PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

UNDERSTANDING AND OPTIMIZING THE DESIGN LAYOUT OF HORIZONTAL RESIDENTIAL CONDOMINIUM

RAMÓN PÉREZ DE ARCE CLARO

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

Advisor:
CLAUDIO MOURGUES ÁLVAREZ

Santiago, Chile (August, 2016)

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Members of the Committee:

CLAUDIO MOURGUES ÁLVAREZ

GUILLERMO THENOUX ZEBALLOS

ARTURO LYON GOTTLIEB

RICARDO PÉREZ CORREA

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To my parents.

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RESUMEN

El diseño de Condominios Residenciales Horizontales (CRH) consiste en un proceso iterativo en el cual los principales elementos de urbanización y su distribución espacial son definidos. Desafortunadamente, la práctica actual fracasa al momento de desarrollar soluciones óptimas debido a una serie de restricciones que limitan el estudio de alternativas, siendo explorada una región acotada del espacio de diseño.

Esta investigación aplica optimización de diseño paramétrico en el diseño de urbanizaciones de CRH para extender esta exploración. Los investigadores intentan contestar las preguntas de investigación y contribuir al conocimiento a través del desarrollo de un modelo de optimización. Una formalización del proceso de diseño es necesaria en orden de poder generar el modelo paramétrico en el que se basa la herramienta computacional desarrollada. Esta busca apoyar a los diseñadores en la etapa de diseño conceptual de CRH; mejorar el espacio de diseño estudiado y presentar alternativas adicionales que se escapan de las soluciones sub-óptimas que la industria alcanza.

El proceso de formalización conduce al grupo de las principales variables consideradas por los desarrolladores en el proceso de diseño. Con estas se desarrolla una estructura del problema de diseño que facilita la selección de variables y la implementación para el modelo de optimización. Los resultados de los diferentes escenarios de simulación muestran que la aplicación de la herramienta ofrece una gama más amplia de alternativas de diseño y cuenta con soluciones que normalmente no son consideradas en el proceso.

Palabras claves: Condominios residenciales horizontales, diseño paramétrico, optimización de diseño, variables de diseño, urbanización.

ABSTRACT

The design of Horizontal Residential Condominiums (HRC) consists of an iterative process in which the main urbanization elements and their spatial distribution are defined. Unfortunately, the actual practice fails to develop optimal solutions due to several constraints that limit the study of the alternatives, exploring a partial range of the design space.

This research applies parametric design optimization in the urbanization design of HRC to enhance this exploration. Researchers intend to fulfil the investigation questions and contribute to the knowledge through the development of an optimization model. A formalization of the design process is necessary to generate the parametric model in which a computational tool is based. The tool endeavours to support designers in the conceptual design stage of HRC; enhancing the design space studied and presenting additional alternatives that escape from the suboptimal solutions found in the industry.

The formalization process led to the group of main variables considered by developers in the design process. A structure of the design problem was developed which facilitated the selection and implementation for the optimization model. The results of different simulation scenarios showed that the application of the tool provides a broader range of design alternatives and comprises solutions that normally are left aside in the process with no analysis.

Keywords: Horizontal residential condominiums, parametric design, design optimization, design variables, urbanization.

1. INTRODUCTION

1.1 Problem definition

The development of Horizontal Residential Condominiums (HRC) is a relevant urban development mechanism. The design of these projects has important impacts on social aspects, such as the neighbour's travel behaviour (Aditjandra, Cao, & Mulley, 2012) and their physical activity (Lee & Moudon, 2008), and on the project´s economic success , which is the main interest of the decision makers (private developers).

With their principal goal being to maximize utility and sales velocity, private developers need to generate an attractive solution for the clients. This solution is constrained by several factors, such as:

a) There is a limited physical space for the condominium elements.

b) Developers are obliged to comply with the relevant regulations.

c) The solutions must consider construction technological capabilities.

d) Opposition from neighbours for which it is vital to satisfy social requirements.

e) Resource limitations hinder the exploration of multiple design alternatives.

Taking into account the above considerations; designers, planners and engineers need to converge to a design solution that is aligned with the company's goal as well as with the preferences of the market in which it is confined.

Besides the obvious relevance of the house designs within a HRC project, the urbanization features have an important effect on the project's economical results and the clients' interaction with their surroundings. Fiedler (1972) studied the uneven sales distribution of the apartments on a building and assessed the preferences of the clients between combinations of view, height, size and price to predict the set of prices for an evenly sell out. Donovan and Butry (2010) used a hedonic price model to estimate the impacts of street trees on sales price and time-on-market of houses. Spetic, Kozak, and Cohen (2008) identified segments of the Canadian market that value healthy houses from the standpoint of indoor environmental quality and energy efficiency.

The ever increasing project, technological and market demands make the design process a key phase as it is the moment where houses and urbanization features are defined. The possibility to affect the project's results with a few changes in the design makes decision makers look with concern to this process. However, despite the importance of this phase and the concern of the decision makers, the design process usually explores a very limited number of options which leads to suboptimal solutions. Some of the reasons for this limited exploration of the design space can be time constraints, professional competencies, risk aversion, and industry culture.

A technology that could provide an important opportunity to increase the explored design space and thus to improve the solutions is the use of parametric design to enable design optimization.

Design optimization originated in structural engineering problems (Bendsoe & Kikuchi, 1988; Sved & Ginos, 1968). It took a major progress due to two developments in the aircraft industry: development of computer-aided design and a change of focus from a performance-centred approach to one that prioritizes lifecycle costs. And it was used with great success in aerospace and automotive industries (Simpson, Mauery, Korte, & Mistree, 2001; Sobieszczanski-Sobieski & Haftka, 1996; Yang, Gu, Tho, & Sobieszczanski-Sobieski, 2001). In the Architecture, Engineering and Construction (AEC) industry its use is emerging. Ihsan, Merati, Poulopoulou, and Soulos (2011) proposed a novel design process by using computational iterations to produce near-optimal urban city designs. They used a parametric design tool (CATIA) and PIDO (Process Integration and Design Optimization) as optimization platform. Schumacher (2009) indicates how Zaha Hadid Architects embodies the key features of parametricist urbanism in their proposal for One-North Masterplan, Soho City in Beijing, the mixed-use masterplan for Bilbao and the Kartal-Pendik Masterplan.

There is an important opportunity to apply parametric design optimization to the urbanization design of HRC. These methods allow designers to explore much larger design spaces as a collaboration tool for conceptual design.

However, it is required for their application that the design problem is clearly defined. Once a rigorous formalization is completed it is noteworthy to consider the impacts of design optimization; there is no evidence of the benefits and challenges present in the application of these methods in the context of urbanization design, neither strategies to use them in this particular design problem.

1.2 Research objectives

After analysing the problem the objectives are defined starting from a series of research questions. Research methods and tasks will facilitate the clarification of these through the study. The main questions are:

- What are the main variables relevant for the design of HRC?

A formalization of the general design problem is intended, from which the importance of the variables will be determined.

- How to use parametric modelling to optimize the design?

A selection of variables among those considered important will lead to the definition of the model for the design problem. Implementation will consist of an iterative process in which several alternatives are tested and strategies outlined to formalize the computational problem.

- What is the impact of using a parametric model supporting the conceptual design of HRC?

The process of implementation and use of the optimization model will seek to elucidate its contribution as a support tool for designers in the conceptual design process. Some of the extents aimed are: the number of alternatives studied; the size of the design space explored; and the time to develop multiple analyses.

- Which are the challenges of using parametric modelling in this particular design problem?

The process as well will determine challenges and barriers to the application of parametric modelling in the design problem of HRC.

The main objectives for this research are:

i) Formalizing the design problem for HRC;

ii) Identifying the main design variables affecting urbanization in HRC projects; and

iii) Using parametric design optimization as a support tool in the conceptual design phase of HRC projects.

1.3 Methodology

Figure 1.1 shows the methodology used which consists in two main stages.

1. The first stage explores and formalizes the urbanization design problem in HRC projects using a combination of a bottom-up and a top-down approach. Chapter 2 describes the procedure and results obtained.

2. The second stage develops a tool to support the designer's work in which multiple conceptual design alternatives are generated to operate as suggestions for the decision makers for a particular project. Chapter 3 presents the analyses of these results.

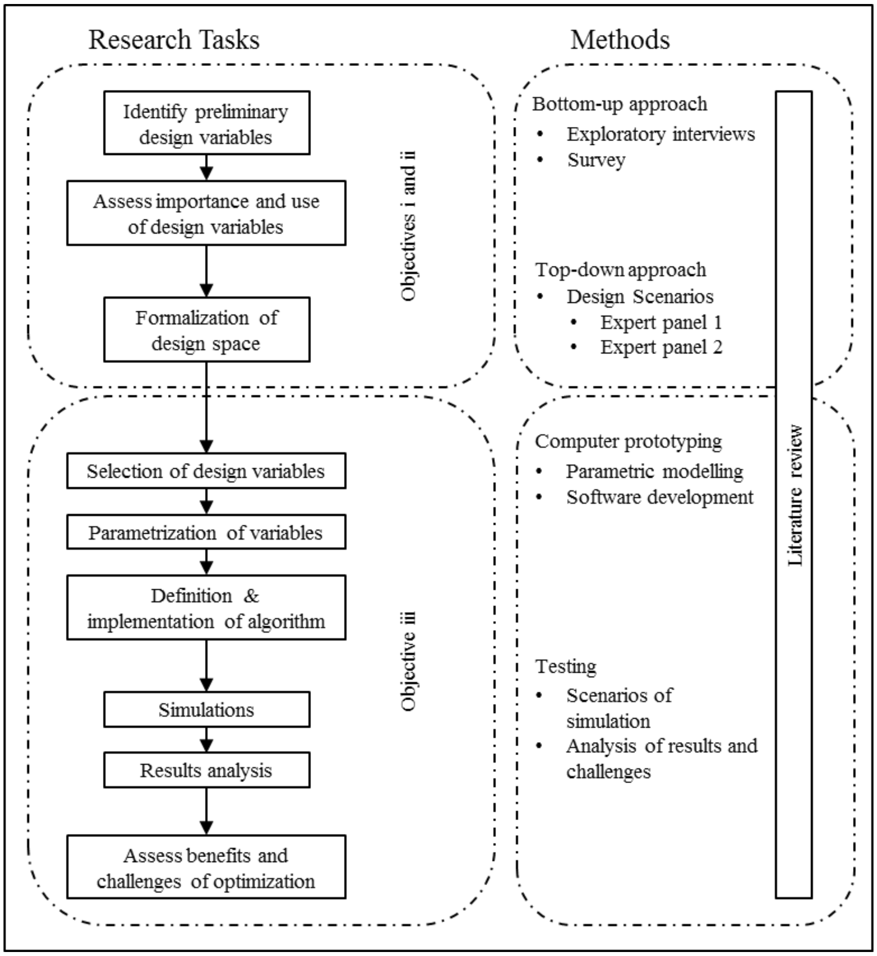

Figure 1.1: Research methodology

1.4 Thesis structure

This thesis is structured around two journal papers that address the research objectives stated in section 1.2. Additionally to those papers, the thesis includes an introduction and a conclusion section that connects the papers and summarizes their main contributions.

Chapter 2 elaborates on the formalization of the design criteria, it focuses on objectives i and ii. Initially through a bottom-up approach it identifies design variables and assesses their importance and use. Finally with the help of a top-down approach it formalizes the design space.

Chapter 3 is oriented to objective iii and shows an analysis of the results of the parametric modelling. It begins with the computer prototyping for which variables are selected and parameterized to implement the design tool. Different scenarios are then simulated and the impacts of the use of the tool are evaluated.

Chapter 4 encloses the process and provides conclusions regarding this thesis work. It responds to the research questions, states the contribution of this work and proposes future researches in the topic.

2. IDENTIFYING AND FORMALIZING URBANIZATION VARIABLES IN THE DESIGN OF HORIZONTAL RESIDENTIAL CONDOMINIUMS

The urbanization design involved in Horizontal Residential Condominiums (HRC) has an important impact on project success because of characteristics such as the quantity and distribution of different houses throughout the property; the type, size and location of amenities; road distribution and construction costs; and features related to sustainability. These factors can affect the attractiveness of HRC to clients, and thus the speed of sales. Despite its relevance, this design process is usually limited to the exploration of a very small number of alternatives, and their assessment is mainly based on experience and professional intuition, leading to potentially suboptimal solutions.

One of the factors hindering the use of more sophisticated computational methods – such as parametric design optimization – to support this design process is the lack of formalization of the design problem.

This research explores and formalizes the urbanization design problem in HRC projects using a combination of a bottom-up and a top-down approach. The first approach uses exploratory interviews and an industry survey to improve our understanding of the relevance and use of different design variables, while the second approach uses two expert panels to apply the Design-Scenarios (DS) methodology.

The results of the bottom-up approach show strong interdependencies among the design variables identified, but a factor analysis allowed the identification of five relevant factors from the developers’ perspective and four factors from the clients’ perspective. The top-down approach was unable to formalize the generic problem explored in this research but nevertheless provided interesting insights.

Further research is needed to analyse whether studying more HRC design alternatives will increase the chances of higher profits and whether more alternatives can be evaluated by clearly defining the main variables. Implementing a methodology that evaluates the impact of changes in the value of variables on clients' preferences and economic results would benefit the industry.

2.1 Introduction

The development of horizontal residential condominiums (HRC) is an important form of urban growth that has an enormous impact on the development of cities. In these projects, in addition to the obvious relevance of the houses' characteristics, urbanization design plays a key role in commercial success because of its impact on both costs and appeal to clients (the final owners of the house), both of which affect sales speed and prices. For example, Figure 2.1 depicts two road layouts that yield very different land uses, traffic speeds and safety levels, house orientations, privacy levels, and costs, among other factors. Chakrabarty (1998) shows that a vast number of alternatives must be considered and that no single element of these projects should be treated independently of other elements.

Figure 2.1: Grid and loop neighbourhoods (Imagery: Google)

In addition to road layouts, there are many other design decisions that must be made regarding urbanization, and they can produce very different results. Figure 2.2 exemplifies the impact of changes to just a few urbanization variables at the same project site.

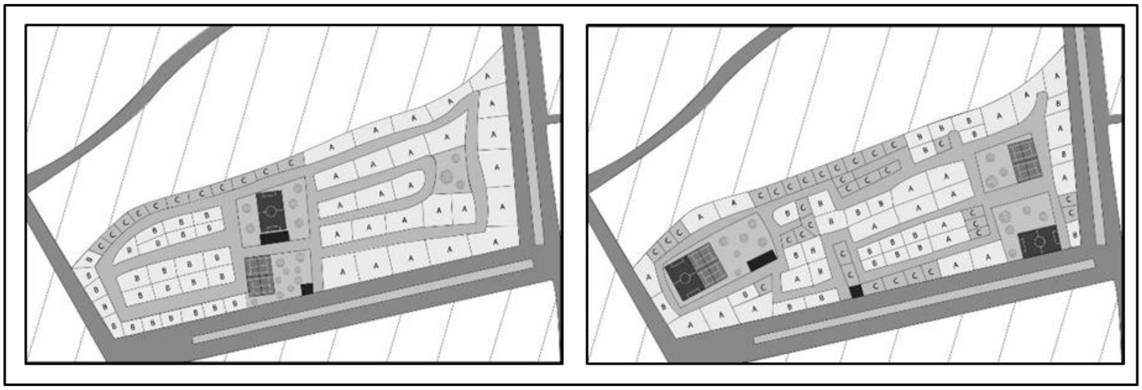

Figure 2.2: Urbanization design alternatives

The urbanization design process usually begins with previous designs that are adjusted to the new project's site and iteratively improved based on the design criteria. In practice, this iteration is limited by the scarcity of design resources, which may result in suboptimal solutions. Exploring the design space is a time-consuming task for design teams. In confronting this task, professionals must decide between two different strategies identified by researchers as problem-solving approaches: high breadth–low depth or low breadth–high depth (Goldschmidt, 2006; Woodbury & Burrow, 2006). The first approach studies a variety of different alternative scenarios for the problem but with an analysis that is limited in its detail. The second approach defines a clearly circumscribed range of alternative scenarios, but performs a more comprehensive analysis of each.

