (Place: Boston, MA Publisher: Springer US)

Beck, D., Ferasso, M., Storopoli, J., & Vigoda-Gadot, E. (2023, May). Achieving the sustainable development goals through stakeholder value creation: Building up smart sustainable cities and communities. *Journal of Cleaner Production*, *399*, 136501. Retrieved 2023-11-09, from https://linkinghub.elsevier.com/retrieve/pii/S0959652623006595 doi: 10.1016/j.jclepro.2023.136501

Binnekamp, R. (2010, January). Preference-Based Design in Architecture.

Bongo, M. F., & Sy, C. L. (2023, March). Can diverse and conflicting interests of multiple stakeholders be balanced? *Annals of Operations Research*. Retrieved 2023-10-23, from https://link.springer.com/

10.1007/s10479-023-05253-1 doi: 10.1007/s10479-023-05253-1

Bounds, L. (2023, October). *How we work with data at One Click LCA.* Retrieved from https://www.oneclicklca.com/how-we-work-with-data-at-one-click-lca/

Bremen, J. M. (2023, April). *Measuring The True Costs Of Innovation.* Retrieved from https://www.forbes.com/sites/johnbremen/2023/04/27/measuring-the-true-costs-of-innovation/

Brouwer, H., Hiemstra, W., van Vugt, S., & Walters, H. (2013). Analysing stakeholder power dynamics in multi-stakeholder processes: insights of practice from Africa and Asia. *Knowledge Management for Development Journal*, *9*(3), 11–31.

Carnevale, D. G., & Wechsler, B. (1992, February). Trust in the Public Sector: Individual and Organizational Determinants. *Administration & Society*, *23*(4), 471–494. Retrieved 2023-11-28, from http://journals.sagepub.com/doi/10.1177/009539979202300404 doi: 10.1177/009539979202300404

Carson, J. (2002). Model verification and validation. In *Proceedings of the Winter Simulation Conference* (Vol. 1, pp. 52–58). San Diego, CA, USA: IEEE. Retrieved 2023-11-26, from http://ieeexplore.ieee.org/document/1172868/ doi: 10.1109/WSC.2002.1172868

Chang, K.-H. (2015). Chapter 5 - Multiobjective Optimization and Advanced Topics. In K.-H. Chang (Ed.), *Design Theory and Methods Using CAD/CAE* (pp. 325–406). Boston: Academic Press. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780123985125000050 doi: https://doi.org/10.1016/B978-0-12-398512-5.00005-0

Christopher Frey, H., & Patil, S. R. (2002, June). Identification and Review of Sensitivity Analysis Methods. *Risk Analysis*, *22*(3), 553–578. Retrieved 2023-11-22, from https://onlinelibrary.wiley.com/doi/10.1111/0272-4332.00039 doi: 10.1111/0272-4332.00039

Ciaburro, G., & Iannace, G. (2021, February). Acoustic Characterization of Rooms Using Reverberation Time Estimation Based on Supervised Learning Algorithm. *Applied Sciences*, *11*(4), 1661. (Publisher: MDPI AG)

Crawley, D. B., Lawrie, L. K., Pedersen, C. O., & Winkelmann, F. C. (2000). Energy plus: energy simulation program. *ASHRAE journal*, *42*(4), 49–56. (Publisher: ASHRAE AMERICAN SOCIETY HEATING REFRIGERATING)

De Araujo Passos, L. A., Ceha, T. J., Baldi, S., & De Schutter, B. (2023, February). Model predictive control of a thermal chimney and dynamic solar shades for an all-glass facades building. *Energy*, *264*, 126177. Retrieved 2023-10-29, from https://linkinghub.elsevier.com/retrieve/pii/S0360544222030638 doi: 10.1016/j.energy.2022.126177

De Araujo Passos, L. A., Van Den Engel, P., Baldi, S., & De Schutter, B. (2023, January). Dynamic optimization for minimal HVAC demand with latent heat storage, heat recovery, natural ventilation, and solar shadings. *Energy Conversion and Management*, *276*, 116573. Retrieved 2023-10-29, from https://linkinghub.elsevier.com/retrieve/pii/S0196890422013516 doi: 10.1016/j.enconman.2022.116573

Deb, K., & Sundar, J. (2006, July). Reference point based multi-objective optimization using evolutionary algorithms. In *Proceedings of the 8th annual conference on Genetic and evolutionary computation* (pp. 635–642). Seattle Washington USA: ACM. Retrieved 2023-10-13, from https://dl.acm.org/doi/10.1145/1143997.1144112 doi: 10.1145/1143997.1144112

DesignBuilder Software Ltd - About Us. (n.d.). Retrieved from https://designbuilder.co.uk/about-us

DoE, U. (2009). EnergyPlus engineering reference: The reference to EnergyPlus calculations. *Lawrence Berkeley National Laboratory.*

Edelenbos, J., & Klijn, E.-H. (2006, July). Managing Stakeholder Involvement in Decision Making: A Comparative Analysis of Six Interactive Processes in the Netherlands. *Journal of Public Administration Research and Theory*, *16*(3), 417–446. Retrieved 2023-10-22, from http://academic.oup.com/jpart/article/16/3/417/934207/Managing-Stakeholder-Involvement-in-Decision doi: 10.1093/jopart/mui049

Eilon, S., Ackoff, R. L., Tanenbaum, M., & Holstein, W. K. (2023, August). *Operations research \textbar Definition, History, Examples, Characteristics, & Facts.* Retrieved from https://www.britannica.com/topic/operations-research

Fanger, P. O. (1970). *Thermal comfort. by P. O. Fanger \textbar Open Library.* Retrieved from https://openlibrary.org/books/OL14095842M/Thermal comfort.

Ferreira, J. C., Fonseca, C. M., & Gaspar-Cunha, A. (2007, July). Methodology to select solutions from the pareto-optimal set. *Proceedings of the 9th annual conference on Genetic and evolutionary computation.* (Place: New York, NY, USA Publisher: ACM)

Fumo, N., Mago, P., & Luck, R. (2010, December). Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. *Energy and Buildings*, *42*(12), 2331–2337. Retrieved 2023-10-31, from https://linkinghub.elsevier.com/retrieve/pii/S0378778810002574 doi: 10.1016/j.enbuild.2010.07.027

Gembicki, F., & Haimes, Y. (1975, December). Approach to performance and sensitivity multiobjective optimization: The goal attainment method. *IEEE Transactions on Automatic Control*, *20*(6), 769–771. Retrieved 2023-10-24, from http://ieeexplore.ieee.org/document/1101105/ doi: 10.1109/TAC.1975.1101105

Goldberg, D. E., & Kuo, C. H. (1987, April). Genetic Algorithms in Pipeline Optimization. *Journal of Computing in Civil Engineering*, *1*(2), 128–141. Retrieved 2023-10-18, from https://ascelibrary.org/doi/10.1061/%28ASCE%290887-3801%281987%291%3A2%28128%29 doi: 10.1061/(ASCE)0887-3801(1987)1:2(128)

Gordillo, G. C., Ruiz, G. R., Stauffer, Y., Dasen, S., & Bandera, C. F. (2020, January). EplusLauncher: An API to Perform Complex EnergyPlus Simulations in MATLAB® and C#. *Sustainability*, *12*(2), 672. (Publisher: MDPI AG)

Guenther, S., & Guenther, S. (2023, June). *What Is PMV? What Is PPD? The Basics of Thermal Comfort.* Retrieved from https://www.simscale.com/blog/what-is-pmv-ppd/

Haidar, A. D. (2015, September). Operations Research and Optimization Techniques. *Construction Program Management – Decision Making and Optimization Techniques*, 131–157. (Place: Cham Publisher: Springer International Publishing)

Hamida, A., & Ding, E. (2021). *Assessment of Acoustical Quality for Auditorium (Lecture)/Seminar Setting* (Unpublished doctoral dissertation).

Harrington, E. C. (1965). The desirability function. *Industrial quality control*, *21*(10), 494–498.

Hazelrigg, G. A. (1998, December). A Framework for Decision-Based Engineering Design. *Journal of Mechanical Design*, *120*(4), 653–658. Retrieved 2023-10-24, from https://asmedigitalcollection.asme.org/mechanicaldesign/article/120/4/653/432397/A-Framework-for-DecisionBased-Engineering-Design doi: 10.1115/1.2829328

Heravi, A., Coffey, V., & Trigunarsyah, B. (2015, July). Evaluating the level of stakeholder involvement during the project planning processes of building projects. *International Journal of Project Management*, *33*(5), 985–997. Retrieved 2023-10-22, from https://linkinghub.elsevier.com/retrieve/pii/S0263786314002154 doi: 10.1016/j.ijproman.2014.12.007

I, K. (2020, May). *Glare Light \textbar What is glare, forms, types, pollution, prevention.* Retrieved from https://lightjourney.com.sg/blogs/articles/glare-light

Islam, H., Jollands, M., Setunge, S., & Bhuiyan, M. A. (2015, January). Optimization approach of balancing life cycle cost and environmental impacts on residential building design. *Energy and Buildings*, *87*, 282–292. Retrieved 2023-10-29, from https://linkinghub.elsevier.com/retrieve/pii/S0378778814010044 doi: 10.1016/j.enbuild.2014.11.048

Kim, K.-J., & Lin, D. K. J. (1998, January). Dual Response Surface Optimization: A Fuzzy Modeling Approach. *Journal of Quality Technology*, *30*(1), 1–10. Retrieved 2023-10-29, from https://www.tandfonline.com/doi/full/10.1080/00224065.1998.11979814 doi: 10.1080/00224065.1998.11979814

Kleijnen, J. P. (1995, April). Verification and validation of simulation models. *European Journal of Operational Research*, *82*(1), 145–162. Retrieved 2023-11-26, from https://linkinghub.elsevier.com/retrieve/pii/0377221794000166 doi: 10.1016/0377-2217(94)00016-6

Kluwer, W. (2021, November). *Nieuw model Bouwteamovereenkomst Bouwend Nederland 2021 creëert een ongemakkelijk dilemma.*

Koppenjan, J. F. M., & Klijn, E.-H. (2004). *Managing uncertainties in networks: a network approach to problem solving and decision making.* Psychology Press.

Lenferink, S., Tillema, T., & Arts, J. (2013, May). Towards sustainable infrastructure development through integrated contracts: Experiences with inclusiveness in Dutch infrastructure projects. *International Journal of Project Management*, *31*(4), 615–627. Retrieved 2023-11-09, from https://linkinghub.elsevier.com/retrieve/pii/S0263786312001287 doi: 10.1016/j.ijproman.2012.09.014

Lingegård, S., Havenvid, M. I., & Eriksson, P.-E. (2021, October). Circular Public Procurement through Integrated Contracts in the Infrastructure Sector. *Sustainability*, *13*(21), 11983. Retrieved 2023-11-09, from https://www.mdpi.com/2071-1050/13/21/11983 doi: 10.3390/su132111983

Machairas, V., Tsangrassoulis, A., & Axarli, K. (2014, March). Algorithms for optimization of building design: A review. *Renewable and Sustainable Energy Reviews*, *31*, 101–112. (Publisher: Elsevier BV)

Marcher, C., Giusti, A., & Matt, D. T. (2020, September). *Decision Support in Building Construction: A Systematic Review of Methods and Application Areas.* Retrieved from https://www.mdpi.com/2075-5309/10/10/170

Marler, R. T., & Arora, J. S. (2010, June). The weighted sum method for multi-objective optimization: new insights. *Structural and Multidisciplinary Optimization*, *41*(6), 853–862. Retrieved 2023-10-13, from http://link.springer.com/10.1007/s00158-009-0460-7 doi: 10.1007/s00158-009-0460-7

McManus, J. (2002, January). The influence of stakeholder values on project management. *Management Services*, *46*, 8–15.

