ENERGY RETROFITTING IN RELATION TO DEGREE OF IMPROVEMENT: AN EVALUATION OF SIMULATION VERSUS THE REALITY OF HOUSING IN CHILE

[1]Soto Muñoz, J.; [2]Pérez Fargallo, A.; [3]García, R.
[1]Bío-Bío University, Departament of Construction Sciences
Collao 1202. Concepción. Chile.
[2]University of Seville, Department of Architectural Constructions II
Avda. Reina Mercedes, 4 A, 41012-Sevilla. España.
[3] Bío-Bío University, Department of Architectural Design and Theory
Collao 1202. Concepción. Chile
e-mail: jsotom@ubiobio.cl, alexisfargallo@us.es, rgarcia@ubiobio.cl

ABSTRACT

Homes are one of the major energy consumers and generate significant environmental impact in Chile and globally. The improvement of existing buildings or new projects is a procedure based on multidimensional simulations and the energy evaluation of housing. However, there is a lack of strategies to identify appropriate modifications. Normally, the original situation is compared with an improved scenario according to general estimates, but without analyzing the most effective alternatives, building process, economic projections or acceptability for the occupants.

Based on the study of a dozen, representative dwellings in south-central Chile, in which construction records, computer models, environmental monitoring, and occupancy patterns were compared, this work presents a methodology for the effective analysis of residential environmental improvement. Considering a selection of relevant existing or projected conditions, energy simulation was carried out according to consolidated background information, and alternatives were identified according to a catalog of suitable building solutions for each type of housing studied. Thus, performance results were analyzed using a methodology known as Life-Cycle Cost Analysis (LCCA) for the financial analysis of the simulated alternatives in order to determine the most effective action packages.

In this way, construction proposals were created, applied through computer simulations and implemented in reality. The purpose of this work is to compare the values of energy savings produced by improvements obtained with energy efficiency analysis programs, with the results of building monitoring.

Keywords: housing, improvements, efficiency, energy, technical and economic feasibility.

1. Introduction

In Chile, improvements to housing traditionally have a logic based on increasing the state of preservation of a property during its life cycle or increasing the floor area or volume of a building. Energy efficiency and a reduction in the environmental impact of the country's households are more recent aims, which have resulted from the substantial increase in energy costs and increased pollution in cities. Nationwide, approximately 142,000 building permits are issued per year, of which the majority, 70.5%, corresponds to dwellings between 35.1 and 70 m^2, and 16% to housing between 70.1 and 100 m^2 [1]. This study focuses on urban dwellings located in the south-central area of Chile, on particular cases in the Bío-Bío Region. In this area, said housing is characterized by a certain typology and size: detached buildings of one or two floors, from 60 to 140 m^2, with a predominant materiality of 77-87% reinforced masonry on the first floor and wooden structural walls on the second floor. In addition, there has been an increase in residential construction; according to the 2002 Census [2], said increase in private homes was 28% and is currently estimated to be above that figure given the need for replacement that arose from the earthquake on February 27, 2010.