In addition to its cognitive limitations (Woodbury & Burrow, 2006), this time-consuming process can only assess a small number of alternatives for a given project. As Gane and Haymaker (2010) showed in their study of high-rise projects, no more than three different options are typically explored.

Similarly, the design of HRC is usually limited to exploring two to four alternatives, and their assessment is mainly based on experience and professional intuition. Consistent with the above literature, some of the reasons for this limited and informal exploration of alternatives are the time demands of the analysis, the lack of formalized design criteria, and the lack of proper tools to assess the value of each design alternative. This manual and limited design process leads to potentially suboptimal solutions, risking the revenue of the residential developers and preventing the city's customers from accessing the best possible options.

Parametric design optimization methods allow designers to explore much larger design spaces and to do so using a more explicit and systematic procedure. However, these methods require that the design problem be clearly defined. This study aims at identifying the main design variables affecting urbanization in HRC projects and at understanding their uses and relevance.

2.2 Literature Review

Land subdivision and the design of housing solutions require a number of interrelated components. Different disciplines must address these variables to accomplish their objectives and identify constraints (Chakrabarty, 1991).

Guttery (2002) indicates that subdivision designs impact residential housing values. He studies the effects of rear-entry alleyways on house prices using regression analysis on a sample of over 1,500 home sales. The results show that the alleyway subdivision discounts sale prices by 5%. Guttery also notes that the value assigned to a home should change when it depends on certain characteristics (e.g., street width, sidewalk characteristics and drainage).

Morrow-Jones, Irwin, and Roe (2004) took an empirical approach and experimentally varied the characteristics they studied. Using a choice-based conjoint analysis, they examined the preferences of householders and explored the impact of four characteristics, including neighbourhood layout/density and parks. Their results showed that neotraditional designs with higher densities were less preferred on average; this aversion may be countered by the addition of open spaces or other amenities.

Charmes (2010) also discusses the residential effect of cul-de-sacs, superblocks and environmental areas and concludes that different layouts affect through-traffic, sometimes generating barriers in neighbourhoods. Furthermore, he notes the different considerations that are important when implementing these designs, such as how cul-de-sacs are more adaptable to topographic conditions.

Southworth and Ben-Joseph (1995) studied the evolution of suburban street standards. Their review traces this history from the initial need to fight the environmental impacts of population growth. At this time, controlling street width and direction were thought to be sufficient to ensure long-term development. Their study continues through historic changes, when different layouts for street planning and intersections were proposed and recommended. Congestion and safety issues were addressed, leading to differentiation by road type: moreover, cross sections and street widths were varied to distinguish between main, secondary and local streets. Other variables such as street trees, alignments and setting houses back from the street were included as well.

Crompton (2005) found that the property value of a house that shares a common boundary with a park can increase by as much as 20%. A substantial influence was found at distances of approximately 150–200 m, and a smaller influence was found at distances of 450–600 m. There may be economic benefits at greater distances, but the overlapping of elements will be more complex. Researchers have found that factors in addition to proximity may have an impact, such as the park's level of maintenance, maturation level, type of use, and ratio of supply to demand.

Luttik (2000) used the hedonic pricing method to determine the influence of trees, lakes and open spaces on house prices. Cumulative effects of 5–10% were found for these variables (when it was possible to demonstrate such effects). Correll, Lillydahl, and Singell (1978) discuss the implications of green belts on rising prices, financing and tax increments.

Kauko (2006) used an analytic hierarchy process between experts in the real estate market to determine preferences for various amenities. Factors such as accessibility, infrastructure, environment and social considerations were evaluated. The evaluation grouped results by different profiles and distinguished between single-family houses and multi-storey apartments.

Benson, Hansen, Schwartz, and Smersh (1998) analysed the value of different types of views (ocean, lake and mountain) and their effects on prices. They concluded that the contribution of ocean views to selling price varies between 8 – 60%.

Bond, Seiler, and Seiler (2002) statistically examined the effect of a view of Lake Erie on the value of a home. They studied the effects of more than ten aspects of a home, including rooms, size, view, age, and construction quality. Their results revealed that the main significant variables are lot size, home size and view.

Li, Cheung, and Sun (2015) studied Hong Kong’s larger housing properties, which have higher per-square-meter prices than smaller properties. They justify this anomaly with respect to general markets (in which there is a tendency for unit price to decrease as size increases) and attribute it to the limited supply that results from the characteristics of a compact city.

It is important to recognize that clients can assign different levels of relevance to design variables depending on their context and interests. Features such as density of development, street network connectivity and land use are valued differently across different neighbourhood types (Song & Quercia, 2008).

Below is a list of variables important to the design process that has been determined based on a review of the literature. By varying the values of these elements, developers can reach definitive solutions. These variables conform to the initial list of design variables used in the interviews with real estate practitioners that were performed as part of this study (see research methodology).

a) Street layouts: the way in which the interior streets of the HRC are laid out.

b) Street width: the distance from kerb face to kerb face.

c) Street pavement materials.

d) Median strip and sidewalk widths.

e) Sidewalk characteristics (slab materials, slab patterns, height).

f) Size of green spaces: total surface, unit dimensions and form factor.

g) Other amenities (gymnasiums, multipurpose courts, multipurpose halls).

h) Topography (impact on privacy, view, security).

i) Lot size.

j) Houses’ orientation.

Despite this initial list of design variables that impact a project’s success, the literature does not propose a formalization of the design domain (i.e., design variables, constraints and value definitions). Such a formalization is fundamental if we wish to generalize an optimization method to support the urbanization design of HRC projects.

2.3 Methodology

Figure 2.3 depicts the main research methods and their outputs.

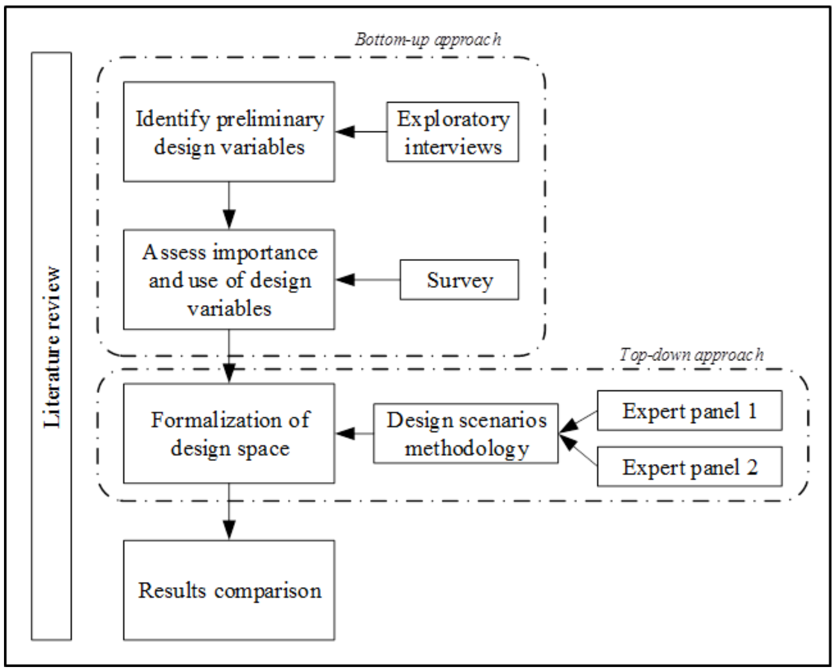

Figure 2.3: Research methodology

The research methodology includes two different approaches: a bottom-up and a top-down approach. The bottom-up approach defines a list of design variables, and the developers determine their importance to the business results. The top-down approach starts from the global perspective of how the business' success is evaluated and then decomposes the design procedure, ultimately concluding with a definition of the variables.

The bottom-up approach identifies preliminary design variables based on the literature (initial list of design variables) and semi/structured interviews. Based on this list of preliminary design variables, we created a survey aimed at assessing how Chilean urbanization designers approach these variables in terms of their importance and use.

The top-down approach is based on the Design-Scenarios (DS) methodology (Gane & Haymaker, 2009), which aims at formalizing design spaces to address problems of design optimization. This formalization requires the definition of the design variables, their value ranges and their constraints. We applied this methodology through two expert panels.

Finally, we compared the results obtained from both approaches.

2.4 Bottom-up approach – Interviews and survey

Interviews

The literature review provided an initial list of design variables that served as the input for the exploratory interviews, the main objectives of which were to:

i) Understand the conceptual design process;

ii) Identify urbanization design variables; and

iii) Identify advantages and challenges in increasing the number of evaluated HRC urbanization alternatives.

The interviewees were four practitioners representing three real estate developers with different responsibilities that ranged from architectural design to executing technical tasks (feasibility and operations). The developers included two major market leaders who handle various types of projects and a smaller developer specializing in HRC projects with small numbers of houses.

Regarding the first objective, Figure 2.4 depicts the general design process.

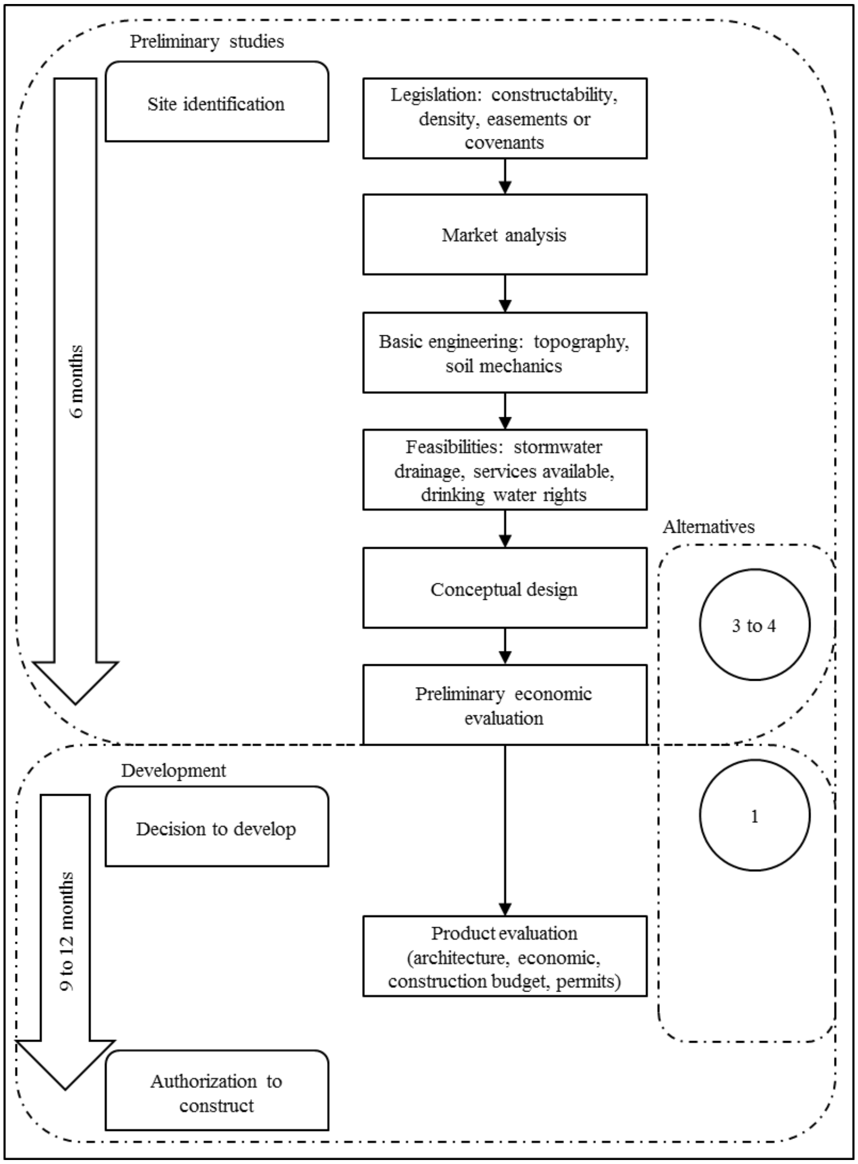

Figure 2.4: Design process

Figure 2.4 shows the typical design process for an HRC project, starting with site identification and continuing to the authorization to construct, if a decision is made to develop the project. We focused on the conceptual design stage, where the current design practice explores three to four alternatives. The number of alternatives is promptly reduced to only one, based upon which further analyses are executed. This is consistent with observations from the literature and represents an opportunity that can be exploited.

It has been shown that some stakeholders in the design process consider it important and worthwhile to take the time to analyse extra alternatives during the conceptual design phase, while other stakeholders consider such analysis to be a waste of time. In the first group there are young architects and professionals who take a business approach. In contrast, the second group typically comprises those in charge of the more technical areas of the project, who tend to appreciate situations that require no new official documents after a congruent solution is found.

The interviews also allowed us to revise the design variables identified in the literature by adding the following new variables:

a) The number of access points: the quantity of access points to the HRC.

b) The type of access: the characteristics that define costs as well as the security provided by the access points, e.g., gates or security booths with permanent guards.

c) The porter’s lodge: the quality of the installations available for security personnel.

d) The level of streetlight service: the quality of public lighting equipment.

e) The electrical distribution system: the visibility of public electrical installations, such as aerial or underground distribution systems.

f) Stormwater drainage: strategies to manage storm water drainage, such as floodable areas.

g) The location of green spaces: the spatial distribution of green spaces, such as a centralized park, homogenously distributed parks, median-strip park, etc.

h) The number of house types: the quantity of different types of houses that are usually sold at different prices.

i) House type distribution: the spatial distribution of the house types.

j) The number of parking lots: the number of parking lots assigned to each dwelling unit.

Some of these variables may be related, but we did not prejudge their quality because their correlation is part of a later analysis.

The above list does not consider two additional points extracted from the interviews. The first is the ability of developers to assess the features that clients value and the second is the existence of effective metrics to determine the results of a project.

Currently, some developers take into consideration the feedback provided by clients (and sometimes visitors) in relation to which aspects of a house or development they value and which they tend to dislike. However, this is generally done informally and only once the project is already built. Only those professionals involved in the project revisit this information and learn from this experience because it is not formalized into reports that transcend the project and are then shared within the developer organization.

A similar problem occurs with the results' metrics: they tend to be broad, such as sellable land percentage or sales velocity, with no extra information included to explain them. Therefore, it requires a huge effort to understand – and to take into account – the reasons why a previous project produced good or bad results.