Metrics, S. (2002). *Tetra Quickstart Guide.* Retrieved from https://scientificmetrics.com/

Miller, B., & Ziemiański, L. (2023, October). Multi-Objective Optimization of Thin-Walled Composite Axisymmetric Structures Using Neural Surrogate Models and Genetic Algorithms. *Materials*, *16*(20), 6794. Retrieved 2023-11-22, from https://www.mdpi.com/1996-1944/16/20/6794 doi: 10.3390/ma16206794

Nguyen, A.-T., Reiter, S., & Rigo, P. (2014, January). A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy*, *113*, 1043–1058. Retrieved 2023-10-13, from https://linkinghub.elsevier.com/retrieve/pii/S0306261913007058 doi: 10.1016/j.apenergy.2013.08.061

Olander, S., & Landin, A. (2005, May). Evaluation of stakeholder influence in the implementation of construction projects. *International Journal of Project Management*, *23*(4), 321–328. Retrieved 2023-10-22, from https://linkinghub.elsevier.com/retrieve/pii/S0263786305000232 doi: 10.1016/j.ijproman.2005.02.002

Opdenakker, R. (2006, September). Advantages and Disadvantages of Four Interview Techniques in Qualitative Research [Electronic Journal]. *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, *7*.

Oreskes, N. (1998, December). Evaluation (not validation) of quantitative models. *Environmental Health Perspectives*, *106*(suppl 6), 1453–1460. Retrieved 2023-11-22, from https://ehp.niehs.nih.gov/doi/10.1289/ehp.98106s61453 doi: 10.1289/ehp.98106s61453

Oreskes, N., Shrader-Frechette, K., & Belitz, K. (1994, February). Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science*, *263*(5147), 641–646. Retrieved 2023-11-22, from https://www.science.org/doi/10.1126/science.263.5147.641 doi: 10.1126/science.263.5147.641

Pereira, J. L. J., Oliver, G. A., Francisco, M. B., Cunha, S. S., & Gomes, G. F. (2022, June). A Review of Multi-objective Optimization: Methods and Algorithms in Mechanical Engineering Problems. *Archives of Computational Methods in Engineering*, *29*(4), 2285–2308. Retrieved 2023-10-13, from https://link.springer.com/10.1007/s11831-021-09663-x doi: 10.1007/s11831-021-09663-x

Pollack, J., Helm, J., & Adler, D. (2018). What is the Iron Triangle, and how has it changed? *International journal of managing projects in business*, *11*(2), 527–547. (Publisher: Emerald Publishing Limited)

Ponta, L., Puliga, G., & Manzini, R. (2021, June). A measure of innovation performance: the Innovation Patent Index. *Management Decision*, *59*(13), 73–98. (Publisher: Emerald)

Quint ao, C., Andrade, P., & Almeida, F. (2020, August). How to Improve the Validity and Reliability of a Case Study Approach? *Journal of Interdisciplinary Studies in Education*, *9*(2), 273–284. (Publisher: STAR Scholars Network)

R Edward, F. (2010). *Strategic management: A stakeholder approach.* Cambridge university press.

Reuer, J. J., & Ariño, A. (2007, March). Strategic alliance contracts: dimensions and determinants of contractual complexity. *Strategic Management Journal*, *28*(3), 313–330. Retrieved 2023-11-09, from https://onlinelibrary.wiley.com/doi/10.1002/smj.581 doi: 10.1002/smj.581

Robinson, E. (2021, November). *Multi-stakeholder decision-making in low-energy building design optimization.* (Published: /articles/thesis/Multi-stakeholder decision-making in low-energy building design optimization/16545687/1)

Sabine, W. C., & Egan, M. D. (1994, June). *Collected Papers on Acoustics. The Journal of the Acoustical Society of America*, *95*(6), 3679–3680. Retrieved 2023-10-17, from https://pubs.aip.org/jasa/article/95/6/3679/660344/Collected-Papers-on-Acoustics doi: 10.1121/1.409944

Sahu, M., Bhattacharjee, B., & Kaushik, S. (2012, October). Thermal design of air-conditioned building for tropical climate using admittance method and genetic algorithm. *Energy and Buildings*, *53*, 1–6. Retrieved 2023-11-28, from https://linkinghub.elsevier.com/retrieve/pii/S0378778812002903 doi: 10.1016/j.enbuild.2012.06.003

Si-X — Co-Creation Centre op The Greenvillage Delft. (2023, February). Retrieved from https://si-x.nl/project/co-creation-centre-op-the-greenvillage-delft/

Stanitsa, A., Hallett, S. H., & Jude, S. (2022, August). *Investigating key factors influencing decision-making in the design of buildings and places: A survey of stakeholders' perception - Architecture, Structures and Construction.* Retrieved from https://link.springer.com/article/10.1007/s44150-022-00058-5

Storteboom, A., Wondimu, P., Lohne, J., & Lædre, O. (2017). Best Value Procurement - The Practical Approach In The Netherlands. *Procedia Computer Science*, *121*, 398–406. Retrieved 2023-11-09, from https://linkinghub.elsevier.com/retrieve/pii/S1877050917322470 doi: 10.1016/j.procs.2017.11.054

Søderberg, A.-M., & Romani, L. (2017, April). Boundary Spanners in Global Partnerships: A Case Study of an Indian Vendor's Collaboration With Western Clients. *Group & Organization Management*, *42*(2), 237–278. Retrieved 2023-10-30, from http://journals.sagepub.com/doi/10.1177/1059601117696618 doi: 10.1177/1059601117696618

Tabadkani, A., Tsangrassoulis, A., Roetzel, A., & Li, H. X. (2020, August). Innovative control approaches to assess energy implications of adaptive facades based on simulation using EnergyPlus. *Solar Energy*, *206*, 256–268. Retrieved 2023-10-18, from https://linkinghub.elsevier.com/retrieve/pii/S0038092X20305879 doi: 10.1016/j.solener.2020.05.087

Tan, T., Mills, G., Papadonikolaki, E., & Liu, Z. (2021, January). Combining multi-criteria decision making (MCDM) methods with building information modelling (BIM): A review. *Automation in Construction*, *121*, 103451. Retrieved 2023-11-10, from https://linkinghub.elsevier.com/retrieve/pii/S0926580520310311 doi: 10.1016/j.autcon.2020.103451

Terje Karlsen, J., Græe, K., & Jensvold Massaoud, M. (2008, January). Building trust in project-stakeholder relationships. *Baltic Journal of Management*, *3*(1), 7–22. Retrieved 2023-11-28, from https://www.emerald.com/insight/content/doi/10.1108/17465260810844239/full/html doi: 10.1108/17465260810844239

Thacker, B., Doebling, S., Hemez, F., Anderson, M., Pepin, J., & Rodriguez, E. (2004, October). *Concepts of Model Verification and Validation* (Tech. Rep.). United States. Retrieved from http://inis.iaea.org/search/search.aspx?orig_q=RN:36030870 (LA–14167)

Tian, Z., Zhang, X., Jin, X., Zhou, X., Si, B., & Shi, X. (2018, January). Towards adoption of building energy simulation and optimization for passive building design: A survey and a review. *Energy and Buildings*, *158*, 1306–1316. Retrieved 2023-11-09, from https://linkinghub.elsevier.com/retrieve/pii/S0378778817317899 doi: 10.1016/j.enbuild.2017.11.022

Todeschini, B. V., Cortimiglia, M. N., & De Medeiros, J. F. (2020, April). Collaboration practices in the fashion industry: Environmentally sustainable innovations in the value chain. *Environmental Science & Policy*, *106*, 1–11. Retrieved 2023-10-24, from https://linkinghub.elsevier.com/retrieve/pii/S1462901119306410 doi: 10.1016/j.envsci.2020.01.003

van den Engel, P., Bokel, R., Brembilla, E., Passos, L., Luscuere, P., Denengel@tudelft, P., … Nl, L. (2022, June). CONVERGE: low energy with active passiveness in a transparent highly occupied building..

Van Den Engel, P., Malin, M., Kodur Venkatesh, N., & Antonio De Araujo Passos, L. (2023). Performance of a Phase Change Material Battery in a Transparent Building. *Fluid Dynamics & Materials Processing*, *19*(3), 783–805. Retrieved 2023-10-29, from https://www.techscience.com/fdmp/v19n3/50049 doi: 10.32604/fdmp.2022.021962

Vandersleen, C., & Dodia, S. L. (2010, December). The public relations of project management. North America, Washington, DC. Newtown Square, PA.

Vogwell, D. (2003). Stakeholder Management. In *PMI® Global Congress 2003—EMEA.* The Hague, South Holland, The Netherlands: Project Management Institute. (event-place: Newtown Square, PA)

Watson, T., Osborne-Brown, S., & Longhurst, M. (2002, March). Issues Negotiation™ – investing in stakeholders. *Corporate Communications: An International Journal*, *7*(1), 54–61. Retrieved 2023-11-10, from https://www.emerald.com/insight/content/doi/10.1108/13563280210416044/full/html doi: 10.1108/13563280210416044

Waycaster, G., Bes, C., Bilotkach, V., Gogu, C., Haftka, R., & Kim, N. H. (2015). The Effect of Stakeholder Interactions on Design Decisions. *Computational Methods in Applied Sciences*, 413–425. (Place: Cham Publisher: Springer International Publishing)

Wetter, M., & Wright, J. (2004, August). A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization. *Building and Environment*, *39*(8), 989–999. Retrieved 2023-11-28, from https://linkinghub.elsevier.com/retrieve/pii/S0360132304000332 doi: 10.1016/j.buildenv.2004.01.022

Wondimu, P. A., Klakegg, O. J., & Lædre, O. (2020, January). Early contractor involvement (ECI): ways to do it in public projects. *Journal of Public Procurement*, *20*(1), 62–87. Retrieved 2023-11-09, from https://www.emerald.com/insight/content/doi/10.1108/JOPP-03-2019-0015/full/html doi: 10.1108/JOPP-03-2019-0015

Wright, J., & Alajmi, A. (2016, June). Efficient Genetic Algorithm sets for optimizing constrained building design problem. *International Journal of Sustainable Built Environment*, *5*(1), 123–131. Retrieved 2023-11-28, from https://linkinghub.elsevier.com/retrieve/pii/S2212609015300054 doi: 10.1016/j.ijsbe.2016.04.001

Xu, K., Lin, D. K., Tang, L.-C., & Xie, M. (2004, May). Multiresponse systems optimization using a goal attainment approach. *IIE Transactions*, *36*(5), 433–445. Retrieved 2023-10-25, from http://www.tandfonline.com/doi/abs/10.1080/07408170490426143 doi: 10.1080/07408170490426143

Yang, D., Wang, L., & Ji, G. (2022). Optimization-Assisted Building Design - Cases study of design optimization based on real-world projects. In (pp. 609–618). Ghent, Belgium. Retrieved 2023-10-13, from http://papers.cumincad.org/cgi-bin/works/paper/ecaade2022_127 doi: 10.52842/conf.ecaade.2022.1.609

Yang, J., Shen, G. Q., Ho, M., Drew, D. S., & Xue, X. (2011, October). Stakeholder management in construction: An empirical study to address research gaps in previous studies. *International Journal of Project Management*, *29*(7), 900–910. Retrieved 2023-10-22, from https://linkinghub.elsevier.com/retrieve/pii/S0263786310001171 doi: 10.1016/j.ijproman.2010.07.013

Yuan, X., Karbasforoushha, M. A., Syah, R. B. Y., Khajehzadeh, M., Keawsawasvong, S., & Nehdi, M. L. (2022, December). An Effective Metaheuristic Approach for Building Energy Optimization Problems. *Buildings*, *13*(1), 80. Retrieved 2023-10-18, from https://www.mdpi.com/2075-5309/13/1/80 doi: 10.3390/buildings13010080

Zamanifar, M., & Hartmann, T. (2020, October). Optimization-based decision-making models for disaster recovery and reconstruction planning of transportation networks. *Natural Hazards*, *104*(1), 1–25. Retrieved 2023-11-22, from https://link.springer.com/10.1007/s11069-020-04192-5 doi: 10.1007/s11069-020-04192-5

Zhilyaev, D., Binnekamp, R., & Wolfert, A. M. R. (2022, April). Best Fit for Common Purpose: A Multi-Stakeholder Design Optimization Methodology for Construction Management. *Buildings*, *12*(5), 527. (Publisher: MDPI AG)

Zitzler, E., Laumanns, M., & Bleuler, S. (2004). A Tutorial on Evolutionary Multiobjective Optimization. In G. Fandel, W. Trockel, X. Gandibleux, M. Sevaux, K. Sörensen, & V. T'kindt (Eds.), *Metaheuristics for Multiobjective Optimisation* (Vol. 535, pp. 3–37). Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved 2023-10-13, from http://link.springer.com/10.1007/978-3-642-17144-4_1 (Series Title: Lecture Notes in Economics and Mathematical Systems) doi: 10.1007/978-3-642-17144-4_1

Appendix A: Fanger's Comfort Model

Over recent decades, research has focused on understanding the thermal, physiological, and psychological responses of people to their environment. This has led to the development of mathematical models for predicting these responses. Building occupants' thermal comfort is influenced by personal, environmental, and physiological variables.