Today, energy retrofitting is a factor of housing improvement that focuses on the problem of low envelope insulation or inefficient environmental comfort strategies, which require the incorporation of modifications into original buildings. In this sense, on average 56% of total household energy consumption corresponds to heating [3]. Other research [4] indicates that it is important for Chilean families to have dwellings that can correctly insulate cold and heat. In 2007, the Chilean government modified its General Ordinance on Urban Planning and Construction (OGUC) to include a standard for regulating thermal conditions in housing. However, it does not establish reference parameters for monitoring the energy demand in each building, but rather focuses thermal requirements on losses due to thermal transmittance (U). These thermal regulations[5] have begun to establish minimum U (W/m^2 °C) requirements for zone 4, the Bío-Bío Region: for floors (0.6), walls (1.7), roofing (0.38), and windows, according to the maximum percentage of glazed surface relative to vertical walls in the envelope (3.6-2.4 and less). However, there are variations in behavior according to zone and dwelling type. Data from the Chilean Chamber of Construction's Technology Development Corporation [3] indicate that energy consumption varies according to housing layout. In addition, the government has established subsidies for homes identified as social housing and middle class dwellings through different improvement programs. These single-family residential buildings are eligible for benefits from the Ministry of Housing and Urban Development's (MINVU) Supreme Decree (D.S.) Number 255 [6], more specifically under Title II on improvement projects for dwellings, that is, dwellings whose tax appraisal value does not exceed $26,650 USD and that based on an official government survey, have an appropriate social characterization for the purpose of the public program. At present, Supreme Decree Number 25 is being processed, which will repeal the previously mentioned D.S. 255 and will increase state support for improvement projects through technological innovation in energy efficiency and sustainability [7]. According to studies by the Chilean Chamber of Construction [8], the relationship between subsidies paid out/subsidies awarded is 90% on average of the total benefits provided by the government to lower income families. However, there is a lower rate of effectiveness regarding D.S. 255, primarily because of problems with the completion of the construction process by contractors and government inspecting agents have no experience in this type of construction processes with inhabited dwellings.

In this way, the discussion on energy retrofitting focuses on a dwelling's thermal performance during its life cycle and the associated costs. It is not only about estimated costs but also the conditions that these provide for their inhabitants. According to the study "Determination of the Hygrothermal Comfort Baseline in the Residential Sector" [9], the variables that should be considered in the evaluation of inhabitants' thermal perception of housing interiors should involve humidity, temperature and airspeed inside the dwelling. This may be related to the collateral costs of indoor environmental comfort, linked to a good night's sleep and the health of members of the household. Measurements made by this research team in 50 dwellings in the south-central area of the country describe the comfort level at which Chileans live inside their homes. Four central areas were investigated, among them the effective temperature, which shows a correlation between effective temperature and thermal comfort. It also indicates that in winter the average temperature of most households is 15-17 °C. A second area of interest is the heating fuel used. In the south-central zone of Chile, after firewood, the preferred fuel for most families is liquefied petroleum gas. Since May of 2012, natural gas has shown a 2.48% increase in use, while paraffin and liquefied petroleum gas have demonstrated an increase of 5.85% and 3.6% respectively [10].

Based on the above, the improvement of residential construction makes traditional building more environmentally friendly, given that it is an opportunity to reduce the environmental impact of heating and cooling systems by lowering emissions, carbon footprint and energy consumption. What is interesting is tackling the problem from the point of view of the effectiveness of possible actions, by studying the effects of building systems considered in the improvement, whether on technical feasibility, implementation and/or performance. The effect on the perception of families and their communities should be studied as well. Furthermore, the process should assess the feasibility for each socioeconomic group and the opportunities the government provides through related subsidies.

2. Case Study Selection

The study involved the analysis of dwellings in the south-central area of Chile, specifically in the Province of Concepción. In addition, it focuses on common building typologies for mid-level socioeconomic groups that correspond to the majority of dwellings in the country. For the research, 12 cases were selected under the criteria set out by Johansson [11], i.e. each dwelling was characterized as a complex functioning unit considering its context in the contemporary reality. Thus, one of the cases was chosen for in-depth study; the dwelling is located in the coastal town of Dichato, which belongs to zone 4 of the Thermal Regulation [5]. Its residential building characterization was reviewed in comparison with common building typology, as well as the family's habits and perceptions, and energy consumption. Also, pre- and post-improvement monitoring was carried out in winter and summer.

During the first stage, the 12 dwellings studied were characterized and compared to national references. In this way, it was proven that in Chile close to half of housing built corresponds to mid-to-low income homes financed by the government, while housing for the remaining mid-to-high income levels is financed privately. The construction industry provides a diverse supply of public and private residential buildings with a range of designs and building systems. In recent years, the private housing market has received warnings regarding the increase in unjustified or overvalued cost of new dwellings, which makes access to these dwellings through bank financing more difficult. Regarding the housing, the average rate of occupancy is a little less than four inhabitants per dwelling. Dwellings for all socioeconomic levels are relatively well-equipped and have an average electricity consumption of

2,100 kWh/year and expenses of approximately $600 USD/year. The total energy consumption of dwellings for heating based on electricity, gas, oil and/or wood is between 5,000 and 20,000 kWh/year, equivalent to 30 and 130 kWh/year/m^2. By monitoring the cases studied, it was established that indoor temperatures are lower than traditional standards, averaging between 16 and 18 °C, and humidity and indoor air pollution problems frequently occur in low income, government-subsidized housing.

