PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

SELECTION OF ENVELOPE-WALL SYSTEMS FOR RESIDENTIAL PROJECTS

JOSE ESTEBAN MARTABID CRUTCHIK

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
CLAUDIO MOURGUES ÁLVAREZ

Santiago de Chile, Enero, 2015

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

SELECTION OF ENVELOPE-WALL SYSTEMS FOR RESIDENTIAL PROJECTS

JOSE ESTEBAN MARTABID CRUTCHIK

Members of the Committee:

CLAUDIO MOURGUES A.

RICARDO SERPELL C.

AUGUSTO HOLMBERG F.

HERNAN SANTAMARIA O.

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Santiago de Chile, Enero , 2015

To my grandmother, Georgette.

ACKNOWLEDGEMENTS

This work was supported by the National Commission for Science and Technology (CONICYT) under the research project FONDEFD09I1018: Solutions of envelope walls of concrete' houses based on energy-thermal, structural and constructive performance criteria.

I would like to thank my advisor Dr. Claudio Mourgues for support and guidance over this time, which has lead me to get interested in research and the study of new topics. His knowledge and research experience has helped me to develop journal papers and this thesis.

My special thanks to the coordinators of the real estate committee and the committee of social housing committee of the Chilean Chamber of Construction (CCHC), for their support in the dissemination and implementation of surveys. I am also very grateful to the companies that received me and allowed me to develop my research in their projects.

I would like to thank all my colleagues and professors of the Department of Construction Engineering and Management for their collaboration and friendship. Finally, I would like to thank my family and friends for their patience and support for my academic pursuits. I feel very fortunate to have wonderful people around.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

During the early stages of the design process, major decisions that have the greatest influence on the results of a project are taken. One of these decisions is the selection of the envelope materials and designs. Unofortunately, the criteria used in this selection vary based on the decision makers do not consider all the relevant aspects, leading to suboptimal decisions. Moreover, the decisions usually do not consider all the relevant stakeholders.

In order to compare alternatives walls of houses before making the final decision is necessary to identify the criteria that should be present in this comparison. Also, it is imperative to know all the stakeholders of the selection process. This research, based on the existing literature and industry practices, proposes criteria set to select the most convenient envelope walls for residential houses. Surveys were conducted to identify and validate the set of criteria using statistical analysis. Additionally, relative weights of each criterion are calculated using surveys.

Also several multi-resolution methodologies found in the literature are discussed, identifying constraints and its application in the selection of houses envelopes walls. The research, using the criteria set, proposes a new methodology to improve the selection process in the Chilean industry. Study cases are used to validate the methodology.

The results indicate that the criteria set considered all the relevant criteria and the methodology improves the traditional method currently used in Chile by the real state companies. Thus building professionals can understand the rationale behind the selection of the building envelope materials and designs.

RESUMEN

Durante las primeras etapas del proceso de diseño, se toman las decisiones que tienen mayor influencia en los resultados de un proyecto. Al tomar la decisión de qué materiales y diseños usar para la envolvente en casas residenciales, los criterios utilizados por los tomadores de decisiones varían en función de cada persona y por lo general, no tienen en cuenta todos los aspectos relevantes. Por lo tanto, en algunos casos la envolvente escogida puede no ser la óptima. Este proceso de selección tiene varios requisitos y condiciones que tienen que ser tomados en consideración simultáneamente.

Con el fin de comparar los muros de envolvente en casas casas antes de tomar la decisión final es necesario identificar los criterios que deben estar presentes en esta comparación. Además, es imprescindible conocer todos los actores presentes en el proceso de selección. Esta investigación, basada en la literatura existente y las prácticas de la industria, propone un set criterios para seleccionar los muros de envolvente más convenientes en proyectos residenciales. Se llevaron a cabo encuestas para identificar y validar el conjunto de criterios usando análisis estadístico. Además, se calculan los pesos relativos de cada criterio con los resultados de las encuestas.

También se discuten varios métodos de resolución multi-atributo de la literatura, se identifican sus restricciones y su posible aplicación a la selección de muros de envolventes de viviendas. Por último esta investigación, utilizando el set de criterios definido previamente, propone una nueva metodología para mejorar el proceso de selección en la industria chilena. Se utilizan estudios de casos para validar la metodología.

Los resultados indican que el set de criterios considera los más relevantes y la metodología es un aporte para el tomador de decisiones, mejorando varios aspectos del método actualmente usado en Chile por las empresas inmobiliarias.

1. INTRODUCTION

1.1. Background information

The building envelope is the interface between the interior space and the environment to which it is exposed outside the building. Its function is to protect the building from the elements and pollution and thermal and acoustic insulation (Kibert 2012).

It can be made of a mixture of different construction materials. Also the building envelope is three-dimensional, multilayer and multi-material. It can be made of a mixture of different construction materials. Extending from the inner face of the innermost layer (paint or wallpaper) to the outer face of the outermost layer (painting, roofing shingles). The envelope meets the human need for protection, it provides an environment to stay safe.

The main functions of the envelope building are (Straube and Burnett 2005):

- **Support:** Support, resist, distribute and transfer all structural loads.
- **Distribution:** Throughout the envelope are distributed facilities (sanitary, electricity, gas, climate, lighting).
- **Control:** Control, regulate and moderate environmental loads (mass and energy flows).
- **Terminations:** surface terminations must meet performance requirements visual, aesthetic, use, impact, durability, etc.

The large increase in population in the last decades and the economic growth has meant an increase in the demand for houses. To meet an urgent need due to the increasing of population and the higher life quality standards, an important amount of houses are being built in the world. Building envelope's performance affects occupant comfort and productivity (Figure 1-1), energy use and running costs, structural behavior, durability, esthetics appeal of a building, among other interesting factors (Chew 2001; Chua and Chou 2010). Zavadskas et al. (2008) add that the highest standards of quality of life, new welfare requirements and lifestyle changes have led to an increased demand for better envelope behaviors.

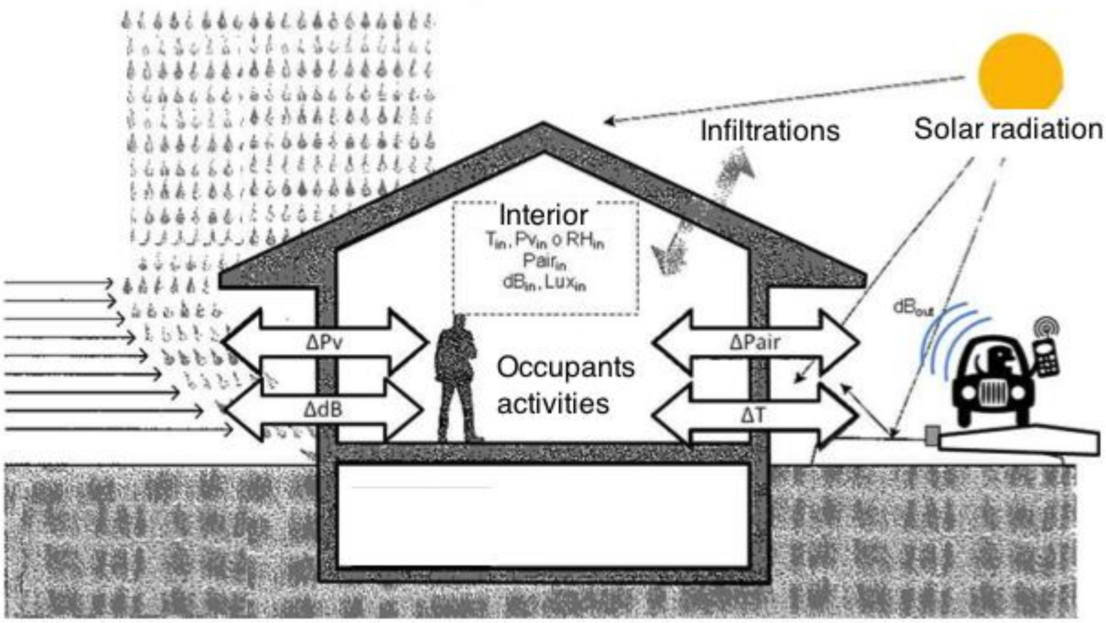


Figure 1-1. Influence of external loads on occupants' comfort and productivity (Straube and Burnett, 2005)

In addition, Passe and Nelson (2012) add that the building envelope serves multiple functions apart from heat retention that are tied to structure, safety, and visual appeal or aesthetics. A thoughtful building envelope can make a building work more effectively for its builders and occupants. Its performance is reflected by the energy costs, thermal comfort, and air quality of the building (Fazio et al. 1997). Thus, success of the project is tied with the assessment and selection of building envelope materials and designs that can satisfy requirements of the stakeholders (Singhaputtangkul et al. 2013).

1.2. Problem definition

The selection of an effective building envelope among a vast number of alternatives is an important problem in project management. Nevertheless, the selection of an effective envelope is not a simply task. It requires large amount of information and inputs from a design team that have to be taken into consideration simultaneously.

Figure 1-2 presents the building envelope design process in a common residential project.

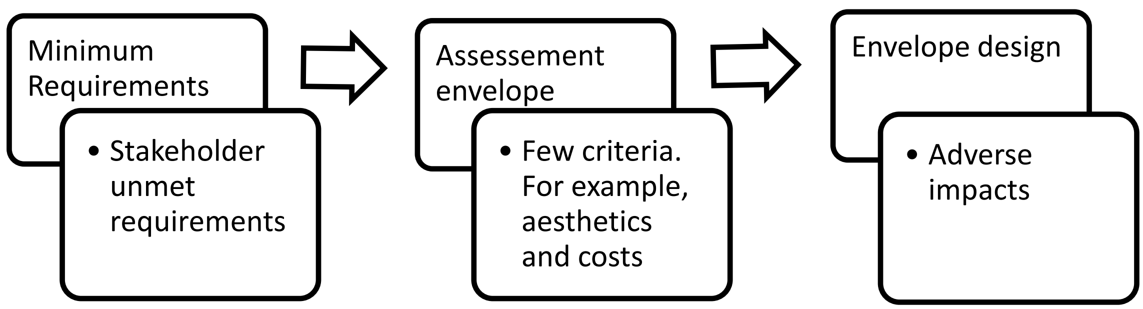


Figure 1-2. Building envelope design process

In the first stage the design team is responsible for meeting the minimum requirements. In all projects there are certain requirements that must necessarily approved, e.g. building regulations and standards. However, it was found that compliance with these minimum requirements does not satisfy all the stakeholders' requirements and preferences.

Then, architects and engineers assess the envelope design based on some criteria. Criteria used by decision makers vary according to each person and might do not take into account all relevant aspects. Sometimes professionals choose a material type or shape of the envelope based on past experiences, the expertise of the company or by intuition. Several studies highlighted that building professionals, in the early design stage, tend to assess building materials and designs with respect to only a few criteria, for example, aesthetics and costs (Granadeiro et al. 2013; Singhaputtangkul et al. 2013).

Therefore, the chosen envelope-wall system may not be the optimal. As a result, this inadequate consideration of requirements may lead to numerous adverse impacts on a project during different project phases, such as:

- **Inadequate consideration of requirements:** Leads to poor performances of construction projects. Authors suggest that inadequate consideration of building envelope requirements by designers tends to lead to redesigning activities, particularly when new assessment criteria have to be additionally considered.
- **Inadequate consideration of possible materials and designs:** Architects and engineers typically select materials drawn from their personal collection of literature and their knowledge of what is available in the market, and frequently use short cuts based on their experience in order to save time. This consequently seems to reduce a number of possible building envelope materials and design alternatives that could satisfy requirements of the stakeholders.
- **Lack of efficiency and consistency:** This problem leads to delay, lack of confidence and participation among members of the team, and eventually affect a client's satisfaction.
- **Subjective and uncertain requirements:** Designers have faced problems in interpreting several requirements, in particular, under vague and uncertain circumstances especially in the early design stage.

For instance, wood-frame houses energy efficiency 1980 and 1990 in the United States. The energy-efficient wood-frame houses of the 1980s and 1990s are one of the most expensive, the most comfortable, and very likely the least durable residential structures ever built in the United States. Declining technology transfer, dubious designs, not consideration of the maintenance, poor construction practices, and new wood products that have not performed as promised share the blame (Smulski 1999).

Another example, several housing complexes were built in Buenos Aires, Argentina where the premature aging and lack of maintenance of the houses and surroundings accelerated the degradation of the houses' envelope. Authors try to identify the minimum criteria of performance that should have been considerate in the project to avoid these problems, as considering maintenance costs as an investment, not an expense (Dunowicz and Hasse 2005).

Hassanain and Harkness (1998) reported other failure examples of building envelope components due to poor consideration of the selection criteria, such as a major problem of moisture penetration from the hot and moist exterior environment into the air-conditioned interior of a 10-floor building, and roof permeability problems.

Envelope components, such as walls, windows, shading devices, etc., impact differently on the behavior of houses. Analogously, different envelope components contribute differently to the cost, structural behavior, constructability, aesthetics, etc. For example, in a non-insulated building, which could be situated in different climate conditions, heat-losses can vary between 10–20 % (through floors), 30–35 % (through outer walls), 25–30 % (through attic slabs and roof plates) and 30–35 % (through windows) of the total heat loss (Passe and Nelson 2012). In many countries low quality walls cause nearly a half of all heating losses. Ginevičius et al. (2008) add that a very high economic effect is achieved by wall insulation. In this respect, it is even higher than the replacement of windows.

Within the envelope of houses, envelope-wall systems (EWS) are a key component and its selection is one of the most important technical and economical tasks for both the Designer and the Investor (Granadeiro et al. 2013). In addition, usually the highest price within these elements is that of the walls. Thus, its selection is made separately from the other components of the building envelope as a unique and complete process.

The selection of a house's evelope-walls is a decision characterized by multiple attributes and multiple participants. Clients want to minimize the likely costs of the project, but they also want to achieve highest acceptable quality standards as well as to satisfy technological, architectural, and comfort requirements. Other participants of construction process (e.g. designer, contractor) are interested in maximizing profits; they are also concerned with other attributes such as company growth, market share, and the state institutions' interests. Hence, the choice of a rational alternative becomes a significant research and practical problem (Ginevičius et al. 2008).

In conclusion, in order to select the most convenient walls of the envelope building is essential to define the list of criteria that is going to be used in the selection of the envelope by the decision-makers (DMs) at the preliminary stage of design in order to avoid possible adverse effects such as those discussed in this section.

Methodologies to select the building envelope found in literature have some limitations to use them in selecting the EWS in residential projects. Also in the industry, none of these methodologies is being used. Therefore, there is a need to create a new methodology focus only on the walls of the house and that includes the characteristics of each project and all the stakeholders. This methodology should be user-friendly and adaptable to the construction industry.

1.3. Objective

The general objective of this research is to help the decision-makers to choose an appropiate envelope-wall system for each residential project.

Specific objectives

a) Identify and formalize the criteria that should be considered in the selection process of the envelope-wall system of houses.

b) Identify and formalize stakeholders and external factors that influence the selection process of the envelope-wall system of houses.

c) Develop a comprehensive methodology to determine the solution of the building envelope walls using multi-criteria analysis. The methodology should improve efficiency, consistency and traceability of the selection process.

1.4. Scope

The research is framed within the context of the Chilean construction industry. Specifically, it aims to support the design team of residential projects, which are usually developed by real estate companies; the latter could be private or social enterprises.

Furthermore, the research focuses on the behavior of the wall systems of house envelopes and not the whole envelope.

1.5. Hypothesis

Formalizing the selection process of envelope-wall systems of houses, allows choosing superior solutions in terms of thermal, structural and constructive performance, when compared to the traditional selection process.

1.6. Methodology

A series of activities were conducted to lead to results, which demonstrate the contributions to knowledge in the area of interest. Figure 1-2 shows the flowchart with the research tasks and methods that were performed to meet the objectives of the research. The methodology consists in two main stages:

1. Determine a holistic criteria set for assessing the envelope-wall system of houses; this is a knowledge gap that this thesis tries to fill. State of art produce an initial set of criteria, confirmed by interviews with companies related to the real state market. A pilot survey refined and formalized this initial set, using a factor analysis. Finally a scenario-based survey and a regression analysis captured the preferences of the

decisión-makers for the formalized criteria. This stage is more explored and detailed in Chapter 3 of this thesis.

2. Develop and validate a multi-criteria multi-participant methodology to support the selection process of the envelope-wall system of houses. The methodology determines performances ratings of each alternative, and therefore prioritizes all possible alternatives for different projects. This stage formalizes the EWS selection procces and identified all the stakeholders and factors involved, through literature review, interviews with decision-makers and the application of a pilot survey. Then, study cases validate the new methodology. This is useful to show that the new methodology improves different aspects regarding the methodology currently used in industry. This stage is more explored and detailed in Chapter 4 of this thesis.

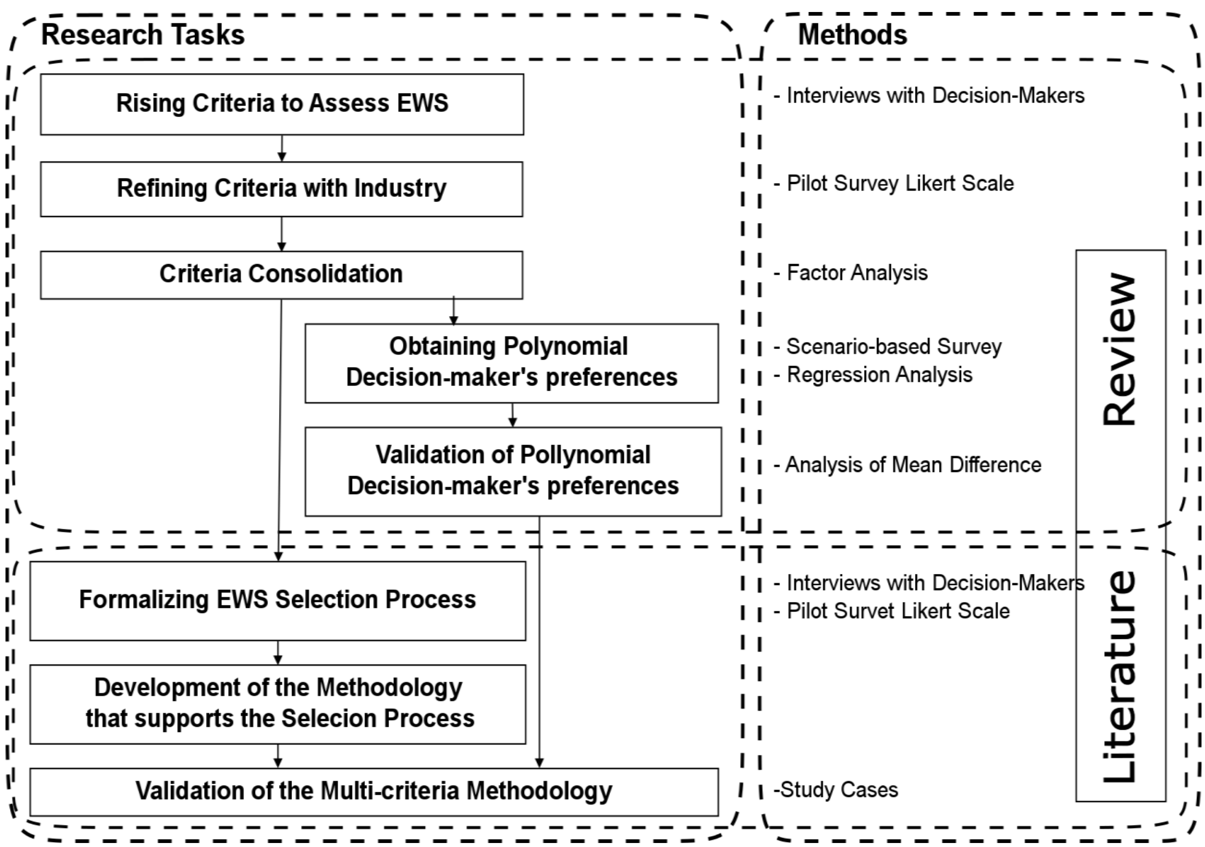


Figure 1-3. Methods and Research Tasks

1.7. Thesis structure

The structure of this thesis is based on the presentation of two papers that display the main findings of the research plus other chapters that complement and connect these papers.

Chapter 1 is an introduction section; which presents the background information, problem definition, objectives, scope, hyphotesis, methodology and expected results of the research.

The second chapter presents a literature review about building envelope assessment criteria, multi-criteria and multiple-participant decision-making, existing methodologies to select the envelope building and statistics and scales used in this research.

Chapter 3 corresponds to a journal article that identifies and formalizes criteria that should be considered in the selection of the envelope-wall systems.

Chapter 4 presents another journal article in which the selection of the envelope-wall system must is addressed as a problem of multiple participant-multiple criteria decision-making. This paper develops a methodology that helps the decision-makers to choose the envelope-wall system satisfying stakeholders' preferences and project requirements.

Finally chapter 5 shows the main conclusions of this thesis work. It also presents contributions of this thesis and suggests future researches.

1.8. Expected results

- Criteria and their relative weigths (preferences of the decision-maker) to select the most convenient envelope-wall system.
- A methodology that considers preferences of all the stakeholders, requirements and external impacts of each project.

- Study cases results that prove the benefits of the methodology with respect to traditional method.

Also the methodology implementation in the Chilean industry will:

- Increase productivity in the decision making process.
- Provide records to justify decisions.
- Quantitatively consider end user preferences or market.
- Reduce adverse effects in the construction and operation phases.

2. LITERATURE REVIEW

This section examines in depth the thematics that are relevant to the development of this research.

Begins by identifying the criteria used in the literature for assessing and comparing building envelopes, then multi-criteria and multi-participants methods are studied along with their respective normalization procedures. Finally, we identify and discuss existing methodologies in the literature to select the building envelope and statistical analyses used in this research are presented.

2.1. Criteria used to assess and select the envelope-wall system

This chapter explores the literature to identify the criteria that is being used to assess and select the building envelope.

Literature identifies several criteria relevant for the selection of building envelope solutions. These studies focus on certain criteria based on their research objectives. For instance, some authors focus mainly in thermal behavior and energy efficiency; others integrate thermal behavior with constructability or costs with environmental impacts of the building envelope. Some authors are listed below with a brief summary of their studies.

Tan et al. (2007) suggest that as building envelope separates occupants in an interior environment from the exterior environment affected by outdoor conditions including heat, moisture, light, sound and other conditions, the criteria to assess the building envelope performance are functionality, durability and efficiency in protecting against thermal, moisture, solar and acoustic influences while considering the cost constraints. Authors add that much of building science is focused on the thermal and moisture, the success or failure of a building in terms of thermal and moisture control can be predictable from the behavior of physical effects and the properties of building materials and assembly.

A different research suggests that the level of a design of external walls efficiency of multi-storey residential buildings depends on very many factors, including: cost of the construction work, used materials and building mechanisms, aesthetics, properties of service, thermal insulation properties, durability, etc (Zavadskas et al. 2005).

Zavadskas et al. (2008) select the effective dwelling house walls by applying attributes values determined in intervals, authors based on:

- Durability of walls (frost resistance in cycles)
- Thermal transmittance (W/m*K)
- Costs ($\$/m^2$)
- Weight (kg/m^2)
- Human work expenditures ($hours/m^2$)

However, authors add that the following points could be considerated in the selection process: Mechanical resistance and stability, Safety in case of fire, Hygiene, health and environment, Safety in use, Protection against noise, Heat retention, Quality of components, Work execution level and Maintenance levels. On the other hand, regarding to customers or buyers, the study adds that they also enter the selection process because they want to reduce to a minimum the costs of your home and also have the highest standards of quality, technology, architectural and comfort.

Furthermore, for Granadeiro et al. (2013) the efficiency of a building or house depends mainly on the following variables: the envelope material, the shape of the envelope and windows areas. These three variables are designed in the early stages of a project; the author proposes a tool to obtain information on the energy performance of design variations provides an indicator of energy efficiency design or Related Energy Envelope-Demand (ERED) which depends on the envelope (floors, walls, roofs and windows), the thermal transmittance values of the materials of the envelope and heat gain due to solar radiation conditions in the building site. The researcher validates the indicator with detailed simulations of different designs that vary in shape and materials of the envelope and window areas.

In addition, Horvat and Fazio (2006) implement a building envelope performance assessment tool (BEPAT). The following aspects are evaluated: effect external moisture, thermal energy efficiency, structural performance of the building envelope, acoustic performance and fire resistance of the building envelope. The structural performance was revised only checking that the strength of the alternative complies with the rules and regulations; therefore it has no influence on the choice or assessment tool.

Also Martinez (2005) indicates that the behavior of the envelope of a house depends on its adaptation to the local climate and its effectiveness to provide comfort conditions. The author adds that there are some important aspects to take into consideration when making design decisions that fundamentally affect the overall performance of the building, such as different materials of the envelope and the orientation of the house. On the other hand, Martinez (2005) criticizes that design decisions and construction of the houses are made without direct intervention from the end user. They are based on economic aspects of initial investment and subsequent profit, and do not take into account the energy costs to be paid in order to achieve acceptable indoor comfort conditions. These costs are greatly inceased if the envelope is not suitable to the climate of the place thus presenting a poor thermal-energy behavior.

Singhaputtangkul et al. (2014) identify the criteria for achieving sustainability and buildability for the assessment of building envelope materials and designs for high-rise residential buildings. Results of their research are showed below**:**

Sustaintability:

- **Environmental impacts:** Energy consumption; Resource consumption; Waste generation**.**
- **Economical impacts:** Initial costs; Long-term burdens; Durability.
- **Social impacts:** Energy efficiency; Appearance demands; Health, safety and security of occupants and society; Weather protection performance; Acoustic

protection performance; Visual performance.

Buildability:

- Health and safety of workers; Community disturbance; Simplicity of design details; Material deliveries from suppliers; Material handling; Ease in construction with respect to time.

Wang et al. (2006) comment that too often decisions on the building shape are based on aesthetics only, which has the evident disadvantage of limiting the potential of performance improvement. Shape optimization can help overcome this disadvantage by exploring more design alternatives at the conceptual design stage for specific criteria such as environmental and economical performance. Since the building shape determines the size and the orientation of the exterior envelope exposed to the outdoor environment, it can affect building performance in many aspects: energy efficiency, cost and aesthetics. They present a methodology to optimize building shapes in green building based on minimum life-cycle cost and minimum life-cycle environmental impact.

Other examples were found in the literature that use different criteria to assess building envelope's components, such as Kaklauskas et al. (2006) who prioritize architectural appearance, energy for heating, cooling and other appliances, impact on the environment, indoor climate and costs, in order to realize an effective selection of windows in a building's retrofit. Ginevičius et al. (2008) asses alternative solutions of wall insulation of buildings based on the materials used, labour expenditure and other aspects (Costs, thermal transmittance , weight, warranty period, service life , duration of the installation).

Table 2-1 presents a summary table with the criteria used in the literature to evaluate the building envelope.

Criterion / Author (s)	Tan et al. (2007)	Zavadskas et al. (2005)	Zavadskas et al. (2008)	Granadeiro et al. (2013)	Horvat and Fazio (2006)	Martinez (2005)	Singhaputtangkul et al.(2014)	Wang et al. (2006)	Kaklauskas et al. (2006)	Ginevičius et al. (2008)
Acoustic performance	X		X		X		X			
Aesthetics		X					X	X	X	
Complexity of construction		X	X				X			X
Costs	X	X	X			X	X	X	X	X
Durability or maintenance	X	X	X			X	X			X
Duration of construction		X	X				X			X
Envelope materials (quality)	X	X	X	X		X	X			
Environmental impact							X		X	
Location conditions				X		X	X			
Moisture resistance	X				X		X			
Safety or fire resistance	X				X		X			
Shape and/or orientation				X		X		X		
Structural performance			X		X					
Thermal performance	X	X	X	X	X		X		X	X
Users intervention			X			X				
Windows areas				X						

Table 2-1. Criteria used on the assessment of the envelope building

On the other hand, the constructability of a project can have an important bearing on the success of the project. Many of the design decisions made early in the design process affect the construction of the project. Consequently, construction complexity is often incorporated in the design process to improve the constructability of the design (Pulaski and Horman 2005). In addition, the best time to influence project costs is early in design and the potential advantages of incorporating constructability information early in design have also been documented and constructive aspects should be considerate (Russell et al. 1992; Jergeas and Put 2001).

Although these authors identify several criteria, the literature review did not find studies with a more comprehensive approach to the behavior of the envelope-wall system. In other words, most of the publications discussed are applied to the analysis and study of the whole building envelope or for other components of the envelope, not specific for wall systems of houses.

Despite the above, the discussed criteria are used as starting point for our investigation. Specifically for the formalization of criteria for selecting EWS developed in chapter 3 of this thesis.

2.2. Multi-criteria Decision-making (MCDM)

Multi-criteria decision-making is the most well known branch of decision-making. It is a branch of a general class of operations research models, which deal with decision problems under the presence of a number of decision criteria.