Key personal variables include:

- Thermal resistance of clothing (I_{cl}), measured in "clo". The 1985 ASHRAE Handbook suggests a factor of 0.82 for calculating the overall clo value of clothing ensembles.
- Metabolic rate (H/A_{Du}), indicating the internal heat production rate per unit of "Dubois" body surface area (A_{Du}) in m^2. According to Fanger (1967), an area of 1.8 m^2 represents the surface area of an average person (70 kg, 1.73 m). In EnergyPlus, this is a standard for all thermal comfort models. Metabolic rate is measured in mets, where 1 met = 58.2 W/m^2.

Environmental variables influencing thermal comfort include Air Temperature (T_a), Mean Radiant Temperature (T_r), Relative air velocity (v), and Water vapor pressure in ambient air (P_a).

Physiological variables impacting thermal comfort encompass Skin Temperature (T_{sk}), Core Temperature (T_{cr}), Sweat Rate, Skin Wettedness (w), and Thermal Conductance (K) between the core and skin.

An important aspect in thermal comfort is asymmetrical heating or cooling, such as drafts or radiant flux. Fanger (1967) and ASHRAE (1984) note that humans can tolerate asymmetrical radiant flux, with a reasonable upper limit of $15°C$ difference in mean radiant temperature (T_r) from opposite directions, lower in high air velocity zones.

For further details, refer to the following URL: https://bigladdersoftware.com/epx/docs/9-3/engineering-reference/occupant-thermal-comfort.html#fanger-comfort-model

Appendix B: MATLAB Code (Equal Wights Distribution)