While the south-central area of Chile is characterized by coastal plains, the coastal mountain range and a central valley prior to the Andes mountain range, most of the population is located on the coast of the Pacific Ocean. The case study was selected from among 12 cases due to its representativeness with respect to location, social context and building typology. It is located in the town of Dichato, Municipality of Tomé, Bío Bío Region. Also taken into consideration was the fact that this area was strongly affected by the earthquake and subsequent tsunami of February 27, 2010. Consequently, state reconstruction programs for the replacement of affected dwellings were implemented in the following two years; the region represented 25% of the investment of this type carried out by public programs. Also, the search included dwellings provided by the state through subsidies available from the Ministry of Housing and Urban Development for C2 and C3 level socioeconomic groups, which have a monthly income of between $480 and $1,100 USD. The architectural features of the case study represent a single-family dwelling, in the house not apartment category, which nationwide accounts for 83% of housing types and 89% in the region under study [2].

3. Development

During the initial characterization of the 12 dwellings, a self-building phenomenon was observed in almost all buildings, which accounted for changes in dwelling size and alterations to the original building typology. This shows that the indicators associated with building permits do not represent the reality of the sector, since neither all permits requested result in constructed buildings, nor are the required legal permits solicited from the corresponding municipality in order to modify dwellings. This affects and distorts the data used to develop public policies related to the sector in the country.

For the case study, the dwelling located in the town of Dichato, it was necessary to perform a series of quantitative and qualitative data-collection activities during 2012, 2013 and 2014. Built in 2011, the dwelling has 2 levels and a usable floor area of 51.24 m^2. The first floor of the building was constructed of confined masonry, with an interior mortar facing, exterior elastomeric wall coating, and reinforced concrete slab. The second floor has a wood-frame structure, interior drywall and exterior vinyl siding cladding. It includes 2 bedrooms, a living-dining room, kitchen and one bathroom. The commercial appraisal value is $18,500 USD. However, since it is state-subsidized housing that has sales limitations, the tax appraisal value is $2,500 USD. The household was composed of 3 people, in comparison to the national reference of 3.6 inhabitants per dwelling [2]. A variable monthly family income between $240 and $750 USC was recorded. Basic services are provided to the dwelling, which is equipped with a stove, washing machine, TV, microwave, water heater, refrigerator and cable/Internet service. The aforementioned classifies it in the C2-C3 group according to socioeconomic level [12].

After characterization, the dwelling was studied by monitoring in winter and summer to identify its energy behavior (Fig.1). Heat flows were identified in the envelope through thermal flow tests and the installation of sensors for surface temperature, relative humidity and ambient temperature. It was also possible to measure CO_2

concentrations and the amount of natural lighting. Using thermographic cameras, thermal bridges, their locations and dimensions were identified. Moreover, through building airtightness tests, infiltration levels in the building were determined. And, through validated surveys and instruments, the inhabitants' post-occupancy habits, construction characteristics and real energy consumption in the building were recorded.