The selection of the envelope-wall system in residential projects is a problem with several possible alternatives and evaluates many attributes. Then is addressed as multi-attribute or multi-criteria decision-making problem. Therefore, it is important to investigate this type of decision-making.

2.2.1. A General Overview of MADM

Brugha (2004) presents multi-attribute decision-making as a process of shaping information that satisfies the following criteria. The information should be accessible, differentiable, abstractable, understandable, verifiable, measurable, refinable and usable.

Multi-criteria decision-making (MCDM) refers to screening, prioritizing, ranking, or selecting a set of alternatives usually under independent, incommensurate or conflicting attributes (Stanujkic et al. 2013).

Although MCDM methods may be widely diverse, many of them have certain aspects in common. Triantaphyllou et al. (1998) give notions of alternatives, and attributes (or criteria, goals) as described next.

- **Alternatives:** Alternatives represent the different choices of action available to the decision maker. Usually, the set of alternatives is assumed to be finite, ranging from several to hundreds. They are supposed to be screened, prioritized and eventually ranked.
- **Multiple attributes:** Each MCDM problem is associated with multiple attributes. Attributes are also referred to as "goals" or "decision criteria". Attributes represent the different dimensions from which the alternatives can be viewed.
- **Conflict among attributes**: Since different attributes represent different dimensions of the alternatives, they may conflict with each other. For instance cost may conflict with profit, etc.
- **Incommensurable units:** Different attributes may be associated with different units of measure. For instance, in the case of buying a used car, the attributes "cost" and "mileage" may be measured in terms of dollars and thousands of miles, respectively. It is this nature of having to consider different units that makes MADM to be intrinsically hard to solve.
- **Decision weights:** Most of the MCDM methods require that the attributes be assigned weights of importance. Usually, these weights are normalized to add up to one.
- **Decision matrix:** An MCDM problem can be easily expressed in matrix format, as shown below.

$$XF = [xf_1, \dots, xf_n] = \begin{bmatrix} xf_{11} & \dots & xf_{1n} \\ \vdots & & \vdots \\ xf_{m1} & \dots & xf_{mn} \end{bmatrix} \quad (1)$$

$$W = [w_1, \dots, w_m] \quad (2)$$

where n alternatives are evaluated over a set of m criteria. xfij is the performance rating of ith alternative with respect to jth attribute, and wj is a weight (significance) of jth attribute or criterion.

In a typical MCDM evaluation, attributes can be classified into two main categories: cost attributes and benefit attributes. In the case of benefit attributes, the higher score is assigned to the alternative which performance rating is higher, i.e., preferable is a maximum of jth attribute. In contrast to the previous, in the case of cost attributes, higher score is assigned to the alternative which performance rating is lower, i.e., the minimum of jth attribute is preferable (Stanujkic et al. 2013).

Then, the most widely used multicriteria methods are described to have a basic understanding of the main advantages and disadvantages of each method.

2.2.2. MCDM methods

Recently, multi-criteria evaluation methods have been successfully used to quantitatively evaluate complex and controversial phenomena. To apply them, there are three steps in utilizing any decision-making technique involving numerical analysis of alternatives (Triantaphyllou et al. 1998):

1. Determining the relevant criteria and alternatives.
2. Attaching numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
3. Processing the numerical values to determine a ranking of each alternative.

Chapter 3 of this thesis aims to comply with point 1, ie, determining a set of relevant criteria for the selection process of the envelope-wall systems. The following sections discuss points 2 and 3.

Given is a set where m alternatives are evaluated over a set of n criteria. Then the problem is to rank the alternatives in terms of their total preferences when all the decision criteria are considered simultaneously.

2.2.2.1. Attaching numerical measures to the relative importance of the criteria (relative weights)

Decision-makers could define the relative weights directly, however, in literature there are methods to calculate the relative weights. Some of these methods are described below.

- **Ranking methods**

Arranging attributes in rank order is the simplest method for assessing the importance of weights; that is, every attribute under consideration is ranked in the order of the decision-maker's preference. Either straight ranking (the most important = 1, second important = 2, etc.), inverse ranking (the least important = 1, next least important = 2, etc.), or using the dominance count method. Once the ranking is established for a set of attributes, several procedures for generating numerical are available, such as: rank sum, rank reciprocal, rank exponent, and rank order centroid (Kabli 2009).

- **Rating methods**

The rating methods require the decision-makers to estimate weigths on the basis of a predetermined scale; for example, a scale of 0 to 100 can be used. The most popular approaches are: direct rating and point allocation. The direct rating method uses direct numerical ratio judgments of relative attribute importance. In the point allocation method, the decision-maker allocates 100 points across the attributes of interest. Specifically, it is based on allocating points ranging from 0 to 100, where 0 indicates that the attribute can be ignored and 100 represents the situation where only one attribute need be considered in a given decision situation. The more points an attribute receives, the greater its relevant importance (Kabli 2009).

- **Pairwise comparison Method**

This method involves pairwise comparisons to create a ratio matrix. It takes as an input the pairwise comparisons and produces the relative weights as output. Analytic hierarchy process (AHP) and Analytic Network Process (ANP) are the most popular approaches.

AHP is based on decomposing a complex MCDM problem into a system of hierarchies. The final step in the AHP deals with the structure of an m×n matrix (where n is the number of alternatives and n is the number of criteria). This matrix is constructed by using the relative importances of the alternatives in terms of each criterion. The vector (ai1, ai2, ai3, ..., aiN) for each i is the principal eigenvector of an n×n reciprocal matrix which is determined by pairwise comparisons of the impact of the m alternatives on the ith criterion (Saaty 1989). The purpose of AHP is to allow the decision-maker to structure a multi-criteria problem visually, giving it the form of a hierarchy of attributes, which contain minimally three levels: the overall purpose or objective of the problem is located at the top, various criteria defining alternatives in the middle, and competing alternatives in the bottom of the diagram. To the extent that the criteria are very abstract, such as a human being, or ability, for example, may include more operational sub-criteria sequentially between the level of criteria and alternatives, which then gives rise to a multilevel hierarchy (Maurtua 2006).

ANP is a more general form of the AHP. AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network. Both then use a system of pairwise comparisons to measure the weights of the components of the structure, and finally to rank the alternatives in the decision (Saaty 1989).

- **Other methods to determine relative weights**

Yang et al. (2003) proposed a method to calculate the relative weights using fuzzy weighted average. In this method a fuzzy weighted sum of the relative weights of all members of the design team is developed. It considers the importance given to each criterion by the members of the design team. Other method to calculate the relative weights is the Delphi method. This method reachs commun consensus in decision-making and conflict resolution, and therefore determines the criteria weights (Hartman 1981). The Delphi technique is a useful approach for accessing expert opinions, for analyzing and synthesizing results, and for setting priorities among numerous variables or criteria (De Vos et al. 2006). In conclusion, it implicitly considers the preferences of the decision makers allowing calculating a representative configuration of relative weigths.

2.2.2.2. Processing the numerical values to determine a ranking of each alternative

- **Weighted Sum method**

The Weighted Sum (WS) method, more often known as the Simple Additive Weighted (SAW) method is probably the best known and most widely used MCDM method (Hwang and Yoon 1981).

If there are m alternatives and n criteria then, the best alternative is the one that satisfies the following expression:

$$S_i^* = \max \sum_{j=1}^{n} w_j * q_{ij} \quad \text{for } i = 1, 2, \dots, m. \qquad (3)$$

Where S_i^* is the WS score of the best alternative, n is the number of decision criteria, q_{ij} is the actual value of the ith alternative in terms of the jth criterion, and w_j is the weight of importance of the jth criterion.

The assumption that governs this model is the additive utility assumption. In single-dimensional cases, in which all the units are the same (e.g., dollars, feet, seconds), the WSM can be used without difficulty. Difficulty with this method emerges when it is applied to multi-dimensional decision-making problems. Then, in combining different dimensions, and consequently different units, the additive utility assumption is violated and the result is equivalent to "adding apples and oranges" (Triantaphyllou et al. 1998). In this case, in order to eliminate computation problems that can be caused by using different units of measures a normalization procedure is needed. Then, q_{ij} would be he normalized value of the ith alternative in terms of the jth criterion. It should be noted, however, that the order obtained with this method is not independent of the normalization procedure applied (Maurtua 2006).

- **Weighted Product method**

The weighted product (WP) method is very similar to the WS. The main difference is that instead of addition in the model there is multiplication. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In general, in order to compare the alternatives A_K and A_L, the following product has to be calculated (Triantaphyllou et al. 1998):

$$R(A_K/A_L) = \prod_{j=1}^{n} \left(\frac{a_{Kj}}{a_{Lj}}\right)^{w_j} \tag{4}$$

Where n is the number of criteria, a_{ij} is the actual value of the ith alternative in terms of the jth criterion, and $w_j$is the weight of importance of the j-h criterion.

If the term $R(A_K / A_L)$ is greater than one, then alternative A_K is more desirable than alternative A_L (in the maximization case). The best alternative is the one that is better than or at least equal to all the other alternatives.

The WPM is sometimes called dimensionless analysis because its structure eliminates any units of measure. Thus, the WPM can be used in single- and multi-dimensional decision-making problems. An advantage of the method is that instead of the actual values it can use relative ones.

- **TOPSIS method**

TOPSIS (the Technique for Order Preference by Similarity to Ideal Solution) was developed by Hwang and Yoon (1981) as an alternative to the ELECTRE method. TOPSIS is based on the concept that the most preferred alternative should not only have the shortest distance from the positive ideal solution, but also have the longest distance from the negative ideal solution. This concept has been widely used in various MCDM models for solving practical decision problems. This is due to: (a) its simplicity and comprehensibility in concept; (b) its computational efficiency; and (c) its ability to measure the relative performance of the decision alternatives in a simple mathematical form (Yeh 2002).

An ideal solution is defined as a collection of ideal levels (or scores) in all attributes considered, such a solution may be that normally unreachable or is not feasible. This notion is based on the idea that achieving this goal lies in the rationality of human choice. The vector composed of the best values of the jth attribute regarding all possible alternatives is called positive ideal solution. In contrast, the vector containing the worst achievable scores on attributes would give negative ideal solution.

Thus it may happen that a selected from the point of view of its shortest distance from the ideal positive alternative solution must compete with other alternative, which is farthest from the negative ideal solution. Therefore, and in order to define the ideal solution, the method defines a TOPSIS similarity index (or relative proximity) which is constructed by combining the positive ideal proximity and distance relative to negative ideal.

The method is developed in a series of stages: first the scores assigned to the various alternatives are normalized; then normalized weighted scores are calculated; there are identified and/or define the ideal positive and ideal negative solution of the problem under analysis, in terms of the weighted normalized values.

In addition, the steps of separation or distance between the ideal alternative solutions are calculated by some notion of distance metrics, which can be the Euclidean. Whichever concept of distance used, this is calculated from the ideal relative positive and negative solution to the ideal solution. Finally, the similarities are constructed as positive ideal solution from the ideal index negative solution, which implies that this index combines the two aspects or goals defined. The preference order by placing solutions alternatives arises in descending order of similarities estimated in the last step as the higher value represents the alternative that is closer to the positive ideal relative to the distance from the negative ideal (Maurtua 2006).

- **SMART method**

Simple Multi-Attribute Rating Technique (SMART) is based on Edwards and Barron (1994), has been widely applied because of the simplicity of both the responses required of the decision maker and the manner in which the responses are analysed. SMART uses a systematic procedure to estimate criteria weights, as regression fits data with a linear function (Hwang and Yoon 1981). The main stages of the SMART technique are eight stages as follows (Kabli 2009):

Stage 1: Identify the decision maker (or decision makers).
Stage 2: Identify the alternative courses of action.
Stage 3: Identify the attributes, which are relevant to the decision problem.
Stage 4: For each attribute, assign values to measure the performance of the alternatives on that attribute.
Stage 5: Determine a weight for each attribute.
Stage 6: For each alternative, take a weighted average of the values assigned to that alternative.
Stage 7: Make a provisional decision.

Stage 8: Perform sensitivity analysis to reach the final decision.

- **COPRAS method**

COPRAS (Complex Proportional Assessment of alternatives) method uses a stepwise ranking and evaluating procedure of the alternatives in terms of significance and utility degree (Zavadskas et al. 1994). Useful when problems involve both, uncertainty and more than one attribute. In problems involving multiple attributes are often too large for a decision-maker to comprehend in their entirety.

This model and solution results have practical and scientific interests. It can be adapted to various cases, for example when values of initial data are given in the intervals, in applications of the Grey system theory or can be applied to the solution of wide range discrete multi-attribute assessment problems in construction (Zavadskas et al. 2008).

The specific steps of the COPRAS method are not listed in this literature review because they are beyond the level of detail required.

- **ELECTRE method**

The ELECTRE (for Elimination and Choice Translating Reality; English translation from the French) method was first introduced in Benayoun et al. (1966). The basic concept of the ELECTRE method is to deal with "outranking relations" by using pairwise comparisons among alternatives under each one of the criteria separately.

The outranking relationship of A_i , A_j describes that even when the ith alternative does not dominate the jth alternative quantitatively, then the decision maker may still take the risk of regarding A_i as almost surely better than A_j. Alternatives are dominated, if there is another alternative, which exceeds them in one or more attributes and equals in the remaining attributes.

The ELECTRE method begins with pair wise comparisons of alternatives under each criterion. Next, the decision maker is requested to assign weights or importance factors to the criteria in order to express their relative importance.

Finally, the ELECTRE method yields a whole system of binary outranking relations between the alternatives. Because the system is not necessarily complete, the ELECTRE method is sometimes unable to identify the preferred alternative. It only produces a core of leading alternatives. This method has a clearer view of alternatives by eliminating less favorable ones, especially convenient while encountering few criteria with large number of alternatives in a decision making problem (Triantaphyllou et al. 1998).

In summary, ELECTRE method is a composed by a family relationships based methods to overcome to decide on the determination of a solution, which can not be considered satisfactory optimal; plus get a hierarchy of actions, alternatives under analysis (Maurtua 2006).

2.2.2.3. Choosing by Advantages (CBA)

Choosing by advantages (CBA) is a decision-making method that supports decisions by fostering greater transparency (Arroyo et al. 2014). CBA has the follow steps:

- Identify alternatives
- Define attributes
- Define the “must”/”want to have” criteria for each attribute
- Summarize the attributes of each alternative
- Decide the advantages of each alternative
- Decide the importance of each advantage
- Evaluate cost/data

In general terms, CBA is based on the following states:

- Decisions must be based on the importance of advantage
- An attribute is a characteristic, quality, or consequence of one alternative
- An advantage is a difference between the attributes of two alternatives

Arroyo et al. (2014) add that CBA treats cost as a constraint, in order to describe and value the advantages and then evaluate if they have suficcient money for the project. As seen, in CBA decision-makers need to discuss the relative importances of the advantages, not the attributes as in regular MADM. Although, researchers acknowledge that no decision-making method is entirely objective and all require subjective trade-offs. Authors conclude that CBA creates more transparency, does not assume lineal trade-offs between attributes, focuses on differentiating between alternatives more than weigthing rating and calculating in MADM. In a different research, Arroyo et al. (2014b) comment that in traditional MCDM methods, the result of the decision may change if irrelevant factors are taken out of the decision.

However, regarding the ranking and rating of alternative ideas using lists of advantages and disadvantages, paired comparisons, and weighted factors, CBA points out that, without exception, the advantage of one alternative is the disadvantage of the other with which it is compared (otherwise there would be no advantage). As the number of alternatives increases, keeping track of advantages and disadvantages becomes increasingly complicated and potentially quite inaccurate (Suhr 1999).

2.2.3. Normalization procedures

Criteria generally have different units of measure and differ in the sense optimization. As it can be seen from MADM method chapter, we should have normalized performance ratings or values in order to eliminate computation problems that can be caused by using different units of measures in a decision-making matrix.

There are several normalization methods, with different complexity and scales. Some MCDM methods have their recommended normalization methods (for example, COPRAS method, according to Zavadskas et al. (1994), is based on the use of linear transformations). On the other hand, others MCDM methods can be used with different normalization methods. Some characteristic normalization procedures are:

- **Linear Scale Tranformation - Max method**

This method provides the simplest normalization procedure. In Linear Scale Transformation - Max (LST-Max) method, the performance rating of each alternative is divided by a maximum performance rating for that attribute (Van Delft and Nijkamp 1977).

The LST-Max method is represented as,

$$xf_{ij} = \frac{xf_{ij}}{\max(xf_j)} \quad (5)$$

Where $\max(xf_j)$ is the largest value of jth criterion. In order to transform cost to benefit type performances, the normalized performance ratings are calculated using the following formula:

$$xf_{ij} = \frac{\min(xf_j)}{xf_{ij}} \quad (6)$$

Where $\min(xf_j)$ is the smallest valueof jth criterion.

- **Linear Scale Tranformation - MaxMin method**

Linear Scale Transformation - MaxMin (LST-MaxMin) method considers both the maximum and minimum performance ratings of attributes during the calculation (Zavadskas and Turskis 2008). The normalized value is obtained by using the formula:

$$xf_{ij} = \frac{xf_{ij} - \min(xf_j)}{\max(xf_j) - \min(xf_j)} \quad (7)$$

In order to transform cost to benefit type performances, the normalized performance ratings are calculated using the following formula:

$$xf_{ij} = \frac{\max(xf_j) - xf_{ij}}{\max(xf_j) - \min(xf_j)} \quad (8)$$

- **Linear Scale Transformation - Sum method**

In Linear Scale Transformation - Sum (LST-Sum) method the sum of all performance ratings, with respect to the considered attribute, is used as the denominator (Van Delft and Nijkamp 1977).

$$xf_{ij} = \frac{xf_{ij}}{\sum_{i=1}^{n} xf_{ij}} \quad (9)$$

- **Vector normalization method**

The Vector normalization (VN) uses the square root of sum of squares of performance ratings as the nominator (Van Delft and Nijkamp 1977).

$$xf_{ij} = \frac{xf_{ij}}{\sqrt{\sum_{i=1}^{n} (xf_{ij})^2}} \quad (10)$$

- **Non-linear normalization method**

Non-linear normalization (NL) method is represented as (Zavadskas and Turskis 2008):

$$xf_{ij} = \left(\frac{xf_{ij}}{\max(xf_j)}\right)^2 \quad (11)$$

- **Logarithmic normalization method**

Logarithmic normalization may be used in the cases when the values of the criteria differ considerably and segregates more normalized values than the other ones (Zavadskas and Turskis 2008). Turskis et al. (2009) developed a multi-criteria resolution methodology using different types of normalization methods, such as vector, linear scale, and non-linear and new logarithmic techniques. According to the author, logarithmic normalization of a decision-making matrix yields more stable results in solving multi-criteria decision problems. Logarithmic normalization is represented as

Preferable max xf_{ij}

$$xf_{ij} = \frac{\ln(xf_{ij})}{\ln\left(\prod_{i=1}^{n} xf_{ij}\right)} \quad (12)$$

Preferable min xf_{ij}

$$xf_{ij} = \frac{1-\frac{\ln(xf_{ij})}{\ln\left(\prod_{i=1}^{n} xf_{ij}\right)}}{n-1} \tag{13}$$

Note that the sum of normalized final behavior values for each criterion is always equal to 1.

- **Conclusions of normalization procedures**

Nominators, used in LST-Sum and VN, have an effect on values of normalized performance ratings, but do not change anything fundamentally in relation to the formula of LST-Max. Using these normalization procedures, that belong to the performance-based normalization procedures, performance ratings are transformed into dimensionless values that are in the interval [0,1], while the alternative with the best performance rating has the highest value of normalized performance rating. As can be seen from LST-Max, LST-Sum and VN, the performance-based normalization procedures do not permit inclusion of the decision-makers preferences in the process of normalization (Stanujkic et al. 2013).

In LST-MaxMin method, instead of using performance ratings as nominators, the distance between performance ratings of alternatives and appropriate reference points is used; therefore, this type of normalization can be classified as the distance-based normalization procedure. The denominator used in this method, transform the obtained distances to dimensionless values that belong to the interval [0,1], whereby the normalized performance of the alternative with the best performance ratings to the considered attribute has the value 1, and worst has the value 0 (Stanujkic et al. 2013). Besides, in NL method values are diminished more than when using other methods (Zavadskas and Turskis 2008).

The multi-criteria decision-making is used in various fields of human activity. The criteria may be qualitative and quantitative. As stated above, the criteria generally have different units of measure and differ in the sense optimization. Then a method of normalization is required. The normalization aims at obtaining comparable scales of criteria values. Turskis et al. (2009) develope a multi-criteria resolution methodology using different types of normalization methods, such as vector, linear scale, non-linear and new logarithmic techniques. According to the author, logarithmic normalization of a decision-making matrix yields more stable results in solving multi-criteria decision problems. The logarithmic normalization method used in solving the problems segregates more normalized values than the other ones.

2.2.4. Multi-participant Decision-making

This section discusses the various methods that consider more than one decision-maker simultaneously in the decision-making process. Our research considers these methods because it was observed that the selection process of the EWS contains more than one decision-maker (chapter 4).

To formalize the selection process is necessary to consider all the project stakeholders. Project stakeholders are groups or individuals who have a stake in, or expectation of, the project’s performance and include clients, project managers, designers, subcontractors, suppliers, funding bodies, users and the community at large (Newcombe 2003).

In many multiple-participant decision-making situations, one or more of the DMs may use multiple criteria for evaluating courses of action or states. In such circumstances, a given participant’s preferences across the states may be different for each of the criteria set (Hipel et al. 1993). It is necessary to recognize explicitly that the decision-making process involve multiple participants. For this reason, we investigate about multiple-participant decision-making (MPDM problems). MPDM problems including many criteria into account has been a major focus, and has made significant progress with the rapid development of operations research, management science, systems engineering, and other disciplines (Chen et al. 2012).

When decisions that are made by more than one person are modeled, the goals of the individual decision-makers may differ such that preferences (weighting factors) are different. Only well-founded weighting factors should be used because weighting factors are always subjective and influence the solution (Zavadskas and Turskis 2008). In a MCDM, it is often hard to obtain a solution due to the possible conflict preferences from different participants and the undeterministic weights assigned to each criterion (Wei et al. 2000). The objective is to integrate the opinions of participants into a sorting.

A number of different techniques have been developed for generating criteria weights for group decision-making, multiple participants or experts. Some of them are presented below.

Kahraman et al. (2003) use different solution approaches of fuzzy multi-attribute group decision-making to solve this type of problems, for example: a fuzzy model of group decision proposed by Blint (1974), the fuzzy synthetic evaluation, Yager (1978) weighted goals method and fuzzy analytic hierarchy process. Although these approaches have the same objective, they come from different theoretic backgrounds and relate differently to the discipline of multi-attribute group decision-making.

Hsu and Chen (1996) propose a method for aggregating individual fuzzy opinions into a group fuzzy consensus opinion. He presents a procedure for aggregating the expert opinions. Herrera and Herrera-Viedma (1996) present a consensus model in group decision-making under linguistic assessments. It is based on the use of linguistic preferences to provide individuals' opinions, and on the use of fuzzy majority of consensus, represented by means of a linguistic quantifier. Li (1999) investigates the problems of decision-making with multiple judge, multiple criteria in a fuzzy environment, where the performance of alternatives and the importance of criteria are imprecisely defined and represented by fuzzy sets. A fuzzy model associated with the solution algorithm is proposed on the basis of an a-level weighted, fuzzy preference relation.

In addition, Davis (1973) assumes a dominant role of members whose opinions are mutually close. Thus, each decision maker is given a weight depending on the centrality of his/her position relative to the other members of the group and the group decision is a weighted sum of the member's preferences. The closer that expert is in his judgement about the relative importance of a decision criterion to the judgements of other group members, the more weight that expert is given in defining the group consensus about the relative importance of this criterion.

Other, more sophisticated, methods such as those based on the concepts of outranking and multi-dimensional scaling have been applied to planning problems as well (Feick and Hall 1999). In this study, authors determine each participant's criteria weightings using eigenvector technique. For each pair of criteria, a participant determines the importance of the first criterion relative to the second.

Tsiporkova and Boeva (2006) proposed a multi-step method to calculate criteria weights in a multi-expert decision making environment in the form of a recursive aggregation algorithm. In this method, each decision maker is supposed to distribute weights between the group members, expressing the relative degree of influence the decision maker is inclined to accept from the rest of the group.

2.3. Existing methodologies to select the building envelope

This section discusses the existing methodologies in literature for selecting the building envelope. The methodologies are studied to see if it is possible to adapt them to the selection of the EWS in residential projects.

Zavadskas et al. (2008) proposes a methodology to assess alternatives of building envelopes defining the utility of an alternative and is proposed as a method of multiple criteria Complex Proportional Assessment of alternatives with Grey relations (COPRAS-G). As shown in Figure 2-1, this methodology aims to meet the increasing demand for quality homes. Zavadskas et al. (2008) indicate that the selection of a envelope-wall system with excellent thermal insulation is one of the technical and economic objectives most important to the designer and the client. On the other hand, regarding to customers or buyers, the study adds that they also enter the selection process because they want to reduce to a minimum the costs of your home and also have the highest standards of quality, technology, architectural and comfort. Besides, there are other participants in the construction process that are interested in minimizing construction costs (construction company).

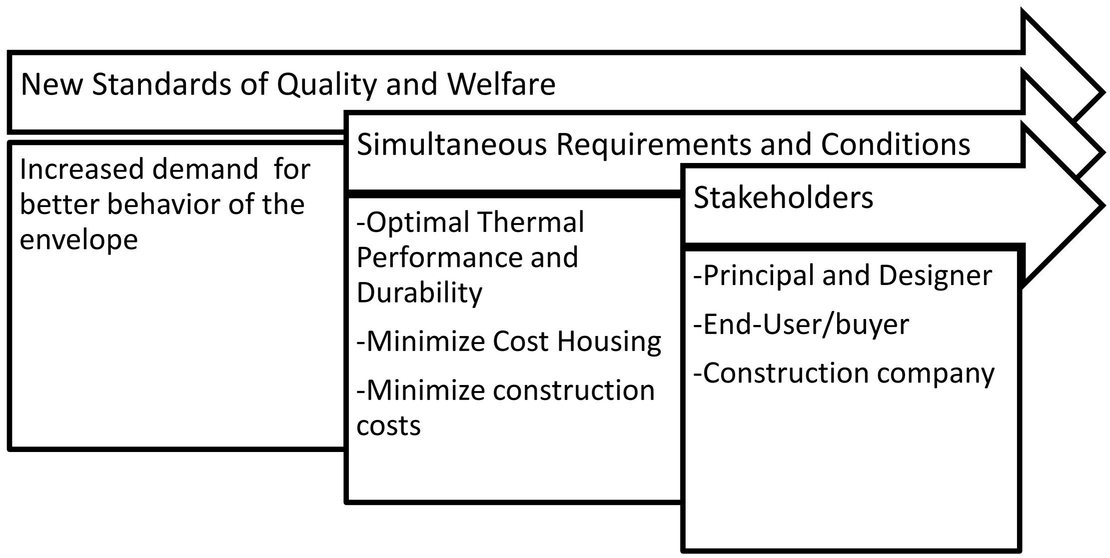


Figure 2-1. Assessment of the building envelope (Zavadskas et al. 2008)

Through a normalization method and using theory for prediction and Grey relational analysis, the research attempts to transform all the criteria (quantitative and qualitative) on the same scale for comparison. It defines the utility of an alternative, evaluating a set of variables given in intervals previously defined.

Ranking the alternatives by applying COPRAS-G with attributes values expressed in interval method includes the following steps:

- Preparing the decision-making matrix
- Normalization of the decision-making matrix
- Weighting normalized decision-making matrix

- Calculation of minimizing indexes for each alternative
- Calculation of maximizing indexes for each alternative
- Calculating the sumns of weighted normalized indexes
- Determining the minimal value of minimizing indexes
- Determining significance of alternatives
- Ranking alternatives according to relative significances of each alternative

This research helps to understand how to evaluate the different attributes of the behavior of the envelope. However, do not define all relevant criteria in the decision making process of the envelope of the house. Furthermore, this methodology only includes characteristics of each alternative and does not take into consideration the effect that could have the characteristics of a project (location, duration, etc.).

In another study, Singhaputtangkul et al. (2013) proposes a methodology that seeks to mitigate the most common problems of decision-making in the selection of the building envelope (e.g. inadequate consideration of the requirements of the project, lack of efficiency of the design team, etc.) To complete this objective, a computational tool is developed that comprises three main elements: Function Deployment Quality (QFD) which seeks to meet the demand of users in design quality, fuzzy set theory that allows gradual and non-binary evaluation of the elements, and knowledge management system that supports the creation, storage and management of information, as seen in figure 2-2.