Note: The detailed description for the below script can be found in the `README.md` in the github account https://github.com/Himanshu2187/PBGA. In addition, the repository includes all the required files pertaining to EplusLauncher API and for running the script.

```
function template_goal_attainment_global
clc, clear, close all

% Saves only the last populaton
    function [state,options,changed] = SaveOut(options,state,flag)
        file_name = 'SaveBest.mat';                                    % Name File
        if strcmp(flag,'init')
            Var = [repelem(0,size(state.Population,1))' state.Population, state.Score];
            save(file_name, 'Var')
        elseif strcmp(flag,'iter')
            Var = [repelem(state.Generation,size(state.Population,1))' state.Population state.
                Score];                                  % Read Previous Results, Append New Value
            save(file_name, 'Var')
        end
        changed=false;
    end


folder=pwd;
NET.addAssembly(fullfile('N:\My Thesis\Tool\variables_codes\EplusLauncher.dll'));
global Launcher;

%% Design variables:
lb = [1 1 0.01 -2 40 60 30 1]; % lower bound
ub = [99 99 300 2.5 200 200 200 3]; % upper bounds
%1.  0.01<Window-wallratio<0.9
%2.  0<interior Surface properties<1
%3.  1<overhang width<2
%4. -2<bulding height<2
%5. 40<roof insulation thickness <200
%6. 60<Floor insulation thickness<200
%7. 30<Wall insulation thickness<200

%TOTAL VARIABLEs = 7
function [c, ceq] = Constr(x) % c stands for nonlinear inequality constraints and ceq - nonlinear
    equality constraitns

c=[];
ceq = [];
end

%Preferences
%Thermal comfort - Predicted Percentage Dissatisfied (PPD)
PPD_Min = 81.07340707; %PPD minima
PPD_Max = 92.37964989; %PPD Maxima
PPD_Int = (PPD_Max+PPD_Min)/2;
Thermal_curve=[PPD_Max PPD_Int PPD_Min;0,30,100];
```

```
xq_t = linspace(PPD_Max,PPD_Min,100);
p_t = pchip(Thermal_curve(1,:),Thermal_curve(2,:),xq_t);

%Energy Consumption - KWh
Econ_Max_Sfctn = 20793.33; %minimum consumption
Econ_Int_Sfctn = 26000;
Econ_Min_Sfctn = 28186.72; % maximum consumption
Econsmp_curve = [Econ_Min_Sfctn,Econ_Int_Sfctn,Econ_Max_Sfctn;0,40,100];
xq_e = linspace(Econ_Min_Sfctn,Econ_Max_Sfctn,100);
 p_e = pchip(Econsmp_curve(1,:),Econsmp_curve(2,:),xq_e);
%plot(p_e)

%Acoustic Comfort- reverbration Time (TR)
TR_min = 1.418687765; %TR maxima
TR_max = 0.648030313; %TR minima
TR_Int = (TR_min+TR_max)/2;
Acoustic_curve = [TR_min, TR_Int, TR_max; 0,40,100];
xq_a = linspace(TR_min,TR_max,100);
 p_a = pchip(Acoustic_curve(1,:),Acoustic_curve(2,:),xq_a);


 % Total Cost- Euros
 CE_min = 766270; %minima
 CE_max = 1055236.06584682; %maxima
 CE_Int = 9.1602e+05; % Current design cost
Cost_curve = [CE_max,CE_Int,CE_min; 0,30,100];
 xq_c = linspace(CE_min,CE_max,100);
 p_c = pchip(Cost_curve(1,:),Cost_curve(2,:),xq_c);


 % Visual Comfort Glare - Daylight Glare Index (DGI)
VG_max = 7.8866; %minima
VG_min = 16.9259480439983; %maxima
VG_int = (VG_max+VG_min)/2;
Glare_curve = [VG_min,VG_int,VG_max; 0,80,100];
xq_g = linspace(VG_min,VG_max,100);
p_g = pchip(Glare_curve(1,:),Glare_curve(2,:),xq_g);


%Visual Comfort illuminance - Horizontal illuminance (lx)
VI_min = 250.1697227; % minima
VI_max = 5096.96; %maxima
VI_int1 = 1000;
VI_int2 = 2000;
VI_int3 = 4000;
Illuminance_curve = [VI_min,VI_int1,VI_int2,VI_int3, VI_max; 0,90,100,70,0];
xq_i = linspace(VI_min,VI_max,100);
p_i = pchip(Illuminance_curve(1,:),Illuminance_curve(2,:),xq_i);
%plot(p_i)

% Aesthetics Comfort - Asthetic index
Ac_min = 0.0535;  %minima
Ac_max = 0.9980; %maxima
Ac_int = 0.3218;
AS_curve = [Ac_min,Ac_int,Ac_max; 0,80,100];
xq_as = linspace(Ac_min,Ac_max,100);
p_as = pchip(AS_curve(1,:),AS_curve(2,:),xq_as);
%plot(p_as)


%Carbon emission - Kg Co2/m2
Ece_min = 42223.0106166003; %minima
Ece_max = 138820.020798083; %maxima
Ece_Int = 84447; % Current design ece
Ece_curve = [Ece_max,Ece_Int,Ece_min; 0,70,100];
xq_ece = linspace(Ece_max,Ece_min,100);
p_ece = pchip(Ece_curve(1,:),Ece_curve(2,:),xq_ece);
```

```
 %% Weights of objective functions
w_Econ=1/8;
w_Thermal=1/12;
w_acoustic = 1/12;
w_cost = 1/8;
w_visualI = 1/24;
w_visualG = 1/24;
w_aesthetic = 1/4;
w_Carbnemission = 1/4;
w_visual = (w_visualG+w_visualI)/2;
w_total=w_Econ+w_Thermal+w_acoustic+w_cost+w_visualG +w_visualI+w_aesthetic+w_Carbnemission;
w_Econ=w_Econ/w_total;
w_Thermal=w_Thermal/w_total;
w_acoustic=w_acoustic/w_total;
w_cost = w_cost/w_total;
w_visual = w_visual/w_total;
w_aesthetic = w_aesthetic/w_total;
  w_visualI = w_visualI/w_total;
  w_visualG = w_visualG/w_total;
  w_Carbnemission = w_Carbnemission/w_total;

%GA Options
opts = optimoptions(@ga, ...
                    'PopulationSize',60,...
                    'MaxGenerations', 90,...
                    'MaxStallGenerations', 10,...
                    'EliteCount', 6,...
                    'Display', 'iter',...
                    'PlotFcn',@gaplotbestf,...
                    'OutputFcn', @SaveOut);



% EnergyPlus simulation configuration
config = EplusLauncher.Configuration();
config.InputFile = fullfile('N:\My Thesis\Tool\variables_codes\idfmodeltry2.idf');  % Path to IDF
    file
config.WeatherFile = fullfile('N:\My Thesis\Tool\variables_codes\weather.epw');  % Path to weather
     file
config.RviFile = fullfile('N:\My Thesis\Tool\variables_codes\model.rvi');  % Path to RVI file
config.EnergyPlusFolder = 'C:\EnergyPlusV9-4-0';  % EnergyPlus installation path
config.OutputFolder = fullfile('N:\My Thesis\Tool\variables_codes\OutputJob');  % Output folder
    path
Tags = {'@@thermal@@','@@visible@@','@@solar@@','@@RFInsulThickness@@', '@@FloorInsulThickness@@',
    '@@WallInsulThickness@@','@@RoofInsulation@@','@@WX@@', '@@WY@@','@@H1@@', '@@H2@@', '@@H3@@',
     '@@H4@@', '@@H5@@', '@@H6@@', '@@H7@@', '@@H8@@', '@@H9@@', '@@H10@@', '@@H11@@', '@@H12@@',
    '@@H13@@', '@@H14@@', '@@H15@@', '@@H16@@', '@@H17@@', '@@H18@@', '@@H19@@', '@@H20@@', '
    @@H21@@', '@@H22@@', '@@H23@@', '@@H24@@', '@@H25@@', '@@H26@@','@@O1X1@@', '@@O1Y1@@', '
    @@O1X2@@', '@@O1Y2@@','@@O2X1@@', '@@O2Y1@@', '@@O2X2@@', '@@O2Y2@@','@@O3X1@@', '@@O3Y1@@', '
    @@O3X2@@', '@@O3Y2@@','@@O4X1@@', '@@O4Y1@@', '@@O4X2@@', '@@O4Y2@@','@@O5X1@@', '@@O5Y1@@', '
    @@O5X2@@', '@@O5Y2@@','@@O6X1@@', '@@O6Y1@@', '@@O6X2@@', '@@O6Y2@@','@@O7X1@@', '@@O7Y1@@', '
    @@O7X2@@', '@@O7Y2@@','@@O8X1@@', '@@O8Y1@@', '@@O8X2@@', '@@O8Y2@@', '@@O9X2@@', '@@O9Y2@@','
    @@O11X1@@', '@@O11Y1@@', '@@O12X2@@', '@@O12Y2@@','@@O16X1@@', '@@O16Y1@@'};
  % Tags to replace in IDF file

%% Objective function

    function Opt = ObjFunction(x)
    % Map the variables

Launcher = EplusLauncher.Launcher();
Launcher.MaxCores = 1;
Launcher.OutputFolderNumber = 0;
Launcher.JobsLogFile = (fullfile(folder,'jobs.csv'));
```

```
addlistener(Launcher,'OutputMessageReceived',@EnergyPlusMessage);
addlistener(Launcher,'SimulationCompleted',@SimulationFinished);
addlistener(Launcher,'JobsFinished',@JobsFinished);

% 1st Variable: Window To Wall Ratio, x(1)
wall_surface_area = 83.748;
wx_min = -31.3348458736;
wx_max = -44.2332898805;
wy_min = 27.167357268;
wy_max = 21.96061338;
 %x(1) = ratio;
window_area = wall_surface_area * x(1)/100;
    wall_area = wall_surface_area - window_area;

    % Calculate the window coordinates
    wx = wx_min + (wx_max - wx_min) * x(1)/100; % Linear interpolation
    wy = ((wy_max - wy_min) / (wx_max - wx_min)) * (wx - wx_min) + wy_min;

    Winw = sqrt((wx-wx_min)^2+(wy-wy_min)^2); %Window width of Wall 1


% 2nd Variable: Interior Surface properties, x(2)
   thermal = x(2)/100;
    visible = x(2)/100;
    solar=x(2)/100;


% 3rd Variable: Overhang width, x(3)

d= x(3)/100;

 %Overhang vertices coordinates in idf
 O1X3 = -45.8263901105;
O1Y3 = 21.3175230289;
O1X4 = -38.3258765263;
O1Y4 = 24.3452722085;
O2X3 = -41.5343269834;
O2Y3 = 23.0501097999;
O2X4 = -34.0338133993;
O2Y4 = 26.0778589796;
O3X3 = -37.2422638563;
O3Y3 = 24.782696571;
O3X4 = -29.7417502722;
O3Y4 = 27.8104457507;
O4X3 = -30.691253435;
O4Y3 = 25.5744651927;
O4X4 = -33.7022574501;
O4Y4 = 33.0267038253;
O5X3 = -32.4060800881;
O5Y3 = 29.8186632635;
O5X4 = -35.4170841032;
O5Y4 = 37.2709018961;
O6X3 = -34.1209067412;
O6Y3 = 34.0628613343;
O6X4 = -37.1319107563;
O6Y4 = 41.515099967;
O7X3 = -35.8357333943;
O7Y3 = 38.3070594052;
O7X4 = -38.8467374094;
O7Y4 = 45.7592980378;
O8X3 = -37.5505600474;
O8Y3 = 42.551257476;
O8X4 = -40.5615640625;
O8Y4 = 50.0034961086;
O9X3 = -38.3250688186;
O9Y3 = 49.0541760608;
O9X4 = -45.8252291255;
O9Y4 = 46.0239145988;
```

```
O11X3 = -46.9092771588;
O11Y3 = 45.5859307633;
O11X4 = -54.4094374657;
O11Y4 = 42.5556693013;
O12X3 = -53.4602572712;
O12Y3 = 44.7920849754;
O12X4 = -50.4489711375;
O12Y4 = 37.3408725764;
O16X3 = -46.6008536659;
O16Y3 = 27.8189808183;
O16X4 = -43.5895675321;
O16Y4 = 20.3677684192;

    O1X1 = O1X4 + sqrt(d^2 / (1 + ((O1X4-O1X3) / (O1Y3-O1Y4))^2));
    O1Y1 = O1Y4 + ((O1X4-O1X3) / (O1Y3-O1Y4)) * (O1X4 + sqrt(d^2 / (1 + ((O1X4-O1X3) / (O1Y3-O1Y4)
        )^2)) - O1X4);
    O1X2 = O1X3 + sqrt(d^2 / (1 + ((O1X3-O1X4) / (O1Y4-O1Y3))^2));
    O1Y2 = O1Y3 + ((O1X3-O1X4) / (O1Y4-O1Y3))* (O1X3 + sqrt(d^2 / (1 + ((O1X3-O1X4) / (O1Y4-O1Y3))
        ^2)) - O1X3);


% Equations for O2
O2X1 = O2X4 + sqrt(d^2 / (1 + ((O2X4-O2X3) / (O2Y3-O2Y4))^2));
O2Y1 = O2Y4 + ((O2X4-O2X3) / (O2Y3-O2Y4)) * (O2X4 + sqrt(d^2 / (1 + ((O2X4-O2X3) / (O2Y3-O2Y4))^2)
    ) - O2X4);
O2X2 = O2X3 + sqrt(d^2 / (1 + ((O2X3-O2X4) / (O2Y4-O2Y3))^2));
O2Y2 = O2Y3 + ((O2X3-O2X4) / (O2Y4-O2Y3))* (O2X3 + sqrt(d^2 / (1 + ((O2X3-O2X4) / (O2Y4-O2Y3))^2))
     - O2X3);

% Equations for O3
O3X1 = O3X4 + sqrt(d^2 / (1 + ((O3X4-O3X3) / (O3Y3-O3Y4))^2));
O3Y1 = O3Y4 + ((O3X4-O3X3) / (O3Y3-O3Y4)) * (O3X4 + sqrt(d^2 / (1 + ((O3X4-O3X3) / (O3Y3-O3Y4))^2)
    ) - O3X4);
O3X2 = O3X3 + sqrt(d^2 / (1 + ((O3X3-O3X4) / (O3Y4-O3Y3))^2));
O3Y2 = O3Y3 + ((O3X3-O3X4) / (O3Y4-O3Y3))* (O3X3 + sqrt(d^2 / (1 + ((O3X3-O3X4) / (O3Y4-O3Y3))^2))
     - O3X3);


% Equations for O4
O4X1 = O4X4 + sqrt(d^2 / (1 + ((O4X4-O4X3) / (O4Y3-O4Y4))^2));
O4Y1 = O4Y4 + ((O4X4-O4X3) / (O4Y3-O4Y4)) * (O4X4 + sqrt(d^2 / (1 + ((O4X4-O4X3) / (O4Y3-O4Y4))^2)
    ) - O4X4);
O4X2 = O4X3 + sqrt(d^2 / (1 + ((O4X3-O4X4) / (O4Y4-O4Y3))^2));
O4Y2 = O4Y3 + ((O4X3-O4X4) / (O4Y4-O4Y3))* (O4X3 + sqrt(d^2 / (1 + ((O4X3-O4X4) / (O4Y4-O4Y3))^2))
     - O4X3);


% Equations for O5
O5X1 = O5X4 + sqrt(d^2 / (1 + ((O5X4-O5X3) / (O5Y3-O5Y4))^2));
O5Y1 = O5Y4 + ((O5X4-O5X3) / (O5Y3-O5Y4)) * (O5X4 + sqrt(d^2 / (1 + ((O5X4-O5X3) / (O5Y3-O5Y4))^2)
    ) - O5X4);
O5X2 = O5X3 + sqrt(d^2 / (1 + ((O5X3-O5X4) / (O5Y4-O5Y3))^2));
O5Y2 = O5Y3 + ((O5X3-O5X4) / (O5Y4-O5Y3))* (O5X3 + sqrt(d^2 / (1 + ((O5X3-O5X4) / (O5Y4-O5Y3))^2))
     - O5X3);

% Equations for O6
O6X1 = O6X4 + sqrt(d^2 / (1 + ((O6X4-O6X3) / (O6Y3-O6Y4))^2));
O6Y1 = O6Y4 + ((O6X4-O6X3) / (O6Y3-O6Y4)) * (O6X4 + sqrt(d^2 / (1 + ((O6X4-O6X3) / (O6Y3-O6Y4))^2)
    ) - O6X4);
O6X2 = O6X3 + sqrt(d^2 / (1 + ((O6X3-O6X4) / (O6Y4-O6Y3))^2));
O6Y2 = O6Y3 + ((O6X3-O6X4) / (O6Y4-O6Y3))* (O6X3 + sqrt(d^2 / (1 + ((O6X3-O6X4) / (O6Y4-O6Y3))^2))
     - O6X3);


% Equations for O7
O7X1 = O7X4 + sqrt(d^2 / (1 + ((O7X4-O7X3) / (O7Y3-O7Y4))^2));
O7Y1 = O7Y4 + ((O7X4-O7X3) / (O7Y3-O7Y4)) * (O7X4 + sqrt(d^2 / (1 + ((O7X4-O7X3) / (O7Y3-O7Y4))^2)
    ) - O7X4);
```

```
O7X2 = O7X3 + sqrt(d^2 / (1 + ((O7X3-O7X4) / (O7Y4-O7Y3))^2));
O7Y2 = O7Y3 + ((O7X3-O7X4) / (O7Y4-O7Y3))* (O7X3 + sqrt(d^2 / (1 + ((O7X3-O7X4) / (O7Y4-O7Y3))^2))
     - O7X3);


% Equations for O8
O8X1 = O8X4 + sqrt(d^2 / (1 + ((O8X4-O8X3) / (O8Y3-O8Y4))^2));
O8Y1 = O8Y4 + ((O8X4-O8X3) / (O8Y3-O8Y4)) * (O8X4 + sqrt(d^2 / (1 + ((O8X4-O8X3) / (O8Y3-O8Y4))^2)
    ) - O8X4);
O8X2 = O8X3 + sqrt(d^2 / (1 + ((O8X3-O8X4) / (O8Y4-O8Y3))^2));
O8Y2 = O8Y3 + ((O8X3-O8X4) / (O8Y4-O8Y3))* (O8X3 + sqrt(d^2 / (1 + ((O8X3-O8X4) / (O8Y4-O8Y3))^2))
     - O8X3);


% Equations for O9

O9X1 = O9X4 + sqrt(d^2 / (1 + ((O9X4-O9X3) / (O9Y3-O9Y4))^2));
O9Y1 = O9Y4 + ((O9X4-O9X3) / (O9Y3-O9Y4)) * (O9X4 + sqrt(d^2 / (1 + ((O9X4-O9X3) / (O9Y3-O9Y4))^2)
    ) - O9X4);
O9X2 = O9X3 - sqrt(d^2 / (1 + ((O9X3-O9X4) / (O9Y1-O9Y3))^2));
O9Y2 = O9Y3 - ((O9X3-O9X4) / (O9Y4-O9Y3))* (O9X3 + sqrt(d^2 / (1 + ((O9X3-O9X4) / (O9Y4-O9Y3))^2))
     - O9X3);


% Equations for O11
O11X1 = O11X4 - sqrt(d^2 / (1 + ((O11X4-O11X3) / (O11Y3-O11Y4))^2));
O11Y1 = O11Y4 - ((O11X4-O11X3) / (O11Y3-O11Y4)) * (O11X4 + sqrt(d^2 / (1 + ((O11X4-O11X3) / (O11Y3
    -O11Y4))^2)) - O11X4);

% Equations for O12

O12X2 = O12X3 - sqrt(d^2 / (1 + ((O12X3-O12X4) / (O12Y4-O12Y3))^2));
O12Y2 = O12Y3 - ((O12X3-O12X4) / (O12Y4-O12Y3))* (O12X3 + sqrt(d^2 / (1 + ((O12X3-O12X4) / (O12Y4-
    O12Y3))^2)) - O12X3);


% Equations for O16
O16X1 = O16X4 - sqrt(d^2 / (1 + ((O16X4-O16X3) / (O16Y3-O16Y4))^2));
O16Y1 = O16Y4 - ((O16X4-O16X3) / (O16Y3-O16Y4)) * (O16X4 + sqrt(d^2 / (1 + ((O16X4-O16X3) / (O16Y3
    -O16Y4))^2)) - O16X4);



% 4th Variable: Building's Height, x(4)

h = [6.02, 5.252, 7.110000004, 7.11, 7.110000002, 7.110000001, 6.192426029, 6.192426038,
    6.896079382, 6.192426035, 6.896079379, 6.192426034, 6.896079379, 6.192426031, 6.896079385,
    6.026094104, 7.027919137, 7.023950821, 8.025005663, 9.026060523, 8.025005672, 9.026060518,
    8.025005667, 8.025005668, 9.026060521, 9.02606052];
addition_factor = x(4); % Change in height
% Add the factor to the heights
h_added = h + addition_factor; % changed height
h_window = h(2) + addition_factor; %new window height
h_wall = h(1) + addition_factor; %new wall height

% 5th Variable: Roof insulation thickness, x(5)
RFInsulThickness = x(5)/1000;

% 6th Variable: Floor insulation thickness, x(6)
FloorInsulThickness = x(6)/1000;

% 7th Variable: Wall insulation thickness, x(7)
WallInsulThickness = x(7)/1000;

% 8th Variable: Roof Insulation Type, x(8)
insulation_type = x(8);
Roof_insulation = {'Roof_XPS_Extruded_Polystyrene', 'Roof_insulation_PTR_rigid_foam', '
    Roof_EPS_Insulation'};
```

```
chosen_insulation = Roof_insulation(insulation_type);

%%
job = EplusLauncher.Job(config);
    job.AddTags(Tags);
   job.AddValues([thermal,visible, solar,RFInsulThickness,FloorInsulThickness, WallInsulThickness,
       chosen_insulation, wx, wy,h_added(1), h_added(2), h_added(3), h_added(4), h_added(5),
       h_added(6), h_added(7), h_added(8), h_added(9), h_added(10), h_added(11), h_added(12),
       h_added(13), h_added(14), h_added(15), h_added(16), h_added(17), h_added(18), h_added(19),
       h_added(20), h_added(21), h_added(22), h_added(23), h_added(24), h_added(25), h_added(26),
       O1X1, O1Y1, O1X2, O1Y2, O2X1, O2Y1, O2X2, O2Y2, O3X1, O3Y1, O3X2, O3Y2, O4X1, O4Y1, O4X2,
       O4Y2, O5X1, O5Y1, O5X2, O5Y2, O6X1, O6Y1, O6X2, O6Y2, O7X1, O7Y1, O7X2, O7Y2, O8X1, O8Y1,