Survey

The survey aimed at assessing the importance and use of urbanization design variables in HRC projects. The importance assessment considered both the developer´s and the client´s perspectives. The design variables included in the survey are those that resulted from the literature review and interviews. The survey was conducted – both online and onsite –among Chilean real estate developers. Out of 201 developers (members of the real estate and housing committee of the Chilean Chamber of Construction (CChC)), the total number of responses was 33. This represents a confidence level of 95% with an estimated error of 8%.

To assess the importance of the design variables, the survey used a 5-point Likert scale ranging from "Very important" to "Without importance". Regarding the importance of the variables to clients, we decided to use the developers' perspective to mimic the general procedure used in the Chilean real estate market, where very limited market studies are conducted to understand the effects of urbanization design variables on clients' purchase decisions. Regarding the level of use, the survey used a binary (yes or no) question.

Additionally, the survey asked the respondents to explicitly describe and explain cases in which they use irrelevant design variables or in which they do not use important variables.

2.5 Survey results

In contrast to responses regarding importance, we noted that responses regarding use were related to particular projects and not to the general design process. To avoid erroneous generalization, we focused our analysis of the results mainly on importance.

The results were analysed in various stages, beginning with a comparison of the average importance results for both perspectives (Figure 2.5). This analysis allows us to understand the tendencies of the results. Figure 2.6 and Figure 2.7 illustrate analyses of the quantity of responses with the category of “Important” or “Very Important” for each perspective. A correlation analysis was performed to determine the dependency of the variables using the correlation matrix, which leads to the Factor Analysis presented later in this chapter. Finally, an analysis of the declared use of the variables is performed.

2.5.1 Importance Analysis

Figure 2.5 shows the results (mean value plus and minus one standard deviation) of the importance of each of the design variables from both perspectives, i.e., the importance related to the economic results of the developer and the importance that the developer believes the client assigns to the variables.

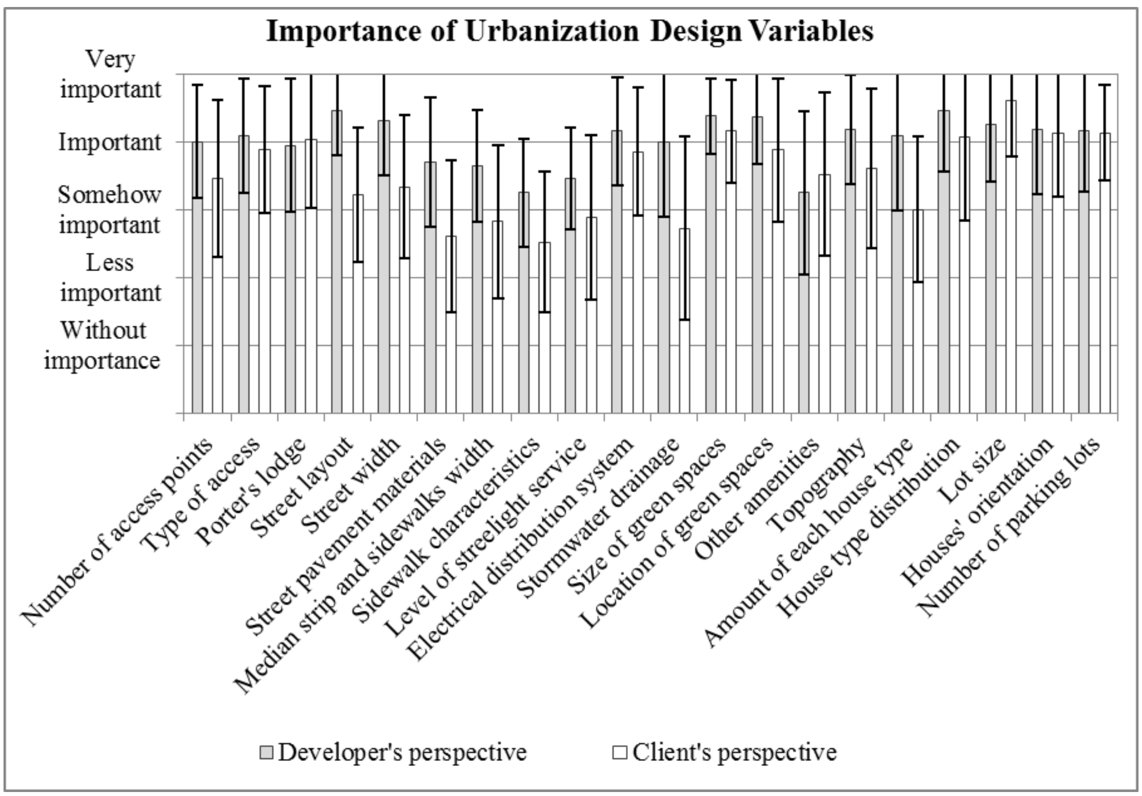

Figure 2.5: Importance results for both points of view

The results show that developers attribute high relevance to the variables for which it is easiest to understand effects in terms of cost and revenue. For years, the initial evaluation has consisted of a study of the ‘efficiency’ of land assignation, comprising a ratio between the surfaces assigned to lots and the total surface. The more common approach is to subtract from the total land area used for public purposes (streets, green spaces, multipurpose halls or gymnasiums). This limited group of variables considered is consistent with the most important variables determined by the experts in the survey.

From the developer´s perspective, the most important variables are the street layout and width; the size and location of green spaces; and certain aspects of the houses (lot size, house type distribution, and houses’ orientation). These results are consistent with those gathered from the interviews, which emphasized efficient land use in terms of how much is directly charged to the clients (i.e., lots) versus indirectly charged (i.e., streets and green areas). From the clients´ perspective, lot size is the most important design variable, followed by the houses’ orientation, parking lots and size of green spaces.

On the other hand, developers consider the least important variables to be the presence of other amenities (e.g., gymnasiums and multipurpose halls) and sidewalk characteristics. The results regarding other amenities have a wide dispersion, showing differences in opinion among different experienced professionals. This might have resulted because some developers only produce small HRC projects that do not consider these extra features, or because these features are less relevant to the habitability of some homes. In the case of the clients’ perspective, the variables at a mid-level of importance are technical aspects such as street pavement materials, median strip and sidewalk width, sidewalk characteristics, streetlight layout, and stormwater drainage, which might be related to the developers’ lack of technical understanding of how these factors affect clients’ preferences. The highest standard deviations are related to the variables that may be less appreciated because they generate uncertainty (such as stormwater drainage, streetlight layout and house type distribution) and to others that are not common to every type of HRC project, such as the presence of other amenities.

The results show that developers attribute high relevance to the variables for which effects are easiest to understand in terms of cost and revenue. This result is consistent with the interviews, in which the experts mentioned that initial evaluations consisted of studies of the ‘efficiency’ of land assignation, measured as a ratio between the surfaces assigned to lots and the total surface area.

Figure 2.6 and Figure 2.7 show another view of the importance evaluation, focusing only on the percentage of responses that consider each of the variables as “Important” or “Very important”.

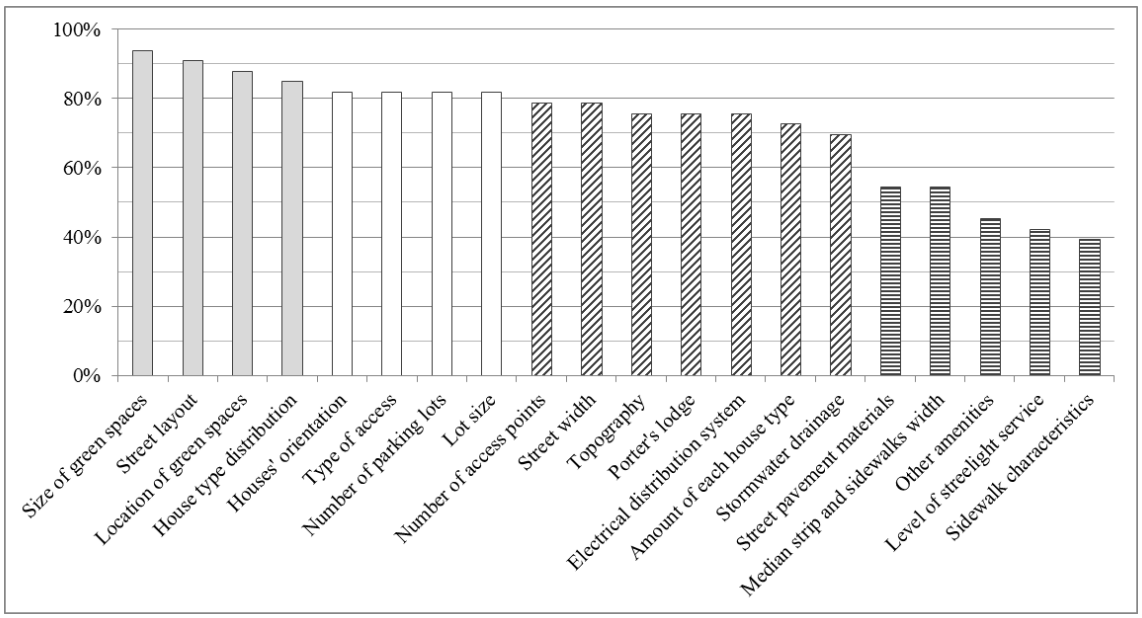

Figure 2.6: Percentage of Important + Very important responses for developers

From the perspective of the developer, almost all respondents considered the size of green spaces either “Important” or “Very important”, and over 85% of respondents also classified the street layout and location of green spaces under these importance levels.

In contrast, fewer than 50% of the respondents considered variables such as other amenities, streetlight layout and sidewalk characteristics as either “Important” or “Very important”.

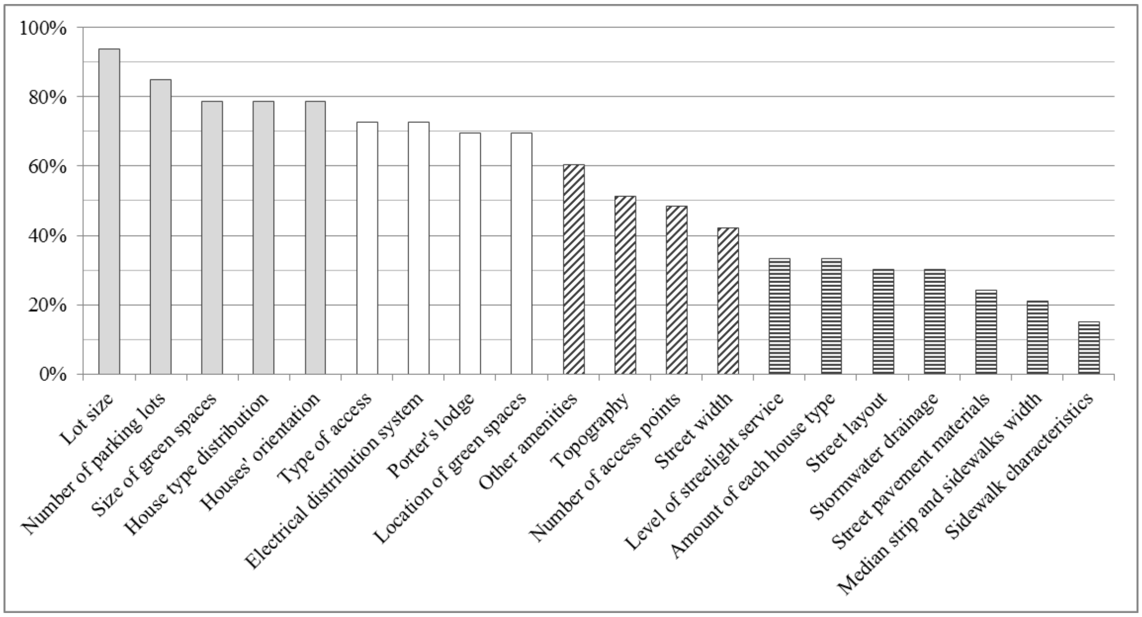

Figure 2.7: Percentage of Important + Very important responses for clients

From the perspective of what is valued by the client, over 85% of the respondents considered lot size and the number of parking lots as either “Important” or “Very important”. These variables reflect that the traditional approach is easily measurable and directly translated into price.

On the other hand, there are several variables that received few responses in these importance categories. Street width, streetlight layout and the number of each house type received fewer than 50% of these responses. Furthermore, less than one-third of respondents considered street layout, stormwater drainage, street pavement materials, median strip and sidewalk width, and sidewalk characteristics as variables that are either “Important” or “Very important”.

The fact that street layout belongs to this group of variables is consistent with a recognized challenge for developers: they must properly evaluate clients´ appreciation of certain variables. In the course of the interviews, professionals expressed their intentions to differentiate themselves from other developers in terms of privacy, security and a “neighbourhood feeling.” Different street layouts directly affect these variables, but most of the survey respondents still believe that layout is not important to clients. The same situation occurs with variables related to the technical aspects of roads and sidewalks or streetlights, which are also related to security and quality of life.

2.5.2 Correlation Analysis

To reduce biases, this research did not prejudge the design variables before using them in the survey, which clearly resulted in some of the variables having different levels of correlation.

From the perspective of the developers, both variables related to green spaces (their size and location) show the strongest Pearson's correlation, $r = 0.74$. Street layout and street width also correlate strongly. The same is true of street pavement materials and sidewalk characteristics, as both variables affect the usage of these elements.

From the clients' perspective, four variables have a strong correlation, with some correlations above the value of 0.80: street pavement materials, median strip and sidewalk width, sidewalk characteristics, and stormwater drainage. The first three are related to the level of road service and therefore tend to be analysed as a group. The fourth variable represents an outlier and does not result in a direct explanation.

Other strong correlations observed are sidewalk characteristics, such as streetlight layout, house type distribution, i.e., number of parking lots, the electrical distribution system (topography and street pavement materials) and streetlight layout.

2.5.3 Factor Analysis

The above correlations suggested the need for a factor analysis to study the nature of the interdependencies we identified. A factor analysis (Henson & Roberts, 2006; Suhr, 1992) is a statistical approach that examines the interdependencies among large numbers of variables to condense these into a smaller set of factors.

The first step is to study how well the variables correlate between one another at a broad scale using the partial correlation matrix and the Kaiser-Meyer-Olkin (KMO) measure of sample adequacy. The KMO measure takes values between 0 and 1. A value near 0 indicates that the sum of the partial correlations is large compared to the sum of the correlations; this means that the correlations are widespread and therefore are not clustering among a few variables, which represents a problem for factor analysis. In contrast, a value near 1 indicates a good behaviour for factor analysis. Values under 0.5 are unacceptable, and these variables therefore must be excluded from the analysis one at a time and the analysis must be rerun.

Variables that are left aside are not included in the generation of the new factors; therefore, they must be added to the final list of components once this process is finished.

Developer´s Perspective

The following six variables were sequentially removed from the developer's point of view: the number of access points, the number of each house type, the porter's lodge, streetlight layout, house type distribution and street width. Table 2.1 shows the results for the complete list of initial variables (first iteration) and those for the 14 variables used as inputs for the analysis (seventh iteration).