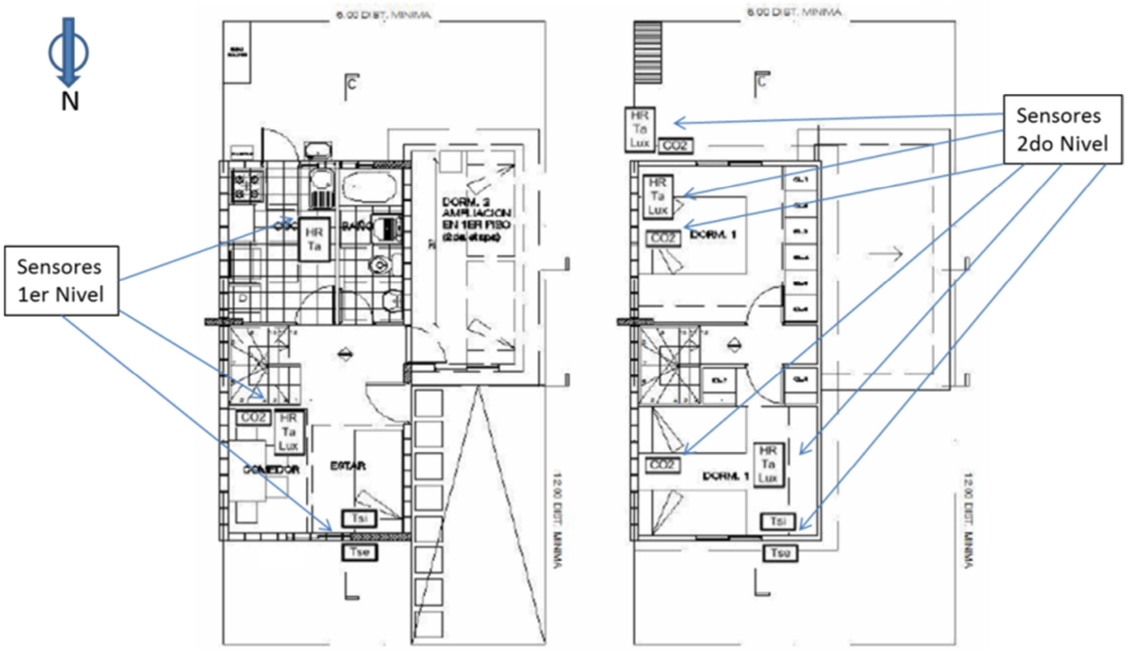

Fig.1. Map and location of monitoring sensors in the dwelling. Source: Author.

In this way and by reviewing the supply of improvement alternatives available on the market in the area, simulations were developed possible solutions from the Official List of Building Solutions for Thermal Conditioning [13]. Using data on ambient temperatures, pressure, and wind speed and direction in the locality, simulations were performed with the sustainable building design software Ecotec to determine the thermal performance and behavior of the system under different assumptions. With this information, solutions were grouped into packages together with the technical feasibility of implementation in the dwelling. The economic cost of these building solution packages corresponds to 5, 10 and 15% of the dwelling's value. They were simulated to obtain the most energy efficient combination to decrease the thermal transmittance of the envelope. The process of studying the energy retrofitting design included information on the main building dimensions, as well as information on the immediate environment, solar orientation, size and type of penetrations, building materials used in the envelope and their thickness, and floor or roof conditions. Subsequently, based on the efficiency of the initial investment and potential thermal improvement, one of the improvement combinations (Table 1) was selected for implementation.

Type of Dwelling	Description	Cost ($USD/m2)
Single-family, Semi-detached, 2-floor dwelling	Installation of an EIFS on first-floor walls	46
	Installation of an EIFS on second-floor walls	55
	Replacement of single-paned, aluminum windows with hermetic, double-paned, PVC windows	161

Table 1. Improvements made to the Dichato dwelling

This improvement was carried out in the spring of 2013, and afterwards the dwelling was monitored at different times of the year. The implementation of building solutions enabled previously estimated costs to be studied. The final cost was $ 2,920 USD, 7.4% less than the original budget principally due to the reuse of original materials. In addition, during the process dwelling occupants were interviewed before and after carrying out improvements. During 2013 and 2014, monitoring of electricity and liquefied petroleum gas consumption was conducted to identify energy requirements for heating. Gas was established as the heating fuel type for 5 months of use, from 18:00 to 22:00 hrs. The family did not use cooling strategies other than increasing ventilation by opening windows in summer. Based on monitoring, the information obtained during the study period is summarized as follows (Table 2).