       O8X2, O8Y2, O9X2, O9Y2, O11X1, O11Y1,O12X2, O12Y2, O16X1, O16Y1]);

    Launcher.Jobs.Add(job);

    Launcher.Run();

%Objective Functions

%Acoustic Objective calculations
% Frequencies and corresponding absorption coefficients,
aIS = 0.62; % average absorption coefficient; average_alpha = mean(alpha_values); alpha_values of
     a 25mm thick HERADESIGN, fine, wood wool= [.4 ,.75,.65,.55,0.75];@frequencies = [125, 250,
    500, 1000, 2000];
a2 = 0.066; % Absorption coefficients of triple glazed glass at different frequencies;
    alpha_values = [0.18, 0.06, 0.04, 0.03, 0.02];@frequencies = [125, 250, 500, 1000, 2000];
a3 = 0.066;
a4 = 0.066;
a1 = 0.066;
aceiling =   0.3660; % ceiling absorption coefficient = [.06 ,.21,.43,.44,.69]
aFloor =  0.4860; % Floor absorption coefficient = [.2 ,.5,.68,.6,.45]
S1 = Winw*h_window; % Surface area of window on wall 1
S2 = 4.47753729810623*5*h_window; % Surface area of the windows on wall 2; 4.47753729810623 =
    width of each window on wall 2; 5 windows on bigger wall; calculation: SQRT
    ((-38.2173796151-(-39.8947444948))^2+(44.2016367245-48.3531168601)^2); coordinates of Block1:
    Zone1_Wall_3_0_0_0_0_4_Win, vertices(1,2)
S3 = 3*4.52857027668468*h_window; %Surface area of the windows on wall 3; 4.52857027668468 = width
     of each window on smaller wall; 3 windows on smaller wall; calculation: SQRT
    ((-31.3923403917+35.5916737368)^2 +(27.1441483266-25.4489939951)^2); coordinates of Block1:
    Zone1_Wall_2_0_0_0_0_2_Win, vertices(3,4)
S4 = 4.47753729810623*5*h_window; % Surface area of the windows on wall 4; 4.47753729810623 =
    width of each window on wall 2; 5 windows on bigger wall
SWall = (13.90971027-Winw)*h_wall; %Suraface area of the project Wall on Wall 1; 13.59 = total
    width of the wall; calculation: SQRT((-31.3348458736-(-44.2332898805))
    ^2+(27.167357268-21.96061338)^2), coordinates of Zone1_Wall_2_0_0; vertices (3,4)
SFnR =  318.687; % Surface area of Floor and Roof W
Absor = S1*a1 + S2*a2 + S3*a3 + S4*a4 + SWall*aIS + SFnR*(aceiling+aFloor); %S=surface area of
    wall 1 glass, a=alpha, WISaIS = innerwall suface and its alpha
K = 0.161; %  dimensionless factor (s/m) in Sabine's equation.
V = 318.687* h_wall; % volume of the room
TR = K*V/Absor; % reverbration time (TR), K=constant, Absor = total absorption


%Cost Objective
Gprice = 600; %Glass price per m2
%Project wall from outer to inner
Concrete_block = 1.34; % cost per m2, thickness = 100mm Recipe Concrete C20/25, environmental
    class XC1, consistency area C1, CEMIII, gravel 4 - 16 mm
Brickwork_outer = .09178; % per piece of Poriso D 100/100, 210 x 100 x 100 mm, full load
Gypsum_Plaster = .63; %per kg
Gypsum_Plaster_Thickness = 0.013; % in m
Gypsum_Plaster_Density = 1000; % Kg/m3

overhang_length = 80.76165463*2; % m, Overhang length including all sides; calculations: (Wall1
    Width+Wall2 Width)*2 + Overhang Projection*4; overhang projection = 1.78;Wall 1 width
    =13.90971027; Wall 2 width = 22.91111705;
```

```
overhang_area = overhang_length*d; %    m2
Cost_overhang = 75.75*overhang_area; %8.81eur/m2 is the cost of Roof trim RAL enamelled aluminium
    with the thickness of 3mm

FinsulThckness_cost = FloorInsulThickness*0.4265; % 25.59/60mm, 8.53/20mm  Floor, basement wall
    and roof insulation, extruded polystyrene rigid foam XPS, 300 kPa
RinsulThcknessXPS_cost = RFInsulThickness*0.4265;%8.53/20mm  Floor, basement wall and roof
    insulation, extruded polystyrene rigid foam XPS, 300 kPa
RinsulThcknessEPS_cost = RFInsulThickness*0.185625; % Roof insulation board, EPS 100,
RinsulThcknessPIR_cost= RFInsulThickness* 1.098888889; % Roof insulation board, PIR rigid foam
Winsulthckness_cost = WallInsulThickness*0.475;  %4.75/10mm  Insulation inside and outside wall,
    extruded polystyrene rigid foam XPS, 300 kPa


    if insulation_type == 1
        cost = RFInsulThickness * 0.4265; %XPS insulation cost/m2
    elseif insulation_type == 2
        cost = RFInsulThickness * 1.098888889; %PIR insulation cost/m2
    elseif insulation_type == 3
        cost = RFInsulThickness * 0.185625;%EPS insulation cost/m2
    else
        error('Invalid␣roof␣type␣selected␣in␣x(8).␣Please␣choose␣1,␣2,␣or␣3.');
    end

Wall_acousticpanel = 20.4; %cost per/m2, Recipe Wood wool panel, fine, 1-layer magnesite-bound,
    inlay (SK-04) or straight edges (GK), thickness 25 mm

Blinds_cost = 88.91; % cost/m2 CCBlinds
%Surface area of wall and windows
S1 = Winw*h_window; % Surface area of window on wall 1
S2 = 4.47753729810623*5*h_window; % Surface area of the windows on wall 2; 4.47753729810623 =
    width of each window on wall 2; 5 windows on bigger wall; calculation: SQRT
    ((-38.2173796151-(-39.8947444948))^2+(44.2016367245-48.3531168601)^2); coordinates of Block1:
    Zone1_Wall_3_0_0_0_0_4_Win, vertices(1,2)
S3 = 3*4.52857027668468*h_window; %Surface area of the windows on wall 3; 4.52857027668468 = width
     of each window on smaller wall; 3 windows on smaller wall; calculation: SQRT
    ((-31.3923403917+35.5916737368)^2 +(27.1441483266-25.4489939951)^2); coordinates of Block1:
    Zone1_Wall_2_0_0_0_0_2_Win, vertices(3,4)
S4 = 4.47753729810623*5*h_window; % Surface area of the windows on wall 4; 4.47753729810623 =
    width of each window on wall 2; 5 windows on bigger wall
SWall = (13.90971027-Winw)*h_wall; %Suraface area of the project Wall on Wall 1; 13.59 = total
    width of the wall; calculation: SQRT((-31.3348458736-(-44.2332898805))
    ^2+(27.167357268-21.96061338)^2), coordinates of Zone1_Wall_2_0_0; vertices (3,4)
SFnR =  318.687; % Surface area of Floor and Roof
Cost_escalation=  (S1 + S2 + S3 + S4)*Gprice + SWall*(Concrete_block+Winsulthckness_cost+
    Brickwork_outer/0.21+(Gypsum_Plaster_Thickness*Gypsum_Plaster*Gypsum_Plaster_Density)+
    Wall_acousticpanel) + Cost_overhang + FinsulThckness_cost*SFnR + cost*SFnR +Blinds_cost*(S1+S2
    +S3+S4);
Cost_other = 633177.62;
Cost_Objective = Cost_other+Cost_escalation;

% Thermal Comfort Objective

data=csvread(fullfile('N:\My␣Thesis\Tool\variables_codes\OutputJob0\eplusout.csv'), 1, 1); %all
    the outputs from e+ as a table
schedule=readmatrix(fullfile('N:\My␣Thesis\Tool\variables_codes\schedule␣occupancy.xlsx'), 'Range'
    ,'C2:C8761'); % schedule
fanger_no_schedule=mean(data(:,4)); %average yearly fanger without taking schedule into account
fanger_with_schedule=dot(data(:,4),schedule)/sum(schedule); %average yearly fanger with schedule
    included

    Thermalcomfort = fanger_with_schedule;

%EnergyConsumption Objective

T=readtable(fullfile('N:\My␣Thesis\Tool\variables_codes\OutputJob0\eplustbl.csv')); %This is the
    file with table reports that DesignBuilder shows. Some values are easier to get from there
```

```
    compared to eplusout.eso.
    Econsumption=str2double(table2array(T(10,3)));

%Visual Comfort Objective
data=csvread(fullfile('N:\My␣Thesis\Tool\variables_codes\OutputJob0\eplusout.csv'), 1, 1); %all
    the outputs from e+ as a table
schedule=readmatrix(fullfile('N:\My␣Thesis\Tool\variables_codes\schedule␣occupancy.xlsx'), 'Range'
    ,'C2:C8761'); % schedule

%Glare
Glare_no_schedule=mean(data(:,11)); %average yearly fanger without taking schedule into account
Glare_with_schedule=dot(data(:,11),schedule)/sum(schedule); %average yearly fanger with schedule
    included

VisualcmfrtG = Glare_with_schedule;

%Illuminance

illumunance_no_schedule=mean(data(:,7)); %average yearly fanger without taking schedule into
    account
illuminance_with_schedule=dot(data(:,7),schedule)/sum(schedule); %average yearly fanger with
    schedule included

VisualcmfrtI = illuminance_with_schedule;
%Aesthetics Objective
   w1 = .2;
   w2 = 0.3;
   w3 = .5;
    % Calculate the aesthetic index (AI) for the window-to-wall ratio
  % x(1) = .99;
    A1 = x(1)/100;

    %x(2) = 2.2;% Calculate the aesthetic index (AI) for the overhang width
  d = x(3)/100;
    if d >= 0 && d <= 2
        A2 = d / 2;
    elseif d > 2 && d <= 4
        A2 = 1 - ((d - 2) / 2);
    else
        A2 = 0; % Placeholder if the overhang width is out of specified range
    end

    % Calculate the aesthetic index (AI) for the change in building height
    a1 = -2.5;
    x1 = 0;
    a2 = 2.5;
    x2 = 1;

    % Check the value of 'a' and calculate 'x' accordingly
 % x(3)= 2;
    if x(4) == a1
        A3 = x1;
    elseif x(4) == a2
        A3 = x2;
    else
        % Linear interpolation between the two points
        A3 = x1 + ((x2 - x1) / (a2 - a1)) * (x(4) - a1);
    end

    A = w1 * A1 + w2 * A2 + w3 * A3;

%Carbon emission Objective
G_ece = 70; %kg CO2e/m2, Insulating glass unit with laminated glass and argon cavity filament,
    triple glazed, 56 mm, 60 kg/m2, CLIMATOP SILENCE CLIMATOP PLANITHERM, ECLAZ, PLANISTAR SUN,
    COOL LITE SKN ET COOL LITE XTREME (SAINT-GOBAIN GLASS FRANCE), kg CO2e ( Original impact)

Concrete_block = 67.715; % kg CO2e/m3, 135.43 kg co2e/m3 for 200mm so for 100mm it is 67.715,
    Ready-mix concrete, normal-strength, generic, C20/25 (2900/3600 PSI), 55% recycled binders in
```

```
    cement (240 kg/m3 / 14.98 lbs/ft3)
Concrete_thickness = 0.1; %meter
Concrete_ece = Concrete_block*Concrete_thickness; %kg CO2e/m2


%XPS_ece = 3.48; %kg CO2e/m2, XPS insulation panels, L=0.033 W/mK, R=1.2 m2K/W, 40 mm, 1.25 kg/m2,
     31.25 kg/m3, compressive strength 300 kPa, 40% recycled polystyrene, CO2 blowing agent,
    Lambda=0.033 W/(m.K) (One Click LCA)

Brickwork_outer = 113; % kg CO2e/m3, Wall bricks, 575 kg/m3 (Ziegel)
Brickwork_thickness = 0.1; % meter
Brickwork_ece = Brickwork_outer*Brickwork_thickness; %kg CO2e/m2

Gypsum_ece = 0.2; %kg CO2e/kg, Gypsum plaster, 1100 kg/m3 (Bundesverband der Gipsindustrie)
Gypsum_Plaster_Thickness = 0.013; % in m
Gypsum_Plaster_Density = 1000; % Kg/m3
PlasterBoard_ece = Gypsum_ece*Gypsum_Plaster_Density*Gypsum_Plaster_Thickness; %kg CO2e/m2


overhang_length = 80.76165463*2; %total overhang length with twice of increment.
overhang_area = overhang_length*d;
Aluminium_ece = 7.5; %kg CO2e/m2 Aluminium façade cladding panel, anodized, 7.5 kg/m2, 70%
    recycled content (One Click LCA)
Aluminium_density = 2700.0; %kg/m3
Aluminium_thickness = 0.003; % meter
Overhang_ece = Aluminium_ece; %kg CO2e/m2


Finsul_ece =69.6*FloorInsulThickness; %kg CO2e/m2,69.6 kg CO2/m3 , XPS insulation panels, L=0.033
    W/mK, R=1.2 m2K/W, 40 mm, 1.25 kg/m2, 31.25 kg/m3, compressive strength 300 kPa, 40% recycled
    polystyrene, CO2 blowing agent, Lambda=0.033 W/(m.K) (One Click LCA)

Winsul_ece = 69.6*WallInsulThickness;  %4.75/10mm  Insulation inside and outside wall, extruded
    polystyrene rigid foam XPS, 300 kPa


    if insulation_type == 1
        Roof_ece = RFInsulThickness * 69.6; %kg CO2e/m2,XPS insulation panels, L=0.033 W/mK, R=1.2
             m2K/W, 40 mm, 1.25 kg/m2, 31.25 kg/m3, compressive strength 300 kPa, 40% recycled
            polystyrene, CO2 blowing agent, Lambda=0.033 W/(m.K) (One Click LCA)
    elseif insulation_type == 2
        Roof_ece = RFInsulThickness * 278.5; %kg CO2e/m2, PIR (polyisocyanurate foam) insulation
            panels, unfaced, generic, L = 0.022 W/mK, R = 4.55 m2K/W (26.7 ft2°Fh/BTU), 100 mm
            (3.94 in), 45 kg/m3 (2.81 lbs/ft3), Lambda=0.022 W/(m.K)
    elseif insulation_type == 3
        Roof_ece = RFInsulThickness * 103.1; %kg CO2e/m2, EPS insulation panels, graphite, L=
            0.033 W/mK, R= 3.03 m2K/W, 100 mm, 3 kg/m2, 30 kg/m3, compressive strength 220 kPa,
            100% recycled polystyrene, Lambda=0.033 W/(m.K) (One Click LCA)
    else
        error('Invalid␣roof␣type␣selected␣in␣x(8).␣Please␣choose␣1,␣2,␣or␣3.');
    end

Acoustic_panel_ece = 5.49; %kg CO2e / m2, Acoustic wood-wool panel, 25 mm, 460 kg/m3, 11.2 kg/m2,
    16% moisture content, Heradesign superfine, Heradesign superfine A2 Heradesign fine,
    Heradesign fine A2 Heradesign macro Heradesign micro Heradesign plano (KNAUF)

Blinds_ece = 132; %kg CO2e / m2, Aluminium venetian blinds, motorized, for exterior use, 0.08 m2K/
    W, 0.5 x 0.7 m, 17.23 kg/m2 (Groupement ACTIBAIE)

S1 = Winw*h_window; % Surface area of window on wall 1
S2 = 4.47753729810623*5*h_window; % Surface area of the windows on wall 2; 4.47753729810623 =
    width of each window on wall 2; 5 windows on bigger wall; calculation: SQRT
    ((-38.2173796151-(-39.8947444948))^2+(44.2016367245-48.3531168601)^2); coordinates of Block1:
    Zone1_Wall_3_0_0_0_0_4_Win, vertices(1,2)
S3 = 3*4.52857027668468*h_window; %Surface area of the windows on wall 3; 4.52857027668468 = width
     of each window on smaller wall; 3 windows on smaller wall; calculation: SQRT
    ((-31.3923403917+35.5916737368)^2 +(27.1441483266-25.4489939951)^2); coordinates of Block1:
    Zone1_Wall_2_0_0_0_0_2_Win, vertices(3,4)
```

```
S4 = 4.47753729810623*5*h_window; % Surface area of the windows on wall 4; 4.47753729810623 =
     width of each window on wall 2; 5 windows on bigger wall
SWall = (13.90971027-Winw)*h_wall; %Suraface area of the project Wall on Wall 1; 13.59 = total
     width of the wall; calculation: SQRT((-31.3348458736-(-44.2332898805))
     ^2+(27.167357268-21.96061338)^2), coordinates of Zone1_Wall_2_0_0; vertices (3,4)
SFnR =  318.687; % Surface area of Floor and Roof
ece_Change=  (S1 + S2 + S3 + S4)*G_ece + SWall*(Concrete_ece +Brickwork_ece+PlasterBoard_ece+
     Winsul_ece+Acoustic_panel_ece) + (Overhang_ece*overhang_area) + Finsul_ece*SFnR + Roof_ece*
     SFnR +(S1 + S2 + S3 + S4)*Blinds_ece;


%All Objectives

Objective_m(1) = pchip(Econsmp_curve(1,:), Econsmp_curve(2,:),Econsumption);
Objective_m(2) = pchip(Thermal_curve(1,:),Thermal_curve(2,:),Thermalcomfort);
Objective_m(3) = pchip(Acoustic_curve(1,:),Acoustic_curve(2,:),TR);
Objective_m(4) = pchip(Cost_curve(1,:), Cost_curve(2,:),Cost_Objective)
Objective_m(5) = pchip(Glare_curve(1,:),Glare_curve(2,:),VisualcmfrtG);
Objective_m(6) = pchip(Illuminance_curve(1,:),Illuminance_curve(2,:),VisualcmfrtI);
Objective_m(7) = pchip(AS_curve(1,:),AS_curve(2,:),A)
Objective_m(8) = pchip(Ece_curve(1,:), Ece_curve(2,:), ece_Change)
w= [w_Econ w_Thermal w_acoustic w_cost w_visualI w_visualG w_aesthetic w_Carbnemission];
goals = 100-Objective_m;

Opt=max(w.*goals,[],2);

end

%% Optimization

numvars=8; % Number of variables
%intvars=[]; % Ineger variables.
IntCon = [2,3,5,6,7,8];

rng('shuffle')

% Now we have everything to run optimization:
[xbest,fbest] = ga(@ObjFunction, numvars, [], [], [], [], lb, ub, @Constr,IntCon, opts);

display(xbest) % Your optimal values of variables
display(fbest) % Your optimal value of objective function

assignin('base','solution',[xbest fbest])

end
```