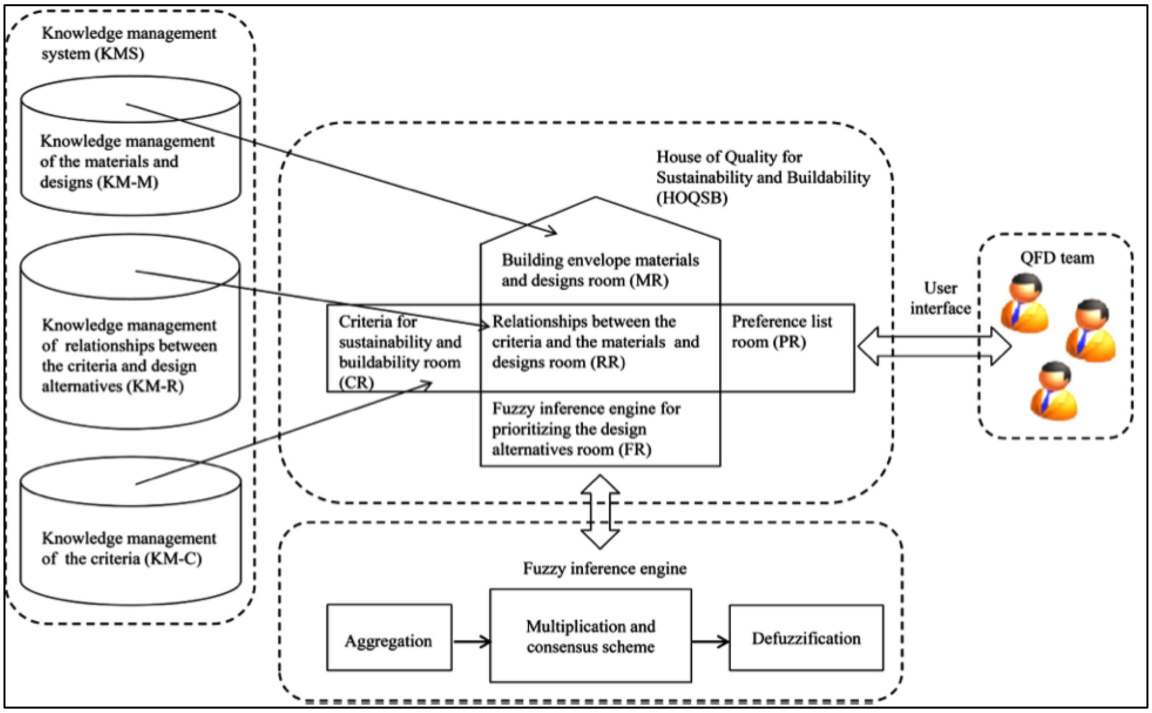


Figure 2-2 Architecture of the computational tool Singhaputtangkul et al. (2013)

Authors built a House of Quality for Sustainability and Buildability (HOQSB) to facilitate the assessment of the building envelope materials and designs. The HOQSB has five major rooms (Figure 2-2). The CR and MR are applied to identify relevant criteria and building envelope design alternatives, respectively. The RR contains the relationships between the criteria and design alternatives. These relationships include a matrix to indicate the parameters affecting each criterion and rules to guide the decision-makers when assessing the building envelope materials and designs. The FR stores fuzzy calculation techniques operated by a fuzzy inference engine for prioritizing the design alternatives. The PR records outputs of the FR in the form of a preference list of the design alternatives ranked by a Sustainability and Buildability Index (SBI). In brief, this index is a function of importance weights of the criteria, contribution weights of the building envelope materials, and performance satisfactions of the materials and design alternatives with respect to the criteria.

This research provides knowledge about management issues, presence of various actors involved in the decision-making process and requirements to be taken into account. Authors add that in all projects there are certain requirements that must necessarily be approved, e.g. regulatory and statutory acceptance. However, compliance with these minimum requirements does not guarantee stakeholder satisfaction because the main regulations do not always cover all key stakeholder requirements

Furthermore, Yang et al. (2003) research provides a methodology based on a fuzzy quality function deployment (QFD) system for buildable design. It assures and improves the alignment of elements of design and construction processes with the requirements of customers. As the methodology seen above, this methodology also adapt the House of Quality to meet the needs of buildable designs in the construction industry and to develop a fuzzy QFD system for buildability evaluation It supports the integrated evaluations of buildable designs through adapting matrices of conventional house of quality. It also uses triangular fuzzy numbers to intuitively represent the nature of decisions and judgments of buildable designs. Yang et al. (2003) proposed a three customers system, composed by clients, designers and contractors. Each customer has their own requirements and therefore their own evaluation design, as shown in Figure 2-3.

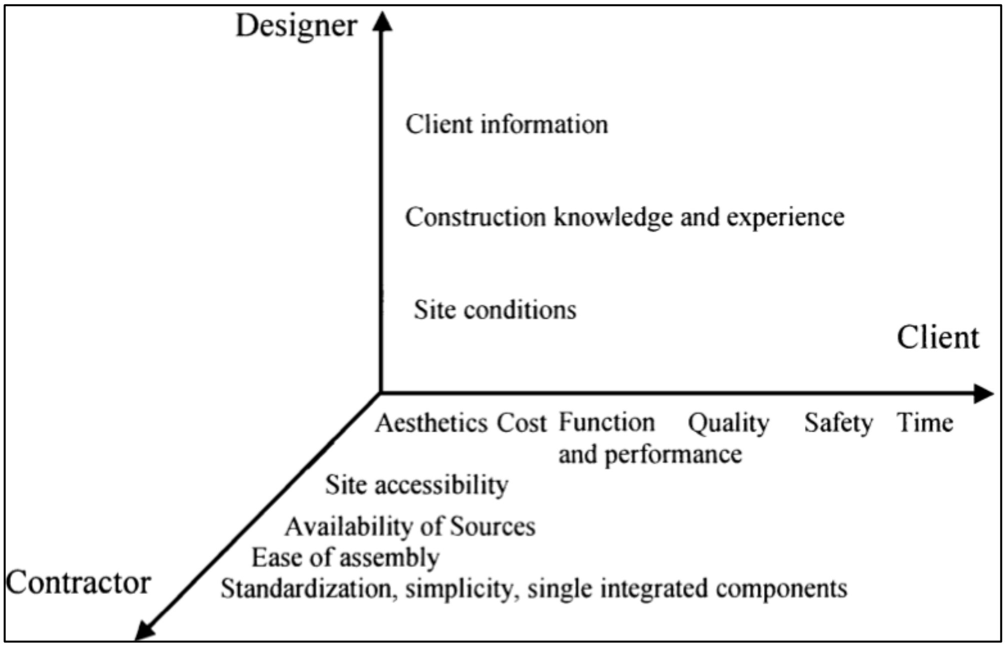


Figure 2-3. Customers and their requirements of buildable designs (Yang et al. 2003*)*

The client is the customer who employs the designers to develop construction documents that the contractors will use to satisfy the client. The client who is also a participant and promoter of buildable design will state his requirements at the outset of the design and expect a high-quality service to satisfy his/ requirements and gain real value for money. The designers are the customers who receive the design-relevant information and requirements from the client as well as the design-relevant construction inputs from the construction professionals that should be involved in creating buildable designs. The contractors are the customers who utilize the designers' products, the drawings, to construct the facility. The knowledgeable and experienced construction personnel are also the contributors of buildable designs. In summary, authors provide a viable decision-making method for quantitative buildability evaluation at the early design phase and help incorporating the knowledge of the presence of various actors involved in the decision-making process. Yang et al. (2003) add that when there is no intercommunication between the stakeholders of the projects, the integration of design and construction heavily depends on the designers' prior construction experience.

However, the designers often are only partially knowledgeable about, and sometimes not aware of, the design-relevant construction inputs. In addition, the decision-making process at early design stages tends to be ill structured and occurs in an unsystematic way (Yang et al. 2003).

In conclusion, the methodologies found serve as a starting point for our research in which a multi-criteria multi-participant methodology is developed to select the EWS in residential projects (chapter 4). However, these methodologies have some limitations, such as: consider all elements of the overall envelope together (walls, windows, elements that generate shadow, etc.), and are focused on high-rise buildings, which certainly differ from houses' behavior. Also, they do not include characteristics of the projects (location, duration, etc.) and all stakeholder's preferences and influences. Finally relevant criteria are not established. Some of the methodologies are not sufficiently accurate because they are too simple; others are too complicated for a practical application. In any case, the accuracy of expert evaluation largely depends on the number of criteria. When this number is growing, the complexity of the methodology is also growing.

Therefore, there is a need to create a new methodology focused only on the envelope-wall system of houses; this methodology should include the characteristics of each project and all the stakeholders.

2.4. Statistics and Scales

In this section we describe the scale used in one of the surveys of the research methodology presented in Chapters 3 and 4. In addition, we discuss and study in depth the statistical methods used in Chapter 3 of the thesis.

2.4.1. Likert-type Scales

Oftentimes information gathered in the social sciences, marketing, medicine, and business, relative to attitudes, emotions, opinions, personalities, and descriptions of people's environment involves the use of Likert-type scales. Likert scales were developed in 1932 as the familiar five-point bipolar response that most people are familiar with today, the author described this technique for the assessment of attitudes. These scales range from a group of categories - least to most - asking people to indicate how much they agree or disagree, approve or disapprove, use or not use, or believe to be true or false (Likert 1932).

A set of items, composed of approximately an equal number of favorable and unfavorable statements concerning the attitude object, is given to a group of subjects. They are asked to respond to each statement in terms of their own degree of agreement or disagreement. Typically, they are instructed to select one of five responses: strongly agree, agree, undecided, disagree, or strongly disagree. The specific responses to the items are combined so that individuals with the most favorable attitudes will have the highest scores while individuals with the least favorable (or unfavorable) attitudes will have the lowest scores (McIver and Carmines 1981).

Spector (1992) identified four characteristics that make a scale a summated rating scale as follows: First, a scale must contain multiple items. Second, each individual item must measure something that has an underlying, quantitative measurement continuum. Third, each item has no "right" answer, which makes the summated rating scale different from a multiple-choice test. Thus summated rating scales cannot be used to test for knowledge or ability. Finally, each item in a scale is a statement, and respondents are asked to give rating about each statement.

Authors agreed on the use of Likert-scales instead of a single ítem for measuring psychological attributes due to: First, individual items have considerable random measurement error, i.e. are unreliable. Measurement error averages out when individual scores are summed to obtain a total score. Second, an individual item can only categorize people into a relatively small number of groups. An individual item cannot discriminate among fine degrees of an attribute. For example, with a dichotomously scored item one can only distinguish between two levels of the attribute, i.e. they lack precision. Third, individual items lack scope. It is very unlikely that a single item can fully represent a complex theoretical concept or any specific attribute for that matter. Social scientist rarely has sufficient information to estimate their measurement properties. Thus their degree of validity, accuracy, and reliability is often unknowable. Those are some benefits of Likert-type scales with their associated multi-item scales and summated rating scores (Gliem and Gliem 2003).

In conclusion, likert scales are preferred by individuals for being simple and "natural" to complete, and tends to show high degrees of reliability and validity.

2.4.2. Mann-Whitney Analysis

The Mann-Whitney test is the non-parametric equivalent of the independent samples t-test. Mann–Whitney tests the null hypothesis that two populations are the same against an alternative hypothesis, specifically which a particular population tends to have larger values than the other. It should be used when the sample data are not ormally distributed, and they cannot be transformed to a Normal distribution by means of a logarithmic transformation. It also has greater efficiency than the t-test on non-normal distributions, such as a mixture of normal distributions, and it is nearly as efficient as the t-test on normal distributions (Conover 1980).

For example, the null hypothesis could be that the differences observed between different groups are due to chance and is not influenced by the characteristics of the groups themselves. The alternative hypothesis would be that level scores vary according to the specific characteristics of the groups.

As a general rule, mean and standard deviation are invalid parameters for likert-type scales of data. Analysis of ordinal data, particularly as it relates to Likert or other scales in surveys are not straightforward and transparent. However, when combining a series of questions measures a particular trait (likert scale), the use of mean and standard deviations to describe the scale are appropriate (Vigderhous 1977; Jakobsson 2004).

Non-parametric procedures, based on the rank, median or range, are appropriate for analyzing these data. Mann-Whitney test for two unpaired groups can provide the same type of results as an analysis of variance, but based on the ranks and not the means of the responses. This test allows two groups or conditions or treatments to be compared without making the assumption that values are normally distributed. This test can be carried out when samples are independent and the scale is ordinal.

2.4.3. Factor Analysis

Variables in general are not always independent of each other. On the contrary, they are strongly interrelated between them and a holistic development of materials, structural systems and building systems would be required simultaneously to find optimal solutions (Chan et al. 2002).

Then, an important aspect of the analysis is the potential correlation between selection criteria. Attributes that are used for evaluation of alternatives sometimes can be mutually dependent. As a result, alternatives whose performance ratings in some way deviate from the preferred performance ratings may be more acceptable. For example, an alternative could be much more acceptable if any of its performance ratings, according to a benefit attribute, exceeded the preferred performance rating without a significant increase of performance ratings of some cost attributes or a slightly worse performance rating of a benefit attribute which significantly affect the decrease of performance ratings of cost attributes (Stanujkic et al. 2013).

Thus, the problem is complex, since the optimal solution is not born from energetic, thermic, structural and constructive aspects optimization separately, but understanding fundamental interactions between variables.

A factor analysis can solve this problem, where the information gain about the interdependencies between the variables can be used to reduce variables, composed solely of independent criteria or variables. The method of factor analysis allows reducing the information into a smaller number of variables, relationships between strategic components are detected and new variables or factors are defined. When variables are redundant with each other, these variables would form a single factor. A factor or component is define as a variable that is not directly observed but is inferred from a set of initial variables (Aaker and Day 1996). In other words, factor analysis is a method for investigating wheter anumer of variables of interest $V_1, V_2, \ldots, V_K$, are linearly related to a smallen number of observable factors $f_1, f_2, \ldots, f_K$.

The factor analysis model is represented as follows (O'Ryan 2011):

$$\mathbf{V_1 = l_{11}\ x\ f_1 + l_{12}\ x\ f_2 + \cdots + l_{1k}\ x\ f_k + e_1} \qquad (14)$$

$$\mathbf{V_2 = l_{21}\ x\ f_1 + l_{22}\ x\ f_2 + \cdots + l_{2k}\ x\ f_k + e_2}$$

$$\vdots$$

$$\mathbf{V_p = l_{p1}\ x\ f_1 + l_{p2}\ x\ f_2 + \cdots + l_{pk}\ x\ f_k + e_p}$$

Where:

$\mathbf{V_p}$ = **Observed variable p**

$\mathbf{f_k}$= **Common factor k**

$\mathbf{l_{jk}}$= **Factor loading of variable j in the p factor**

$\mathbf{e_p}$= **measurement error for** $\mathbf{V_p}$

The observed variables "V" are estimated from the common factors "f". The number of common factors must be less than the number of observed variables in the analysis. Furthermore, common factors should not be correlated. Finally, the observed variables are defined by these common factors and a measurement error “e” for each variable.

Then you need to find a number of common factors that explain most of the variability of all the observed variables. The variance of each variable is expressed as a function of the common charges and the diagonal elements of the covariance matrix of the unique factors as shown below.

$$\mathbf{V_j = 1 = h_j^2 + w_j^2 \quad for\ j = 1..p} \tag{15}$$

Where:

$$\mathbf{h_j^2 = l_{j1}^2 + l_{j2}^2 + \cdots + l_{jp}^2} \tag{16}$$

The commonality (h_j^2) is the part of the variance of the variable V_j due to common factors. The specificity is the part of the variance of the variable V_j due to unique factors. The problem to solve is the estimation of loads factorials ($l_{j1}, l_{j2}, \dots, l_{jk}$) to determine the weight of the different factors in each variable and the variance of each of these explained by the common factors.

Steps in Exploratory Factor Analysis

- Collect and explore data: choose relevant variables.
- Extract initial factors (via principal components)
- Choose number of factors to retain
- Choose estimation method, estimate model
- Rotate and interpret
- Construct scales and use in further analysis

3. CRITERIA FOR SELECTING ENVELOPE-WALL SYSTEMS FOR RESIDENTIAL PROJECTS

Building envelope selection greatly influences the building performance. Specifically, the envelope-wall system (EWS) definition is a critical part of this selection, especially for residential projects. This selection is a complex decision, as it depends on multiple considerations (e.g., cost, structural behavior, energy efficiency) and involves multiple stakeholders (e.g., real estate developers, designers, constructors, final users). Despite the importance and complexity of the decision, simplified approaches considering only a few criteria are often used in the decision-making process, potentially leading to suboptimal solutions.

The literature points out some relevant criteria; however, there is a need to formalize the criteria and to present an integrated approach to the envelope-wall selection problem.

This research identifies and formalizes the criteria for selecting envelope-wall systems for residential projects in Chile and assesses the preference of Chilean decision-makers for these criteria via interviews, a pilot survey and the modified Delphi method.

The results indicate that the decision-making criteria include thermal, acoustic and structural behaviors, cost of the alternatives, complexity of construction, safety (of the occupants and the building process) and environmental impact, durability, and appearance of the envelope. Interestingly, based on the decision makers' preferences, the most important criterion is the structural behavior, while the least important one is the complexity of the construction.

This study will expedite a better and comprehensive assessment of envelope-wall systems and will support a structured and traceable decision-making methodology.

3.1. Introduction

Building envelopes act as the interface between the interior space and the exterior environment, providing protection from the weather and pollution and insulating against the thermal and noise elements. Their performance affects numerous factors, including energy use, operating costs, structural behavior, durability, occupants' comfort and productivity, and aesthetic appeal of the building (Chua and Chou 2010; Passe and Nelson 2012). A well-chosen building envelope can make a building work more effectively for its builders and occupants. Moreover, a timely decision regarding building envelope selection can have significant economic impact on the project. The potential advantages of early incorporation of constructability information in the design have been documented (Russell et al. 1992; Jergeas and Put 2001). Thus, the success of a project involves assessment and selection of building envelope materials and designs that can satisfy the requirements of the stakeholders (Singhaputtangkul et al. 2013).

Selecting an effective building envelope from a vast number of alternatives is a crucial step in project design. Nevertheless, is not a simply task, it requires a large amount of information and inputs from the design team. However, several studies (Singhaputtangkul et al. (2014) and Zavadskas et al. (2008)) highlight that building professionals, especially the architects and engineers in the early design stage, select building materials and designs based on very few criteria, such as aesthetics and costs. Furthermore, Passe and Nelson (2012) report that the stakeholders in the design and construction process tend to use different decision criteria for selecting building materials and design. Therefore, the criteria used by decision-makers vary from person to person, and sometimes, all relevant aspects are not taken into account in the final selection process.

This inadequate consideration of requirements may lead to the selection of suboptimal building envelopes that can have adverse impact on the subsequent project phases, causing delays, an increase in expenses, an increase in manpower required for a building project, and poor client satisfaction. For instance, the energy-efficient wood-frame houses of the 1980s and 1990s in the United States resulted in more expensive and less durable residential structures (Smulski 1999). Another example is the social residential complexes in Buenos Aires that were built without considering durability and maintenance of the walls, resulting in an accelerated degradation of the envelope (Dunowicz and Hasse 2005). Hassanain and Harkness (1998) reported other examples of building envelope component failures due to poor consideration of the selection criteria, including a major problem of moisture penetration from the hot and moist exterior environment into the air-conditioned interior of a 10-floor building and roof permeability problems. These examples suggest the need for a comprehensive criterion set to be included in the design process.

Different envelope components such as walls, windows, roofs, and shading devices have different impacts on the behavior of a project. For example, Zavadskas et al. (2008) estimated the heat-loss contributions from different components of the envelope for a non-insulated building (Figure 3-1).

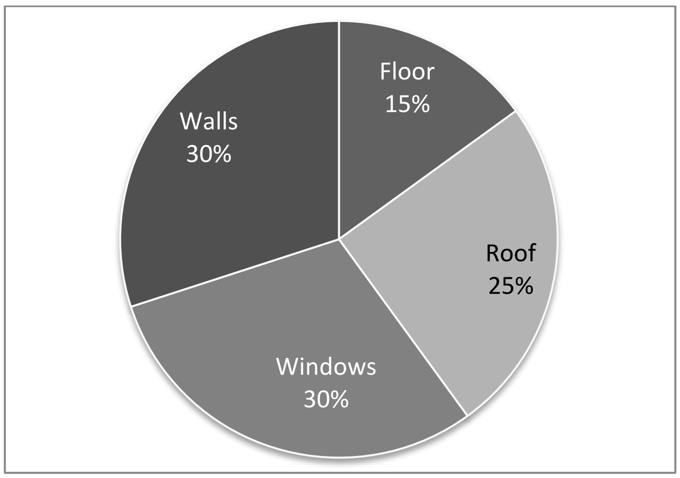


Figure 3-1. Heat losses through the envelope (Zavadskas et al. 2008)

Similarly, different envelope components contribute differently towards factors such as the cost, structural behavior, constructability, and aesthetics. Optimal selection of the envelope-wall systems, a key component for houses, can have a crucial technical and economic impact for both the designer and the investor (Zavadskas et al. 2008).

This research identifies and formalizes the criteria for the selection of envelope-wall systems for houses based on the practice of Chilean residential developers. The study also quantifies the preferences of Chilean decision-makers for these criteria.

3.2. Building Envelope Design and Selection

The literature identifies several criteria relevant for the selection of building envelope solutions. However, these studies tend to focus on a select few criteria depending on their research objectives.

For example, Horvat and Fazio (2006) evaluate the performance of a building envelope based on its air-tightness, moisture management performance, thermal performance, energy performance, structural performance, acoustic performance, and fire resistance. Kaklauskas et al. (2006) prioritize architectural appearance; energy used for heating, cooling and other appliances; impact on the environment; indoor climate; and costs in order to realize an effective selection of windows in a building's retrofit. Wang et al. (2006) present a methodology to optimize building shapes based on the energy performance and construction costs. Zavadskas et al. (2008) select the effective dwelling house walls based on wall durability, thermal transmittance, costs, weight and human work expenditure (duration). Chua and Chou (2010) consider energy efficiency and cost savings as the main criteria in selecting building envelope systems. Granadeiro et al. (2013) present a design indicator of energy performance for residential buildings inspired by the envelope materials, shape and window areas. Singhaputtangkul et al. (2014) identify criteria for achieving sustainability and buildability in the design of the building envelopes for high-rise residential buildings. Passe and Nelson (2012) emphasize the importance of considering the thermal behavior of the building envelope, which is responsible for approximately 50% of residential energy consumptions. Pulaski and Horman (2005) highlight the impact of constructability on project success, adding that required construction expertise or construction difficulty should be incorporated in the selection process of the building envelope to improve the constructability of the design.

Altogether, these studies identify several criteria relevant to characterize wall systems. However, they fail to provide a comprehensive approach to the behavior of an envelope system and they do not focus on the selection of the wall systems. Below, we describe the most recurrent criteria found in the literature that were used as the initial criteria for this research.

- **Thermal performance:** Energy efficiency and heat retention.
- **Structural performance:** Mechanical resistance and stability.
- **Acoustic performance:** Protection against noise.
- **Moisture management:** Limiting intrusion of precipitation and condensation.
- **Costs:** Building envelope material costs and construction costs.
- **Durability:** Maintenance levels and service life.
- **Duration of Construction process**
- **Construction Expertise requirement or Difficulty:** Level of technical skills and the amount of guidelines or rules needed for a proper construction.
- **Environmental Impact:** Waste generation and Resource consumption during the fabrication and installation of the building envelope components.
- **Aesthetics:** Capability to optimize visual comfort and finish.

Criteria such as the project location or buyers' preferences, as recommended by Martínez (2005), were discarded because they are not characteristic of the wall solution; however, they should be taken into account in the selection process.

3.3. Research Methodology

The research methodology followed incremental steps to identify and formalize the criteria relevant to Chilean decision-makers and to assess the relevance of the criteria for these decision-makers. Figure 3-2 depicts the methodology.

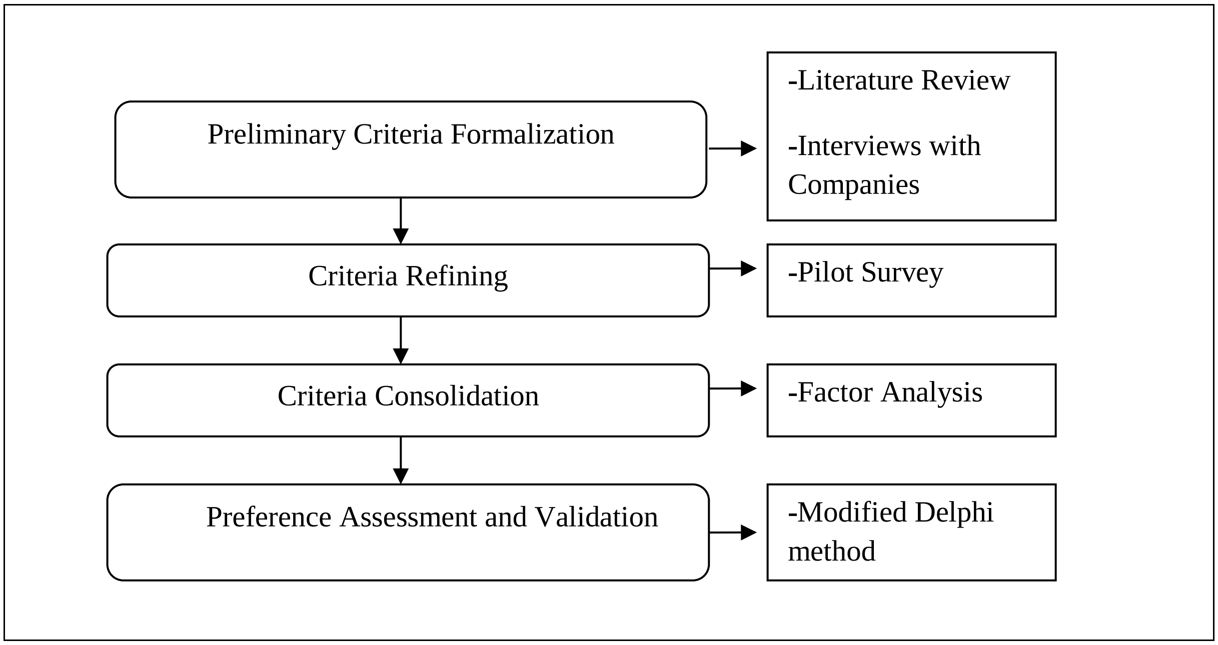


Figure 3-2. Research Methodology

The initial set of criteria was obtained from the literature review. These initial criteria were then confirmed via informal interviews, and new criteria combining the state of art with the state of practice were added. We were able to identify twelve preliminary criteria.

Then, the selection criteria were further refined using a pilot survey that allowed capturing opinions and attitudes from decision-makers regarding the use and importance of the preliminary set of criteria. The respondents were also allowed to add new criteria that they may use in practice.

A factor analysis examining the correlation with the criteria obtained from the pilot survey led to the consolidation of the collected criteria. This factor analysis produced a final list of eight criteria.

Finally, a scenario-based survey captured the preferences of the decision-makers for the formalized criteria. A modified Delphi method – that does not consider iteration – was the basis for the survey analysis and used 75% of the data. The validation used the remaining portion of the survey results.

3.4. Preliminary Criteria Identification

Based on the initial set of criteria collected from the literature, we conducted informal interviews with five experienced professionals who participate in the envelope selection process for residential projects in their respective companies. The interview asked about the use of our initial criteria set, explored other potential criteria, and searched for a formalization (formal definition) of these criteria.

Table 3-1 explains the obtained criteria and their definitions.

Table 3-1. Preliminary Criteria

C1	Thermal Behavior	The ability of the EWS to reduce the amount of heat flow through the wall (thermal transmittance).
C2	Structural Behavior	Maximum compressive stress that the EWS can withstand before failure (compressive strength).
C3	Acoustic Behavior	The ability of the EWS to decrease the intensity of the sound when it is transmitted through the wall (acoustic insulation).
C4	Costs	Total cost that includes material, equipment and installation labor.
C5	Duration of Construction Process	Duration of the on-site construction process.
C6	Difficulty of Construction Process	Complexity, reliability and availability of equipment and labor for the construction process.
C7	Environmental Impact of Construction Process	Amount of waste and noise during construction of the solution and the energy embedded in the solution
C8	Appearance	Appearance and ease to achieve good finish on the envelope-wall system.
C9	Durability	Long-term performance and maintainability. Maintenance costs (painting, remodeling, etc.)
C10	Construction Process Safety	Risk of accidents in the construction process
C11	Occupant Safety	Fire resistance, weather protection and safety.
C12	Moisture Protection	Materials that limit the entry of moisture into the home.

Table 3-1 shows that the respondents confirmed the criteria in the literature review. The respondents agreed that the structural behavior of the house walls was a key factor due to the high seismic activity in Chile. They also asserted that the criteria related to the construction process and costs were essential when selecting the envelope-wall system due to their impact on the budget and project deadlines.