	Original Dwelling	Dwelling with Improvements
Indoor Air Temperature	Without improvements, the average temperature variation with respect to outdoor temperature is 0.8 °C.	With improvement, the temperature gradient increases 5 °C as a result of the decrease in the thermal transmittance of walls and doors.
Superficial Temperature of Walls	A ± 5 °C variation in wall temperatures on the first floor and ± 3 °C on the second floor was recorded.	The variation increases ± 9 °C on the first floor and ± 6 °C on the second floor due to different building systems at the floor level and the increased thermal resistance of walls.
CO_2	It was measured that this indicator remains above 1,000ppm 8.6% of the time.	A 4.8% decrease was observed, which is thought to correspond to decreased infiltration.
Air Infiltration	A blower door method A pressurization test was conducted, which yielded 11.7 l/h air changes per hour at 50Pa.	Air changes per hour decreased to 9.79 l/h given the wood framing, siding and drywall on the second floor.

Table 2. Variation of thermal comfort indicators in the dwelling

Subsequently, different life cycle cost analyses (LCCA) were compared from simulations using data obtained from monitoring in the first stage, then from the improvement alternative implemented, the building process and performance in the third year. The proposed methodology corresponds to ASTM Standard E917 [14], for which a series of assumptions was established that govern the analysis. In addition, increased dwelling appraisal was considered, as well as savings due to wellbeing and health conditions estimated from data on user perception between the case study and the average frequency of respiratory diseases in 10 other similar dwellings in the same housing complex. The LCCA for the different dwelling systems is calculated by considering both actual heating consumption and simulated annual demand. The economic assumptions for the study (Table 3) were obtained from historical references on the construction sector in Chile and data from contractors who work in the area of housing improvement.

Discount Rate	8%
Life cycle of study	20 years
Fuel price escalation rate	Liquefied Petroleum Gas: 13%; Electricity: 5%
Inflation	Not considered
Increase in Building Appraisal	11%
Utilities/Contractor's Overhead Costs	20% / 8%

Table 3. Economic evaluation assumptions

Life cycle cost analysis is an economic evaluation of an item, building system, apparatus or installation during the time frame of its lifespan relative to a reference, considering identical baselines. In this case, the function of the building is residential. The base case is understood to be the original dwelling state at the time of diagnosis, and the improvement packages, a combination of solutions that enable energy efficiency in thermal conditioning systems in construction (Table 4). In this way, the packages described were compared using present value methodology with established assumptions and simulations, thus obtaining the following analysis.