Appendix C: Visual Comfort

The figure Figure C.1 provides the inputs parameters for determining the visual comfort of the Co Creation Cente project.

```
Daylighting:Controls, Block1:Zone1,           !- Name
   Block1:Zone1,                              !- Zone name
   SplitFlux,                                 !- Daylighting Method
   On,                                        !- Availability Schedule Name
   Continuous,                                !- Lighting Control Type
   0.1,                                       !- Minimum Input Power Fraction for Continuous or ContinuousOff Dimming Control
   0.1,                                       !- Minimum Light Output Fraction for Continuous or ContinuousOff Dimming Control
   1,                                         !- Number of Stepped Control Steps
   1,                                         !- Probability Lighting will be Reset When Needed in Manual Stepped Control
   Block1:Zone1 Ref Point 1,                  !- Glare Calculation Daylighting Reference Point Name
   0,                                         !- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis
   22,                                        !- Maximum Allowable Discomfort Glare Index
   1.0,                                       !- DElight Gridding Resolution
   Block1:Zone1 Ref Point 1,                  !- Daylighting Reference Point 1 Name
   1,                                         !- Fraction of Zone Controlled by Reference Point 1
   300;                                       !- Illuminance Setpoint at Reference Point 1 {lux}

Daylighting:ReferencePoint, Block1:Zone1 Ref Point 1,  !- Name
   Block1:Zone1,                              !- Zone Name
   -41.425,                                   !- X-Coordinate of Reference Point {m}
   34.907,                                    !- Y-coordinate of Reference Point {m}
   .851;                                      !- Z-coordinate of Reference Point {m}
```

Figure C.1: Visual Comfort settings in EnergyPlus Model

Appendix D: Insulation Cost

The values for each type of insulation (last column) are determined by averaging the available ranges from the BouwKosten.nl (as shown in column 4).