Table 2.1: KMO measures of sample adequacy

	KMO - 1	KMO - 7
Number of access points	0.20	-
Type of access	0.58	0.68
Porter's lodge	0.23	-
Street layout	0.40	0.63
Street width	0.41	-
Street pavement materials	0.50	0.71
Median strip and sidewalks width	0.36	0.79
Sidewalk characteristics	0.53	0.58
Level of streelight service	0.33	-
Electrical distribution system	0.32	0.76
Stormwater drainage	0.44	0.76
Size of green spaces	0.49	0.62
Location of green spaces	0.39	0.61
Other amenities	0.48	0.59
Topography	0.31	0.62
Amount of each house type	0.24	-
House type distribution	0.37	-
Lot size	0.51	0.75
Houses' orientation	0.49	0.62
Number of parking lots	0.57	0.77
	0.40	0.68

eValue	Rep	Cum
3.94	0.28	0.28
2.21	0.16	0.44
1.89	0.13	0.57
1.12	0.08	0.65
1.01	0.07	0.73
0.78	0.06	0.78
0.74	0.05	0.84
0.57	0.04	0.88
0.50	0.04	0.91
0.34	0.02	0.94
0.29	0.02	0.96
0.26	0.02	0.98
0.21	0.02	0.99
0.14	0.01	1.00
14.00		

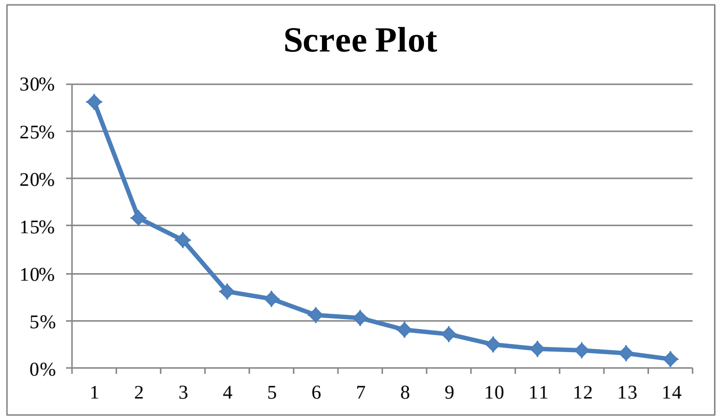

Figure 2.8: Variance accounted for by each eigen value

Figure 2.8 shows the eigenvalues and eigenvectors for each of the variables, the column "Rep" shows the ratio of the variance represented by the corresponding eigenvalue and the column "Cum" shows the cumulative weights.

Using Kaiser's approach, the most common approach used in factor analysis, only factors with eigenvalue ≥ 1.00 are retained. In this case, the first five factors were retained, which explains 73% of the variance.

The loading of factors for each of the variables is calculated using a rotation of the original axes. Varimax rotation (Kaiser, 1958) is used in this case; it maximizes the differences between the loading factors while maintaining orthogonal axes. In Table 2.2, the results for the factors are shown, where all absolute values lower than 0.4 are suppressed in the output. The communalities are also shown for each variable; this is a measure of how close the data are to the model. The variables that are loaded in two factors were assigned to the factor with the highest load, which is generally undertaken to avoid influencing the results although some variables had a logical relation to other factors.

Table 2.2: Rotated loading factors and communalities for five factors

	1.00	2.00	3.00	4.00	5.00	Commun
Type of access					0.89	0.85
Street layout				-0.85		0.81
Street pavement materials	0.86					0.82
Median strip and sidewalks width	0.82					0.75
Sidewalk characteristics	0.58				0.50	0.70
Electrical distribution system				-0.50		0.44
Stormwater drainage					0.73	0.67
Size of green spaces			-0.81			0.85
Location of green spaces			-0.92			0.88
Other amenities			-0.46	-0.62		0.71
Topography		-0.76				0.83
Lot size		-0.51	-0.43			0.55
Houses' orientation		-0.82				0.71
Number of parking lots		-0.67				0.61
	2.32	2.21	2.15	1.57	1.94	10.18

Table 2.3: Factor condensation

	Factor				
	1	2	3	4	5
Variable	Street pavement materials	Houses' orientation	Location of green spaces	Street layout	Type of access
	Median strip and sidewalks width	Topography	Size of green spaces	Other amenities	Stormwater drainage
	Sidewalk characteristics	Number of parking lots		Electrical distribution system	
		Lot size			

Table 2.3 shows the final composition of each of the factors. Factor 1 represents variables related to road features. Factor 3 groups mainly those variables related to green spaces destined for public use. Other factors show a similar behaviour statistically even though they do not directly correspond to related aspects of the urbanization of an HRC.

Client´s Perspective

From the clients' perspective, the following five variables were sequentially removed: Porter's lodge, Number of access points, Type of access, Houses' orientation and Electrical distribution system. Table 2.4 shows the results for the complete list of initial variables (first iteration) and those for the list of 15 variables (sixth iteration) used as input for the analysis.

Figure 2.9 shows the eigenvalues and eigenvectors for each of the variables. For this perspective, four factors were chosen, which add up to 72% of the variance.

Table 2.5 shows the factor scores after the rotation.

Table 2.4: KMO measures of sample adequacy

	KMO - 1	KMO - 6
Number of access points	0.40	-
Type of access	0.30	-
Porter's lodge	0.23	-
Street layout	0.57	0.81
Street width	0.47	0.75
Street pavement materials	0.85	0.91
Median strip and sidewalks width	0.42	0.57
Sidewalk characteristics	0.48	0.67
Level of streelight service	0.49	0.64
Electrical distribution system	0.62	-
Stormwater drainage	0.80	0.84
Size of green spaces	0.56	0.63
Location of green spaces	0.45	0.62
Other amenities	0.67	0.62
Topography	0.62	0.56
Amount of each house type	0.66	0.69
House type distribution	0.52	0.64
Lot size	0.50	0.63
Houses' orientation	0.45	-
Number of parking lots	0.50	0.71
	0.52	0.69

eValue	Rep	Cum
5.81	0.39	0.39
2.34	0.16	0.54
1.45	0.10	0.64
1.20	0.08	0.72
0.92	0.06	0.78
0.69	0.05	0.83
0.58	0.04	0.87
0.55	0.04	0.90
0.41	0.03	0.93
0.30	0.02	0.95
0.25	0.02	0.97
0.20	0.01	0.98
0.15	0.01	0.99
0.09	0.01	1.00
0.07	0.00	1.00
15.00		

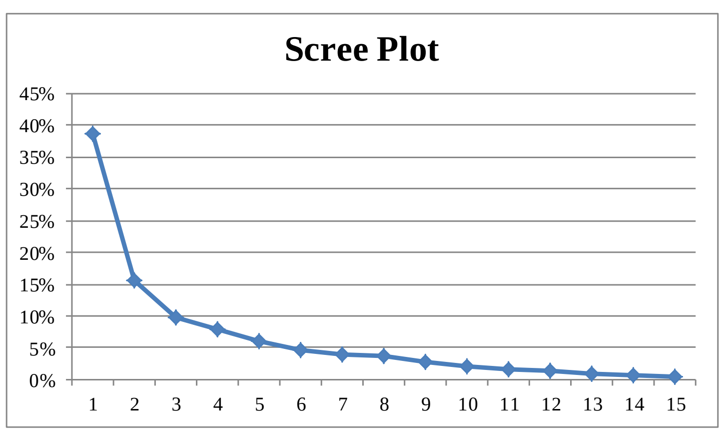

Figure 2.9: Variance accounted for by each eigen value

Table 2.5: Rotated loading factors and communalities for four factors

	1	2	3	4	Commun
Street layout	0.44			0.42	0.53
Street width				0.76	0.78
Street pavement materials	0.85				0.86
Median strip and sidewalks width	0.78				0.70
Sidewalk characteristics	0.91				0.88
Level of streelight service	0.63				0.67
Stormwater drainage	0.68			0.41	0.64
Size of green spaces		-0.76			0.64
Location of green spaces		-0.81			0.79
Other amenities		-0.80			0.71
Topography				0.86	0.82
Amount of each house type			0.51	0.53	0.64
House type distribution			0.78		0.71
Lot size			0.76		0.65
Number of parking lots			0.82		0.77
	3.50	2.43	2.60	2.27	10.80

Table 2.6: Factor condensation

	Factor			
	1	2	3	4
Variable	Sidewalk characteristics	Location of green spaces	Number of parking lots	Topography
	Street pavement materials	Other amenities	House type distribution	Street width
	Median strip and sidewalks width	Size of green spaces	Lot size	Amount of each house type
	Stormwater drainage			
	Level of streelight service			
	Street layout			

With respect to clients' preferences, the variables related to public spaces are clustered in one factor, Factor 2. Factor 3 mainly groups together the variables related to the non-architectural aspects of the houses inside the HRC.

2.5.4 Use Analysis

Figure 2.10 shows the results of the inquiry into whether the variables are used in the design stage.

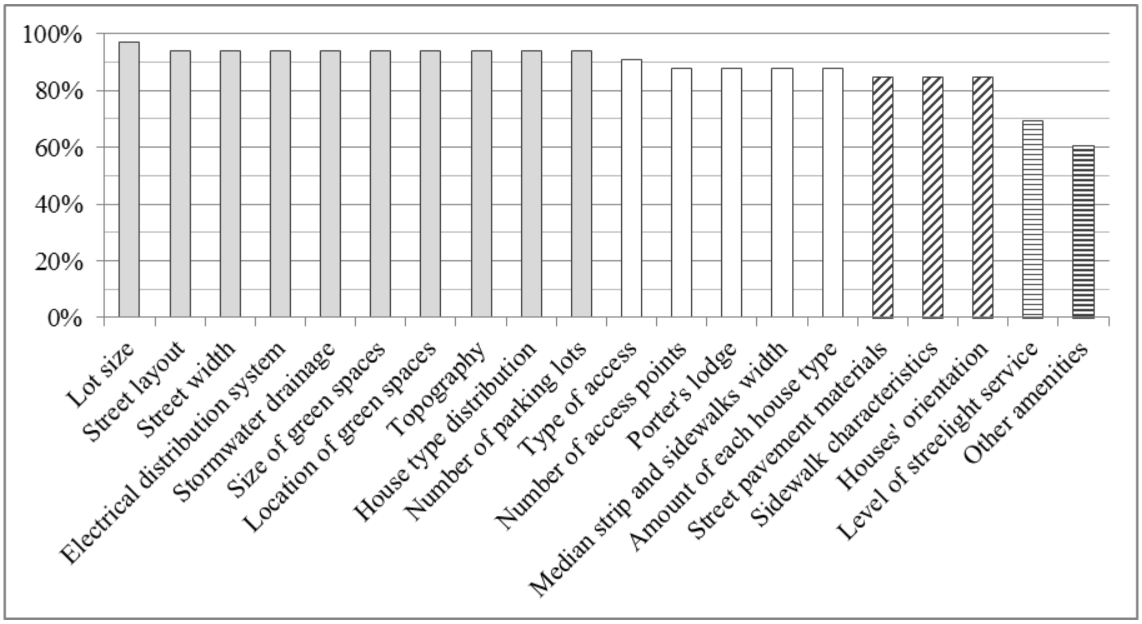

Figure 2.10: Quantity of responses that report using each variable

The first group includes those variables used by over 30 respondents and gathers mainly the design variables normally identified in the first stages of real estate design. The second and third groups show those variables with approximately 85% of the responses affirming their use and include variables related to security and the frontier of the HRC such as type and number of access points and porter's lodge, variables related to streets and sidewalks, and some others related to houses, their orientation, and quantity by type. The fourth and last group includes streetlight layout and other amenities, both of which are used by fewer than 70% of the respondents.

2.6 Top-down approach – Expert panels

The expert panels were designed based on the Design Scenarios methodology (DS) (Gane, Haymaker, Fischer, & Bazjanac, 2014; Gane & Haymaker, 2009, 2012), which proposes a more structured process of conceptual design that facilitates design parameterization and therefore potential automation in generating design alternatives. The DS methodology aims at meeting the essential needs identified by Design Theory and Systems Engineering, namely describing a design space using the following main concepts: objective, alternative, impact, and value spaces (Lin, Chen, & Chen, 2009; Struck, de Wilde, Hopfe, & Hensen, 2009; Suh, 1998).

The objective space is built with the Requirements Model (RM); the logical alternative space is built with the Scenarios Model (SM); the geometric alternative space is built with the Parametric Process Model (PPM); and the impact space and the value space are built with the Alternative Analysis Model (AAM).

The RM consists of three diagrams. In the first, all the constraints for the project are listed with their limit values and are related to each of the disciplines involved in the design process. The second is similar to the first, but it lists the main goals and their target values. Finally, each goal is weighted against the others and an importance diagram is generated. The SM decomposes the requirements into key geometric and/or material parameters and relationships. The PPM defines the structure of dependencies among parameters, geometric constraints, CAD operations, and geometry to translate the previously decomposed parameters into the parametric model and to generate design alternatives. The AAM evaluates the performance of the alternatives generated for every requirement and assigns a value score in relation to goal targets and preferences.

The expert panels were designed to generate only the RM and the SM because the other models are intended to be used for design optimization.

In the RM, the project's stakeholders concurrently decide on the constraints and goals. All design disciplines (architectural, structural and mechanical), collaboratively with the client, define these high level requirements and make them comprehensive. During evaluation, different alternatives and constraints must be satisfied, while goals can be traded off against one another depending on stakeholders' preferences. This model addresses an essential requirement of design teams: it captures and prioritizes stakeholders' and decision makers' requirements.

The SM consists of a breakdown of the requirements into five levels: 1) high level requirements; 2) action items, i.e., descriptions of how to achieve a requirement; 3) strategies, i.e., processes required to achieve certain actions; 4) parameters, i.e., variables denoting properties; and 5) parametric constraints, i.e., the fixed value, limit or increment that a parameter must fulfil. This model addresses essential requirements for design teams: “it decomposes requirements into actionable descriptions about how to achieve them” and “translates the scenarios into qualitative and quantitative input and output parameters to describe physical and functional characteristics of a design”.

The size of each of the expert panels was between four and six professionals. This number allows a wide variety of opinions to generate a productive dialogue of ideas but simultaneously represents a manageable group and allows every expert to give his or her opinion about the process.

First Expert Panel

The first expert panel approached the generation of the Requirements Model.

For the first panel of experts, we defined two development scenarios, with the objective of accounting for the background of the developers surveyed and embracing the breadth of the HRC real estate market.

The first scenario is a small HRC in an opulent area of the city designed for families with adult sons who work and no longer live with their parents. These wealthy elderly couples who are living through the dynamics of an empty nest are looking for the spaciousness of a house but require the strong security measures that can be provided by a gated community.

The second scenario corresponds to a suburban project that represents a new focus of residential expansion targeted at young professional couples. These couples have babies, young children, or are considering starting a family. Thus, they are looking for a bigger house or lot at an affordable price. They love the idea of children growing up in houses with gardens and are willing to live farther from downtown to provide their children with this environment.

The main objectives for this expert panel were as follows:

i) Identify goals for the design problem;

ii) Identify constraints for the design problem.

The five participants were chosen for their experience and diverse characteristics in relation to the HRC problem: a CEO and a Business Development Analyst to provide the general business and commercial mind-set; a Deputy Operations Manager of a large real estate developer to present a more day-to-day operational view; and two Project Development Managers to reveal the complexities of the development of HRC projects.

All participants on the expert panel participated in a dialog led by the moderator with the goal of reaching a consensus. For each of the case study situations, the participants were to reach an agreement about the main goals and constraints related to each of the scenarios previously defined.