Additionally, the responses highlighted the importance of the comfort, safety and productivity of the occupants, as well as of labor safety. These additional considerations were included as two new criteria: Occupant safety, and construction process safety.

3.5. Refinement of the Preliminary Criteria

Our pilot survey allowed us to assess the use and importance of the preliminary criteria for Chilean decision-makers. The survey was conducted online, and it was based on a 5-level Likert scale. This scale has 2 status levels and collects responses by asking people to indicate how much they agree or disagree, approve or disapprove, use or not use, or believe to be true or false, etc. (Likert 1932).

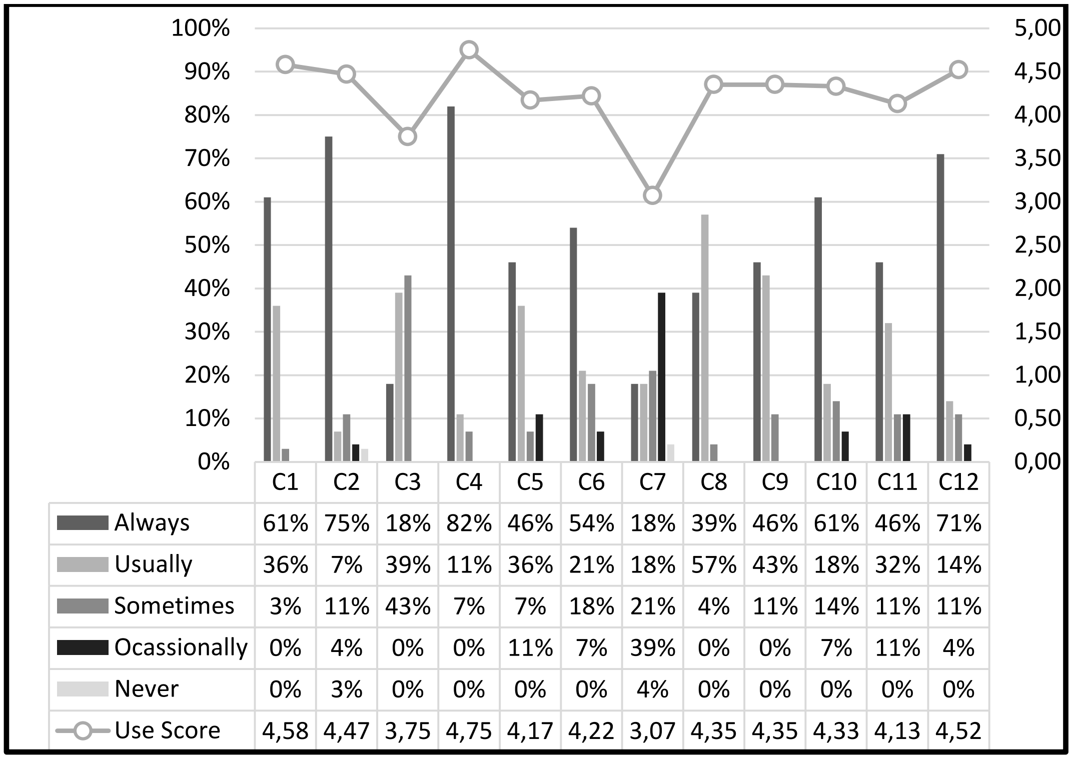
The survey had three parts (see Appendix A.1). The first part contained questions about the respondents' backgrounds: name, e-mail, position, type of company, years of experience in the construction industry, types of projects, types of cities, climates where they have worked the most, and whether they were among the decision-makers in the company regarding the envelope-wall systems.

In the second part, the respondents were asked to express how often they used the 12 preliminary criteria in the selection process of the envelope-wall systems, using a 5-point Likert scale, with 1 being never used and 5 always used.

In the third part, respondents were asked to express their agreement or disagreement with the use of the 12 criteria, expressing the relative importance attributed to them, using a 5-point Likert scale, with 1 being completely disagree and 5 completely agree.

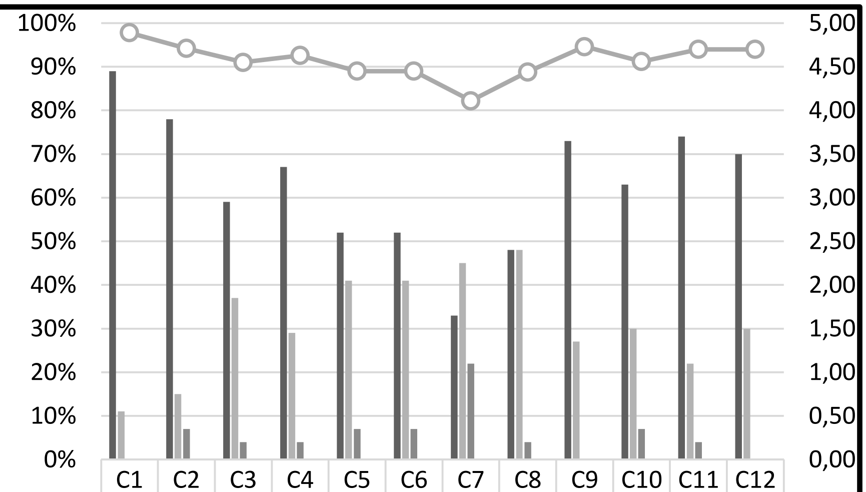
The survey had a 95% confidence level with an error of 8%. The survey was conducted in a universe of 201 companies (members of the real estate and housing committee of the Chilean Chamber of Construction (CCHC)), and the total number of respondents was 31.

Figure 3-3 presents the results regarding the use frequency of the preliminary criteria, and Figure 3-4 shows the results regarding the agreement with the use or importance of the different criteria in the selection process.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Always	61%	75%	18%	82%	46%	54%	18%	39%	46%	61%	46%	71%
Usually	36%	7%	39%	11%	36%	21%	18%	57%	43%	18%	32%	14%
Sometimes	3%	11%	43%	7%	7%	18%	21%	4%	11%	14%	11%	11%
Ocassionally	0%	4%	0%	0%	11%	7%	39%	0%	0%	7%	11%	4%
Never	0%	3%	0%	0%	0%	0%	4%	0%	0%	0%	0%	0%
Use Score	4,58	4,47	3,75	4,75	4,17	4,22	3,07	4,35	4,35	4,33	4,13	4,52

Figure 3-3. Use of preliminary criteria in practice



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Strongly Agree	89%	78%	59%	67%	52%	52%	33%	48%	73%	63%	74%	70%
Agree	11%	15%	37%	29%	41%	41%	45%	48%	27%	30%	22%	30%
Neutral	0%	7%	4%	4%	7%	7%	22%	4%	0%	7%	4%	0%
Disagree	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Strongly Disagree	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Importance Score	4,89	4,71	4,55	4,63	4,45	4,45	4,11	4,44	4,73	4,56	4,70	4,70

Figure 3-4. Level of agreement with the use of preliminary criteria (importance)

Importance score (IS) and use score (US) are a weighted combination of the responses, using a 1-to-5 scale from the most negative to the most positive answers ("strongly agree" and "always" correspond to 5, while "strongly disagree" and "never" correspond to 1). These consolidated scores facilitated the comparison between the importance and use of the different criteria (Table 3-2).

Table 3-2. Importance and Use Scores for preliminary criteria: values, standard deviations and percentage differences.

Criterion	IS	IS σ	US	US σ	Difference
C1	4,89	0,35	4,58	0,56	6%
C2	4,71	0,60	4,47	1,06	5%
C3	4,55	0,57	3,75	0,76	18%
C4	4,63	0,56	4,75	0,65	-3%
C5	4,45	0,63	4,17	0,95	6%
C6	4,45	0,63	4,22	0,96	5%
C7	4,11	0,76	3,07	1,24	25%
C8	4,44	0,57	4,35	0,55	2%
C9	4,73	0,45	4,35	0,70	8%
C10	4,56	0,63	4,33	1,04	5%
C11	4,70	0,53	4,13	1,06	12%
C12	4,70	0,47	4,52	0,85	4%

As Table 3-2 shows, the classification of a criterion as significant does not imply that the decision-makers include or use this criterion in their analysis to select envelope-wall systems. For most of the criteria, the importance score was greater than the use score (positive percentage differences). The criteria with larger positive differences were the acoustic behavior, environmental impact and safety of occupants. This implies that the decision-makers consider these criteria important when assessing the envelope walls but that they do not consider them strongly in the selection process.

On the other hand, it was found that the thermal behavior was considered most important criterion, even though it was not one of the most used criteria in practice (costs). Furthermore, the cost criterion had a negative difference, i.e., it was extensively used in the selection process but was assigned low importance score by the decision-makers.

Table 3-2 also shows that the standard deviations for the importance of the criteria were relatively low, meaning that there was a good level of agreement among the respondents. On the other hand, the standard deviations for the use values were higher, some even larger than 1 (C2, C7, C10 and C11). This result confirms our hypothesis that different decision-makers use different criteria to select the envelope-walls.

In addition to the proposed criteria, the respondents proposed potentially new criteria to evaluate the envelope-wall systems. Table 3-3 describes these criteria and explains the reasons for their inclusion or rejection.

Table 3-3. Analysis of the suggested new criteria

Criterion	**Inclusion**
Location	It was not included because it is not a characteristic of the wall solution. It is a characteristic of the project where the wall system may be used.
House Value	It is not included as it is a characteristic of the project.
MEP Considerations	It is implicitly included in the criteria of construction process difficulty.
Topography	It is not included as it is a characteristic of the project.
Marketing	It is not included as it is a characteristic of the project.
Ease to be repaired	It is implicitly included in the criterion of durability.
Finish	It is implicitly included in the appearance criterion.
Maximum Lifetime	It is implicitly included in the criterion of durability.
Proximity to providers	It is not included as it is a characteristic of the project.

Part 1 of the survey collected a set of context information related to the respondents' experience: years, climate of their projects, types of projects, and sizes of the cities where they worked. To evaluate whether this context information affected the survey responses, we performed a Mann-Whitney test (Table 3-4). The null hypothesis was that the differences observed between the levels of agreement of different groups were due to chance and were not influenced by the characteristics of the groups themselves.

Table 3-4. Mann-Whitney test with 0.05 significance level and 2-tailed hypothesis

	Experience		Project Type		Climate		Size of the Cities	
	Between 0 and 15 years	**More than 15 years.**	**Extension**	**High-rise**	**Moderate**	**Rigorous**	**Big**	**Medium or Small**
U-value	277		288		286		285	
Z-Score	-0,217		0,010		-0,031		-0,052	
P-value	0,413		0,496		0,488		0,460	

From the experimental value (U-value) - amount of information provided by the data - we could calculate the approximation to a normal model (Z-Score) and then compare it with the critical point of the normal distribution with a confidence level of 95% (Z-α = 1.96). For all cases, the Z-Score was smaller than Z-α; therefore the null hypothesis was accepted. This was confirmed by the probability value (p-value), which was greater than the significance level (α = 0.05) in all cases. In conclusion, the results of the pilot survey were not influenced by the context of each group, i.e., years of experience, project type, climate and sizes of cities.

3.6. Criteria Consolidation

Attributes used for the evaluation of alternatives can sometimes be mutually dependent (Stanujkic et al. 2013). Therefore, our selected criteria could present dependencies between themselves that could impact the decisions.

We applied a factor analysis to assess and eliminated these potential interdependencies, reducing the criteria so the final criteria set was composed solely of independent criteria or factors. A factor or component is a variable that may not be directly observed but is inferred from a set of initial variables (Aaker and Day 1996).

The model for the factor analysis is represented as follows (O'Ryan 2011):

$$\mathbf{V_1} = \mathbf{l_{11}} * \mathbf{f_1} + \mathbf{l_{12}} * \mathbf{f_2} + \cdots + \mathbf{l_{1k}} * \mathbf{f_k} + \mathbf{e_1} \quad (17)$$

$$\mathbf{V_2} = \mathbf{l_{21}} * \mathbf{f_1} + \mathbf{l_{22}} * \mathbf{f_2} + \cdots + \mathbf{l_{2k}} * \mathbf{f_k} + \mathbf{e_2}$$

$$\vdots$$

$$\mathbf{V_p} = \mathbf{l_{p1}} * \mathbf{f_1} + \mathbf{l_{p2}} * \mathbf{f_2} + \cdots + \mathbf{l_{pk}} * \mathbf{f_k} + \mathbf{e_p}$$

Where:

V_p = Observed variable p

f_k = Common factor k

l_{pk}= Loading of variable p on factor k

e_p = Measurement error for variable p

The observed variables "V" are estimated from the common factors "f" and the measurement error. The number of common factors must be less than the number of observed variables in the analysis and must explain most of the variability of the variables. The factor analysis estimates the loadings ($l_{p1}, l_{p2}, \ldots, l_{pk}$) – i.e., the weight of the different factors in each variable – and the variance of the variables that is explained by each of the common factors.

Before estimating the loadings, it is necessary to look at the inter-correlations between variables. A preliminary analysis with all criteria showed that variables presented multicollinearity problems (i.e., variables were highly correlated). The correlation matrix's determinant was lower than the necessary value (0.00001), which meant that some criteria or variables needed to be eliminated from the factor analysis. Based on the interviewed companies' answers and the high value for the importance score obtained in the pilot survey, we decided to remove the first four criteria in the preliminary set: Thermal Behavior, Structural Behavior, Acoustic Behavior and Costs. We repeated this analysis with the remaining 8 criteria (C5, C6, C7, C8, C9, C10, C11 and C12). In this case, none of the correlation coefficients were extremely large (greater than 0.9), and the determinant value was greater than the necessary (see Table 3-5). Therefore, there was no need to eliminate any more criteria, and we could continue with the analysis (see Appendix A.2).

Table 3-5. Correlation Matrix with the remaining 8 criteria

		C5	C6	C7	C8	C9	C10	C11	C12
Correlation	C5	1,000	,742	,267	,155	,168	,283	,111	,222
	C6	,742	1,000	,469	,354	,379	,480	,319	,291
	C7	,267	,469	1,000	,390	,493	,626	,626	,259
	C8	,155	,354	,390	1,000	,491	,315	,603	,539
	C9	,168	,379	,493	,491	1,000	,667	,697	,535
	C10	,283	,480	,626	,315	,667	1,000	,602	,435
	C11	,111	,319	,626	,603	,697	,602	1,000	,426
	C12	,222	,291	,259	,539	,535	,435	,426	1,000
Significance (1-tailed)	C5		,000	,094	,224	,206	,080	,295	,138
	C6	,000		,008	,038	,028	,006	,056	,074
	C7	,094	,008		,024	,005	,000	,000	,101
	C8	,024	,038	,024		,005	,059	,001	,002
	C9	,206	,028	,005	,005		,000	,000	,002
	C10	,080	,006	,000	,059	,000		,001	,013
	C11	,095	,056	,000	,001	,000	,001		,015
	C12	,138	,074	,101	,002	,002	,013	,015	
Determinant = ,013									

To confirm sampling adequacy - which predicts whether data are likely to factor well based on the correlations between variables - we used Kaiser-Meyer-Olkin (KMO) statistics and Bartlett's Test.

KMO indicates that the partial correlations should not be very large if one is to expect distinct factors to emerge from factor analysis. Kaiser (1974) recommends accepting values greater than 0.5 to proceed with factor analysis (values below this require to either collect more data or rethink which variables to include in the analysis). In our case, the value was 0.767.

Bartlett's test indicates the strength of the relationship among variables. This test rejects the hypothesis in which all correlations coefficient are equal to zero. The test is significant when its associated probability (p) is less than 0.005. In our case, p was less than 0.001, so the test was highly significant.

To determine the number of factors that we needed to extract, we used the criterion defined by Kaiser (1974). For this case - less than 30 variables and communalities greater than 0.7 - this criterion suggested to extract all factors with eigenvalues greater than 1, which left us with four factors. The left side of Table 6 shows these four factors and their contributions to explain the variance of the eight initial variables. Therefore, the 4 factors explain 86.63% of the variability of the data considered for this analysis. However, the factor structure (relation between initial values and the factors) is not optimal because factor 1 accounts for considerably more variance than the remaining three. To optimize the factor structure, an orthogonal rotation was carried out (right side of Table 3-6). After the rotation, the relative importance of the four factors was better distributed.

Table 3-6. Total Variance Explained (Extraction Method: Principal Component Analysis)

Component or factor	**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4,058	50,730	50,730	2,505	31,310	31,310
2	1,376	17,194	67,924	1,809	22,618	53,928
3	,880	11,006	78,9303	1,342	16,778	70,705
4	,616	7,700	86,630	1,274	15,924	86,60

Table 3-7 shows the loadings of the 8 variables (criteria) on each of the factors after the rotation. Loadings smaller than 0.4 were suppressed in the output, which explains the empty spaces in the matrix. The variables that are loaded in two factors/components (C9 and C11) were assigned to the factor in which they had a higher load.

Table 3-7. Rotated Component Matrix

	Factor/Component			
	1	2	3	4
C10	,821			
C7	,813			
C11	,734			,505
C9	,537		,682	
C5		,943		
C6		,864		
C12			,868	
C8				,884

Table 3-8 shows the final criteria set, which contains the criteria initially left out from the factor analysis in conjunction with the new criteria obtained in this analysis.

Table 3-8. Final Criteria Set

C1	Thermal Behavior
C2	Structural Behavior
C3	Acoustic Behavior
C4	Costs
C5’	Construction Complexity[1]
C6’	Safety and Environmental [2]
C7’	Durability[3]
C8’	Appearance

Notes:

(1) Construction Complexity Criterion includes Duration and Difficulty of the Construction Process

(2) Safety and Environmental Criterion includes Environmental Impact of Construction Process, Construction Process Safety and Occupants Safety.

(3) Durability Criterion includes Durability and Moisture Protection

3.7. Preference Assessment and Validation

Once the final set of criteria was defined, a scenario-based survey was utilized to assess the preferences of Chilean residential developers regarding these criteria. This survey is based on a modification of the Delphi method, and it does not consider iterations. It implicitly considers the preferences of the decision makers through assessment of different scenarios where the criteria adopt specific values (see Appendix B.1).

To define these scenarios, each criterion was categorized into two groups based on the performance of the envelope-wall system solution for that criterion compared to the average of all the considered solutions. Therefore, for each wall solution, each criterion can adopt two values: high/good or low/bad behavior. This frame generated a total of 256 possible scenarios. Table 3-9 shows the final 8 criteria, their measurement properties and units, and the states they can adopt for the purpose of the survey.

Table 3-9. Measurement Units criteria and the states they can adopt

	Criteria	Property	Unit	Possible States
C1	Thermal Behavior	Thermal transmittance	[W/m^2·K]	Good/Bad Behavior
C2	Structural Behavior	Compressive strength	[kgf/cm^2]	Good/Bad Behavior
C3	Acoustic Behavior	Insulation capacity	[dBA]	Good/Bad Behavior
C4	Costs	Materials, equipment and on-site labors costs	[\$/m^2]	High/Low Savings
C5'	Construction Complexity	Expected duration (duration considering the construction difficulty)	[MH/m^2]	High/Low Simplicity
C6'	Safety and Environmental Impact	Average score of safety of occupants, construction safety and environmental impact	Score [0-1]	High/Low Score
C7'	Durability	Annual maintenance costs	[\$/m^2-year]	High/Low Durability
C8'	Appearance	Labor time to obtain a good finishing	[MH/m^2]	Good/Bad Appearance

In order to aid the respondents in answering, we decided to maintain a common pattern for all criteria, in which a high state corresponds to a better performance. Then, the criteria of cost and complexity can adopt the following states: high or low savings and high or low simplicity, respectively.

The sampling technique for finite populations allows determination of the minimum number of scenarios needed to ensure that both the reliability and the error will be within a preset range (De Solminihac et al. 2009).

$$n = \frac{n_o}{1+\frac{n_o}{N}} \text{ where } n_o = Z^2 * \frac{S^2}{e^2} \qquad (18)$$

Where:

n = number of scenarios considered for the study

Z = confidence

S = standard deviation

e = expected error

N = total number of possible scenarios

Then, with a 95% confidence level and 10% error, the minimum number of scenarios is 22 (Table 3-10). The values of the standard deviation (25%) and error were corroborated with the results.

Table 3-10. Number of Scenarios based on expected Error and Confidence Levels

Number of Scenarios					
	Confidence level (%)				
Error (%)	50	65	75	85	95
1	133,86	173,73	195,46	213,77	231,33
5	10,75	19,94	29,28	43,11	69,84
10	2,78	5,29	8,01	12,34	**21,95**
15	1,24	2,38	3,62	5,63	10,24

In this survey, the respondents were asked to quantify 25 different scenarios rating them from 1 to 10.

Prior to the actual survey, some test surveys were applied to a smaller group of experts in order to test the survey format and the parameters associated with the sampling error. In order to have a representative sample, using the same method as section 5, the number of respondents was calculated according to the total population contained all members of the Chilean Chamber of Construction (CCHC) belonging to real estate and housing committee. Thus, the sample size was 31 respondents.

From these, we analyzed representative values per scenario in order to check the consistency and homogeneity of the survey results. To verify data consistency, we used the Chebychev Theorem, according to which 95% of the data are within two times the standard deviation around the mean of the sample (Runyon and Haber 1982). Homogeneity was tested using the coefficient of variation. We accepted values lower than 50% to reduce the dispersion of the results. Figure 3-5 shows the mean and standard deviation values for each of the scenarios. The mean value represents the EWSP (Envelope-Wall System Performance).

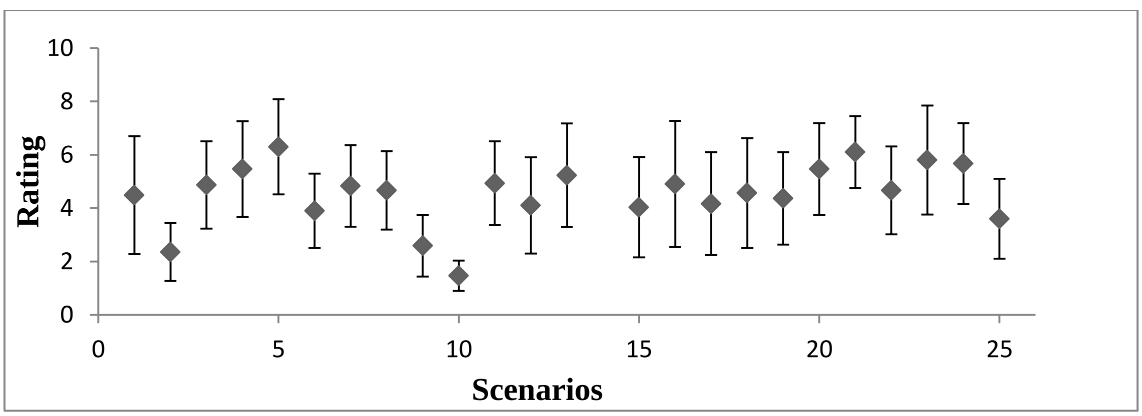


Figure 3-5. Ratings of scenarios (scenario 14 was an outlier)

The preferences of the decision-makers were obtained through a linear regression analysis with a confidence level of 95% (see Appendix B.2). We used the Minimum Squares Method to estimate the linear relationship between the dependent variable (EWSP) and independent variables (Criteria Set).

For the statistics of the regression, a determination coefficient higher than 90% is considered as acceptable, and an R^2 of 98% was obtained. We used an ANOVA f-test to analyze the statistical significance of the entire sample. Once we obtained a P-value smaller than 0.001, it was unlikely that we would have obtained an F greater than the F-value (168.64). Therefore, we rejected the null hypothesis in favor of the alternative hypothesis, and we can say that the equation obtained is reliable and representative.

The equation considering regression parameters is defined as:

$$\boldsymbol{EWSP = 0,133 * C1 + 0,333 * C2 + 0,049 * C3 + 0,184 * C4 + 0,078 * C5' + 0,148 * C6' + 0,065 * C7' + 0,010 * C8'} \quad (19)$$

To evaluate the independent variables' significances, we performed t-tests. The t-tests confirmed that C3, C7' and C8' were not statistically significant to estimate the EWSP. The rest of the criteria, with 90% significance, were needed.

Then, the final equation used to calculate EWSP is defined as:

$$\boldsymbol{EWSP = 0,151 * C1 + 0,380 * C2 + 0,210 * C4 + 0,089 * C5' + 0,170 * C6'} \quad (20)$$

The importance assigned for each criterion by the experts in the pilot survey differs significantly from the importance obtained from the scenario-based survey. This can be explained by the difference in the assessment instruments: the first survey directly asked the importance, and the second one used an indirect process to obtain it.

We separated 25% of the total responses to validate the polynomials obtained from the regression analysis. Figure 3-6 shows a comparison of the results obtained by entering the decision scenarios variables to the polynomial (Calculated EWSP) with respect to the EWSP of the respondents (Observed EWSP). The T-test for the differences between the calculated and observed EWSP was successful (p-level=0,419) with a confidence level of 95%.

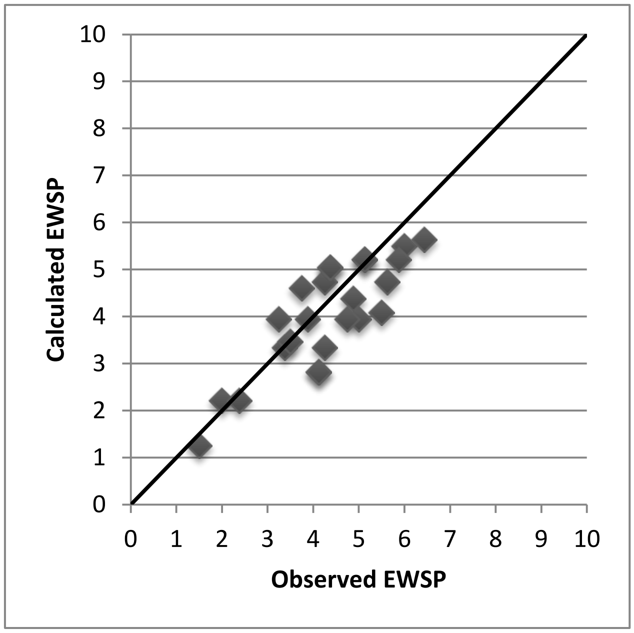


Figure 3-6. Comparison of the observed (remaining 25% of the survey data) and calculated (polynomial) EWSP

Results showed that the structural behavior was the highest preference criterion, originating from the decision-makers' opinion that structural behavior was a key component in a seismic country like Chile. On the other hand, complexity of construction was found to be the lowest preference criterion. This could be attributed to the fact that decision makers were using similar construction processes in all their projects. Costs, thermal behavior, safety and environmental impact were also found to be among the criteria preferred by the Chilean decision-makers.

3.8. Conclusions

This study identified and formalized eight criteria for selecting EWS for housing projects. The criteria were thermal behavior, structural behavior, acoustic behavior, costs, complexity of construction, safety (of the occupants and the building process), environmental impact, durability, and appearance of the envelope.

In addition, the study captured the preferences from Chilean real estate developers regarding the formalized criteria. The most preferred criterion was the structural behavior, which is consistent with the country's seismic condition and the respective regulations. The second most important criterion was the cost, followed by safety, environmental impact, and thermal behavior. Safety and environmental impact accounted for a compound criterion (from the factor analysis), which contributed to its high preference.

The preference analysis also showed that the acoustic behavior, durability and appearance criteria were not statistically significant for the EWS selection. This is aligned with the observed practice in Chile, as these criteria are usually not considered.

An important observation from the collected data was that the decision makers presented a high variability in the criteria they used in practice. This was aligned with our initial assumption in the definition of the problem.

Overall, the criteria and preferences presented in this study contribute to the knowledge for a more comprehensive analysis of envelope-wall systems. This knowledge can be used by decision-makers in their analysis and to develop decision support systems to facilitate the selection of EWSs.

The study is limited to the context of the Chilean industry. Decision-makers in other countries may differ regarding the relevant criteria to select the EWS and its relative importance (preferences). However, this research represents a starting point for further studies that could include other countries.

Our future research will use this study's results to define a selection methodology that includes the different stakeholders relevant in the decision-making of a residential project (developers, house buyers, construction companies), the selection criteria, and the external impacts that influence the selection process, for example, project conditions and code requirements.

4. SELECTING ENVELOPE-WALL SYSTEMS FOR RESIDENTIAL PROJECTS CONSIDERING MULTIPLE-CRITERIA FROM MULTIPLE DECISION-MAKERS

The selection of envelope-wall systems (EWS) in residential projects has an important impact in the technical performance and business success of the project. However, designers and developers make this decision based on past experiences, the expertise of the company or just by intuition. Part of the reasons for this informal selection methodology is the complexity of the problem due to the multiple criteria and stakeholders that are relevant for the decision.

This research proposes a methodology to select EWS for houses. The methodology considers the behavior of the alternatives of EWS for different criteria, the impacts of the project site and contractor characteristics on the EWS behavior, constraints from design/construction codes and project goals, and the developer´s and final buyer´s preferences.