Component	Insulation name (BouwKosten)	unit	cost/unit	thickness	Cost Difference	thickness difference	Cost/ m2 for 1 mm thick insulation
XPS (Floor and Roof)	Floor, basement wall and roof insulation, extruded polystyrene rigid foam XPS, 300 kPa | 130 kPa, Rd 1.80 m2. P/W, thickness 60 mm	m2	8.53	20	8.53	20	0.4265
		m2	17.06	40	8.53	20	
		m2	25.59	60	8.53	20	
		m2	34.12	80	8.53	20	
		m2	42.65	100	8.53	20	
		m2	51.18	120	8.53	20	
		m2	59.71	140	8.53	20	
		m2	68.24	160	8.53	20	
		m2	76.77	180	8.53	20	
		m2	85.3	200			
XPS (Wall)	Insulation inside and outside wall, extruded polystyrene rigid foam XPS, 300 kPa | 130 kPa, Rd 0.90 m2. P/W, thickness 30 mm	m2	14.25	30	4.75	10	0.475
		m2	19	40	4.75	10	
		m2	23.75	50	4.75	10	
		m2	28.5	60	9.5	20	
		m2	38	80	9.5	20	
		m2	47.5	100	9.5	20	
		m2	57	120	9.5	20	
		m2	66.5	140	9.5	20	
		m2	76	160	9.5	20	
		m2	85.5	180	9.5	20	
		m2	95	200			
EPS (Roof)	Roof insulation board, EPS 100, Rd 1.10 m2. P/W, 1 side brominated glass fleece, 1,200 x 1,000 x 40 mm	m2	13.37	40	0.9	10	0.185625
		m2	14.27	50	1.93	10	
		m2	16.2	60	1.89	10	
		m2	18.09	70	1.94	10	
		m2	20.03	80	1.93	10	
		m2	21.96	90	1.89	10	
		m2	23.85	100	1.94	10	
		m2	25.79	110	1.93	10	
		m2	27.72	120	1.89	10	
		m2	29.61	130	1.94	10	
		m2	31.55	140	1.89	10	
		m2	33.44	150	1.93	10	
		m2	35.37	160	1.94	10	
		m2	37.31	170	1.89	10	
		m2	39.2	180	1.93	10	
		m2	41.13	190	1.94	10	
		m2	43.07	200			
PIR (Roof)	Roof insulation board, PIR rigid foam, Rd 1.10 m2. P/W, 2 sides glass fleece,	m2	57.09	40	8.75	10	1.098888889
		m2	65.84	50	8.67	10	
		m2	74.51	60	10.28	10	
		m2	84.79	70	9.71	10	
		m2	94.5	80	12.34	10	
		m2	106.84	90	12.95	10	
		m2	119.79	100	26.51	20	
		m2	146.3	120	22.58	20	
		m2	168.88	140	23.31	20	
		m2	192.19	160			

Figure D.1: Cost Estimation for different insulations

Appendix E: Invitation Letter

Invitation for Participation in a Tool Validation interview for research in Optimization in Design Process

Dear [respondent],

My name is Himanshu Patel, and I am currently pursuing a Master's degree in Construction Management & Engineering at TU Delft. A few months back, I sought your input to understand your objectives, requirements, and values in relation to the Co-creation Center project. This inquiry was part of my graduation research, where I am developing a tool based on an optimization strategy known as the Preference-based Goal Attainment (PBGA) tool, intended for design decision-making processes.

I would like to express my gratitude for your contributions to the initial phase of this research. Since then, I have incorporated the information gathered into the tool I've been developing over these past months, which has now produced results. The next stage of this research includes the validation of the tool by the project's stakeholders. Your role as a pivotal stakeholder makes your input extremely valuable for the validation phase of this research.

The interview will take no more than one hour of your time and will cover the following topics:

- An introduction to the PBGA tool;
- Your feedback on the results it has generated;
- Your perspective on the tool's application in decision-making processes.

We can conduct the interview either in person at a location that suits you or via an online video call platform, depending on your preference. I would like to mention that I will request your consent to record our conversation before we begin the interview. The recording will only be used to transcribe the discussion accurately, and no personal information will be included in the research data. Please be assured that your participation in this interview is entirely voluntary.

I invite you to propose a convenient date and time for this meeting, or if you have any questions about the study, please do not hesitate to reach out.

I am looking forward to learning from your experiences and insights.

Contact

TU Delft h.patel

Appendix F: Consent Form

The Consent form along with, data management plan have been approved by the Human Research Ethics Committee (HREC) at TU Delft.

INFORMED CONSENT

You are being invited to participate in a research study titled "Developing and implementing Preference-Based Goal Attainment approach for multi-stakeholder design optimization and decision-making" conducted by Himanshu Patel from TU Delft.

Study Purpose:

The purpose of this research study is to test and validate a new optimization-based approach, preference-based Goal Attainment, in a building project to facilitate the decision-making in the design process.

Your Involvement:

As a project participant in the Design and Construction of the Co-creation centre, your interview as a key stakeholder will be invaluable to this research. The interview sessions will be audio-recorded and held in-person or online, lasting approximately 60 minutes.

Data Usage:

The information/data collected during these interviews only be related to the Co-creation centre project. It will be used to set up the optimization problem to develop the tool, understand the design process of the current building design, and gather insights on the use of such tools in the design decision-making process. Your viewpoints on the implementation and utilization of optimization-based tools in practical projects, as well as your objectives with regards to the Co-creation Centre project in the Green Village in Tu Delft Campus, will be sought.

Risks:

1. The information provided may include the project name and stakeholder role (e.g., Architect, contractor, glass expert). This could potentially be used to identify your individual identity through available project-related information on the internet.
2. The interview transcript will be anonymous and shared in the master's thesis appendix.

3. The master's thesis containing the project-related data and interview transcripts will be publicly available on the TU Delft repository website.

Voluntary Participation:

Your participation in this study is entirely voluntary, and you have the right to withdraw at any time. You are free to omit any questions. Data related to the project will be destroyed at the end of this master's thesis, except for the data used in the master's thesis report.
Himanshu Patel

Appendix F: Material EPDs

ENVIRONMENTAL IMPACTS Aggregation of the various modules to produce a "Stage Total" or "Lifecycle Total".					
Impacts/Flows *unit*	Production stage	Construction stage	Step of use	End-of-life stage	**Total life cycle**
Environmental impact					
Global warming - *kg $_{CO2}$ equiv/UF*	70,0	1,46	7,92E-02	1,02	**72,6**
Ozone depletion *kg CFC 11 equiv/UF*	3,05E-06	2,40E-16	3,94E-09	4,56E-15	**3,05E-06**
Soil and water acidification - *kg $_{SO2}$ equiv/UF*	3,20E-01	4,41E-03	3,82E-04	5,55E-03	**3,30E-01**
Eutrophication - *kg $(_{PO4})^{3-}$ equiv/UF*	3,27E-02	1,07E-03	6,51E-04	6,85E-04	**3,51E-02**
Photochemical ozone formation *Ethene equiv/UF*	1,53E-02	1,62E-04	2,59E-05	4,27E-04	**1,59E-02**
Depletion of abiotic resources (elements) *kg Sb equiv/UF*	5,21E-04	1,21E-07	2,56E-06	3,17E-07	**5,24E-04**
Depletion of abiotic (fossil) resources *MJ/UF*	839	19,9	1,29	13,4	**874**
Water pollution - *m /UF^3*	42,4	3,31E-01	9,31E-01	1,73E-01	**43,8**
Air pollution - *m /UF^3*	34 600	56,2	19,7	102	**34 778**

Figure G.1: Triple Glass Facade EPDs

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED)																
PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND	MND

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT: 1 kg GYPSUM PLASTER

Parameter	**Unit**	**A1-A3**
Global warming potential	[kg CO_2-Eq.]	0.14
Depletion potential of the stratospheric ozone layer	[kg CFC11-Eq.]	2.29E-11
Acidification potential of land and water	[kg SO_2-Eq.]	2.04E-4
Eutrophication potential	[kg $(PO_4)^{3}$-Eq.]	2.65E-5
Formation potential of tropospheric ozone photochemical oxidants	[kg ethene-Eq.]	2.09E-5
Abiotic depletion potential for non-fossil resources	[kg Sb-Eq.]	1.84E-5
Abiotic depletion potential for fossil resources	[MJ]	2.11

Figure G.2: Gypsum PlasterBoard EPDs

Materials	Material names from One Click LCA
G_ece	Insulating glass unit, triple glazed, CLIMATOP SILENCE CLIMATOP PLANITHERM, ECLAZ, PLANISTAR SUN, COOL LITE SKN ET COOL LITE XTREME
Concrete_block	Ready-mix concrete, normal-strength, generic, C20/25, 55% recycled binders
Brickwork_outer	Wall bricks, Ziegel
Gypsum_ece	Gypsum plaster, Bundesverband der Gipsindustrie
Aluminium_ece	Aluminium façade cladding panel, anodized, 70% recycled content
Finsul_ece	XPS insulation panels, L=0.033 W/mK, R=1.2 m2K/W, 40 mm, 1.25 kg/m2, 31.25 kg/m3, 40% recycled polystyrene, CO2 blowing agent
Winsul_ece	Insulation inside and outside wall, extruded polystyrene rigid foam XPS, 300 kPa
Acoustic_panel_ece	Acoustic wood-wool panel, 25 mm, 460 kg/m3, 16% moisture content, Heradesign
Blinds_ece	Aluminium venetian blinds, motorized, for exterior use, Groupement ACTIBAIE