The results for the small residential project are shown in Table 2.7 and Table 2.8. Most design constraints are necessary for the benefit of the intended public. Due to the possibilities of difficulties in displacement, levelled land is required for both the lot and the roads and access points. In this case, the client anticipates living in a house for the next 20 years and therefore cannot wait for trees and landscaping to develop. This leads to the necessity of providing green spaces that offer the client's desired features from the beginning. Some constraints, such as the average target price, are relevant to every type of real estate project.

Professionals concur that the first basic goal when developing a real estate project is the economic result – the capabilities of the project to guarantee an expected margin. Consistent with this intention, public designers cite the importance of providing a high level of privacy. Consistently, the life cycle that the client assigns to the product is approximately 20 years, therefore it is important to the client to make one large initial investment that includes specifications and low maintenance costs.

Table 2.7: Requirements Model constraints for small HRC project

Discipline - Constraint category	Constraint
Design – Physical	Topography (slope limit)
Design – Land efficiency	Minimize roads (use sidewalks as green spaces)
Design – Habitability	One floor houses
Design – Security	Porter's lodge fully equipped
Design – Serviceability of public spaces	Green spaces with children's games
Design – Serviceability of public spaces	Green spaces with mature species
Developer – Economic results	Target price

Table 2.8: Requirements Model goals for small HRC project

Discipline - Goal category	Goal
Developer – Economic results	Profit
Design – Habitability	Privacy of houses (neighbour spacing, insulation, etc.)
Developer – Commercial	High quality urbanization with low maintenance cost (high initial investment and low common expenses, all features included from the beginning)

The results for the project in the newly expanded suburban area are reported in Table 2.9 and Table 2.10.

Once again, the target price is included in the model for this type of project. As the competitors are other real estate projects in the same area with similar characteristics, the intended price is an input that must be considered to ensure the economic results. The surrounding elements include constraints while designing the master plan for urbanization. The existence of different elements may limit the possibilities of the components assigned to the borderline: for instance, the presence of a noisy railroad may require a solution that uses a row of trees to provide acoustic insulation.

As new generations value sustainability and resource use efficiency, in this situation the developers decided that achieving low levels of energy consumption is an important goal for the houses and for urbanization. Due to the extension of the project, it is important that public spaces are distributed so that most neighbours can use them and feel a sense of ownership. Taking into account the number of children in HRC, it is important that traffic speeds on streets that access the houses are low; this can be achieved through design modifications in the layout.

Table 2.9: Requirements Model constraints for Suburban HRC project

Discipline - Constraint category	Constraint
Architecture – Legislation	Comply with densification regulation
Architecture – Physical	Land occupancy and constructability
Design – Physical	Frontier characteristics (vacant lot, train railroad, etc.)
Design – Physical	Access points (feasibility of access at different points, without the need for additional roads)
Developer – Economic results	Target price

Table 2.10: Requirements Model goals for suburban HRC project

Discipline - Goal category	Goal
Developer – Economic results	Profit
Design – Energy efficiency	Low consumption
Design – Security	Limited access from surrounding area
Design – Security	Mainly low speed streets to access houses
Design – Distribution of public spaces	Scattered and with different service levels
Design – Serviceability of public spaces	Green spaces designed for children's usage

Second Expert Panel

The results of the first panel were used for the second expert panel. Beginning from the two analysed scenarios and their requirements, the discussion was intended to generate a global Scenarios Model for the HRC design problem.

The second panel intended to work with the two previously defined scenarios, but participants took a more general view of the problem without considering distinctions between the two cases. Particular projects have different values for the limits of the parameters, but the parameters should be similar. The cases were used to assist designers in relating to the process and to define a general solution starting from singular ones.

The objectives for the second expert panel were as follows:

i) To comprehend the actions, strategies and parameters that accommodate a project's constraints and goals;

ii) To contrast the methodologies used, i.e., the bottom-up and the top-down approaches.

Due to the characteristics of the SM, the group of four on this expert panel consisted of two architects for large real estate developers, with one acting as Development Head and the other as Architect of Development Projects. Complementing the architects, two civil engineers also participated. One had experience as a Divisional Development Head and the other as a Construction Project Manager.

The panel consisted of two activities. The first involved collaboration among the designers, taking into account the two scenarios previously defined and rationalizing the mental process that had been followed when studying the various aspects of an HRC project. Beginning with the requirements defined for both study cases, a logical alternative space was created. Determination of the different actions and strategies was needed to achieve the requirements and the parameters that best described the design characteristics related to these actions and strategies. An adaptation of the requirements was performed to develop a general solution as intended. For this, new requirements were taken into account and some original ones were combined or eliminated. The second activity was a brief open discussion related to the results of the survey, specifically regarding the two scenarios studied.

Figure 2.11 shows the SM model for a general HRC project. The model starts with the goals and constraints nodes that are generalized from the RM model generated in the first expert panel, and these are decomposed into actions, strategies, parameters and parameter limits in some cases. For instance, the action related to defining the road characteristics confronts the strategy of defining a road profile for each segment. This road profile has a series of parameters, such as the houses' height differences, the kerb, materiality, afforestation, the house-street-house composition, the street width, the design velocity, the streetlight layout and the segment's extension. In some cases, such as in cul-de-sacs, this last parameter has additional effects limiting the number of houses accessed by this street.

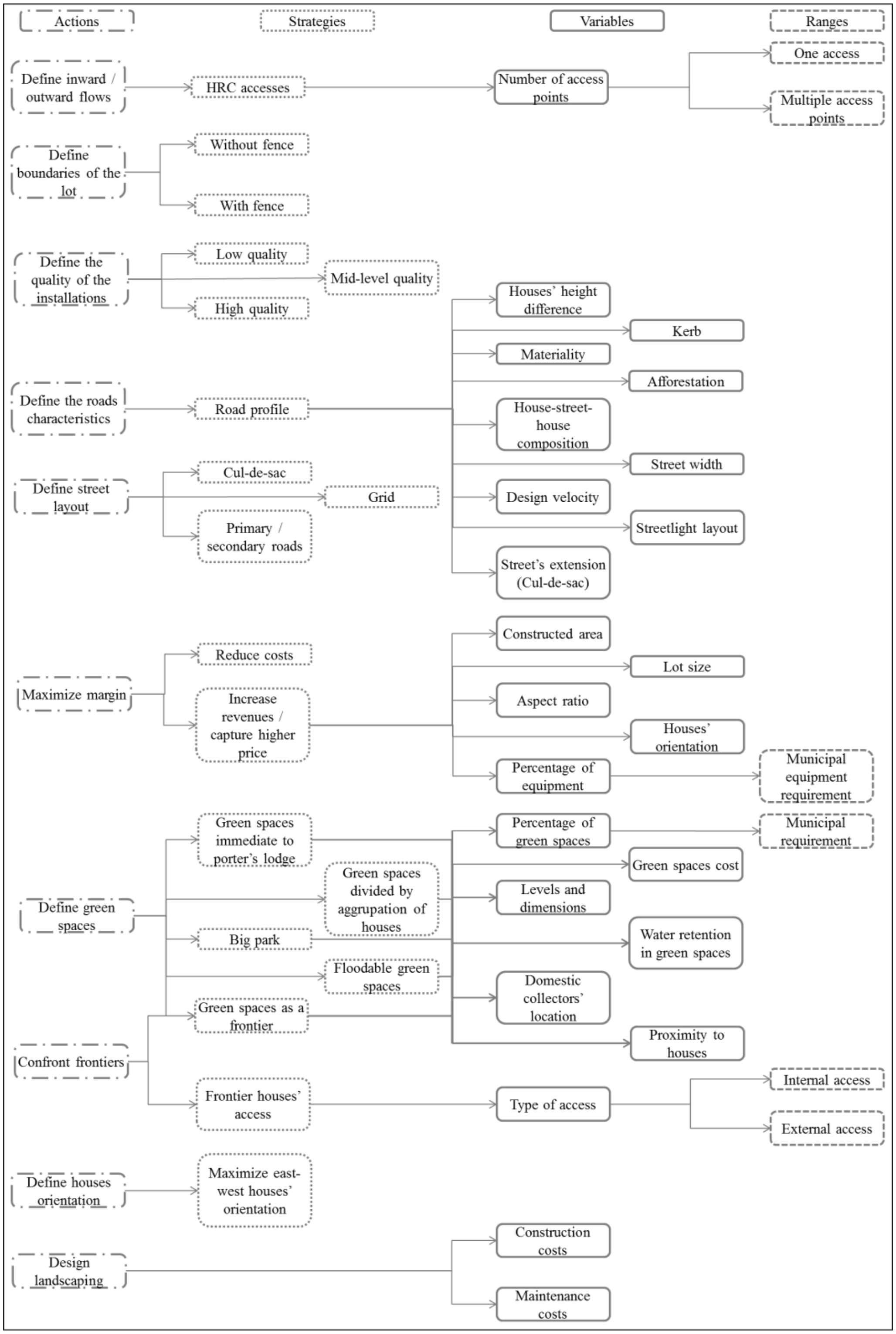

Figure 2.11: Scenarios Model

2.7 Conclusions

This study used two different approaches to explore and formalize the urbanization design problem in HRC projects.

The first approach (bottom-up) delivered a detailed view of the design variables used by Chilean decision makers in HRC projects. The results showed strong interdependencies, but a factor analysis identified five factors that are relevant to the urbanization design of HRC projects from the perspective of developers and four factors from the perspective of clients (as perceived by the developers). This approach also made it clear that there are some differences between the importance that developers and clients attribute to these variables.

Through the survey, experts assigned different levels of importance to the different variables. However, variables related to green spaces, size and location, lot size and houses' orientation were important to both developers and clients. Street layout is considered the most important variable for developers, but it is one of the least important for clients. This finding is inconsistent with the results from both the interviews conducted and the panels of experts, through which it was determined to be one of the main tools to provide other features that clients valued as part of habitability: privacy and security.

The second approach (top-down) allowed a more structured analysis of the problem, but it failed to obtain detailed results, as the DS method is designed to be used for specific problems and not for the generic problem that this research aimed to address. This difference made it difficult for the panel participants to reach consensus.

The expert panels allowed the researchers to determine that some requirements are specific to each development scenario and that some are general to the HRC problem. In some cases, studied constraints such as green spaces with mature species or frontier considerations are related to each project type. Other factors are relevant to all projects, such as target price, land occupancy and constructability, as well as the profit goal. Furthermore, for each particular real project the target values and constraint limits vary depending on additional considerations. For the scope of this research, where researchers analysed the general spectrum of the HRC projects, this was not considered.

Both approaches, bottom-up for the survey and top-down for the panels of experts, reached different results for the design variables and their importance in the process. The methodology of the survey revealed some inconsistencies in some of the responses with respect to the relation between some desired characteristics and the variables that provide them. These may be due to the restricted definitions of variables and the concrete verbalization of a process that developers normally analyse in a more ambiguous manner. In a more dialogical process, the expert panels instead allowed to explain and concretize the variables used, the links between them, and the requirements previously defined.

DS methodology was demonstrated to be a strong tool for recollecting information and understanding the design process from the perspective of professionals. Its application to generalized design problems, as used by researchers, presents some challenges. For the RM, preferences among goals depended on particular situations and could not be calculated. Researchers recommend the use of the Analytic Hierarchy Process for this multicriteria decision making, as used by Kauko (2006). In the case of the SM, reaching parameter constraints in the breakdown of the process proved unattainable for most of the variables. Restraints depend on the locations, regulations, market segments and budgets of concrete projects.

An important limitation of this research is that it separates clients' preferences from their personal standpoint. We used an approach in which developers indicated the value they thought clients assigned to different variables. We consider the clients' opinion to be of major importance for a correct understanding of the design variables and recommend the addition of this aspect in future studies. The results clearly showed that developers fail to evaluate their clients' preferences, and when they do, such evaluations are limited only to the gathering of information in some cases (after the development of a project) and, in more rare situations, to constrained market studies. This information is not used outside of professionals involved in the project, and it is never used to generate manuals and documents about best practices.

Therefore, future research should aim to evaluate clients' appreciation of several features of urbanization. It is also important to develop a methodology to evaluate the levels of service provided by several variables of urbanization, such as green spaces and streetlight systems.

Housing is a general problem at every level of society, from vulnerable populations to wealthy citizens. Different stakeholders, from private developers to public agencies, tend to focus on the smaller subdivisions of this problem. This investigation only addresses projects developed by private developers and does not address public agencies, which have completely different objectives when making investments.

Finally, future research will use this study's results as the basis of urbanization design optimization through the use of parametric optimization methods. There is a need for metrics that will enable better evaluations both of project results and of the effects of specific design modifications that aim to satisfy both clients' preferences and developers' goals. This problem remains unsolved.

3. URBANIZATION OPTIMIZATION FOR HRC

The design of Horizontal Residential Condominiums (HRC) benefits from the exploration of alternatives to produce profitable developments, the reallocation of urbanization elements allows numerous possibilities. Unfortunately, the current practice considers the exploration of a limited design space taking the risk of leaving aside better solutions from the spectrum.

Computational methods have shown beneficial in their application to problems in different areas of engineering, being used to generate and explore large design spaces to support design optimization.

This research generates an optimization model for the conceptual design of HRC. A computational tool is developed based on the model, using genetic algorithms as the optimization engine, and tested in different simulation scenarios.

Urbanization design results showed better profit values for design solutions with central reservation or perimeter parks. The computational method provided the possibility to study over 95,000 design alternatives, using different green spaces strategies. The duration of the different analyses clarified the advantages of the use of the computational method as additional input for designers.

Further research is needed to include new variables to the urbanization design and to measure clients' preferences and its effects in the results, leading to a generalization of the objective function to be applied in projects of different areas including public housing.

3.1 Introduction

The current practice for the urbanization design of Horizontal Residential Condominiums (HRC) manually and informally explores a limited design space, leading to suboptimal solutions. This is true as well in a broader level as current design methods manage only a few potential designs without a deep understanding of their multi-attribute performance (Gane & Haymaker, 2010).

On the other hand, computational methods are being used to generate and explore large design spaces to support design optimization in different areas. For example, Flager, Welle, Bansal, Soremekun, and Haymaker (2009) applied design optimization to a classroom building project and were able to study over 5,600 alternatives. Also, Cao et al. (2011) managed to analyse tens of thousands of land use solutions for trade-off sets of objectives expanding the classical Pareto frontier.

This computational exploration stands on the idea that computers may be of help in the exploration of ideas which – as stated by Woodbury and Burrow (2006) – rests in three premises: exploration of alternatives is a strong procedure to execute actions observed in designers and suggests beneficial ideas to support their work; there is a benefit in the use of tools that amplify their abilities to represent goals and problem spaces; and that there are computational representations and algorithms that provide suitable amplification for design exploration.

One of the requisites to use these computational methods is to formalize the design problem so the design variables can be represented with parameters that can be iteratively changed during the optimization process. This requisite is challenging in many design fields, and in particular in the urbanization design of HRC projects, as the design process is usually an informal, creative process. Within the residential domain, there have been several studies that have identified relevant design factors or variables. Saaty (1990) defined the effect that a series of factors have on the preference of buyers when looking for a house; aspects such as size, neighbourhood, condition of the house as well as financing where the most preponderant in the decision. Bond, Seiler, and Seiler (2002) included other aspects related to the house characteristics such as number of bedrooms, roof style and basement among other. In relation to the neighbourhood arrangement, Charmes (2010) and Morrow-Jones, Irwin, and Roe (2004) studied the effect of street layout and density. Southworth & Ben-Joseph (2004) made a comparison between different street layouts. Pérez de Arce and Mourgues (2016) focused on the urbanization design of HRC and used two methods to identify a list of design variables, among which they found street layout, topography, and location and size of green spaces.