The retrospective application of this methodology on two case studies demonstrated the applicability and the effectiveness of the proposed methodology, leading to increases in the traceability and productivity of this decision-making process.

4.1.Introduction

A thoughtful building envelope can make a building work more effectively for its builders and occupants. Its performance is reflected by the energy costs, occupants' comfort and productivity, air quality, structural behavior, durability, and aesthetics appeal of a building, among other factors (Chua and Chou 2010). Additionaly, Zavadskas et al. (2008) indicate that the higher standards of quality of life, new welfare requirements, and lifestyle changes have led to an increased demand for better envelope behaviors. Thus, a project success is tied with the assessment and selection of building envelope materials and designs that can satisfy the stakeholders' requirements (Singhaputtangkul et al. 2013).

Nevertheless, the selection of an effective building envelope is not a simply task. The designers often are only partially knowledgeable about, and sometimes not aware of, the design-relevant construction inputs. In addition, the decision-making in the design process tends to be ill structured and unsystematic (Yang et al. 2003). Parrish and Toommelein (2009) add that because decision-making is subjective, it is important to document why and on what basis decisions are made so they can be revisited at a later time on that project, should new considerations or facts become available, and on future projects. The latter emphasizes the importance of traceability in the selection procces.

To develop an effective decision-making process, it is important to take into account the rational estimation of economic, climatic, social conditions and traditions in order to better satisfy architectural, functional, service, comfort and other requirements of the client (Zavadskas et al. 2005). Therefore, this is a multi-criteria decision problem.

On the other hand, residential facilities are usually made-to-order products that are based on the specific requirements of clients. These requirements are related to the basic needs that the facility is intended to fulfill (Kamara et al. 1999). Even when these projects are not made-to-order, the preferences of the clients or final buyers are key for the sales and final success of the projects. Nair et al. (2010) discuss about homeowner's preferences, they cite: "It is likely that home-owners will adopt those measures that best fulfill their prioritized need". Furthermore, the preferences of the final buyers is not always aligned with the preferences of other project stakeholders, therefore, this is a multi-participant decision problem. Clients want to minimize the likely costs of the project, but they also want to achieve highest acceptable quality standards as well as to satisfy technological, architectural, and comfort requirements. Other participants of construction process (e.g. designer, contractor) are interested in maximizing profits; they are also concerned with other attributes such as company growth, market share, and the state institutions' interests. Hence, the choice of a rational alternative of this operation becomes a significant research and practical problem (Ginevičius et al. 2008).

Different envelope components contribute differently towards factors such as the cost, thermal behavior, structural behavior, constructability, and aesthetics. Optimal selection of the envelope-wall systems, a key component for houses, can have a crucial technical and economic impact for both the designer and the investor (Zavadskas et al. 2008).

The challenges of this multi-criteria and multi-participant decision lead to an informal consideration of partial criteria with numerous adverse impacts on the construction and operation of the project. This research formalizes the process of selecting envelope-wall systems for residential houses, identifying the relevant stakeholders and factors affecting the decision. This formalization produces a methodology that allows DMs (Decision Makers) to choose an appropriate alternative for each Project.

This article first explores the literature regarding multi-criteria decision making (MCDM) and existing methodologies for the selection of building envelopes. Then, it presents the research methodology and a formalization of the selection procces of the Chilean industry. in the Chilean. Continuing with the development of a multi-criteria multi-participant methodology to support DMs, then a numerical example helps explain the operation of the methodology. Finally two case studies validate the methodology.

4.2. MCDM methods

MCDM used in various fields of human activity, recently, multi-criteria evaluation methods have been successfully used to quantitatively evaluate complex and controversial phenomenas (Ginevičius et al. 2008). To apply them, the procedures should be performed in three steps: a set of criteria describing the object considered should be developed, the criteria weights and significances should be determined and an appropriate multi-criteria method should be chosen.

MCDM problem can be concisely expressed in the matrix format as shown below:

$$\mathrm{XF} = [\mathrm{xf}_1, \ldots, \mathrm{xf}_n] = \begin{bmatrix} \mathrm{xf}_{11} & \ldots & \mathrm{xf}_{1n} \\ \vdots & & \vdots \\ \mathrm{xf}_{m1} & \ldots & \mathrm{xf}_{mn} \end{bmatrix} \tag{21}$$

$$\mathrm{W} = [\mathrm{w}_1, \ldots, \mathrm{w}_m] \tag{22}$$

where n alternatives are evaluated over a set of m criteria. xf_{ij} is the performance rating of ith alternative with respect to jth attribute, and w_j is a weight (significance) of jth attribute or criterion.

Once we have the set of criteria, is necessary to determine criteria or relative weights. Decision-makers could define the relative weights directly, however, there are methods to calculate the relative weights. Some of these methods are (Kabli 2009):

- **Ranking methods:** Arranging attributes in rank order is the simplest method for assessing the importance of weights; that is, every attribute under consideration is ranked in the order of the decision-maker's preference.
- **Rating methods:** Require the decision-makers to estimate weigths on the basis of a predetermined scale; for example, a scale of 0 to 100 can be used.
- **Pairwise comparison Method:** This method involves pairwise comparisons to create a ratio matrix. It takes as an input the pairwise comparisons and produces the relative weights as output. Analytic hierarchy process (AHP) and Analytic Network Process (ANP) are the most popular approaches (Saaty 1989).
- **Other methods to determine relative weights:** Yang et al. (2003) proposed a method to calculate the relative weights using fuzzy weighted average. In this method a fuzzy weighted sum of the relative weights of all members of the design team is developed. It considers the importance given to each criterion by the members of the design team. Also a modified Delphi technique can be used to reach commun consensus in decision-making and conflict resolution, and therefore to determine the criteria weights (Hartman 1981). Experts are asked to qualify different scenarios. The Delphi technique is a useful approach for accessing expert opinions, for analyzing and synthesizing results, and for setting priorities among numerous variables or criteria (De Vos et al 2006).

Then, we have to use a MCDM method. In literature we found several methods: Simple Additive Weighting (SAW), Weighted Product Method (WPM), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Complex Proportional Assessment of alternatives (COPRAS), Simple Multi-Attribute Rating Technique (SMART), Choosing by Advantages (CBA), among others.

The basic logic of the SAW method is to obtain a weighted sum of performance ratings of each alternative over all attributes, when criteria weights are knowns. Hwang and Yoon (1981) added that: "The linear form of trade-offs between attributes used by the SAW method produces extremely close approximations to complicated nonlinear forms, while being far easier to use and understand". SAW method does not make a difference between benefits and cost type attributes, that is why the normalization procedure used with SAW method must at the same time transform performance ratings of cost type attributes into the adequate benefit performance ratings (Stanujkic et al. 2013).

On the other hand, WPM method, the attributes are connected by multiplication and contrary to the SAW method, the different measurement units here do not have to be transformed into a dimensionless scale by a normalization process. In TOPSIS, the chosen alternative should have the shortest distance from the positive–ideal solution and the longest distance from the negative-ideal solution (Hwang and Yoon 1981). COPRAS (Complex Proportional Assessment of alternatives) method uses a stepwise ranking and evaluating procedure of the alternatives in terms of significance and utility degree (Zavadskas et al. 1994). SMART is based on Edwards and Barron (1994), has been widely applied because of the simplicity of both the responses required of the decision maker and the manner in which the responses are analysed.

A different method for decision-making is Choosing by advantages (CBA). CBA creates more transparency, does not assume lineat trade-offs between attributes, focuses on differentiating between alternatives more than weigthing rating and calculating in MCDM (Arroyo et al, 2014). CBA is based on the following states: Decisions must be based on the importance of advantage. An attribute is a characteristic, quality, or consequence of one alternative. An advantage is a difference between the attributes of two alternatives. However, as the number of alternatives increases, keeping track of advantages and disadvantages becomes increasingly complicated and potentially quite inaccurate (Suhr 1999). In a different research, Arroyo et al (2014b) criticizes traditional MCDM methods. Authors say that the result of the decision may change if irrelevant factors are taken out of the decision, which does not happen in CBA.

To choose an appropriate multi-criteria evaluation method we discussed the adaptation of some methods to our case. We decided to use the SAW method in order to rank envelope-wall systems alternatives due to its simplicity and efficiency. In addition, we use a new procedure (weighted sum of preferences) to determine criteria weights.

4.3. Existing methodologies to select the building envelope

Zavadskas et al. (2008) proposes a methodology to assess alternatives of building envelopes using a modified COPRAS method with Grey relations. Through a normalization method, using Grey relational analysis, the research attempts to transform all the criteria (quantitative and qualitative) to the same scale. It defines the utility of an alternative, evaluating a set of variables given in intervals with their relative importance previously defined. This research helps to understand how to evaluate the different attributes of the behavior of the envelope.

Singhaputtangkul et al. (2013) propose a methodology that seeks to mitigate the most common problems of decision-making in the selection of the building envelope (e.g. inadequate consideration of the requirements of the project, lack of efficiency of the design team, etc.). The authors use fuzzy linguistic terms to reach consensus of DMs and determine criteria weigths. They developed a computational tool that improves efficiency as well as consistency in making the decisions for the assessment of the building envelope evaluating a specific set of criteria. This research provides knowledge about the assessment of the building envelope materials and designs, stakeholders involved in the decision-making process, and requirements to be taken into account.

Yang et al. (2003) provides a methodology based on a fuzzy quality function deployment system for buildable design. This methodology, adapting a house of quality, intends to meet the needs of buildable designs in the construction industry. Yang et al. (2003) proposed a three customers system, composed by clients, designers and contractors. Each customer has their own requirements and therefore their own evaluation design. It also uses triangular fuzzy numbers to intuitively represent the nature of decisions and judgments of buildable designs.

Turskis et al. (2009) use cost benefit analysis approach for investment decision-making from an economic perspective. Authors, based on multi-criteria analysis, evaluate the effect of various normalization methods of a decision-making matrix and the effect of the applied solution method on numerical results. The research developed a multi-criteria assessment model of multi-layered external walls.

As seen, literature presents some methods to find the most effective envelope for buildings with multi-criteria decision-making or other mathematical methods (Yang et al. 2003; Zavadskas et al. 2008; Turskis et al. 2009; Singhaputtangkul et al. 2013). These methods evaluate all the components of the building envelope together (walls, windows, roof, doors, , etc.) which provides a more holisitic approach to the problem but it does not reflect the way decisions are usually made on the projects. The literature also focuses on high-rise buildings, which differs from the selection of building envelopes for houses, eg the seismic behavior of each type of building is estimated differently. Furthermore, existing methodologies do not include characteristics of the projects, such as site location or project duration, but they only consider characteristics intrinsic to the envelope solution.

4.4. Research Methodology

The research methodology follows incremental steps to identify and formalize the selection process criteria and to develop and validate the resolution methodology. Figure 4-1 depicts the methodology.

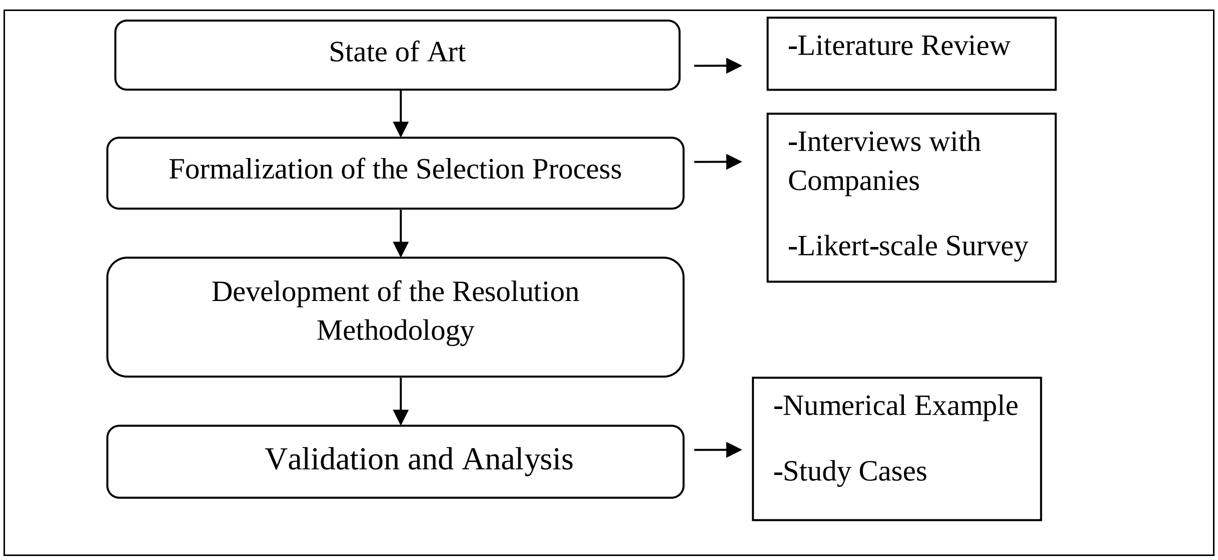


Figure 4-1. Research Methodology

To achieve the proposed objectives, the research methodology begins with a thorough literature review to understand the decision-making method in buildable design. Also to know all the factors, such as stakeholders and requirements, those have to be considered simultaneously in the selection. In addition, it raises the knowledge about MCDM methods.

Then we developed a formalization of the selection process, including answers from interviews and a likert-scale survey applied to Chilean industries attaching the state of art with the state of practice.

It continues with the development of the resolution methodology to select the envelope-wall systems considerating preferences, regulations and external impacts of each project.

Then a numerical example explains accurately the proposed methodology. After that, we used study cases of assessing and selecting the envelope-wall systems cases to demonstrate the applicability and the effectiveness of the proposed approach.

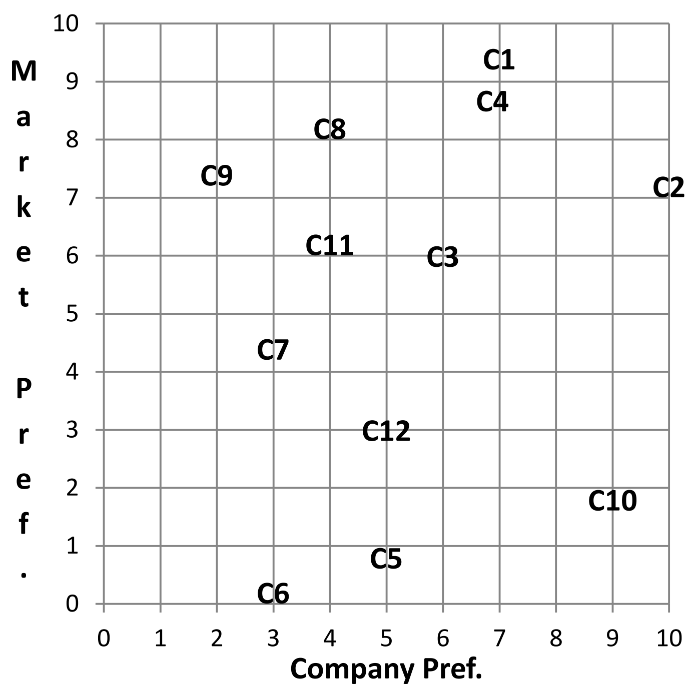
Finally, analyzing the results of study cases we proved the benefits of the methodology with respect to traditional method. Revising variables such as productivity, records, etc.

4.5. Formalization of the Selection Process of the Envelope-wall System

In order to formalize the current selection process used in the industry, we interviewed 5 real estate companies. Integrating the responses obtained from interviews and literature, factors affecting the selection process were defined.

Responses showed that not considering the preferences of the market may have a negative influence on the project, specifically getting very slow speeds sales because the selected EWS is not valued by the market. Respondents added that they have had to adapt their projects in advanced stages to suit the market requirements, increasing costs and project deadlines.

In many multiple participant decision making situations, one or more of the DMs may use multiple criteria for evaluating courses of action or states. In such circumstances, a given participant's preferences across the states may be different for each of the criteria set (Hipel et al. 1993). In other words, preferences of the market and the company are usually different. A brief survey (scale 0 to 10) shows the averaged preferences, over a not specified criteria set, of five potential buyers of a residential project in Santiago and the preferences of the company that sells and finances the project (Figure 4-2). For this reason, the selection of the envelope-wall system must be addressed as a problem of multiple-criteria multiple-participant decision-making (MCMPDM).



C1	Thermal Performance
C2	Structural Behavior
C3	Acoustic Behavior
C4	Costs
C5	Duration Construction Process
C6	Difficulty Construction Process
C7	Environmental Impact of
C8	Appearance
C9	Durability
C10	Construction Process Safety
C11	Occupants Safety
C12	Moisture Protection

Figure 4-2. Market Preferences vs. Company Preferences

The market and the company developing the project are the participants. The research must simultaneously consider the preferences of both participants.

Multiple-participant problems including many criteria into account has been a major focus, and has made significant progress with the rapid development of operations research, management science, systems engineering, and other disciplines (Chen et al. 2012). Only well-founded weighting factors should be used because weighting factors are always subjective and influence the solution (Zavadskas and Turskis 2008). In a MCMPDM, it is often hard to obtain a solution due to the possible conflict preferences from different participants and the undeterministic weights assigned to each criterion (Wei et al. 2000). The objective is to integrate the opinions of participants into a sorting. Participants need only specify preference directions over criteria. A number of different techniques have been developed for generating criteria weights for multiple participants or experts. Saaty (1989) used an eigenvector technique. Davis (1973) assumes a dominant role of members whose opinions are mutually close. Thus, each DM is given a weight depending on the centrality of his/her position relative to the other members of the group and the group decision is a weighted sum of the member's preferences. Other, more sophisticated, methods such as those based on the concepts of outranking and multi-dimensional scaling have been applied to planning problems as well (Feick and Hall 1999). Tsiporkova and Boeva (2006) proposed a multi-step method to calculate criteria weights in a multi-expert decision making environment in the form of a recursive aggregation algorithm.

However, these techniques have in common that there are several DMs. In our case, only one is the final DM (the company) and the other participant only influence the decision-making process. Then, as participants of the problem are not in the same level, the market influences the company, which makes the final decision. Hence, the company is the final DM and decides "how much" are they going to meet the preferences of buyers, and therefore fail to meet their own needs.

On the other hand, interviewed added that there are other factors to consider, such as the availability of labor and equipment on the project site. Currently the development of the construction has generated a deficit of workers specialists in some construction methods. We also obtained other cases where site location, weather, topography, construction company expertise or competitive advantages sellers showed a fundamental role for success of the project

Factors and their definitions obtained from literature review and interviews companies are shown in Table 4-1. To validate the list, we applied a likert-scale survey to raise the factors that are being used by the Chilean industry and their perception of the importance of taking into account them in the selection process.

Table 4-1. Factors to consider in the selection process

F1	Market Preferences	End-user perception and preferences of the behavior of the house (e.g., market interest for thermal insulation).
F2	Regulations	Laws and regulations from design and construction codes.
F3	Company Preferences	Priorities of the principal or real estate company on the behavior of the wall-envelope system of the house.
F4	Impacts of the Project Location and Construction Company	Possible impacts on where the project is located (e.g., climate, distance to suppliers, accessibility, etc.) and impact due to the expertise of the construction company in a labor construction method, or equipment availability.
F5	Project Requirements	Requirements previously established in the design phase of the project (e.g., deadlines or budgets).

We chose a pilot survey using Likert as the research tool because of its suitability for collecting opinions or attitudes. In this case, the Likert scale is useful because tends to show high levels of reliability and validity, □also is preferred by the respondents for being simple and "natural" to complete and the results of the Likert survey are categorical, ordinal (data in which an ordering or ranking of responses is possible but no measure of distance is possible) and not normally distributed. The detailed explanation of these tests escapes the scope of this report.

Respondents expressed how often they consider 5 impacts or factors in the selection process of the envelope-wall system. Using a standard 5-point Likert scale, with 1 being never used and 5 always used. They also expressed their agreement or disagreement with using the 5 factors, in accordance with the relative importance attributed, using a standard 5-point Likert scale, with 1 being completely disagree and 5 completely agree.

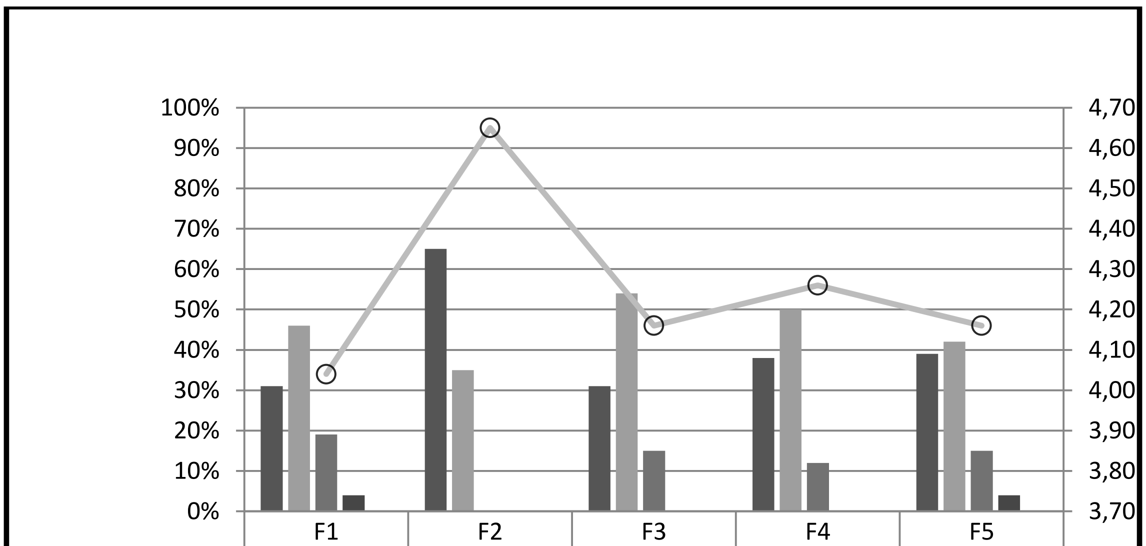
In order to have a representative sample, 31 companies related to the real state market comprised the sample of the study. To define the universe of the space of inference, all partner companies of the Chilean Chamber of Construction (CCHC) belonging to real state and housing committee were considered. For details of the calculation of the sample see

Table 4-2. They answered the survey on an online platform.

Table 4-2. Likert-scale survey sample and error

Universe	N	201
Confidence Interval	Z=95%	1,96
Standard Deviation	σ	0,25
Error	8%	0,08
Sample	**n**	**31**

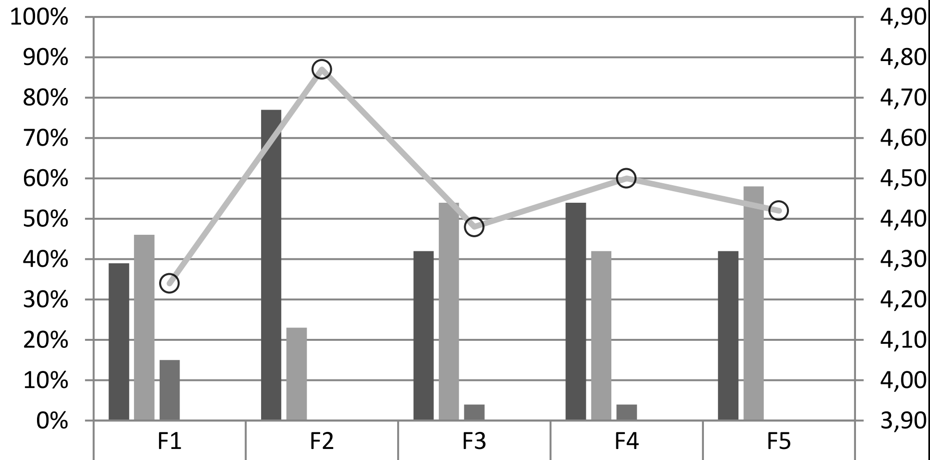
Figure 4-3 presents the results regarding the frequency of use of the factors.



	F1	F2	F3	F4	F5
Always	31%	65%	31%	38%	39%
Usually	46%	35%	54%	50%	42%
Sometimes	19%	0%	15%	12%	15%
Ocassionally	4%	0%	0%	0%	4%
Never	0%	0%	0%	0%	0%
Use Score	4,04	4,65	4,16	4,26	4,16

Figure 4-3. Use of factors in the selection process

Figure 4-4 shows the results regarding the agreement with the use (importance) of the different factors. This reflects the importance that these factors have in the selection process.



	F1	F2	F3	F4	F5
Strongly Agree	39%	77%	42%	54%	42%
Agree	46%	23%	54%	42%	58%
Neutral	15%	0%	4%	4%	0%
Disagree	0%	0%	0%	0%	0%
Strongly Disagree	0%	0%	0%	0%	0%
Importance Score	4,24	4,77	4,38	4,50	4,42

Figure 4-4. Level of agreement of considering factors in the selection process

Importance score (IS) and use score (US) were calculated as a weighted combination of the responses, using a 1-to-5 scale from the most negative to the most positive answers ("strongly agree" and "always" correspond to 5 while "strongly disagree" and "never" correspond to 1). These consolidated scores facilitate the comparison between the importance and use of the different factors. Table 4-3 shows that comparison.

Table 4-3. Difference between Importance and Use Scores of factors

Factor	**IS**	**IS σ**	**US**	**US σ**	**Difference**
F1	4,24	0,71	4,04	0,82	5%
F2	4,77	0,43	4,65	0,49	3%
F3	4,38	0,57	4,16	0,67	5%
F4	4,5	0,58	4,26	0,67	5%
F5	4,42	0,50	4,16	0,83	6%

Regulations are considered in almost all cases, because of their status as mandatory (lowest standard deviation). On the other hand, responses about the use of the other factors tend to the category "usually" and their standard deviations values are relatively large, specifically market preferences and project requirements. Confirming our hypothesis, that there is not an established methodology in Chilean practice.

Regarding to the importance, respondents said that regulations are the most important factor because they must necessarily be fulfilled. However, this does not indicate that other factors were considered unimportant. Close to 90% of the responses were in the category of agreement (Strongly Agree and Agree) when considerating factors F2, F3, F4 and F5. And 85% of respondents agreed with the consideration of factor Market Preferences.

Small percentage differences show a correlation between the importance of factors and their use in practice. However, in all cases the importance score is greater than the use score, indicating that factors are not are not sufficiently considered.

Besides the proposed factors, respondents added potentially new factors to consider in the selection of envelope-wall system. Table 4-4 shows these criteria and explains whether they were included or not.

Table 4-4. Potential new factors and their inclusion analysis

Criterion	Inclusion
Costs	It was not included because it is not characteristic of the project. It is a characteristic of the specific wall solution.
Innovation of new alternatives	It is not included as it is a characteristic of the specific wall solution.
Industrialized production	It is not included as it is a characteristic of the specific wall solution.
Sale Price	It is implicitly included in the factor of project requirements.
Acoustic performance	It is not included as it is a characteristic of the specific wall solution.
Constructive method	It is not included as it is a characteristic of the specific wall solution.
Definition of subdivision	It is implicitly included in the factor of project requirements.
Service life	It is not included as it is a characteristic of the specific wall solution.

4.6. Development of the MCMPDM Methodology

4.6.1. The Overall Framework

This section develops the MCMPDM methodology to rank envelope-wall system alternatives. Figure 4-5 gives an overview of the methodology. The steps, beginning with the evaluation of the alternatives' behavior, the calculation of the final behavior, then checking compliance of the requirements and finally calculation of the overall performance rating to obtain a priorization of the alternatives and evaluate the results.