Figure G.3: Names of the material from One Click LCA

Appendix G: Preference Curves

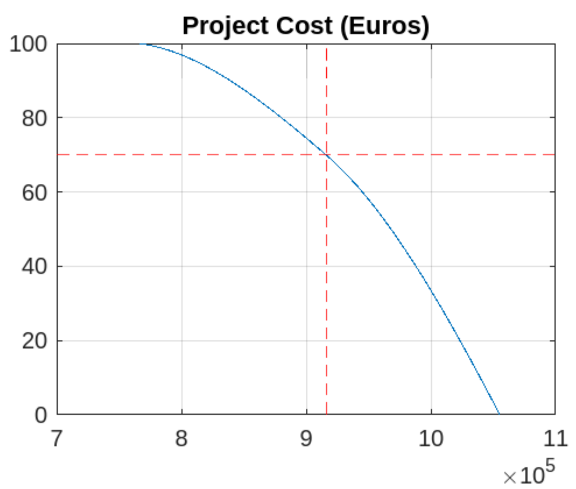


Figure H.1: Project Cost

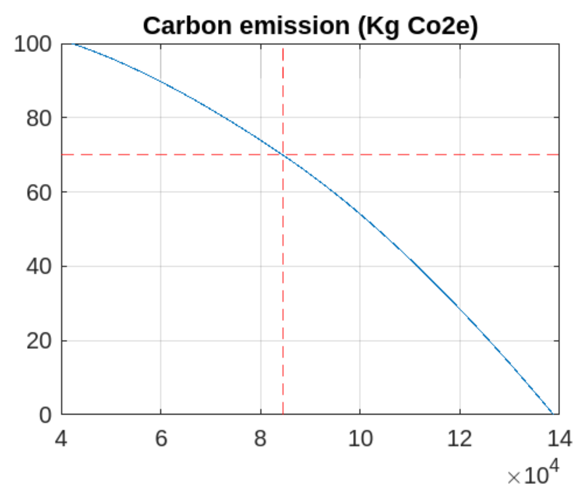


Figure H.2: Carbon Emission

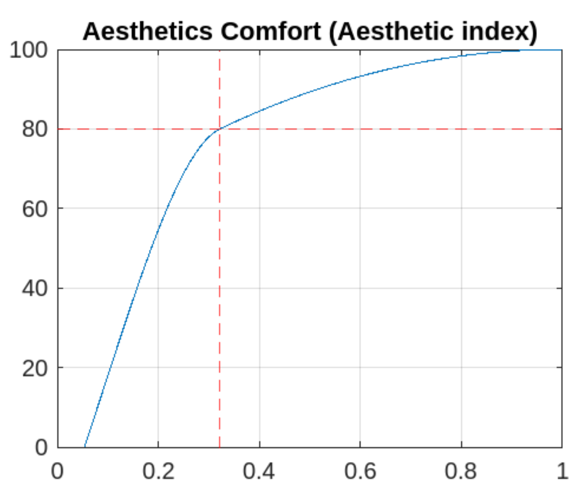


Figure H.3: Aesthetic Index

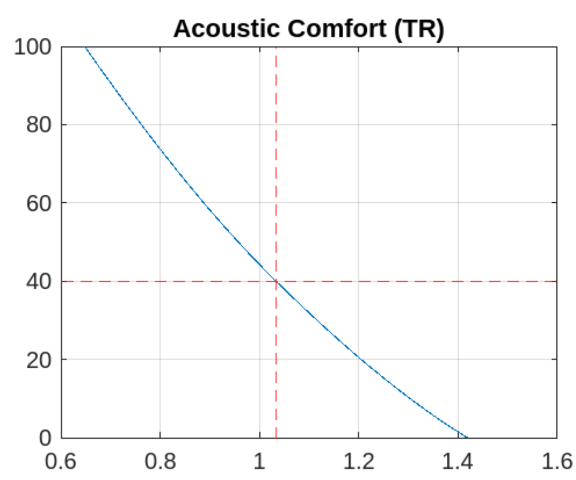


Figure H.4: Acoustic Comfort

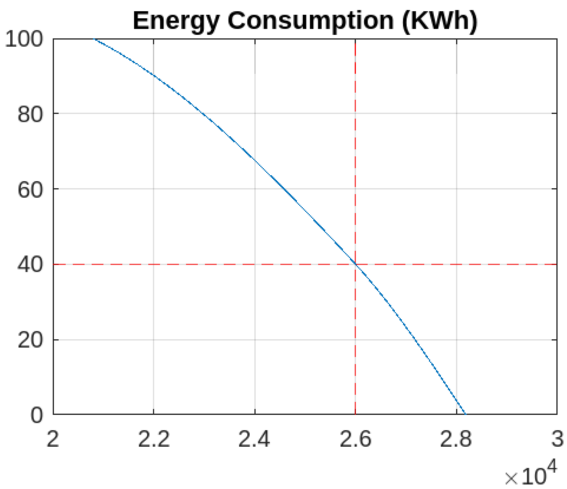


Figure H.5: Energy Consumption

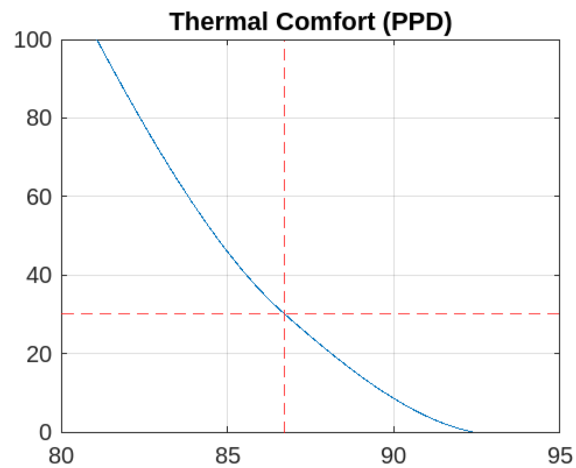


Figure H.6: Thermal Comfort

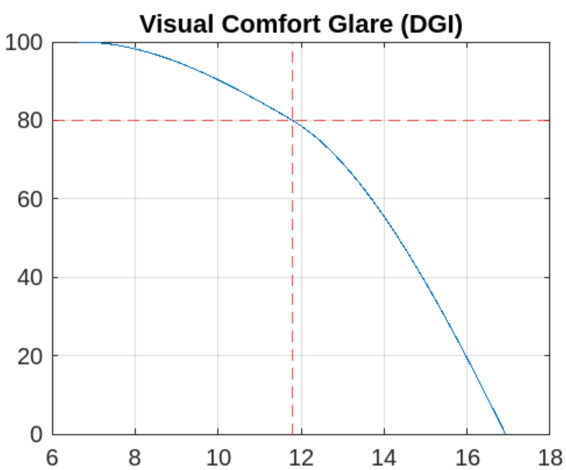


Figure H.7: Glare

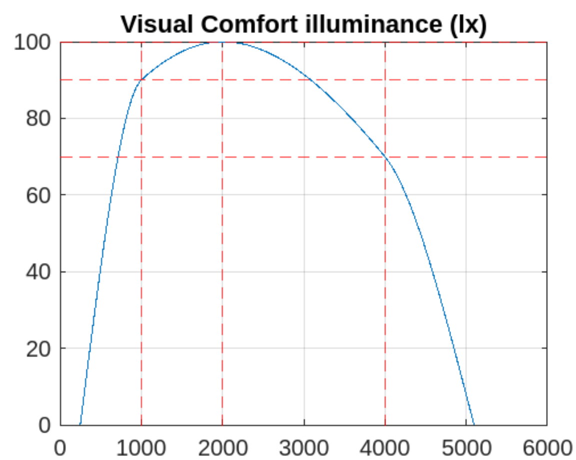
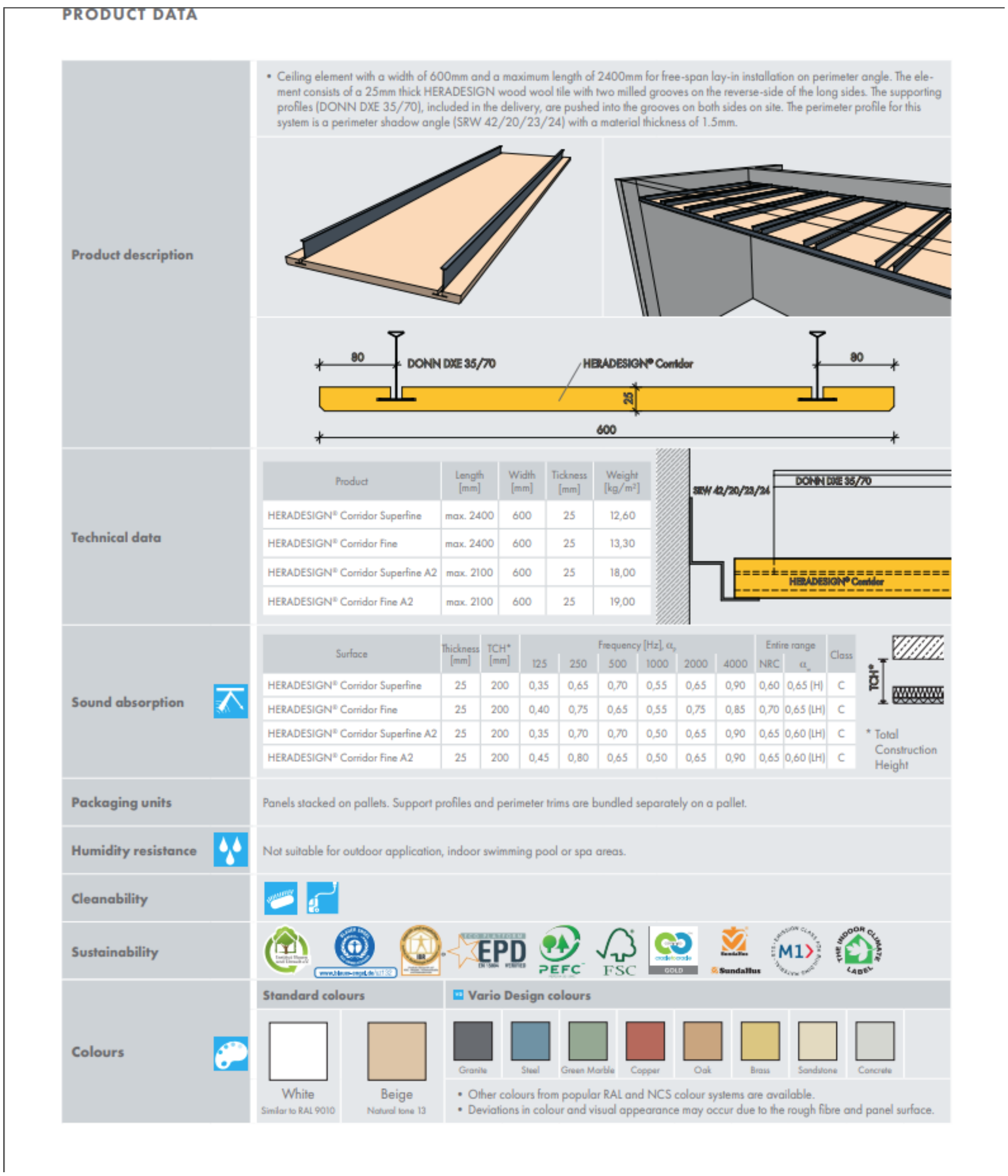


Figure H.8: Illuminance

Appendix H: Absorption Coefficients



PRODUCT DATA

Product description

- Ceiling element with a width of 600mm and a maximum length of 2400mm for free-span lay-in installation on perimeter angle. The element consists of a 25mm thick HERADESIGN wood wool tile with two milled grooves on the reverse-side of the long sides. The supporting profiles (DONN DXE 35/70), included in the delivery, are pushed into the grooves on both sides on site. The perimeter profile for this system is a perimeter shadow angle (SRW 42/20/23/24) with a material thickness of 1.5mm.

Technical data

Product	Length [mm]	Width [mm]	Tickness [mm]	Weight [kg/m²]
HERADESIGN® Corridor Superfine	max. 2400	600	25	12,60
HERADESIGN® Corridor Fine	max. 2400	600	25	13,30
HERADESIGN® Corridor Superfine A2	max. 2100	600	25	18,00
HERADESIGN® Corridor Fine A2	max. 2100	600	25	19,00

Sound absorption

Surface	Thickness [mm]	TCH* [mm]	Frequency [Hz], α_p						Entire range		Class
			125	250	500	1000	2000	4000	NRC	α_w	
HERADESIGN® Corridor Superfine	25	200	0,35	0,65	0,70	0,55	0,65	0,90	0,60	0,65 (H)	C
HERADESIGN® Corridor Fine	25	200	0,40	0,75	0,65	0,55	0,75	0,85	0,70	0,65 (LH)	C
HERADESIGN® Corridor Superfine A2	25	200	0,35	0,70	0,70	0,50	0,65	0,90	0,65	0,60 (LH)	C
HERADESIGN® Corridor Fine A2	25	200	0,45	0,80	0,65	0,50	0,65	0,90	0,65	0,60 (LH)	C

* Total Construction Height

Packaging units

Panels stacked on pallets. Support profiles and perimeter trims are bundled separately on a pallet.

Humidity resistance

Not suitable for outdoor application, indoor swimming pool or spa areas.

Cleanability

Sustainability

Colours

Standard colours: White (Similar to RAL 9010), Beige (Natural tone 13)

Vario Design colours: Granite, Steel, Green Marble, Copper, Oak, Brass, Sandstone, Concrete

- Other colours from popular RAL and NCS colour systems are available.
- Deviations in colour and visual appearance may occur due to the rough fibre and panel surface.

Figure I.1: Absorption coefficient of wood wool panel