Therefore, there is an important opportunity to apply computational methods to optimize the urbanization design of HRC projects. However, there is no evidence of the impact that these methods can have in the context of urbanization design neither the strategies to use the methods or the challenges particular to this design problem.

This research explores the use of parametric design optimization in the conceptual design phase of HRC projects, analysing their impact, challenges and application strategies.

This paper presents the formalization of the optimization problem, the results of the simulations in different scenarios, and the analysis of the results and challenges.

3.2 Literature Review

Optimization problems can be found in diverse areas such as design, planning, control and manufacturing. They are also transverse to different industries such as biomedical, energy, materials and structural engineering among other.

Design optimization had early advances in structural problems and has been used with great success and improvement in aerospace and automotive industries (Simpson et al., 2001; Sobieszczanski-Sobieski & Haftka, 1996; Yang et al., 2001).

The use of parametric design has been integrated as well in the Architecture, Engineering and Construction (AEC) industry. In civil engineer design optimization has been used in several researches. The application has had varied scopes since the development of computer-aided design: in the definition of structural elements (Bendsoe & Kikuchi, 1988; Sved & Ginos, 1968); spatial problems such as land and use allocation has (Chuvieco, 1993; Ligmann-Zielinska, Church, & Jankowski, 2005); as well as energy performance of buildings (Jedrzejuk & Marks, 2002; Marks, 1997; Oh, Kim, Park, & Kim, 2011).

The optimization in land use allocation has been studied with socio-economic benefits reducing rural unemployment subject to ecological, financial and technical constraints

(Arthur & Nalle, 1997; Chuvieco, 1993). Ligmann-Zielinska et al. (2005) developed a land use allocation model that promotes infill development, balances conflicts of neighbouring land uses, encourages accessibility to existing urban areas, and analyses trade-off between the conversions of undeveloped land and redevelopment. They work with a hypothetical problem of 400 raster cells and a dataset of five land uses: commercial, industrial, recreational, residential and undeveloped and analysed results for each objective. For city planning design optimization has been a support for new tendencies related to ecology and sustainable cities. Qian, Pu, Zhu, and Weng (2010) optimize ecology to attain the local government policy plan; they focus on agricultural land use, planning, and management for land productivity. Authors built a digital elevation model in GIS technique of Yangshan Town, Wuxi City, China and classified land use in four groups: construction land, cultivate, orchard and woodland. Geyer and Buchholz (2012) proposed Parametric Systems Modelling (PSM) as a tool for building and city planning. The application to a building-greenhouse-city interaction illustrates how this approach may be a contribution in the management of non-geometrical properties. Energy requirements and consumption of water are some of the parameters of the built space system, further parameters such as the capacity of food production and irradiation of the sun are also used.

Despite of the examples in the literature of design optimization at various levels, from structural elements to building efficiency and city planning, and in different areas of architecture, engineering and construction at a specific and multidisciplinary level, there is no evidence about the impacts that these computational methods could have in the urbanization design of HRC.

Regarding the methodologies for design optimization, the literature includes the use of different types of modelling technologies (e.g., CAD, parametric, building information models), integration approaches between discipline analysis (e.g., wrapper software, integration platforms), and optimization engines. Geyer (2009) outlined a method that, with a systematic breakdown of architectural components into optimization models, would enable the use of design optimization integrated with usual object-oriented CAD environments. Oh et al. (2011) performed the optimization of architectural design using Building Information Modelling (BIM) software. The optimization sought the best exterior double glazing systems for minimizing the energy use and satisfying thermal comfort. Flager et al. (2009) integrated the different discipline analyses needed for the design optimization using a PIDO (Process Integration and Design Optimization) platform. Kämpf and Robinson (2010) developed a new evolutionary algorithm for optimizing building and urban geometric forms for the utilization of solar irradiation.

Lately, genetic algorithms (GA) have become a popular optimization engine to solve various problems in the AEC and urbanization industries (Bucking, Zmeureanu, & Athienitis, 2013; Cao et al., 2011; Oh et al., 2011; Wang, Rivard, & Zmeureanu, 2006). Bucking et al. (2013) used GA in a net-zero energy home case study to optimize trade-offs in passive solar gains and active solar generation. Cao et al. (2011) used GA for problems of land use with three distinct objectives: minimizing conversion costs, maximizing accessibility, and maximizing compatibilities between land uses. Wang et al. (2006) presented a methodology to optimize building shapes in plan using the genetic algorithm.

Some authors have studied limitations and strategies for the application of design optimization. Flager and Haymaker (2007) revised the application of design optimization processes in AEC and aerospace industries to determine similarities and opportunities to be applied in AEC projects. Part of the limitations found are that designer’s tools prioritize the generation of static models rather than facilitate the exploration of the space of solutions; and that when producing documentation and models these are not thought to perform multidisciplinary analysis. To confront these authors propose the application of methods and tools based on the procedures of the aerospace industry within the AEC distinctive context: parametric geometry generation system, software integration tools and quantification of system effectiveness. García and Lyon (2013) suggest general methodological considerations of parametric design in architecture to integrate constructive conditions and improve its performance. The authors expose three examples of their work: structural optimization of the façade of a building, minimize energy consumption of a modular pavilion, and the structural optimization of slabs.

For the context of this research, we decided to use GA on a parametric model implemented from scratch within a numerical computing environment (MATLAB).

3.3 Research Methodology

Figure 3.1 depicts the main research methods and the process followed.

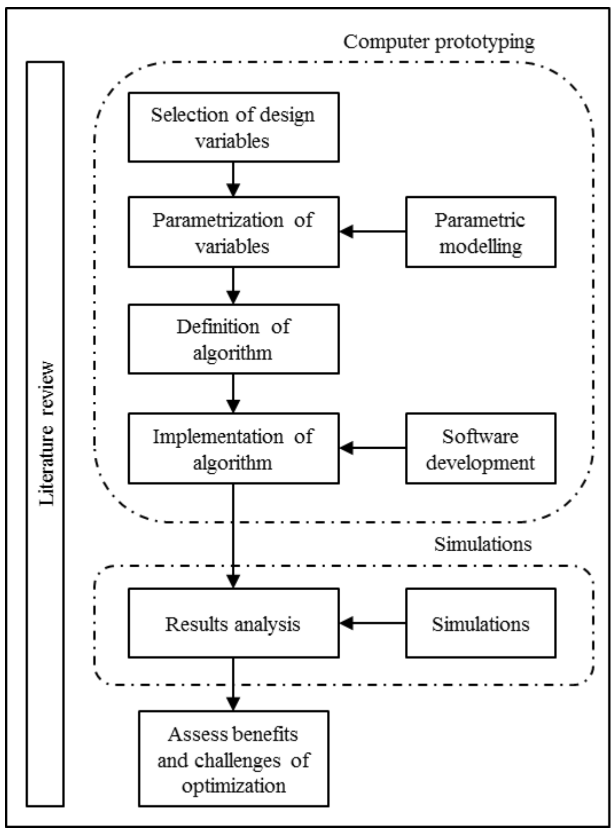

Figure 3.1: Research methodology

The research methodology includes two stages: the design and development of the optimization model, and the testing of its contribution for the conceptual design of urbanizations in HRC projects.

The development of the optimization model started with the selection of the design variables to be considered in the optimization problem. Previous research showed the complexity of the design problem (Shi, 2010). To increase the feasibility of this research, we selected a limited number of variables to be included in the design optimization problem, leaving the many challenges of including other relevant variables to be addressed by future research. In parallel to the parametrization of these variables, we defined the optimization algorithm using genetics algorithms as the optimization engine.

The testing of the optimization model consisted of a set of simulations to evaluate metrics related to the identified problem such as the size of the explored design space, the analysis duration, and the economic results, measured by the optimization utility function.

3.4 Selection and parametrization of design variables

The design variables selected for the model are grouped in three global attributes of a HRC design. The features related to interior mobilization, the features related to the houses and public spaces.

The mobilization is affected by the street layout, their width as well as the dimension of spaces for pedestrian displacement. Elements such as median strip and sidewalk as well as lane size are considered in the design. A grid style layout is defined for the tool with primary and secondary streets.

The design requires that every house is accessible from a street; therefore blocks are constrained in depth and secondary streets are added. Wide streets increase the design velocity reducing the land available for lots, having effects in the liveability.

One important aspect in the design stage is the product definition, for which architects define the architectural house styles. They define between different styles and availability of each. The size of the lot in which the house is immersed varies also depending on the product and market segment aimed by the designers.

For the optimization model different house/lot combinations are considered without consideration of their architecture, the differences between them are minimum and maximum lot dimensions and profit divided in a fixed value for the dwelling and a second value dependant on the lot’s size. The spatial distribution of the houses is considered as well in the results of the tool.

Green spaces are a relevant aspect of urbanizations and in this intent regulation requires complying with a minimum. Developers may follow different strategies related to this, providing the mandatory minimum or planning with a greater value affecting the quality of life of its future residents. An increase in the total area of green spaces generates a reduction of saleable land, but a rise in the price of each property due to the improvements in liveability.

Related to the location of green spaces the optimization model considers five strategies (Figure 3.2):

i. Perimeter parks: the green areas are distributed in two or three of the HRC border areas that have a minimum width. This alternative promotes sport activities such as running and favours the mitigation of negative aspects found on the surroundings.

ii. Central reservation parks: green areas in the median strip and sidewalks. Distributing green spaces throughout the main roads increases the safety as well as it provides residents the feeling of ownership over them promoting their use and care. It has an effect on a broad number of landlords as it is always present in the flows made through the urbanization.

iii. Central park: a big green space located in the centre of the condominium suppling space for different social activities.

iv. Distributed parks: green areas are located in several blocks uniformly distributed throughout the condominium. The reduction of the average distance between each house and its nearest green space promotes its effective use.

v. Combination: A fifth strategy considers any combination of two of the previous strategies.

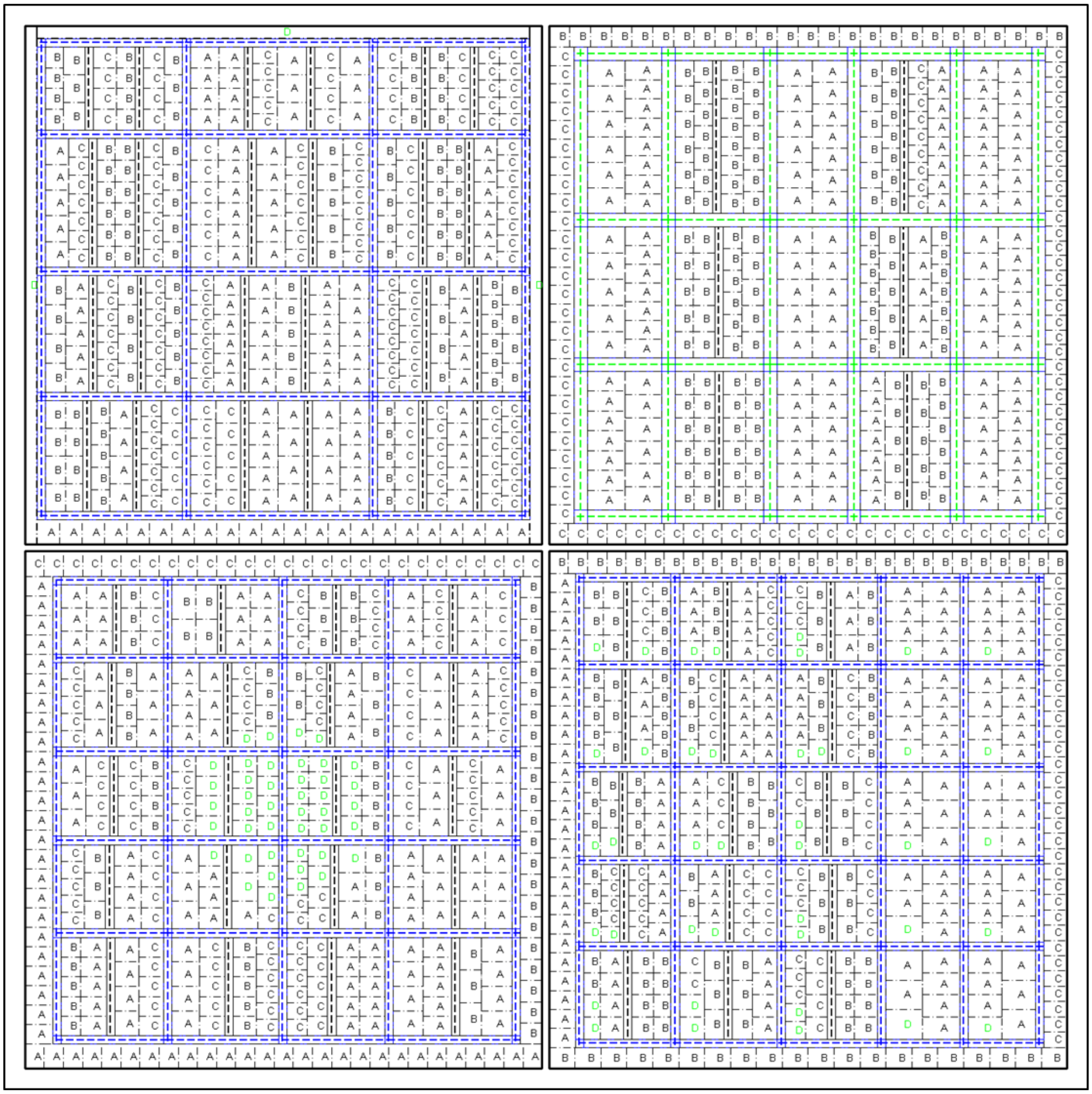

Figure 3.2: Green spaces strategies - perimeter parks (top-left), central reservation (top-right), central parks (bottom-left) and distributed parks (bottom-right). Areas marked as D as well as green wide streets (in central reservation) correspond to green spaces

3.5 Definition and implementation of the algorithm

The optimization procedure used genetic algorithms. In this case, the characteristics of the problem reveal the presence of both continuous and discrete variables; a great interrelation between the variables; and strong spatial components. This problem is different from such as rectangle packing (de Bruin, 2013; Marszałkowski, Mizgajski, & Mokwa, 2016; Perdeck, 2011) or nesting/cutting problems with nonconvex polygons

(Carravilla, Ribeiro, & Oliveira, 2003; Nielsen, 2007). In this case all lots in addition to their location in a particular rectangular block need to have an entrance adjacent to a street. Different strategies must be found to resolve this problem.

In the particularities of this, each block is generated by a random number of rows of houses, each row containing a unique type of house, this in order to reduce construction costs of having different houses together, grouping houses with similar characteristics. Secondary streets are added to guarantee access to each house in the block.

An initial generation is generated heuristically by the algorithm and through processes of mutation and elitism new generations are created. We studied multiple combinations of initial generation size and number of generations to determine advantages and disadvantages of these.