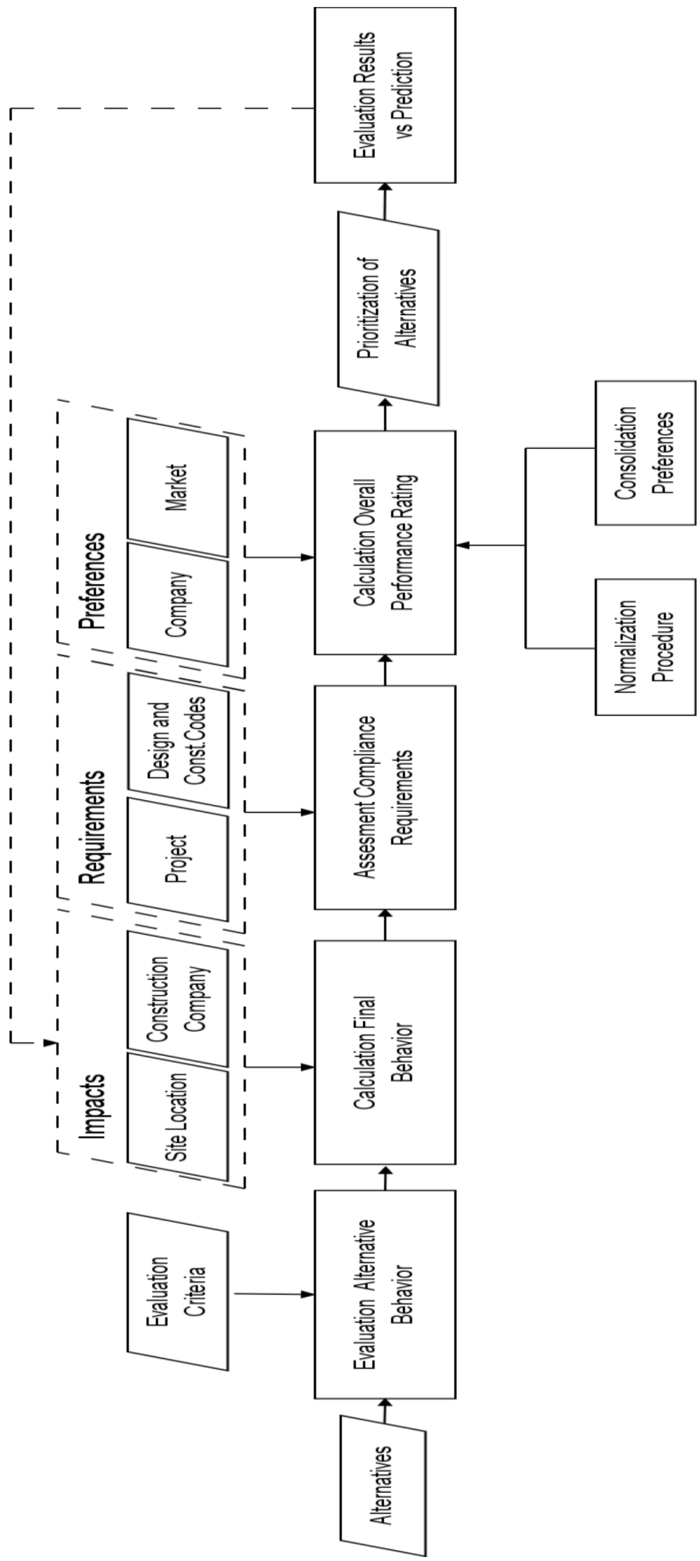


Figure 4-5. Flowchart of the MCMPDM Methodology

4.6.2. Criteria to Evaluate Envelope-wall systems

In MCMPDM the accuracy of expert evaluation largely depends on the number of criteria. When this number is growing, the complexity of the methodology is also growing (Ginevičius et al. 2008). A well-constructed and verified criteria tree facilitates the measurement of MCDM preferences (Brugha 2004). The resolution methodology uses the criteria for selecting envelope-wall systems for residential projects suggested in chapter 3 of this thesis (Table 4-5). In addition, the resolution methodology allows add new criteria by the user or DM.

Table 4-5. Criteria for selecting envelope-wall systems for residential projects

C1	Thermal Performance	Evaluates whether the solution satisfies surround good shape given by the standard thermal needs.
C2	Structural Behavior	Evaluates whether the solution satisfies surround good shape given by the structural needs standard.
C3	Acoustic Behavior	Evaluates whether the solution satisfies surround sound needs the good way. The ability of the shell to protect the indoor environment from noise impacts.
C4	Costs	Cost of the final solution.
C5	Construction Complexity	Duration in days of the construction process. Complexity, reliability and availability of equipment and labor for the construction process.
C6	Safety and Environmental	Risk of accidents and amount of waste and noise during the construction process of the solution. Envelope-wall system behavior associated with fire resistance, weather resistance and to provide security.
C7	Durability	Long-term performance and maintainability. Maintenance costs (painting, remodeling, etc.) Capacity limitation moisture exchange.
C8	Appearance	Appearance and easiness to give a good finish to the envelope-wall system.

4.6.3. Steps of the MCMPDM Methodology

Assuming n alternatives of envelope-wall systems and each alternative is evaluated over a set of m criteria.

a) Evaluation Alternative Behavior

As we have n possible envelope-wall systems and each alternative is evaluated over a set of m criteria, the vector that represents the behavior of each alternative is defined by,

$$x_i = \begin{bmatrix} x_{i1} \\ \vdots \\ x_{im} \end{bmatrix} \quad \text{is given for each alternative } i = 1,\ldots,n. \qquad (23)$$

Note that each value in the vector must be consistent with the units of measurement of the evaluation criteria set forth previously.

b) Calculation Final Behavior

In all projects there are certain requirements that must necessarily be approved, e.g. regulatory and statutory acceptance. However, compliance with these minimum requirements does not guarantee stakeholder satisfaction because the main regulations do not always cover all key stakeholder requirements (Singhaputtangkul et al. 2013). DMs may desire achieving performances superior to regulatory and statutory requirements.

In economics and decision making it is essential to be able to take into account the impacts of cultural, social, moral, legislative, demographic, economic, environmental, governmental and technological change, as well as changes in the business world on international, national, regional and local markets (Turskis et al. 2009).

Then, performances of the EWSs are affected by external factors negatively or positively. It is necessary to include the economic, technological change, environmental, climatic, among others impacts. For instance, knowledge base of life-time process of constituent parts of a building consists of information on alternative construction sites, buildings, designers, contractors, suppliers and so on (Ambrasas et al. 1996). Contractors and experienced construction personnel are also the contributors of buildable designs. They contribute their knowledge and expertise to the various buildability issues, e.g., the alternative construction methods and the site issues, and expect to optimize the design for ease of construction and make profits (Yang et al. 2003). An example of a positive impact, proximity to a supplier can reduce transportation cost of materials and therefore the final cost of the solution of the envelope-wall system. On the other hand, lack of specialists in the construction method in the project area would cause an increase in the duration of construction.

The methodology includes the impacts of site location (site conditions, site accessibility, climate, etc.), represented for each criterion to evaluate as

$$\mathrm{is} = \begin{bmatrix} \mathrm{is}_1 \\ \vdots \\ \mathrm{is}_m \end{bmatrix} \quad (24)$$

And impacts of the construction company (availability of sources, equipment availability, expertise of the construction personnel, etc.) defined by the vector

$$\mathrm{ic} = \begin{bmatrix} \mathrm{ic}_1 \\ \vdots \\ \mathrm{ic}_m \end{bmatrix} \quad (25)$$

Influence of external impacts

Then, possible solutions are affected by external impacts. Impacts are an input in the methodology and generate a new porcentual vector representing the final behavior of the alternative.

$$\mathrm{xf}_i = \begin{bmatrix} x_{i1} \\ \vdots \\ x_{im} \end{bmatrix} + \begin{bmatrix} \mathrm{is}_{i1} \\ \vdots \\ \mathrm{is}_{im} \end{bmatrix} + \begin{bmatrix} \mathrm{ic}_{i1} \\ \vdots \\ \mathrm{ic}_{im} \end{bmatrix} \quad (26)$$

Note that the values of is and ic may be positive or negative.

c) Assesment of Compliance Requirements

Different institutions regulate construction projects. There are certain technical, environmental, safety, among other regulations and laws that have to be fulfilled in order to get the acceptance by the institutions relevant to the case. When choosing the envelope-wall constructive method and materiality, this regulatory and statutory acceptance must be considered (Pan et al. 2012).

Then, for each criterion (set of m criteria) requirements from design and construction codes are represented as

$$rc = \begin{bmatrix} rc_1 \\ \vdots \\ rc_m \end{bmatrix} \tag{27}$$

On the other hand, design-relevant construction inputs exist in every project, such as deadlines or limited budgets. Those are called requirements of the project and also influence the selection process of the envelope-wall system in the resolution methodology.

Then, the next vector defines requirements of the project

$$rc = \begin{bmatrix} rp_1 \\ \vdots \\ rp_m \end{bmatrix} \tag{28}$$

Compliance of requirements

The methodology identifies the alternatives that are feasible for the project, i.e., that meet requirements from design and construction codes and requirements of the project. Reviewing the above, the choice becomes a possible solution and therefore enters into the ranking. Otherwise, the alternative is discarded for this project.

To check the status of acceptable alternative preliminarily the direction of improvement must be known for each criterion. They may change in different directions, i.e. in some cases, the increasing criterion value can indicate a better situation, and while in others it means a worse state (Ginevičius et al. 2008).

Then, assuming that the solution meets the requirements when the final alternative behavior is greater than the requirement for all criteria, the alternative becomes a possible solution if

$$xf_i = \begin{bmatrix} xf_{i1} \\ \vdots \\ xf_{im} \end{bmatrix} \geq \max\left(\begin{bmatrix} rc_1 \\ \vdots \\ rc_m \end{bmatrix} + \begin{bmatrix} rp_1 \\ \vdots \\ rp_m \end{bmatrix} \right) \tag{29}$$

Note that the values of rs and rc may be null.

d) Calculation Overall Performance Rating

To choose an appropriate multi-criteria evaluation method we discussed the adaptation of some methods to our case. After reviewing the literature of MCDM, we decided to use a variation of the SAW method in order to rank envelope-wall systems alternatives due to its simplicity and efficiency. The difference of our method is that criteria weights are determined through weighted sum of the participants' preferences. Therefore, the overall performance rating of each alternative is obtained by using the following formula:

$$S_i = \sum_{j=1}^{n} w_j * nxf_{ij} \tag{30}$$

where Si is the overall performance rating of the ith alternative; w_j is the weight of jth attribute; and nxf_{ij} is a normalized performance rating of ith alternative with respect to jth attribute. The greater the value (Si), the more preferred the alternative (Ai). Finally overall performances rating composed the priorization of the altenatives, the output of the methodology.

In order to obtain nxf_{ij} and w_j we must apply a normalization procedure and consolidation of preferences respectively. Both tasks are explained below.

d.1) Normalization Procedure

Criteria generally have different units of measure and differ in the sense optimization. Then a method of normalization is required. The normalization aims at obtaining comparable scales of criteria value and eliminates computation problems that can be caused by using different units of measures in a decision-making matrix

Normalizations methods and their impact on decision-making process, such as vector, linear and non-linear scale, and logarithmic techniques, have been studied by many authors (Hwang and Yoon 1981; Ginevičius 2008; Ginevičius et al. 2008; Zavadskas et al. 2008; Zavadskas and Turskis 2008; Turskis et al. 2009; Stanujkic et al. 2013). Although some methods have their recommended normalization methods, there are still no rules to choose a particular normalization method to solve a multi-criteria decision-making (MCDM) problem.

Attributes can be classified into two main categories: cost attributes and benefit attributes. In the case of benefit attributes, the higher score is assigned to the alternative which performance rating is higher, i.e., preferable is a maximum of jth attribute. In contrast to the previous, in the case of cost attributes, higher score is assigned to the alternative which performance rating is lower, i.e., the minimum of jth attribute is preferable. These normalization methods transform performance ratings of cost type attributes into the adequate benefit performance ratings.

Based on Ginevičius (2008) and Stanujkic et al. (2013) researches, we decided to use a Linear Scale Tansformation-Max (LST-Max) method to normalize the variables. As we look for establising the priority order of the alternatives and it is necessary to normalize the criteria values of various dimensions. This method, besides being a very simple procedure, preserves the proportionality between variables. The performance rating of each alternative is divided by a maximum performances rating for that criterion.

The LST-Max method is represented as,

$$\mathrm{nxf}_{\mathrm{ij}} = \frac{\mathrm{xf}_{\mathrm{ij}}}{\max(\mathrm{xf}_{\mathrm{j}})} \tag{31}$$

Where $\max(\mathrm{xf}_{\mathrm{j}})$ is the largest value of jth criterion. In order to transform cost to benefit type performances, the normalized performance ratings are calculated using the following formula:

$$\mathrm{nxf}_{\mathrm{ij}} = \frac{\min(\mathrm{xf}_{\mathrm{j}})}{\mathrm{xf}_{\mathrm{ij}}} \tag{32}$$

Where $\min(\mathrm{xf}_{\mathrm{j}})$ is the smallest valueof jth criterion.

d.2) Consolidation of preferences

The method used to generate the weights used in the resolution methodology is a variation of the weighted sum of the participant's preferences, one of the most widely used techniques. This can be represented as:

- **Initial Criterion Weights:** Next, as the company and the market are involved in the process of making the decision. Each DM is given the freedom to assign a vector of weights,

  $$\mathrm{wc} = \begin{bmatrix} \mathrm{wc}_1 \\ \vdots \\ \mathrm{wc}_m \end{bmatrix}, \mathrm{wm} = \begin{bmatrix} \mathrm{wm}_1 \\ \vdots \\ \mathrm{wm}_m \end{bmatrix} \qquad (33)$$

  Where $\sum_{j=1}^{m} \mathrm{wc}_j = 1, \sum_{j=1}^{m} \mathrm{wm}_j = 1$ and $\mathrm{wc}_j, \mathrm{wm}_j \in [0,1]$ for $j = 1, \dots, m$. These weights are reflecting the individual judgement of the company (wc) and the market (wm) about the relative importance of the different criteria for the particular problem in question.

- **Aggregation over Preferences:** The final DM is allowed to distribute weights between the market (the other participant) and itself, expressing the relative degree of influence the company is inclined to accept from the market when forming a judgment for the different alternatives. Thus, the company defines a vector of weights,

  $$\mathrm{v} = \begin{bmatrix} \mathrm{v}_c \\ \mathrm{v}_m \end{bmatrix}, \qquad (34)$$

  Where $\mathrm{v}_c + \mathrm{v}_m = 1$ and $\mathrm{v}_c, \mathrm{v}_m \in [0,1]$. Note that the value of v_c is the percentage of satisfied preferences of the company and therefore v_m is the percentage of market preferences satisfied that the company desired.

- **Final Criterion Weights:** combining the initial weights with the aggregation over preferences indicated by the company behind the project final weights are obtained,

$$w = \begin{bmatrix} w_1 \\ \vdots \\ w_m \end{bmatrix} = v(1) * \begin{bmatrix} wc_1 \\ \vdots \\ wc_m \end{bmatrix} + v(2) * \begin{bmatrix} wm_1 \\ \vdots \\ wm_m \end{bmatrix} = v_c * \begin{bmatrix} wc_1 \\ \vdots \\ wc_m \end{bmatrix} + v_m * \begin{bmatrix} wm_1 \\ \vdots \\ wm_m \end{bmatrix} \quad (35)$$

Where $\sum_{j=1}^{m} w_j = 1$ and $w_j \in [0,1]$ for $j = 1, \dots, m.$ These weights are reflecting the both participants judgment about the relative importance of the different criteria simultaneously.

e) Evaluation Results vs Prediction

In many decisions the consequences of the alternative courses of action cannot be predicted with a certainty (Zavadskas et al. 2008). In the proposed methodology, the decision maker estimates the external impacts. External impacts assists the DMs translating subjective and uncertain external influences into a more useful format. However, assessment of impacts is subjective and will differ between different DMs, this uncertainty can affect the value of the performance rating of an alternative with respect to an specific criterion and therefore the overall performance rating of the alternative. In case the values of the performances of two alternatives are close, the uncertainty of the determination of the values of the impacts may alter the final results. The above considerations lead to the need of performing an evaluation of the results.

This action corresponds to manual work in which it is confirmed that the performance of the alternative was as calculated by the methodology (with external impacts).

In the event that the actual behavior of the alternatives differ with the calculated, it is necessary to redefine the values of external impacts. In this way the generated alternative ranking methodology will be accurate.

4.6. Ranking EWS for residential projects with MCMPDM methodology

In this section, we consider a numerical example in order to explain accurately the proposed methodology. Suppose that the design team and the market assign the importance to attributes trough the method discussed in section 4.6.3 (d.2). Table 4-6 shows assigned values and calculated attributes' weights.

Table 4-7 presents attributes' weights, unite of measures, optimization type, and alternatives' performances (initial decision-making matrix). The influence of external impacts is added to the behavior of the alternatives in Table 4-8. Impacts are given by any of the situations explained in section 4.6.3(b).

After creating the final decision-making matrix with the final behaviors, for each alternative, compliance of the requirements must be checked. Alternative 3 does not meet regulatory acceptance (C1 and C6), thus discarded as a possible alternative and removed from the analysis.

Then we apply the normalization, effects of normalization are shown in Table 4-9. In the next step, multiplying elements in columns of normalized decision-making matrix by the corresponding weights forms the weighted normalized decision-making matrix. After that, the overall performance rating (S_i) for all the possible alternatives can be finally determined, as well as the ranking results (Table 4-10).

Based on the results, it can be easily seen that the best ranked is the alternative 2, with the overall performance rating of 0,880. The runner alternative is the alternative 1, with a slightly lower overall performance rating, which is 0,866

Table 4-6. Consolidation of preferences

Initial Criterion Weights	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Company	0,1	0,2	0,1	0,2	0,2	0,1	0,05	0,05
Market	0,15	0,1	0,15	0,2	0	0,15	0,15	0,1
Aggregation Over Preferences	**Degree of Influence**							
Vc (Over Company)	0,8							
Vm (Over Market)	0,2							
Final Criterion Weights	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
	0,11	0,18	0,11	0,2	0,16	0,11	0,07	0,06

Table 4-7. Initial decision-making matrix

Attributes	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Unit of Measures	U [W/mK]	Fc [kgf/cm²]	Insul. [dBA]	\$/m²	MH/m²	Risk [0-1]	\$/m²-year	MHf/m²
Optimization	min	max	max	min	min	min	min	min
Weigths (wj)	0,11	0,18	0,11	0,2	0,16	0,11	0,07	0,06
Envelope-wall	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Alternative 1	1,5	160	48	25000	2,5	0,15	5000	1
Alternative 2	0,6	130	46	20000	2	0,35	4000	0,5
Alternative 3	1,9	125	50	25000	1,5	0,55	5000	2
Alternative 4	1,3	145	50	30000	2	0,2	6000	2,5

Table 4-8. Influence of external impacts – Final decision-making matrix

Envelope-wall System	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Impacts A1				-10%	-20%	8%	5%	-20%
Final Behavior A1	1,50	160	48	22500	2,00	0,16	5250	0,80
Impacts A2				-5%	15%	-5%	5%	10%
Final Behavior A2	0,60	130	46	19000	2,30	0,33	4200	0,55
Impacts A3				-5%	10%	5%	5%	5%
Final Behavior A3	***1,90***	125	50	23750	1,65	***0,58***	5250	2,10
Impacts A4				-15%	10%	-5%	5%	10%
Final Behavior A4	1,30	145	50	25500	2,20	0,19	6300	2,75
Requirements	**1,70**	**120**	**45**	**35000**	**3,00**	**0,50**	**-**	**-**

Table 4-9. The effects of normalization

Envelope-wall System	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Alternative 1	0,400	1,000	0,960	0,844	1,000	1,000	0,800	0,688
Alternative 2	1,000	0,813	0,920	1,000	0,870	0,487	1,000	1,000
Alternative 4	0,462	0,906	1,000	0,745	0,909	0,853	0,667	0,200

Table 4-10. Weighted normalized decision-making matrix and results of ranking alternatives

Envelope-wall System	C1	C2	C3	C4	C5	C6	C7	C8	S	Rank
Alternative 1	0,044	0,180	0,106	0,169	0,160	0,110	0,056	0,041	**0,866**	**2**
Alternative 2	0,110	0,146	0,101	0,200	0,139	0,054	0,070	0,060	**0,880**	**1**
Alternative 4	0,051	0,163	0,110	0,149	0,145	0,094	0,047	0,012	**0,771**	**3**

4.7. Validation of the Resolution Methodology

We conducted two retrospective cases of study to validate and demonstrate the applicability and the effectiveness of the proposed methodology.

We gathered all the information needed to develop the methodology on each project, ie, alternatives evaluated and their technical characteristics, project and regulatory requirements, external impacts (construction company and site location) and preferences of both DMs. In order to compare methodology results with the actual results of the project, information about evaluation criteria and their definitions, time and human capital spent in the decision-making, and how satisfied they were with the selected alternative was collected.

Meetings between the researcher and each DM prior to aplicate the methodology allowed collecting all the required information.

The first case study was a middle class residential project of 104 houses of 55 square meters. The project evaluated five possible envelope-wall systems alternatives: The first alternative consisted in a prefabricated wooden panel made by the construction company, the second is a prefabricated structural insulated panel (SIP) also made by the construction company. While the third alternative is a traditional masonry wall-system, the fourth corresponds to an insulated concrete form or wall (ICF) containing a layer of expanded polystyrene (EPS). The last alternative is a prefabricated structural panel composed by metal sections coated on both sides, it also has an insulating material inside (see Appendix

C.1). Results of the case study are showed in Table 4-11 and Figures 4-6 and 4-7.

Table 4-11. Results of ranking alternatives case study 1

Attributes	C1	C2	C3	C4	C5	C6	C7	C8
Unit of Measures	U [W/mK	Fc [kgf/cm^2	Insul. [dBA]	\$/m^2	MH/m^2	Risk [0-1]	\$/m^2-year	MHf/m^2
Optimization Type	min	max	max	min	min	min	min	min
Weigths (wj)	0,137	0,137	0,050	0,113	0,126	0,135	0,126	0,174
Normalized Final Behavior	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Alternative 1	0,507	0,383	0,818	1,000	1,000	0,589	0,463	0,652
Alternative 2	1,000	0,467	0,855	0,832	0,758	0,547	0,476	0,652
Alternative 3	0,215	0,417	0,818	0,777	0,529	1,000	1,000	1,000
Alternative 4	0,292	1,000	1,000	0,709	0,519	0,246	0,667	1,000
Alternative 5	0,811	0,500	0,818	0,915	0,692	0,506	0,476	0,652

Overall Performance Rating	Si	Rank
Alternative 1	0,655	4,000
Alternative 2	0,682	2,000
Alternative 3	0,718	1,000
Alternative 4	0,665	3,000
Alternative 5	0,654	5,000

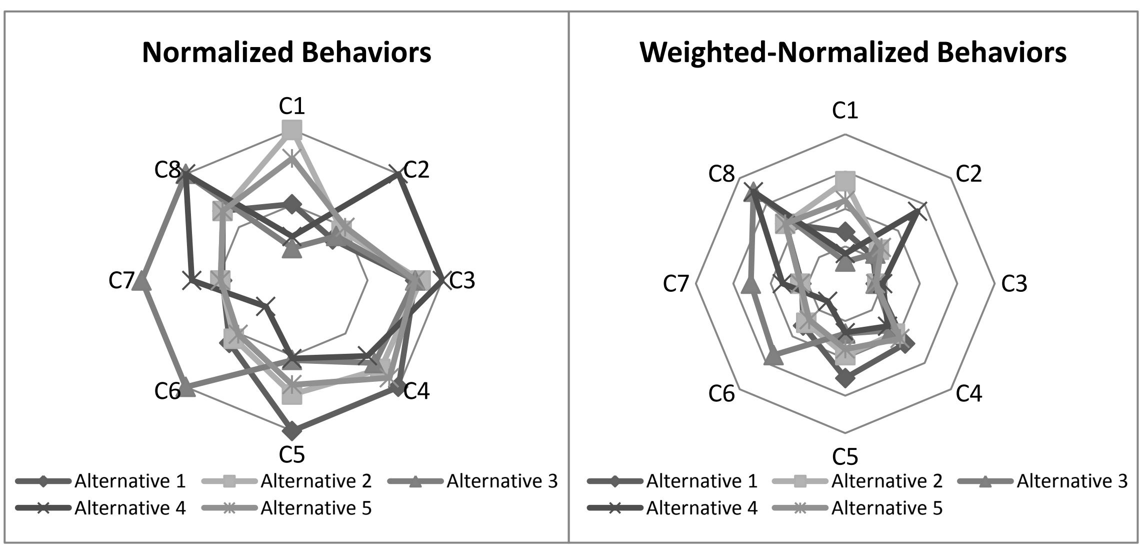


Figure 4-6. Alernatives study case 1

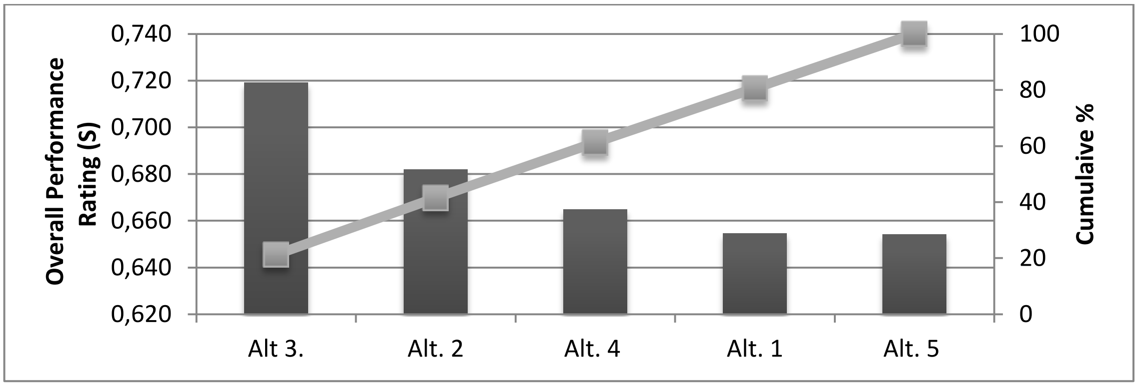


Figure 4-7. Pareto chart study case 1

Alternative 3 is the most recommended for this project. In the actual project, using the traditional method desicion makers opted for alternative 1 (fourth place in our ranking) obtaining slow sales. The company took this decision based on the effects of a recent earthquake that caused significant damage in typical houses of the zone (masonry and mud brick) and the government encouraged the use of industrialized systems to speed up the reconstruction process. The project was not well received by the users, as their preferences were not being satisfied, they preferred more solid and rigid walls. Potential buyers criticized the "hollow sound" of the EWS, indicating that it was not a definitive construction, but temporary. Besides, the competitors in the area had houses with at least the first floor in masonry. In a second stage of the project, it was decided to change the envelope to a masonry EWS (Alternative 3), coinciding with the recommendation of our methodology. This was chiefly due to two reasons: a) the traditional method did not consider in a good way market preferences and their culture; b) large external impacts associated to the project, specifically on the criteria of appearance, as the new solution was more aligned with the residential environment of the area. This had an immediate market reaction. During the process of construction, the project already had a 40% presale. The DM concluded that in the decision process is crucial to consider the cultural variable, listening to what people like and prefer.

Figure 4-6 shows the behavior of all alternatives with and without the influence of preferences of DMs. Both graphs depicts that the alternative recommended by the methodology (3) controls only in some criteria, however these criteria have a high importance level. Figure 4-7 illustrates the Pareto chart in which the overall performance ratings are compared, ordered from highest to lowest performance rating.

The second case was a second home residential project located in a vacational town in southern Chile. The project evaluated two possible envelope-wall systems alternatives: The first alternative is a prefabricated structural insulated panel (SIP) made by the construction company, it consists of a structure of two compressed Oriented Strand Board (OSB) with insulation inside (EPS). The second alternative is a prefabricated wooden panel made by the construction company with Fiberglass (insulation) and coated with plasterboards (see Appendix C.2). Results of the case study are showed in Table 4-12 and Figure 4-8.

Table 4-12. Consolidation Results of ranking alternatives study case 2

Attributes	C1	C2	C3	C4	C5	C6	C7	C8
Unit of Measures	U [W/m K]	Fc [kgf/cm ^{2}]	Insul. [dBA]	\$/m^2	MH/m^2	Risk [0-1]	\$/m^2-year	MHf/m^2
Optimization Type	min	max	max	min	min	min	min	min
Weigths (wj)	0,140	0,127	0,125	0,113	0,108	0,140	0,105	0,140
Final Behavior (xf_i)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Alternative 1	0,365	156	47	19635	1,140	0,340	5250	0,900
Alternative 2	0,720	115	45	14560	1,104	0,343	5500	1,000
Normalized Final Behavior (nxf_i)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Alternative 1	1,000	1,000	1,000	0,742	0,968	1,000	1,000	1,000
Alternative 2	0,507	0,737	0,957	1,000	1,000	0,990	0,955	0,900
Overall Performance	**Si**	**Rank**						
Alternative 1	0,967	1						
Alternative 2	0,872	2						

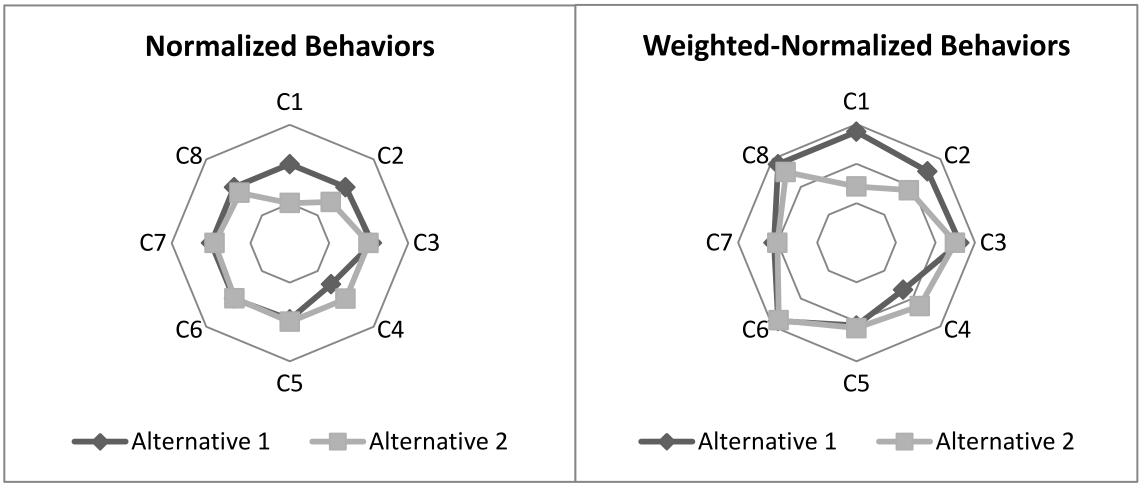


Figure 4-8. Alternatives study case 2

In this case, the methodology recommends alternative 1, coinciding with the alternative chosen in the actual project. This has been well received by the market, since sales of the project have been good. Figure 4-8 illustrates the better performance of alternative 1, compared to the second one in most of the criteria. Its superiority is accentuated with the introduction of the relative weights or preferences of DMs, confirming the choice of this alternative.