The mutation of the parents considers the movement of primary streets and the reallocation of houses in the blocks, varying their size, type and/or location.

The total profit is composed of the difference between all the revenue from the sale of the houses minus the costs of the development.

$$P = \sum_{i=A}^{C} N_i HP_i + \sum_{i=A}^{C} \sum_{j=1}^{N_i} S_{ij} LUP_i - GSS * GSC - \sum_{l=1}^{2} \sum_{m=1}^{M_l} L_{ml} SC_l \qquad (3.1)$$

P: Total profit of the HRC.

N_i: Number of houses of type i.

HP_i: House profit for type i.

S_{ij}: Surface of house j of type i.

LUP_i: Lot's unit profit for house of type i.

GSS: Green spaces surface.

GSC: Green spaces cost.

L_m: Length of segment m of street of type l.

SC_l: Street cost of street of type l.

M_j: Number of street of type l.

3.6 Results analysis

The testing aimed at assessing the impact of the optimization design algorithm and understanding the challenges and strategies to perform the optimization. Table 3.1 shows the experiment design, indicating the number of generations run for different combinations of population size and green spaces strategy. For the simulation of each separate strategy twenty repetitions were made and for the cases that consider all of them ten repetitions were made.

Table 3.1: Experiment design

Green spaces strategy	Population size		
	10	20	100
Frontier parks	-	20	-
Central reservation	-	20	-
Central parks	-	20	-
Distributed parks	-	20	-
Mixed	-	20	-
All	50	-	50

For the simulations, three different house types where defined. Table 3.2 shows the features for each of them in addition to the range in which their aspect ratio and lot area varies.

Table 3.2: Houses features

House Type	Property	Value	Minimum	Maximum
A	Width [m]	-	18.0	22.0
	Depth [m]	-	23.0	28.0
	House profit [UF]	600	-	-
	Lot profit [UF/m^2]	3.1	-	-
	Area [m^2]	-	414	616
	Ratio	-	1.05	1.56
B	Width [m]	-	18.0	24.0
	Depth [m]	-	18.0	24.0
	House profit [UF]	520	-	-
	Lot profit [UF/m^2]	2.7	-	-
	Area [m^2]	-	324	576
	Ratio	-	0.75	1.33
C	Width [m]	-	14.0	18.0
	Depth [m]	-	20.0	25.0
	House profit [UF]	400	-	-
	Lot profit [UF/m^2]	2.6	-	-
	Area [m^2]	-	280	450
	Ratio	-	1.11	1.79

3.6.1 Design results

Study of the design space

The study allowed generating over 95,000 designs using different strategies in contraposition to the 3–4 designs studied in this stage of conceptual design in the practice. The tool as well admits creating designs with specific green spaces strategies to evaluate their behaviour. These makes feasible the scrutiny of a broader spectrum of the design space, allowing the examination of alternatives that otherwise would not be considered by the designers.

Table 3.3 shows the average time spent for the analysis. In average the generation and evolution of 100 HRC designs throughout the design space for 50 generations took less than two hours. In average the particular analysis for each individual strategy took around ten minutes conceding the testing of particular alternatives in brief time.

Table 3.3: Average time, in minutes, spent for each experiment

Green spaces strategy	Population size		
	10	20	100
Frontier parks	-	12.4	-
Central reservation	-	8.7	-
Central parks	-	9.5	-
Distributed parks	-	10.7	-
Mixed	-	10.5	-
All	12.3	-	118.7

Profits

Figure 3.3 shows the results for simulations run using each of the strategies previously defined.

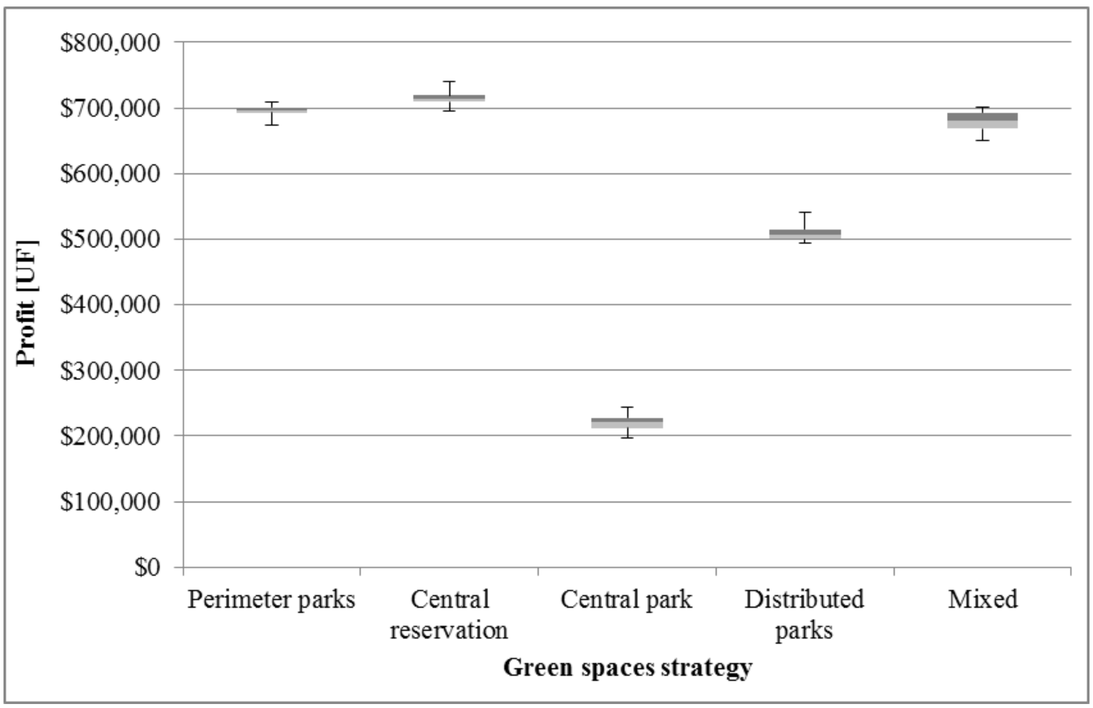

Figure 3.3: Profit results for green spaces strategies

Higher results are found for central reservation and perimeter parks. Mixed strategies behave similar leaning to solutions composed of these two strategies, but the shrinking of alternatives studied with these characteristics, due to the generation of other combinations in the initial population, tend to worst results.

Figure 3.4 show the detail for every green space strategy.

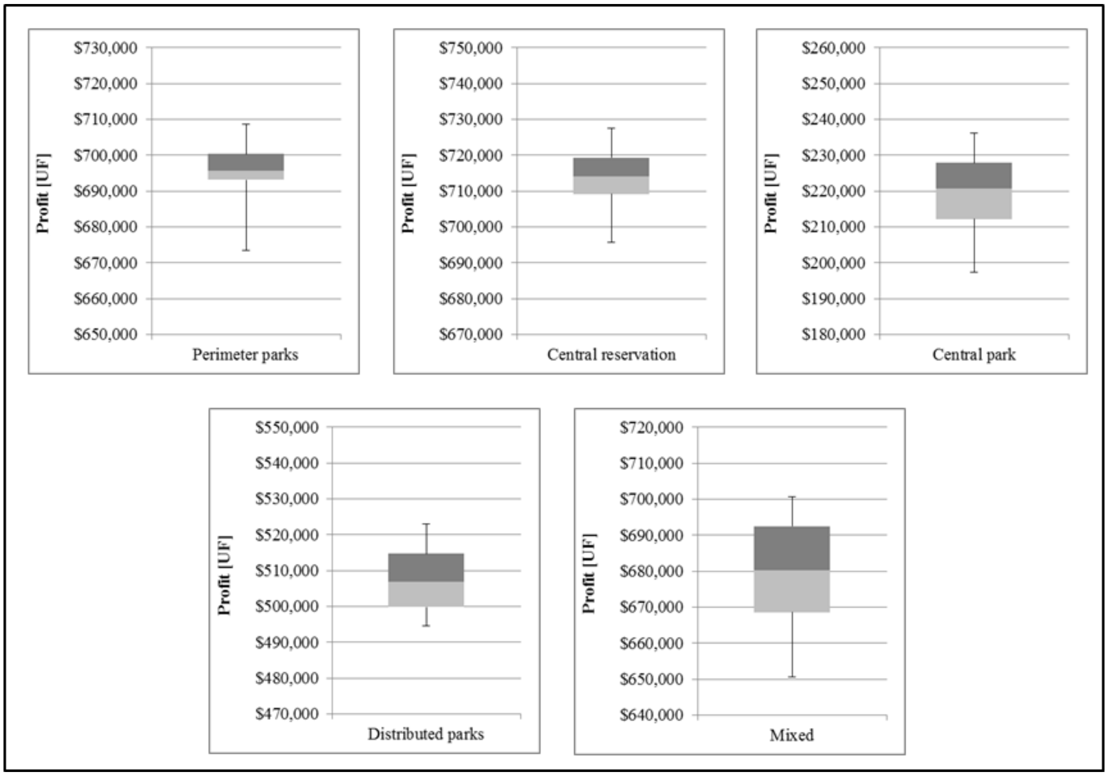

Figure 3.4: Box plot of profit results by green spaces strategy

Figure 3.4 show the distribution of results for every strategy. Mixed combinations present the widest dispersion as observed in the interquartile range, the distribution of values from the first to the third quartile. Depending on the initial population generated results tend to different values. Central and distributed parks strategies have also considerable values of standard deviation. Central parks have a more symmetrical behaviour than distributed parks, which in contraposition are grouped to lower values having a positive skewness.

Alternatives with perimeter parks have less dispersion because all configurations use the frame with three borders of park to fulfil the required area for green spaces, therefore the allocation of blocks and houses tend to similar values. These results show a tendency to be concentrated on top values having a negative skewness.

All results show kurtosis values inferior to the normal distribution, producing fewer outliers.

Figure 3.5 and Figure 3.6 show results for particular cases of experiments with the use of one of the green spaces strategies.

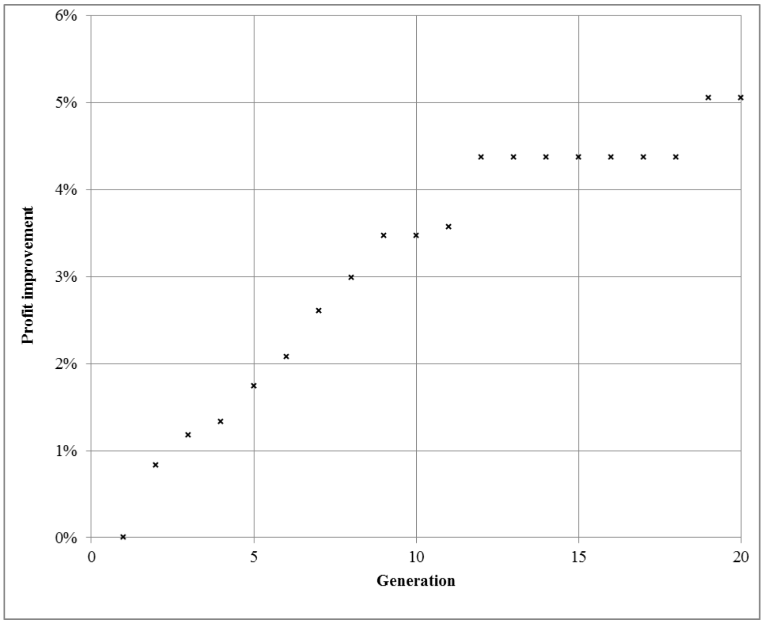

Figure 3.5: Profit improvements for particular simulation with perimeter parks

Figure 3.5 shows the profit improvement results for a simulation using an initial population of twenty HRC with perimeter parks evolved for twenty generations. A total improvement of 5.1% is observed, with a value of 3.5% after the 10th generation representing over two thirds of the improvement in half the number of iterations of the evolutionary process.

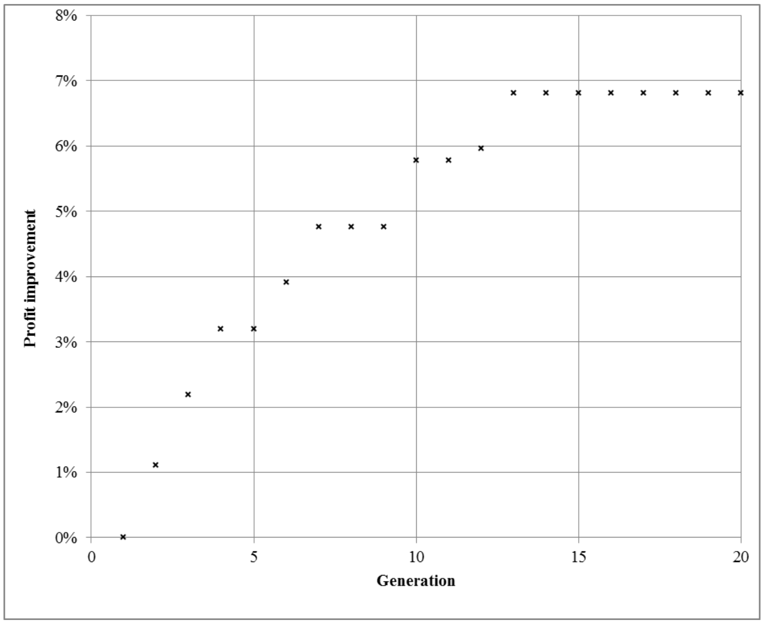

Figure 3.6: Profit improvements for particular simulation with distributed parks

Figure 3.6 shows the profit improvement results for a simulation using an initial population of twenty HRC with distributed parks evolved for twenty generations. A profit improvement of 6.8% is observed. A steep gradient is appreciated in the beginning, with rates of improvement of 0.7% for the first seven generations and after this a decrease in the pace, converging to the final result in the 13th generation.

Figure 3.7 shows results for one experiment using all strategies.

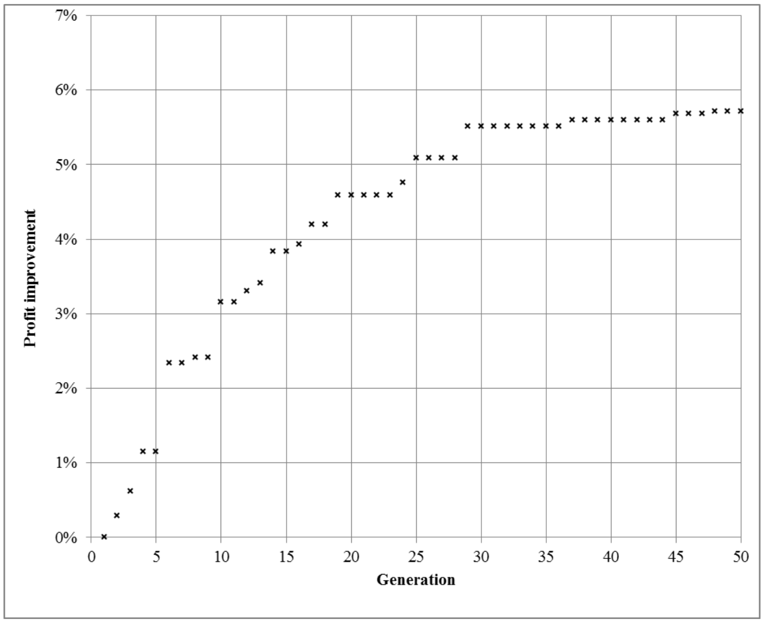

Figure 3.7: Profit improvements for particular simulation with all strategies

Figure 3.7 shows the profit improvement results for a simulation using an initial population of 100 HRC with all strategies activated evolved for 50 generations. The improvement after the 10th generation is 3.2%, over half the final value achieved in a fifth of the iterations. After half of the iterations are completed the value for improvement is 5.1% corresponding to almost 90% of the total improvement value of 5.7% achieved in the 50th generation. It is observed a clear convergence from generation 30 onwards.

Sensitivity analysis

Grefenstette (1986) studies the effect in the final results of several control parameters for GA for a set of numerical optimizations problems. For our case, in order to optimize the results, we intended to increase the design space studied with GA by two approaches. One alternative consisted of increasing the population size and the other to increase the modifications and iterations done over this initial set, by increasing the number of generations studied.

Figure 3.8 and Figure 3.9 show the results of simulations done to test the contribution of each of these approaches. Tests used a combination of all green spaces strategies for different sizes of populations. Results are registered every ten iterations and include the median value as well as the distribution.

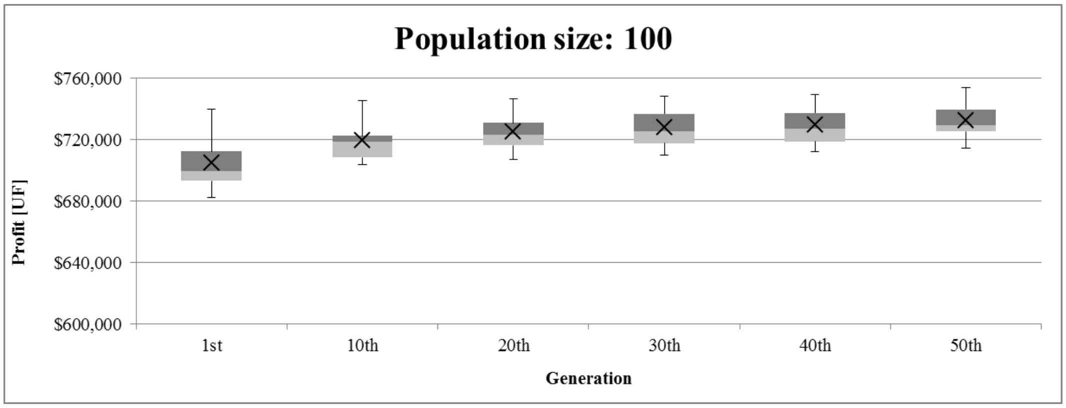

Figure 3.8: Sensitivity analysis - Population size 100

Figure 3.8 shows the results for a population size of 100. A mean value of $705,000 UF after the first iteration is observed reaching a final value of $733,000. Standard deviation values decrease with the iterations, maintaining an interquartile range relatively constant. The average profit improvement corresponds to a 4.0%, with a 50% achieved after the first ten iterations and a 75% after the twentieth.

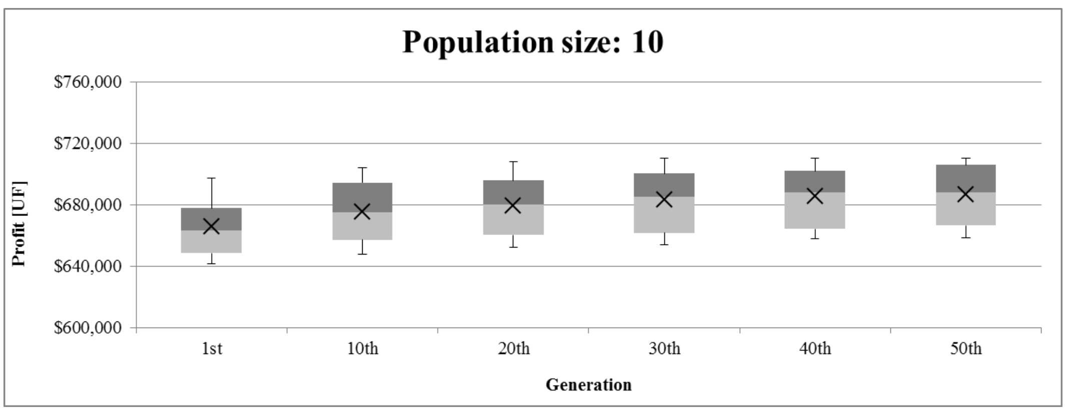

Figure 3.9: Sensitivity analysis - Population size 10

Figure 3.9 shows the results for a population size of ten. Mean profits starting in $666,000 increase to a value of $687,000. Standard deviation values remain steady and values in the interquartile range appear more disperse throughout the last iterations. The average profit improvement corresponds to a 3.1%, with a 46% achieved after the first ten iterations and a 66% after the twentieth.

Studying a bigger set of initial designs in our model displays better global results. The study of more HRC in the first population allows escaping of local optimal points. Figure 3.8 and Figure 3.9 show that results obtained in the analysis of a ten times larger generation increase a 5.9% before any evolutionary procedure is applied. After 50 iterations results for the larger population are over 6.7% higher. This exhibits more significant improvements from the increase in population size than from the increase of iterations.

The time spent with the trade-off between population size and number of iterations is as well favourable to the first approach. Table 3.4 shows the average time per HRC design in the initial population, an average of nine seconds per each and does not vary in great measure in relation to population size.

Table 3.4: Average time, in seconds, spent per HRC design in the initial population of each experiment

Green spaces strategy	Population size		
	10	20	100
Frontier parks	-	9.0	-
Central reservation	-	7.4	-
Central parks	-	8.7	-
Distributed parks	-	9.1	-
Mixed	-	8.8	-
All	9.2	-	8.5

3.6.2 Simulation results

Figure 3.10 show the simulation problems encountered during the tests executed with the tool. In some situations unnecessary secondary streets remain in the design after reallocation of elements in the block (i). This represents a redundancy having houses with multiple accesses and the simple solution is eliminating it from the design, reducing costs. Certain designs due to heuristic rules have corner houses that are left without access (ii); the solution for this is generating a small cul-de-sac in corner intersections allowing houses to have access. This can be done without great losses in lot total surfaces considering lots of irregular shapes and spreading the difference through a bigger number of properties.

The model does not include intersections as a smart object, therefore after several iterations and the superposition of the constrained street movements per mutation discontinuities appear (iii). Modifications similar to the previous ones resolve this problem, eliminating the extra segments of streets and developing different types of intersections.

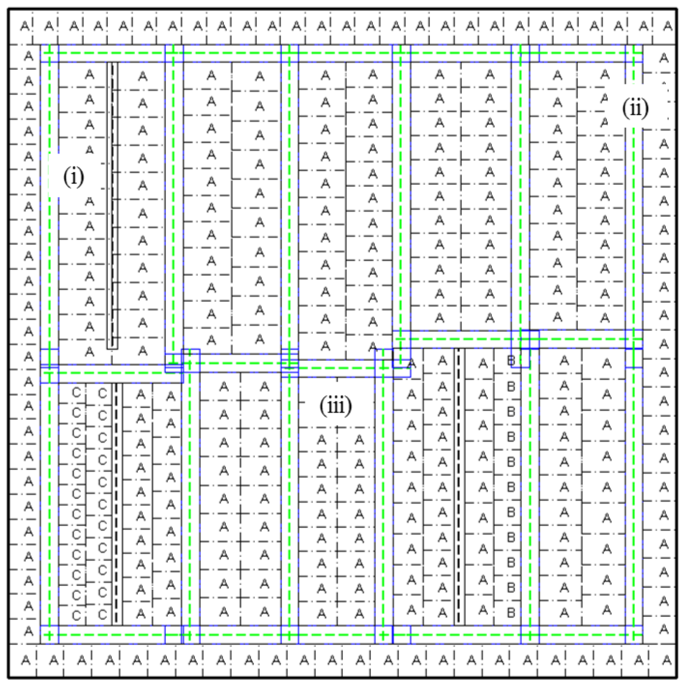

Figure 3.10: Simulation glitches

3.7 Conclusions

This study generated contributions in two areas: urbanization designs for HRC projects and computational methods for the urbanization design optimization.

Regarding the urbanization designs, the simulations showed that – given the assumptions implicit in the problem formalization – the best green area strategy is using the central reservations followed closely by the frontier parks. Although the mixed strategy was also close, the best solutions in this strategy had mainly parks in the central reservations.

Regarding the computational method for the urbanization optimization, the study showed an enormous increment in the design space and reduction in the design time (without considering the modelling time) compared with current practice. More than 95,000 design alternatives were studied for different strategies outperforming actual practice.

Even though the model used considers various simplifications of the design problem the time that takes to analyse is minimum in relation to the seven weeks spent in the practice to generate initial alternatives as determined in the benchmark by Flager and Haymaker (2007). The less than two hours used to study over 5,000 alternatives with the tool represent a substantial margin in relation to the industry. Additional complexities may be included in the model still showing great time advantages.

Results show an improvement of profits during the iterative process of between 2.0-7.0%. The sensitivity analysis to evaluate the trade-off between population size and number of generations showed advantages for greater populations. The results for evaluations with population of size 100 showed absolute profit values 6.0% higher than those for populations of size ten. In contraposition, the analysis of the increase of generations showed that 50% of the profit improvement is already achieved in the first 10 of 50 generations and a 75% after the 20^{th}.

These represents a contribution to the designers’ work as an input of design alternatives to which they can incorporate additional aspects not considered in the optimization model. It is noteworthy to consider that the computational methods in any case replace design teams; these methods support the design process by reducing the time spent in generating conceptual designs and increasing the number of explored alternatives. The experience and know-how of developers is vital for the selection of the best solution for any particular case, due to different aspects that no model can consider as decision makers.

It is possible to observe that the solutions generated do not leave aside some relevant intangible aspects that designers evaluate in early stages of the design. Some examples of these are: circulation velocities, security, sense of neighbourhood and local community, as well as behaviour towards the physical and social surroundings.

The parametric modelling used in the optimization presented some weaknesses such as overlapping intersections of streets and lots without access to the streets. These glitches may be easily solved by designers during the detailed design and they do not invalidate the performed analyses since they have a very small impact on the profit equation (optimization utility function).

It is important to bear in mind that the actual profit improvements are dependent on the selected variables and other assumptions used in the optimization model. While these results are promising, values may vary once additional elements are integrated to the model. In further developments of this tool other elements that affect this may be added, such as costs related to earthmoving and excavations due to topography reconfiguration; houses views and orientations; sale velocities; and clients' preferences for certain features.

The study also generated other key learnings regarding the optimization and simulation strategies. The strong interrelation between the design variables that make intricate to develop a chromosome led to the impossibility to apply crossover in the way the algorithm is formalized. This represents one of the main weaknesses of the genetic algorithm used, and should be included in an enhanced version. Controlled street movements and redistribution of houses in a block are used as mutation strategies.

The existence of both discrete and continuous variables and the adjacency in the assignation of figures inside the blocks make this a particular nesting problem. Heuristic rules were used to confront the assignation of lots in blocks; with rows of similar houses used and secondary streets were added to ensure accesses when necessary.

Further research should work in strategies to increase additional variables and design aspects such as the topographic surface; different street layouts that develop variated types of neighbourhoods (such as loops and cul-de-sac); a more sophisticated objective function which considers the addition of the sales velocity effects in the profits; as well as the option to generate initial solutions starting from raw sketches done by designers.

4. CONCLUSIONS

The main contributions to knowledge of this thesis are enclosed in four main areas: the design variables relevant for the urbanization of HRC and their importance; the challenges and differences of the two methods used to formalize the design space; the simulation results related to the design of HRC; and the benefits and challenges of the application of parametric design optimization in this particular design problem.

The results of this thesis generated a list of variables relevant in the design of the urbanization of HRC. Strong interdependencies were found among the variables, a factor analysis grouped them and identified five factors that are relevant to the urbanization design of HRC projects from the perspective of developers and four factors from the perspective of clients (as perceived by the developers).

Differences and similarities were retrieved between the importance that developers and clients attribute to these variables. Among the variables those related to green spaces, size and location; lot size; and houses' orientation were important to both developers and clients. However, street layout is considered the most important variable for developers, but it is one of the least important for clients. This finding is inconsistent with the results from both the interviews conducted and the panels of experts, through which it was determined to be one of the main tools to provide other features that clients valued as part of habitability: privacy and security.

Both methods used, the bottom-up and the top-down approaches, gave clarity of the design problem with several limitations. The first approach (bottom-up) delivered a detailed view of the design variables used by Chilean decision makers in HRC projects. The second approach (top-down) allowed a more structured analysis of the problem, but it failed to obtain detailed results, as the Design Scenarios (DS) method is designed to be used for specific problems and not for the generic problem that this research aimed to address.

DS methodology demonstrated to be a strong tool for recollecting information and understanding the design process from the perspective of professionals. Its application to generalized design problems, as used by researchers, presents some challenges.

Both approaches are limited in that they separate clients' preferences from their personal standpoint. Clients' opinion is an important factor to understand the design problem and should be included in further work.

The optimization model allows the use of five different green spaces strategies for the generation of design alternatives. Simulation results show that the higher profits are found for central reservation and perimeter parks. Perimeter parks as well show the smallest dispersion of results; in contraposition mixed combinations show the widest interquartile range due to the impact that the different initial populations generated have in the average profit results.

The implementation of the optimization model allowed a significant increment in the number of alternatives studied. It provided the opportunity to analyse 95,000 alternatives for the HRC design, taking less than two hours for each of the complete analyses of 5,000 alternatives in comparison to the three alternatives studied in the industry. This exploration of the design space concedes the possibility to escape from local optimal points in which designers might be falling.

Results show an improvement of profits during the iterative process of between 2.0-7.0%. The GA selection procedure promotes preserving best results of each generation through elitism and a selection of good solutions that are mutated which results in better alternatives for the design team. This represents a course for the selection of solutions to continue the design process.

The sensitivity analysis to evaluate the trade-off between population size and number of generations showed advantages for greater populations. The profit results for evaluations with population of size 100 showed absolute values 6.0% higher than those for populations of size ten. This represents an improvement to the increase of generations, where in the first 10 of 50 generations a 50% of the profit improvement is already achieved and 75% after the 20th.

As stated, the design problem presents a greater complexity to the one used for the model. This research is bound to a sub list of the design variables. Future work should include additional design variables as well as a more sophisticated objective function.

The integration of variables such as the topography of the site will add to the model further levels of analysis to study technical feasibilities of the solutions (stormwater drainage, houses orientations and views).

An important extension to this analysis would be to modify the objective function to be able to include other relevant aspects. The development of methodologies to measure clients' preferences as well as social benefits and the effect these has in prices and sale velocities, having a direct impact in the financial costs of a project, allows the optimization model to include not only private developments but also public housing projects.

This research has important implications for both the academia and the private sector. Researches related to academia can proceed with the approach used and proceed in various topics: include extra variables to the analysis; use other simulations engines; adapt the objective function to expand the extent of the optimization model; apply the model to different problems, interiorizing in the architectural design of houses or in a broader perspective for the design of cities. On the other hand, this model shows design recommendations that might promote good practices in the real-estate industry where developers might use the tool to study initial alternatives for certain sites or companies in the software developers industry can integrate the optimization model to existing analysis software.

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