Results from both study cases show that this method can be implemented as an effective decision aid in the selection of the EWS for residential projects. The comparison of performance between the traditional method and the methodology are in terms of effort or productivity, measured in the time used for decision-making and the traceability, measured in the data records to justify the choice.z

The methodology may require additional time in collecting information than the traditional method because of the important number of evaluation criteria, the estimation of impacts, requirements and preferences of the DMs. However, it is assumed that the suppliers of the solutions provide the technical information of each alternative. Despite this, the simplicity and efficiency of the methodology allows to increase productivity in the selection process and to maintain consistency with the fulfillment of the stakeholders' objectives.

Regarding to traceability, the methodology leaves a record that can prove and justify the selected alternative. With the traditional method, the above is difficult in the case that the person who made the decision no longer works in the company or the decision was made based on intuition or past experiences.

4.7.Conclusions

A methodology to select the envelope-wall system in residential projects using multi-criteria multi-participant decision-making methods is proposed. The feasibility of the methodology is demonstrated using a numerical example and validated by retrospective case studies. Results from the study cases show that the MCMPDM methodology can be used to support the DMs when selecting the EWS in residential projects satisfying stakeholders' preferences and project's requirements. It also improves productivity as well as traceability in the selection process by offering a friendly and efficient methodology and producing records that justify the decision.

Conclude that the quality of the solution recommended by the proposed methodology is better than another and that the performances of the house would improve is complex, such as in the case of the case studies. This is because it would be necessary to track the behavior of the envelope-wall system in long-term, including factors such as after sales care, brand perception of the selling company, among other things.

Importantly, the findings of this study pave the way for the industry to move towards improving the selection proccess. This knowledge can be used by DMs in their analysis, and also to develop a computerized intelligent decision support system for quantitative buildability evaluation in the group decision-making environment. Using the study results a computational tool with the methodology embedded in it can be developed. The tool will support the DM in the selection process.

The multi-criteria multi-participant methodology could be extended to other components of the building envelope or to other research fields unrelated to the construction industry.

5. CONCLUSIONS

The selection of the EWS in residential houses has the objective to achieve a comfortable and healthy building environment for the occupants with high energy, thermic, structural and constructive performances. The performance of the EWS could be significantly influenced by different criteria and external factors of each project.

One way to enhance the study of the selection of the EWS has been the incorporation of statistical methods, such as factor analysis and a modified Delphi method, to determine a set of criteria, which considers all aspects considered statiscally relevant by decision-makers. MCDM and MPDM have also been embedded in the study of the selection procees.

Consequently, the main objective of this thesis was to develop a comprehensive set of criteria and a methodology that supports and recommends the decision-maker in the selection procces of the envelope-wall system for residential projects.

Results indicate that there are 8 main criteria for achieving good performances in the selection of the EWS. Criteria include thermal, acoustic and structural performances; cost of the alternative, complexity of construction, safety (of the occupants and the building process) and environmental impact, durability and appearance of the envelope.

The methodology associates multi-criteria and multi-participant decision making methods. It considers regulations from design and construction codes, site conditions, stakeholder's preferences, construction company knowledge and experience, structural, thermal and constructive (costs and productivity) criteria for each project. Study cases demonstrate the applicability and the effectiveness of the proposed methodology.

The main conclusions that can be obtained from criteria formalization and the methodology are presented below according to topic covered.

5.1. Criteria for selecting envelope-wall systems for residential projects

This section highlights the main conclusions of the paper described in chapter 3, about the formalization of criteria to select envelope-wall systems for residential projects in Chile:

- The results from the modified dehlphi method suggest that the structural behavior criteria has the highest preference coinciding with the decision-makers' opinions that in a seismic country like Chile structural behavior is a key component.
- Costs, thermal performance and safety and environmental impact (compound criteria) are also within the criteria preferred by the Chilean decision-makers.
- Complexity of construction has the lowest preference. The habit of using similar construction processes so they do not take into account the possible effects of changing the construction process.
- Acoustic behavior, durability and appearance criteria were not statistically significant for the EWS selection. This is aligned with the observed practice in Chile as these criteria are usually not considered.
- Decision-makers present a high variability in the criteria they use in practice.
- Overall, list of the criteria and preferences presented in this study are the basis for a comprehensive analysis of envelope-wall systems.

5.2. Selecting envelope-wall systems for residential projects considering multiple criteria from multiple decision makers

This section highlights the main conclusions of the paper described in chapter 4, about the methodology to select envelope-wall systems for houses:

- Friendly, systematic and simple methodology that improves efficiency as well as consistency in making the decisions for the assessment by facilitating the decision-maker to make a prompt decision.
- Translating subjective and uncertain requirements and impacts into a more useful format, and the consensus scheme betweem the company and the market helps the dinal decision-maker in his decision.
- Meeting requirements of existing rules, law and standards is a priority, however is

not the only aspect to be covered to get an appropriate solution.

- In addition, through the structured decision process offered by the methodology, integration among the decisions makers of the selection process is enhanced.
- Even a slight difference in the importance weights between the criteria could be a potential barrier against the assessment and selection of the envelope-wall system.

5.3. Contributions

The consideration of the external impacts in this thesis work, specifically site location and construction company impacts, allows studying cases with an unconventional location, which could significantly affect the outcome of the selection process of the EWS, e.g. extreme climates, soil types, specific architectural environments, among others.

The consideration of multiple participants in the decision making procces allow extending the information about the difficulties of having more than one decision-maker in any field of study.

Importantly, the findings of this study pave the way for the industry to move towards improving the selection proccess. This knowledge can be used by decision-makers in their analysis and to develop decision support systems to facilitate the selection of EWS.

The implementation of the methodology proposed in this thesis in the Chilean industry will:

- Help the decision makers to choose the envelope-wall system satisfying stakeholders preferences and project requirements.
- Better decisions that improve houses performances and life quality.
- Increased productivity in the decision making process.
- Provide record level to justify decisions and therefore improve traceabiliy of the selection process.
- Reduce adverse effects in the construction phase.
- Contributes to gather detailed information of the constructive method of the EWS before it is built, supporting the planning process of the project in terms of timing and needs for labor or equipment.

5.4. Future work

Based on the performed research, new questions are proposed in order to increase knowledge of the selection process of the EWS for residential projects.

- Determination of the saturation point of criteria. Define by the point at which, although the criterion improves its performance, this is no longer a contribution to the overall performance of the alternative. This can be defined by some technical aspect of each criterion or by the preferences of the decision-makers. For example, acoustic insulation would cease being a contribution by reducing the sound values below the audible range of humans. In other words, once designers have reached a satisfactory level in acoustic performance, it is not necessary to maintain the same preference ratio. Therefore, forcing a linear representation would be inappropriate.
- Determine a way to measure the quality of the solution in long-term, including factors such as after sales care, brand perception of the selling company, among other things.
- The developed methodology was composed specifally for houses. It is propose to extend the cases considering high-rise residential buildings.
- The study is limited to the context of the Chilean industry. Decision-makers in other countries may differ regarding the relevant criteria to select the EWS and its relative importance (preferences), however this research presents a starting point to further studies that could include other countries. It is recommended to extend the criteria analysis to other cultures or countries.
- Future study can be pursued on developing a computerized intelligent decision support system for quantitative buildability evaluation in the linguistic and group decision-making environment. Using the study results a computational tool with the methodology embedded in it can be developed. The tool will support the decision maker in the selection process. The software may have different capabilities such as databases of possible EWS (alternatives), information about regulations and building codes, records of previous projects that have reference information to create new projects, among other features.

- The multi-criteria multi-participant methodology could be extended to other components of the building envelope or to other research fields unrelated to the construction industry. In other words, the findings of this study not only broaden a body of academic knowledge related to the assessment of the building envelope materials and designs, but also guide future studies in developing a practical decision support tool for dealing with decision-making problems in other industrial contexts.

REFERENCES

Aaker, D. and G. Day (1996). Investigación de mercados, 3era. Edición. México, Editorial McGraw-Hill/Interamericana de México.

Ambrasas, G., Kaklauskas, A., & Zavadskas, E. K. (1996). "Demonstration system for development of efficient projects." Journal of Civil Engineering and Management), 2(4), 84-100.

Arroyo, P., Tommelein, I. D., and G. Ballard (2014). "Comparing weighting rating and calculating vs. choosing by advantages for design decisions." Proc. 22nd Ann. Conf. Int'l. Group for Lean Construction, Oslo, Norway.

Arroyo, P., I. Tommelein and G. Ballard (2014b). "Comparing AHP and CBA as Decision Methods to Resolve the Choosing Problem in Detailed Design." Journal of Construction Engineering and Management.

Benayoun, R., B. Roy and B. Sussman (1966). "ELECTRE: Une méthode pour guider le choix en présence de points de vue multiples." Note de travail, 49.

Blint, J. M. (1974). "Fuzzy relations in group decision theory." Journal of Cybernetics, 4 (2), 17-22.

Brugha, C. M. (2004). "Structure of Multi-Criteria Decision-Making." The Journal of the Operational Research Society, 55(11), 1156-1168.

Chan, A. P., D. Scott and E. W. Lam (2002). "Framework of success criteria for design/build projects." Journal of Management in Engineering, 18(3), 120-128.

Chen, L.-H., C.-C. Hung and C.-C. Tu (2012). "Considering the decision maker's attitudinal character to solve multi-criteria decision-making problems in an intuitionistic fuzzy environment." Knowledge-Based Systems, 36(0), 129-138.

Chew, M. Y. L. (2001). "Construction technology for tall buildings." World Scientific. Singapore University Press.

Chua, K. and S. Chou (2010). "Evaluating the performance of shading devices and glazing types to promote energy efficiency of residential buildings." Building Simulation, 3(3), 181-194.

Conover, W. J. (1980). "Practical nonparametric statistics." John Wiley & Sons Inc, New Delhi.

Davis, J. H. (1973). "Group decision and social interaction: A theory of social decision schemes." Psychological Review, 80(2), 97-125.

De Solminihac, H., W. Márquez, F. Halles, A. Chamorro and M. Valdés (2009). "Pavement and shoulder condition models developed with expert surveys: The Chilean application " Arabian Journal for Science and Engineering, 34(1B), 138.

De Vos, E., H. Spivak, E. Hatmaker-Flanigan and R. D. Sege (2006). "A Delphi approach to reach consensus on primary care guidelines regarding youth violence prevention." Pediatrics, 118(4), e1109-e1115.

Dunowicz, R. and R. Hasse (2005). "Diseño y gestión de la vivienda social." Revista Invi, 20(54).

Edwards, W. and F. H. Barron (1994). "SMARTS and SMARTER: Improved simple methods for multiattribute utility measurement." Organizational Behavior and Human Decision Processes, 60(3), 306-325.

Fazio, P., A. Athienitis, C. Marsh and J. Rao (1997). "Environmental Chamber for Investigation of Building Envelope Performance." Journal of Architectural Engineering, 3(2), 97-102.

Feick, R. D. and G. B. Hall (1999). "Consensus-building in a multi-participant spatial decision support system." URISA journal, 11(2), 17-23.

Ginevičius, R. (2008). "Normalization of quantities of various dimensions." Journal of business economics and management, 9(1), 79-86.

Ginevičius, R., V. Podvezko and S. Raslanas (2008). "Evaluating the alternative solutions of wall insulation by multicriteria methods." Journal of civil engineering and management, 14(4), 217-226.

Gliem, J. A. and R. R. Gliem (2003). "Calculating, interpreting, and reporting Cronbach’s alpha reliability coefficient for Likert-type scales." Midwest Research-to-Practice Conference in Adult, Continuing, and Community Education.

Granadeiro, V., J. o. R. Correia, V. t. M. S. Leal and J. P. Duarte (2013). "Envelope-related energy demand: A design indicator of energy performance for residential buildings in early design stages." Energy and buildings, 61(0), 215-223.

Hartman, A. (1981). "Reaching Consensus Using the Delphi Technique." Educational Leadership, 38(6), 495-497.

Hassanain, M. and E. Harkness (1998). "Priorities in Building Envelope Design." Journal of Architectural Engineering, 4(2), 47-51.

Herrera, F. and E. Herrera-Viedma (1996). "A model of consensus in group decision making under linguistic assessments." Fuzzy sets and Systems, 78(1), 73-87.

Hipel, K. W., K. J. Radford and L. Fang (1993). "Multiple participant-multiple criteria decision making." Systems, Man and Cybernetics, IEEE Transactions on, 23(4), 1184-1189.

Horvat, M. and P. Fazio (2006). "BEPAT-Building envelope performance assessment tool: validation, research in building physics and building Eng." Proc.. Of 3rd international building Science/Physics conference, Montreal. London: Taylor and Francis.

Hsu, H.-M. and C.-T. Chen (1996). "Aggregation of fuzzy opinions under group decision making." Fuzzy sets and Systems, 79(3), 279-285.

Hwang, C.-L. and K. Yoon (1981). "Multiple attribute decision making." Springer-Verlag, New York, NY.

Jakobsson, U. (2004). "Statistical presentation and analysis of ordinal data in nursing research." Scandinavian Journal of Caring Sciences, 18(4), 437-440.

Jergeas, G. and J. V. d. Put (2001). "Benefits of constructability on construction projects." Journal of Construction Engineering and Management, 127(4), 281-290.

Kabli, M. R. (2009), "A multi-attribute decision making methodology for selecting new R&D projects portfolio with a case study of Saudi oil refining industry." University of Nottingham.

Kahraman, C., D. Ruan and I. Doğan (2003). "Fuzzy group decision-making for facility location selection." Information Sciences, 157(0), 135-153.

Kaiser, H. F. (1974). "An index of factorial simplicity." Psychometrika, 39(1), 31-36.

Kaklauskas, A., E. K. Zavadskas, S. Raslanas, R. Ginevicius, A. Komka and P. Malinauskas (2006). "Selection of low-e windows in retrofit of public buildings by applying multiple criteria method COPRAS: A Lithuanian case." Energy and buildings, 38(5), 454-462.

Kibert, C. J. (2012). "Sustainable construction: green building design and delivery." John Wiley & Sons Inc, New Delhi.

Li, R.-J. (1999). "Fuzzy method in group decision making." Computers & Mathematics with Applications, 38(1), 91-101.

Likert, R. (1932). "A technique for the measurement of attitudes." Archives of psychology, 22(140), 1-55.

Martínez, C. (2005). "Comportamiento térmico-energético de envolvente de vivienda en SM de Tucumán en relación a la adecuación climática." Revista avances en Energías renovables y Medio Ambiente, 9.

Maurtua, O. (2006). "Criterios de Selección de Personal mediante el uso del proceso de análisis jerárquico." Aplicación en la selección de personal para la Empresa Exotic Foods SAC Lima, Perú: Universidad Nacional Mayor de San Marcos, 1994-1536.

McIver, J. P. and E. G. Carmines (1981). "Unidimensional Scaling. " Volume 07-024 of Sage University Paper series on Quantitative Applications in the Social Sciences, Sage Publications, London, UK.

Nair, G., L. Gustavsson and K. Mahapatra (2010). "Owners perception on the adoption of building envelope energy efficiency measures in Swedish detached houses." Applied Energy, 87(7), 2411-2419.

Newcombe, R. (2003). "From client to project stakeholders: a stakeholder mapping approach." Construction Management and Economics, 21(8), 841-848.

O'Ryan, C. (2011), "Una metodología de análisis para entender el impacto de las estrategias de implementación del diseño y construcción virtual y su interacción con los principios lean." M.S. thesis, Pontificia Universidad Católica de Chile, Chile.

Pan, W., Dainty, A. and Gibb, A. (2012). "Establishing and Weighting Decision Criteria for Building System Selection in Housing Construction." Journal of Construction Engineering and Management, 138(11), 1239-1250.

Parrish, K. and I. Tommelein (2009). Making Design Decisions Using Choosing by Advantages. Proc. 17th Annual Conference of the International Group for Lean Construction (IGLC 17).

Passe, U. and R. Nelson (2012). "Constructing Energy Efficiency: Rethinking and Redesigning the Architectural Detail." Journal of Architectural Engineering, 19(3), 193-203.

Pulaski, M. and M. Horman (2005). "Organizing Constructability Knowledge for Design." Journal of Construction Engineering and Management, 131(8), 911-919.

Runyon, R. P. and A. Haber (1982). "Business statistics." RD Irwin, Homewood, Illinois.

Russell, J. S., J. G. Gugel and M. W. Radtke (1992). "Benefits and costs of constructability: Four case studies." Construction Industry Institute, Austin, Texas.

Saaty, T. L. (1989). Group decision making and the AHP. The Analytic Hierarchy Process, Springer: 59-67.

Singhaputtangkul, N., S. Low, A. Teo and B. Hwang (2014). "Criteria for Architects and Engineers to Achieve Sustainability and Buildability in Building Envelope Designs." Journal of Management in Engineering, 30(2), 236-245.

Singhaputtangkul, N., Low, S. P., Teo, A. L., & Hwang, B. G. (2013). Knowledge-based Decision Support System Quality Function Deployment (KBDSS-QFD) tool for assessment of building envelopes. Automation in Construction, 35, 314-328.

Smulski, S. (1999). "Durability of energy-efficient wood-frame houses." Forest products journal, 49(5), 8-15.

Spector, P. E. (1992). "Summated rating scale construction: An introduction." Thousand Oaks, CA: Sage, 8.

Stanujkic, D., N. Magdalinovic and R. Jovanovic (2013). "A Multi-Attribute Decision Making Model Based on Distance from Decision Maker's Preferences." Informatica, 24(1), 103-118.

Straube, J. F. and E. F. Burnett (2005). "Building science for building enclosures." Westford: Building Science Press, Inc.

Suhr, J. (1999). "The choosing by advantages decisionmaking system." Greenwood Publishing Group.

Tan, X., A. Hammad and P. Fazio (2007). Automated Code Compliance Checking of Building Envelope Performance. Computing in Civil Engineering (2007), American Society of Civil Engineers: 256-263.

Triantaphyllou, E., B. Shu, S. N. Sanchez and T. Ray (1998). "Multi-criteria decision making: an operations research approach." Encyclopedia of electrical and electronics engineering, 15, 175-186.

Tsiporkova, E. and V. Boeva (2006). "Multi-step ranking of alternatives in a multi-criteria and multi-expert decision making environment." Information Sciences, 176(18), 2673-2697.

Turskis, Z., E. K. Zavadskas and F. Peldschus (2009). "Multi-criteria optimization system for decision making in construction design and management." Inzinerine Ekonomika-Engineering Economics, 1(61), 7-18.

Van Delft, A. and P. Nijkamp (1977). "Multi-criteria analysis and regional decision-making." Studies in applied regional science, 8.

Vigderhous, G. (1977). "The Level of Measurement and" Permissible" Statistical Analysis in Social Research." Pacific Sociological Review, 61-72.

Wang, W., Rivard, H. and Zmeureanu, R. (2006). "Floor shape optimization for green building design." Advanced Engineering Informatics, 20(4), 363-378.

Wei, Q., H. Yan, J. Ma and Z. Fan (2000). "A Compromise Weight for Multi-Criteria Group Decision Making with Individual Preference." The Journal of the Operational Research Society, 51(5), 625-634.

Yager, R. R. (1978). "Fuzzy decision making including unequal objectives." Fuzzy sets and Systems, 1(2), 87-95.

Yang, Y. Q., S. Q. Wang, M. Dulaimi and S. P. Low (2003). "A fuzzy quality function deployment system for buildable design decision-makings." Automation in Construction, 12(4), 381-393.

Yeh, C. H. (2002). "A Problem- based Selection of Multi- attribute Decision- making Methods." International Transactions in Operational Research, 9(2), 169-181.

Zavadskas, E., A. Kaklauskas and V. Sarka (1994). "The new method of multicriteria complex proportional assessment of projects." Technological and Economic Development of Economy, 1(3), 131-139.

Zavadskas, E. K., A. Kaklauskas, Z. Turskis and J. Tamošaitiene (2008). "Selection of the effective dwelling house walls by applying attributes values determined at intervals." Journal of civil engineering and management, 14(2), 85-93.

Zavadskas, E. K. and Z. Turskis (2008). "A new logarithmic normalization method in games theory." Informatica, 19(2), 303-314.

Zavadskas, E. K., L. Ustinovičius, Z. Turskis, G. Ambrasas and V. Kutut (2005). "Estimation of external walls decisions of multistorey residential buildings applying methods of multicriteria analysis." Ukio Technologinis ir Ekonominis Vystymas, 11(1), 59-68.

APPENDICES

Appendix A. Pilot Survey

The survey sample consisted of 31 companies related to the Chilean real estate market. To define the universe of the space of inference, all partner companies of the Chilean Chamber of Construction (CCHC) belonging to real state and housing committee were considered. For details of the calculation of the sample see Table A-1.

Table A-1. Pilot survey sample and error

Universe	N	201
Confidence Interval	Z=95%	1,96
Standard Deviation	σ	0,25
Error	8%	0,08
Sample	**n**	**31**

A.1. Survey

Instructions:

Dear responder,

This survey seeks to idenify the relevant criteria to select constructive solutions for envelope-wall systems. This study is part of the project FONDEF: Selecting Envelope Walls for Homes based on structural, energy efficiency and constructive (cost and productivity) criteria.

The survey makers are Professor Claudio Mourgues and student of José Esteban Martabid from the Department of Engineering and Construction Management from the Pontificia Universidad Católica de Chile.

If you want to know more about the survey and research, you can write to: jemartab@uc.cl

You can complete the survey at different levels. To reenter the survey be complete until the last questions answered. The survey has 4 sections and estimates that it will take approximately 10 minutes. All results are confidential, so neither your name nor your company will be notified. If you do not know the answer to a question, make an estimate with the information in their power.

We greatly appreciate your participation

Definitions:

Envelope-wall system: The envelope is the part of the whole structure, above and below ground, which physically separates the external environment indoor environment. It refers to the perimeter wall of a house as a single composite element of one or various materials interacting achieving a certain behavior.

Questions

1. Company Type:

Private housing State Company - Social housing Real State Company - Construction Company - Architects - Office of Engineering

2. Respondent Charge

3. Company Name (Optional).

4. Respondent Name (Optional)

5. Email Respondent 5 (Optional)

6. How many years of experience has on the Construction Industry?

Between 0 and 5 years – Between 5 and 10 years - Between 10 and 15 years - Over 15 years.

7. Most of his experience in construction projects have been:

Houses projects - Housing average height projects (3-5 floors)- Hight rise residential building (6 or more stories)

8. Most of his experience in construction projects has focused on:

Large cities (Santiago, Antogasta, Concepción, etc) - Medium or small cities (Talca, Osorno, etc)

9. Most of his experience in construction projects stood at

Rigorous climates (large temperature differences between Summer or winter, day and night) - Moderate climates (eg Santiago)

10. In projects that your company works, who are the decision makers regarding the selection of the EWS?

Principal – Structural Engineering - Architecture Office - Construction Company - Buyers - Other (specify)

Criteria Glossary

Below, we ask about using a set of criteria, which are introduced below:

- Thermal Performance: Represents the thermal performance of the envelope-wall system (EWS) and evaluates whether it meets the thermal requirements.
- Structural Behavior: Represents the structural performance of the EWS and evaluates whether it meets the structural needs.
- Acoustic Behavior: Represents the acoustic performance of the EWS and evaluates whether it meets the acoustic requirements. The ability of the shell to protect the indoor environment from noise impacts.
- Costs: Cost of the final solution.
- Duration Construction Process: Duration in days of the construction process.
- Difficulty Construction Process: Complexity, reliability and availability of equipment and labor for the construction process.
- Environmental Impact of Construction Process: Amount of waste and noise generated by the construction of the solution and energy absorbed in the solution.
- Appearance: Appearance and / or facility to give a good finish to the enclosure.
- Durability: Long-term performance and maintenance conditions. Maintenance costs (painting, remodeling, etc.).

- Construction Process Safety: Risk of accidents in the construction process of the solution.
- Occupant Safety: Behavior of the envelope associated with fire resistance, resistance to climate impacts (wind, precipitation, etc.) and security against third party actions.
- Moisture Protection: Materials that limit the entry of moisture into the housing.

Answer the following questions. If your company does not selects the type of wall envelope, please answer based on your knowledge.

11. In the currrent selection process of the EWS, How often are considered the following criteria?

Table A-2. Template to answer on the use of criteria

	Never	Ocassionally	Sometimes	Usually	Always
Thermal Performance					
Structural Behavior					
Acoustic Behavior					
Costs					
Duration Construction Process					
Difficulty Construction Process					
Environmental Impact of Construction Process					
Appearance					
Durability					
Construction Process Safety					
Occupant Safety					
Moisture Protection					

12. What other criteria (which are not in the list above) are used in the selection process of the EWS? How often are they used?

Table A-3. Template to add more criteria

	Never	Rarely	Sometimes	Often	Always
Criterion 1					
Criterion 2					
Criterion 3					

13. With regard to the above, regardless if criteria are used or not in practice. How much do you agree with the following criteria considered in the selection process of the EWS?

Please, if you added a criterion in the previous question, be consistent with the numbering of the criteria.

Table A-4. Template to answer on the importance of criteria

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Thermal Performance					
Structural Behavior					
Acoustic Behavior					
Costs					
Duration Construction Process					
Difficulty Construction Process					
Environmental Impact of Construction Process					
Appearance					
Durability					
Construction Process Safety					
Occupant Safety					
Moisture Protection					
Criterion 1					
Criterion 2					
Criterion 3					

Factors that influence the Assessment of the Criteria

Last questions inquired about the criteria for selecting the EWS. Each of these criteria may be influence by several factors, including the standards requirements, preferences market impacts project location, etc.

The following questions seek to identify the factors that influence the evaluation of the listed criteria. Below, we ask about the consideration of factors introduced below:

- Market Preferences: Recovery or end-user perception of the behavior of housing (eg market interest for thermal insulation).
- Standard Requirements: Laws, regulations or ordinances binding.
- Company Preferences: Priorities of the principal or real estate on the behavior of housing.
- Project Impact Location: Possible impacts on where the project is located (eg, climate, distance to suppliers, accessibility, etc)
- Experiences Construction Company: Expertise of the construction company in a labor construction method, or equipment availability.
- Project Requirements: Requirements previously established in the design phase of the project (eg deadlines or budgets).

14. In the current selection process of the EWS, How often are considered the following factors?

Table A-5. Template to answer on the use of factors

	Never	Ocassionally	Sometimes	Usually	Always
Market Preferences					
Standard Requirements					
Company Preferences					
Project Impact Location					
Experiences Construction Company					
Project Requirements					

15. What other factors (which are not in the list above) are used in the selection process of the envelope walls? How often are they used?

Table A-6. Template to add more factors

	Never	Rarely	Sometimes	Often	Always
Factor 1					
Factor 2					
Factor 3					

16. With respect to the above factors that influence the assessment of the criteria, regardless of whether they are used or not in practice. How much do you agree with considering the following factors in the selection process of the EWS?

Please, if you added a factor in the question above, be consistent with the numbering of the factors.

Table A-7. Template to answer on the importance of factors

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Market Preferences					
Standard Requirements					
Company Preferences					
Project Impact Location					
Experiences Construction Company					
Project Requirements					
Factor 1					
Factor 2					
Factor 3					

Thank you very much for answering the survey.

A.2. Factor Analysis

Table A-8. Correlation Matrix with 12 criteria

		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
	C1	1,00	0,24	0,46	0,18	0,07	-0,11	0,25	-0,13	0,32	0,18	0,09	0,28
	C2	0,24	1,00	0,31	0,27	0,13	-0,06	0,10	0,25	0,02	-0,20	0,21	-0,02
	C3	0,46	0,31	1,00	0,16	-0,17	-0,14	0,28	0,36	0,23	0,16	0,32	0,50
	C4	0,18	0,27	0,16	1,00	0,61	0,60	0,43	0,19	-0,11	0,14	0,11	0,14
	C5	0,07	0,13	-0,17	0,61	1,00	0,74	0,27	0,16	0,17	0,28	0,11	0,22
Corre-lation	C6	-0,11	-0,06	-0,14	0,60	0,74	1,00	0,47	0,35	0,38	0,48	0,32	0,29
	C7	0,25	0,10	0,28	0,43	0,27	0,47	1,00	0,39	0,49	0,63	0,63	0,26
	C8	-0,13	0,25	0,36	0,19	0,16	0,35	0,39	1,00	0,49	0,32	0,60	0,54
	C9	0,32	0,02	0,23	-0,11	0,17	0,38	0,49	0,49	1,00	0,67	0,70	0,54
	C10	0,18	-0,20	0,16	0,14	0,28	0,48	0,63	0,32	0,67	1,00	0,60	0,44
	C11	0,09	0,21	0,32	0,11	0,11	0,32	0,63	0,60	0,70	0,60	1,00	0,43
	C12	0,28	-0,02	0,50	0,14	0,22	0,29	0,26	0,54	0,54	0,44	0,43	1,00
	C1		0,12	0,01	0,19	0,36	0,30	0,11	0,26	0,05	0,19	0,34	0,08
	C2	0,12		0,06	0,09	0,27	0,39	0,32	0,11	0,47	0,17	0,15	0,46
	C3	0,01	0,06		0,21	0,20	0,25	0,08	0,03	0,13	0,21	0,06	0,01
	C4	0,19	0,09	0,21		0,00	0,00	0,01	0,17	0,30	0,25	0,29	0,25
	C5	0,36	0,27	0,20	0,00		0,00	0,09	0,22	0,21	0,08	0,30	0,14
Sig. (1-tailed)	C6	0,30	0,39	0,25	0,00	0,00		0,01	0,04	0,03	0,01	0,06	0,07
	C7	0,11	0,32	0,08	0,01	0,09	0,01		0,02	0,01	0,00	0,00	0,10
	C8	0,26	0,11	0,03	0,17	0,22	0,04	0,02		0,01	0,06	0,00	0,00
	C9	0,05	0,47	0,13	0,30	0,21	0,03	0,01	0,01		0,00	0,00	0,00
	C10	0,19	0,17	0,21	0,25	0,08	0,01	0,00	0,06	0,00		0,00	0,01
	C11	0,34	0,15	0,06	0,29	0,30	0,06	0,00	0,00	0,00	0,00		0,02
	C12	0,08	0,46	0,01	0,25	0,14	0,07	0,10	0,00	0,00	0,01	0,02	
Determinant = ,000008													

Then, a second factor analysis with 8 criteria was performed (C5, C6, C7, C8, C9, C10, C11 and C12). In this case, all criteria correlate fairly well, none of the correlation coefficients are particularly large and the determinant value is greater than the necessary; therefore there is no need to consider eliminating more criterions and is possible to go on with the analysis. The following tables show the statistical data obtained in the factor analysis.

Table A-9. KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy	,767
Bartlett's Test of Sphericity Sig.	,000

Table A-10. Descriptive Statistics

	Mean	Standard Deviation	Number of Analysis
C5	4,4615	,64689	26
C6	4,5000	,58310	26
C7	4,1538	,73170	26
C8	4,4615	,58177	26
C9	4,7308	,45234	26
C10	4,6154	,57110	26
C11	4,7692	,42967	26
C12	4,6923	,47068	26

Table A-11. Comunalities

	Initial	Extraction
C5	1,000	,902
C6	1,000	,878
C7	1,000	,825
C8	1,000	,937
C9	1,000	,794
C10	1,000	,870
C11	1,000	,835
C12	1,000	,889

In the following figure the scree plot is shown, this plot is useful to define the number of factors to extract. In this case, the point of inflexion on the curve shows the number of components that should be used according to Kaiser's rule (4 factors).

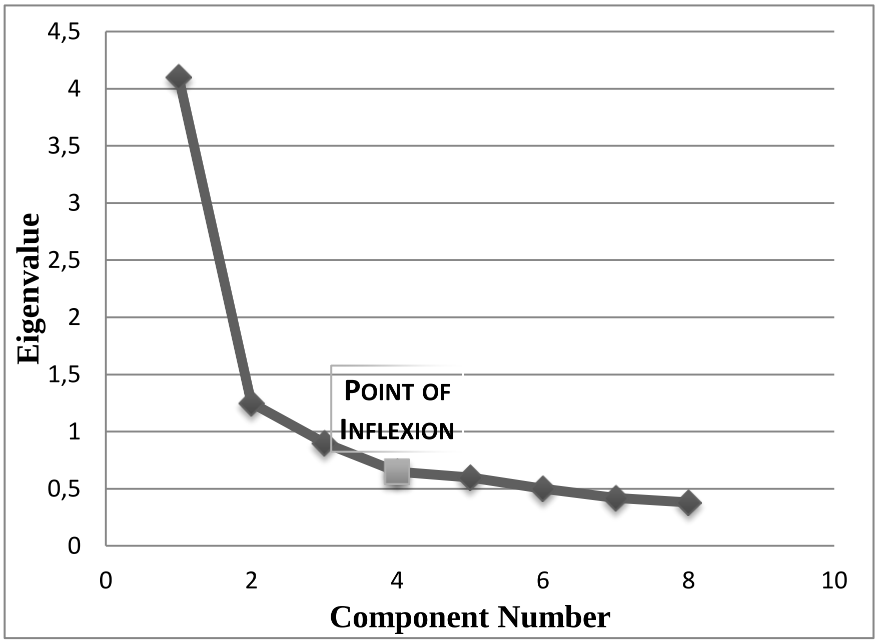


Figure A-1. Scree Plot

The following matrix (component matrix) contains the loadings of each variable onto each factor. It was requested that all loadings less than 0.4 be suppressed in the output, this explains the blank spaces in the matrix.

Table A-12. Component Matrix

	Component			
	1	2	3	4
C9	,810			
C11	,807			
C10	,799			
C7	,745		-,461	
C8	,683		,437	,464
C6	,677	,641		
C12	,649		,565	
C5	,459	,817		

The next step is to group each variable in one of the common factors; however, it is not clear which factor is associated with each variable. To meet this objective and optimize the factor structure an orthogonal rotation is performed. With the rotation the relative importance of the four factors is equalized. Before rotation, factor 1 accounted for considerably more variance than the remaining three.

The graph below shows the trend of the variables belonging to the first three components as it is a three dimensional graph.

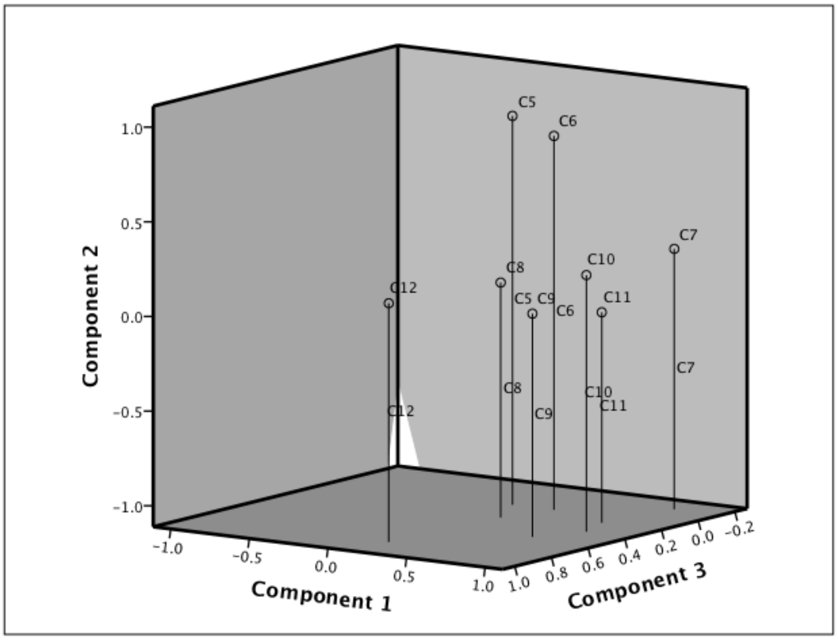


Figure A-2. Grouping the criteria in the first three factors or components in the rotated coordinate system

Appendix B. Scenario-based Survey

B.1. Survey

"Selecting surround walls of houses, under structural criteria, construction, thermal and architectural projects housing extension"

<u>Objective</u>

The aim of this survey is to capture the importance that experts give different structural, construction, thermal and architectural when selecting the material surround the walls of houses in a project extension criteria.

This study is part of the FONDEF D10I1086 "Walls Surround Solutions for Houses of concrete under Energitérmicos Criteria, Structural and Construction" project.

The survey makers are Mourgues teacher and pupil Claudio José Esteban Martabid department Engineering and Construction Management from the Catholic University of Chile.

The individual data collected in the survey will be treated with complete privacy and anonymous and only aggregate data will be disseminated.

If you want to know more about the survey and research, you can write to: jemartab@uc.cl

<u>Identification</u>

Name of Respondent:	
Company:	
Position:	
Years of Experience in Construction Industry:	
Phone Number:	

Email:

Shipping Instructions

Once the survey, please make it available by emailing filled

José Esteban Martabid Crutchik

Engineering and Construction Management, PUC

Vicuña Mackenna 4860, San Agustin Building, Macul

jemartab@uc.cl / jemartabid@gmail.com

Needed time to complete the survey: 10 minutes

Instructions for Completing Survey

Procedure:

The survey presents several scenarios performance envelope walls of houses.

It is considered that social variables are similar for all scenarios, ie, the only variables that are different between the alternatives raised walls are related to the technical and economic aspects.

Similarly, considering that in all scenarios, alternatives raised walls meet current standards. Whether thermal, structural or other.

The respondent is asked to qualify according to their experience each of the proposed scenarios with a whole note in the range of 1 to 10, where 1 represents an undesirable envelope walls and 10 an envelope of optimum walls.

Complementary Definitions:

- **Envelope-wall system:** wall elements that envelop the interior space, and act as an interface with the external environment to which it is exposed housing. Its function is to protect the building from the elements and pollution and provide thermal and acoustic insulation. Your behavior affects the quality of life of the occupants, the energy use of housing, and its stability, durability, and appearance, among others.
- **Evaluation criteria:** Variable evaluation to compare quantitatively different solutions surround walls.

For purposes of the scenarios presented in this survey, the evaluation criteria are presented on 2 levels, based on whether the value is above or below the sample average or alternatives.

The criteria of evaluation are defined:

a) **Thermal Performance:** Represents energy-thermic solution performance envelope walls.

Their categorization is: Good behavior when the thermal transmittance (U [W / m · K]) is less than or equal to the average thermal transmittance of the proposed alternatives, or Poor behavior in the opposite case.

b) **Structural Behavior:** Represents the structural performance of the solution envelope walls.

Their categorization is: Good performance when resistance values slitting (Vn [tonf]), to verify lateral load bearing capacity (seismic) are higher than the average of the strengths of the proposed alternatives, or in the case Poor behavior otherwise.

c) **Acoustic Behavior:** Evaluate whether the solution satisfies surround acoustic needs good way. The ability of the shell to protect the indoor environment from noise impacts.

Their categorization is: Good behavior when their level of acoustic insulation (dBA) is greater than or equal to the average levels of acoustic insulation alternatives raised wall, or Poor behavior in the opposite case.

d) **Costs (Savings):** Cost of the final solution. Their categorization is: High savings when the cost per square meter ($ / m2) is less than or equal to the average cost of the proposed alternatives, or Low savings otherwise.

e) **Complexity (Simplicity) Construction Process:** Complexity and reliability in the availability of equipment and labor for the construction process. Also consider the length of the construction process. Their categorization is: High simplicity when the number of men required for the construction of the wall (HH / m2) hours is less than or equal to the average of the alternatives raised walls, or Low simplicity in the opposite case.

f) **Safety and Environmental Impact:** Behavior of the envelope associated with fire resistance, resistance to climate impacts (rain, wind, etc.) and security to the people. It also considers the risk of accidents and amount of waste and noise produced during the construction process of the solution. Their categorization is: High Security when the probability that this some sort of security issues is less than or equal to the average of the proposed alternatives, or Low Security otherwise.

g) **Durability:** Long-term behavior of the solution. Terms and maintenance costs (painting, repairs, materials that prevent condensation in the envelope, etc.). Their categorization is: High Durability when annual maintenance costs per square meter ($ / m2-year) are less than or equal to the average of the proposed alternatives, or Low Durability otherwise.

h) **Appearance:** Appearance and / or facility to give a good finish to the enclosure.

Their categorization is: Good appearance when the amount of man hours per square meter of wall to give extra work completion (HHT / m2) is less than or equal to the average of the proposed alternatives, or Poor appearance or otherwise.

Example: Below are presented the averages of all possible alternatives and present X wall within the alternatives, which are categorized according to the criteria mentioned above.

Table B-1. Example of an EWS solution performance compared to the average

Criterion	Unita of Measures	Average Possible Alternativs	Wall X	Level
Thermal Performance	U [W/m^2·K]	1,7	1,5	Good Behavior
Structural Behavior	fc [kgf/cm^2]	18	22	Good Behavior
Acoustic Behavior	Insulation[dBA]	35	30	Poor Behavior
Costs (Save)	[$/$m^2$]	36000	45000	Low Savings
Complexity (Simplicity)	[HH/m^2]	5	4	High Simplicity
Safety and Environmental Impact	Risk [0 - 1]	0.2	0.15	High Security
Durability	[$/$m^2$-Year]	1000	800	High Durability
Appearance	[HHt/m^2]	2	2.5	Poor Appearance

<u>Selecting the surround walls:</u> According to the definitions described, rate the following scenarios. Each scenario corresponds to an alternative of envelope-wall in an extension project.

Table B-2. Template to answer the Scenario-based Suvey

Esc.	Thermal (Good / Poor)	Structural (Good / Poor)	Acoustic (Good / Poor)	Savings (High / Low)	Simplicity (High / Low)	Security (High / Low)	Durability (High / Low)	Appearance (Good / Poor)	Rating (1 to 10)
1	Good	Poor	Good	High	High	Low	High	Good	
2	Poor	Poor	Good	High	High	Low	Low	Poor	
3	Poor	Good	Good	Low	Low	High	High	Good	
4	Good	Good	Poor	Low	Low	High	High	Poor	
5	Good	Good	Poor	High	Low	Low	High	Good	
6	Poor	Good	Good	Low	Low	Low	Low	Good	
7	Poor	Good	Good	High	Low	Low	High	Poor	
8	Poor	Good	Good	Low	High	High	Low	Poor	
9	Poor	Poor	Good	High	High	Low	Low	Poor	
10	Poor	Poor	Poor	Low	Low	High	Low	Poor	
11	Poor	Good	Good	High	High	Low	Low	Good	
12	Good	Poor	Poor	High	Low	High	High	Poor	

Table B-3. Template to answer the Scenario-based Suvey (Continuation)

Esc.	**Thermal (Good / Poor)**	**Structural (Good / Poor)**	**Acoustic (Good / Poor)**	**Savings (High / Low)**	**Simplicity (High / Low)**	**Security (High / Low)**	**Durability (High / Low)**	**Appearance (Good / Poor)**	**Rating (1 to 10)**
13	Good	Good	Poor	Low	Low	High	Low	Good	
14	Poor	Good	Poor	Low	Low	Low	Low	Poor	
15	Poor	Good	Poor	High	High	Low	Low	Good	
16	Good	Poor	Poor	High	High	High	High	Good	
17	Poor	Poor	Good	High	High	High	High	Good	
18	Good	Poor	Good	High	High	Low	High	Poor	
19	Good	Poor	Poor	High	Low	High	High	Good	
20	Poor	Good	Good	High	Low	High	Low	Good	
21	Good	Good	Good	Low	Low	Low	Low	Good	
22	Poor	Good	Good	Low	Low	High	Low	Poor	
23	Good	Good	Good	Low	Low	High	Low	Poor	
24	Good	Good	Good	Low	Low	Low	Low	Good	
25	Poor	Poor	Good	High	Low	Low	High	Good	

B.2. Results Analysis

Table B-4. Multiple Linear Regressions

Regression Statistics							
R	0,9941						
R Square	0,9882						
Adjusted R Square	0,9831						
Standard Error	0,6287						
Total Number Of Cases	24						
prom = 1,1257 * C1 + 2,8219 * C2 + 0,4151 * C3 + 1,5561 * C4 + 0,6580 * C5 + 1,2602 * C6 + 0,5473 * C7 + 0,0836 * C8							
ANOVA							
	d.f.	SS	MS	F	p-level		
Regression	8,0000	533,3895	66,67	168,64	5,69544E-14		
Residual	16,000	6,32576	0,395				
Total	24,000	539,7153					
	Coefficients	Standard Error	LCL	UCL	t Stat	p-level	H0 (10%) rejected?
Intercept	0						
C1	1,1257	0,28278	0,631	1,6194	3,98079	0,001	Yes
C2	2,8218	0,26782	2,354	3,2894	10,5364	0,000	Yes
C3	**0,4151**	**0,27956**	**-0,07**	**0,9031**	**1,48481**	**0,157**	**No**
C4	1,5561	0,34458	0,954	2,1577	4,51597	0,000	Yes
C5	0,6580	0,32732	0,086	1,2294	2,01027	0,061	Yes
C6	1,2601	0,24786	0,827	1,6929	5,08429	0,000	Yes
C7	**0,5472**	**0,34934**	**-0,06**	**1,1571**	**1,56652**	**0,136**	**No**
C8	**0,0836**	**0,28092**	**-0,41**	**0,5740**	**0,29766**	**0,769**	**No**
T (10%)	1,7458						
LCL - Lower value of a reliable interval							
UCL - Upper value of a reliable interval							

Table B-5. Comparing Means (t-test assuming equal variances)

Descriptive Statistics			
VAR	Sample size	Mean	Variance
	24	4,55954	1,49754
	24	4,30952	1,54233
Summary			
Degrees Of Freedom	46	Hypothesized Mean Difference	0,00000E+0
Test Statistics	0,70251	Pooled Variance	1,51993
Two-tailed distribution			
p-level	0,48590	t Critical Value (5%)	2,01290
One-tailed distribution			
p-level	0,24295	t Critical Value (5%)	1,67866
G-criterion			
Test Statistics	0,05100	p-level	0,12931
Critical Value (5%)	0,18367		
Pagurova criterion			
Test Statistics	0,70251	p-level	0,51410
Ratio of variances parameter	0,49263	Critical Value (5%)	0,02521

Table B-6. Comparing Means (without C3,C7 AND C8)

Descriptive Statistics			
VAR	Sample size	Mean	Variance
	24	4,02679	1,34248
	24	4,30952	1,54233
Summary			
Degrees Of Freedom	46	Hypothesized Mean Difference	0,00000E+0
Test Statistics	0,81550	Pooled Variance	1,44240
Two-tailed distribution			
p-level	0,41899	t Critical Value (5%)	2,01290
One-tailed distribution			
p-level	0,20950	t Critical Value (5%)	1,67866
G-criterion			
Test Statistics	0,06076	p-level	0,12090
Critical Value (5%)	0,08500		
Pagurova criterion			
Test Statistics	0,81550	p-level	0,58099
Ratio of variances parameter	0,46536	Critical Value (5%)	0,12636

Appendix C. Study Cases

C.1. Study Case 1

I. Project Background

Table C-1. Project Background Study Case 1

Company	Inmobiliaria Martabid
Project Name	La Campiña Talca-Primera 2.1 Etapa
Project Location	Talca-Comuna Maule
Start Date	Abril 2014
End Date	Diciembre 2014
Value Sale	990 UF
Number of Houses	104
M^2	55,16

II. Alternatives

Table C-2. Alternatives Study Case 1

Analyzed Alternatives		
A1: Prefabricated wooden panel (PWP)	A2: Prefabricated structural insulated panel (SIP)	A3: Traditional masonry wall-system (MW)
A4: Insulated concrete form (ICF) containing a layer of expanded polystyrene	A5: Structural panel composed by metal sections coated on both sides with insulating material inside (MET	
Chosen Alternative	A3: Traditional masonry wall-system (MW)	

			Alternatives				
N	**Criterion**	**Unit of Measures**	**A1: PWP**	**A2: SIP**	**A3: MW**	**A4: ICF**	**A5: MET**
C1	Thermal Performance	U[W/m^2·K]	**0,72**	**0,3649**	**1,7**	**1,25**	**0,45**
C2	Structural Behavior	Fc' (kgf/cm^2)	115	140	125	300	150
C3	Acoustic Behavior	[dBA]	45	47	45 db	55	45

C4	Costs (Save)	[$/m2]	16000	18700	21000	23000	17000
C5	Complexity (Simplicity)	[HH/m^2]	1,2	1,5	2	2	1,5
C6	Safety and Environmental Impact	Risk [0-1]	0,333	0,333	0,167	0,667	0,333
C7	Durability	[$/$m^2$-año]	4000	4000	2000	3000	4000
C8	Appearance	[HHt/m^2]	1	1	1	1	1

Safety and Environmental Impact

S1: Risk of accidents in the construction process of the solution.			S2: Behavior associated envelope fire resistance, weather resistance and to provide security impacts.			S3: Amount of waste and noise during construction of the solution and the energy embedded constituent materials.		
HIGH	MEDIUM	LOW	LOW	MEDIUM	HIGH	HIGH	MEDIUM	LOW
1	0.5	0	1	0.5	0	1	0.5	0

Alternative	S1	S2	S3	Risk [0-1]
A1: PWP	0,5	0,5	0	0,333
A2: SIP	0,5	0,5	0	0,333
A3: MW	0	0	0,5	0,167
A4: ICF	1	0	1	0,667
A5: MET	**0,5**	**0,5**	**0**	**0,333**

III. Preferences

Table C-3. Preferences Study Case 1

N	**Criterion**	**Company Preferences (1-10)**	**Market Preferences (1-10)**
C1	Thermal Performance	8	6
C2	Structural Behavior	8	6
C3	Acoustic Behavior	5	1
C4	Costs (Save)	10	3
C5	Complexity (Simplicity)	10	4
C6	Safety and Environmental Impact	6	7
C7	Durability	10	4

C8	Appearance	6	10

How important for the company is to satisfy their own preferences in this project?

Not Important **Very Important**

1	2	3	4	5	6	7	8	9	10

How important for the company is to meet market preferences in this project?

Not Important **Very Important**

1	2	3	4	5	6	7	8	9	10

IV. Requirements

Table C-4. Requirements Study Case 1

Requirements from design and construction codes		
	Unit	**Req.**
Minimum transmittance by zone walls	U [W/m^2·K]	**1,7**
Minimum compressive strength	Kgf/cm^2	100
Sound insulation required by rule	[dBA]	45
Requirements of the project		
Budget for the EWS	[$/m^2]	25000
Maximum duration for construction	[HH/m^2]	3

V. Impacts

If there is an impact on the performance of the alternative, express it as a percentual change. For example: +10% or -15% in thermal performance criteria.

Table C-5. Impacts Study Case 1

	ALTERNATIVES									
	A1: PWP		**A2: SIP**		**A3: MW**		**A4: ICF**		**A5: MET**	
Impacts of site location		**C1**		**C1**		**C1**		**C1**		**C1**
		C2		**C2**		**C2**		**C2**		**C2**
		C3		**C3**		**C3**		**C3**		**C3**
	3	**C4**	**3**	**C4**		**C4**		**C4**	**3**	**C4**
		C5		**C5**		**C5**		**C5**		**C5**
	2	**C6**	**2**	**C6**	**5**	**C6**	**5**	**C6**	**2**	**C6**
	8	**C7**	**5**	**C7**		**C7**		**C7**	**5**	**C7**
	15	**C8**	**15**	**C8**	**-25**	**C8**	**-25**	**C8**	**15**	**C8**
Impacts of the construction company		**C1**		**C1**		**C1**		**C1**		**C1**
		C2		**C2**		**C2**		**C2**		**C2**
		C3		**C3**		**C3**		**C3**		**C3**
	2	**C4**	**5**	**C4**	**2**	**C4**	**3**	**C4**	**5**	**C4**
	-10	**C5**	**-5**	**C5**	**2**	**C5**	**4**	**C5**	**4**	**C5**
	-10	**C6**	**-3**	**C6**	**3**	**C6**	**5**	**C6**	**5**	**C6**
		C7		**C7**		**C7**		**C7**		**C7**
		C8		**C8**		**C8**		**C8**		**C8**

Causes of Impacts

- Cost: increases for delivery work in A1, A2 and A5.
- Complexity: Due to experience in construction process for the builder.

- Security: Rainfall and topography increase the risks of construction and safety issues of the work.
- Durablidad: Cost increase durability by weather.
- Appearance: Concrete and masonry reducing impact due to the compatibility with the living environment of rigid walls.
- Safety: Lower the risk of accidents by the experience of the company in the construction methods

C.2. Study Case 2

I. Project Background

Table C-6. Project Background Study Case 2

Company	Inmobiliaria Los Canales
Project Name	Condominio Alicura Etapa1
Project Location	Pucón
Start Date	Noviembre 2013
End Date	
Value Sale	4230
Number of Houses	
M^2	99, 93 and 66.

II. Alternatives

Table C-7. Alternatives Study Case 2

Analyzed Alternatives	A1: Prefabricated structural insulated panel (SIP)	A2: Prefabricated wooden panel (PWP)
Chosen Alternative	A1: Prefabricated structural insulated panel (SIP)	

			Alternatives	
N	Criterion	Unit	A1: SIP	A2:PWP
C1	Thermal Performance	U $[W/m^2 \cdot K]$	0,3649	0,72
C2	Structural Behavior	Fc' (kgf/cm^2)	156	115
C3	Acoustic Behavior	[dBA]	47	45
C4	Costs (Save)	$[\$/m^2]$	18700	14000
C5	Complexity (Simplicity)	$[HH/m^2]$	1,2	1,2
C6	Safety and Environmental Impact	Risk [0-1]	0,333	0,333
C7	Durability	$[\$/m^2$-año]	5000	5000
C8	Appearance	$[HHt/m^2]$	1	1
		Safety and Environmental Impact		

S1: Risk of accidents in the construction process of the solution.			S2: Behavior associated envelope fire resistance, weather resistance and to provide security impacts.			S3: Amount of waste and noise during construction of the solution and the energy embedded constituent materials.		
HIGH	MEDIUM	LOW	LOW	MEDIUM	HIGH	HIGH	MEDIUM	LOW
1	0.5	0	1	0.5	0	1	0.5	0

Alternative	S1	S2	S3	Risk [0-1]
A1: SIP	0,5	0,5	0	0,333
A2: PWP	0,5	0,5	0	0,333

III. Preferences

Table C-8. Preferences Study Case 2

N	Criterion	Company Preferences (1-10)	Market Preferences (1-10)
C1	Thermal Performance	**10**	**10**
C2	Structural Behavior	10	8
C3	Acoustic Behavior	8	10
C4	Costs (Save)	9	7
C5	Complexity (Simplicity)	10	5
C6	Safety and Environmental Impact	10	10
C7	Durability	7	8
C8	Appearance	10	10

How important for the company is to satisfy their own preferences in this project?

Not Important **Very Important**

1	2	3	4	5	6	7	8	9	10

How important for the company is to meet market preferences in this project?

Not Important **Very Important**

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	9	10

IV. Requirements

Table C-9. Requirements Study Case 2

Requirements from design and construction codes		
	Unit	**Req.**
Minimum transmittance by zone walls	U [W/m^2·K]	**1,1**
Minimum compressive strength	Kgf/cm^2	100
Sound insulation required by rule	[dBA]	45
Requirements of the project		
Budget for the EWS	[$/m^2]	25000
Maximum duration for construction	[HH/m^2]	3

V. Impacts

If there is an impact on the performance of the alternative, express it as a percentual change. For example: +10% or -15% in thermal performance criteria.

Table C-10. Impacts Study Case 2

ALTERNATIVES		
	A1: SIP	**A2: PWP**
Impacts of site location	**C1**	**C1**
	C2	**C2**
	C3	**C3**
	2 C4	**2 C4**

		C5		**C5**
	5	**C6**	**8**	**C6**
	5	**C7**	**10**	**C7**
	-10	**C8**		**C8**
Impacts of the construction company		**C1**		**C1**
		C2		**C2**
		C3		**C3**
	3	**C4**	**2**	**C4**
	-5	**C5**	**-8**	**C5**
	-3	**C6**	**-5**	**C6**
		C7		**C7**
		C8		

Causes of Impacts

- Cost: Both increase by shipping to the job site
- Complexity: due to the experience the company has. The difference is due to the experience level of each construction method.
- Safety: Rainfall and topography increase the risks of construction and safety issues of the work.
- Durablidad: Cost increase durability by weather.
- Appearance: Due to the compatibility with the housing environment SmartSide (SIP) that resembles a shed ventilated timber.