Project Title		Improvements solutions for the thermal envelope			Current configuration		Package A		Package B		Package C	
					Description: Current condition of the dwelling		Description: Sealing of doors and installation of an EIFS on the second floor		Description: Sealing of doors, windows, penetrations, EIFS on first floor and ceiling insulation		Description: installation of EIFS first and second floor, window replacement	
Discount rate		8%										
Life cycle (years)		20										
Currency		Dolares USD$			Estimated cost	Present Value	Estimated cost	Present Value	Estimated cost	Present Value	Estimated cost	Present Value
Initial costs	**Initial costs**											
	Sealing of doors						$ 41	$ 41	$ 41	$ 41		
	sealing of windows								$ 126	$ 126		
	Sealing of penetrations								$ 132	$ 132		
	Sealing of walls								$ 213			
	EIFS installation, first floor								$ 898	$ 898	$ 898	$ 898
	EIFS installation, second floor						$ 1,137	$ 1,137			$ 1,137	$ 1,137
	Hermetic double paned PVC Windows										$ 1,046	$ 1,046
	Roof insullation								$ 620	$ 620		
	Residual value of windows										$ 81	$ 81
	TOTAL OF INITIAL AND COLLATERAL COSTS						$ 1,178	$ 1,178	$ 2,030	$ 1,817	$ 3,162	$ 3,162
	DIFFERENCE IN COSTS IN RELATION TO CURRENT CONFIGURATION											
Replacement costs and residual value	**Replacement costs and residual va**	año	factor valor presente									
	Replacement of door sealing	5	0.68				$ 49	$ 33	$ 49	$ 33		
	Replacement of window weatherstrippin	5	0.68		$ 110	$ 75	$ 110	$ 75	$ 110	$ 75		
	Repainting	5	0.68		$ 360	$ 245	$ 191	$ 130	$ 191	$ 130		
	Replacement of door sealing	10	0.46				$ 49	$ 23	$ 49	$ 23		
	Replacement of window weatherstrippin	10	0.46		$ 110	$ 51	$ 110	$ 51	$ 110	$ 51	$ 110	$ 51
	Cambio Sello Instalaciones	10	0.46						$ 100	$ 46		
	Repainting	10	0.46		$ 360	$ 167	$ 191	$ 88	$ 191	$ 88		
	Repainting of EIFS	10	0.46				$ 361	$ 167	$ 361	$ 167	$ 769	$ 356
	Replacement of door sealing	15	0.32				$ 49	$ 15	$ 49	$ 15		
	Replacement of window weatherstrippin	15	0.32				$ 110	$ 35	$ 110	$ 35		
	Repainting	15	0.32		$ 360	$ 113	$ 191	$ 60	$ 191	$ 60		
	Residual value of windows (7% initial co	20	0.21			$ -					$ 81	$ 17
	TOTAL REPLACEMENT COSTS / RESIDUAL LIFE				$ 1,300	**$ 651**	$ 1,411	$ 678	$ 1,511	$ 724	$ 960	$ 425
	DIFFERENCE IN COSTS IN RELATION TO CURRENT CONFIGURATION						$ 111		$ 211		-$ 340	
Annual costs	**Annual costs**	Price escalation ra	alue factor price escalation									
	Heating with liquefied petroleum gas	13%	33.27		554.0	18433.3	396.0	13176.1	300.0	9981.9	201.0	6687.9
	Respiratory diseases / recovery	2%	11.58		140.0	1621.2	132.0	1528.6	125.0	1447.5	89.0	1030.6
	TOTAL ANNUAL COSTS				$ 694	**$ 20,054**	$ 528	**$ 14,705**	$ 425	**$ 11,429**	$ 290	**$ 7,719**
	DIFFERENCE IN COSTS IN RELATION TO CURRENT CONFIGURATION						$ 166	$ 5,350	$ 269	$ 8,625	$ 404	$ 12,336
Life cycle costs	**Life cycle costs (LCC)**					**$ 20,706**		**$ 16,561**		**$ 13,971**		**$ 11,305**
	Diference LCC IN RELATION TO CURRENT CONFIGURATION							-$ 4,145		-$ 6,735		-$ 9,401
	Variation LCC IN RELATION TO CURRENT CONFIGURATION							-20.0%		-32.5%		-45.4%
Investment analysis	Dwelling appraisal					**$ 20,163**		$ 21,061		$ 21,165		$ 23,009
	Improvements costs / Dwelling appraisal							**5.8%**		**9.0%**		**15.7%**
	Variation of appraisal							4.5%		5.0%		14.1%

Table 4. Economic evaluation of life cycle costs for energy retrofitting

4. Analysis of Results

Data was obtained on ambient temperature, pressure, and wind speed and direction in the locality. With these values, a simulation was conducted to understand the behavior of the system both in its initial state and with the incorporation of improvements, in order to study their energy and economic projection. During the study of the initial cases, it was observed that practitioners who carry out simulations on the implementation of different improvements take into consideration default parameters, scientific reference data or criteria based on experience. However, to reduce demand it is necessary to scale logical analysis by studying each solution separately, then each package of solutions, and finally their total. Otherwise, distortions occur regarding the effectiveness and hierarchy of each solution.

The technical feasibility of the solutions involved in improvement should include market assessment. This means that suppliers, their products, the particular specifications and construction process are made known. It is not easy to establish in advance the weaknesses that each solution may present during implementation and performance, but it is desirable to develop tests or prototypes that provide clarity on the techniques, substrates upon which improvements are applied, weather conditions, production scales, reuse of materials and maintenance measures. This becomes relevant when carrying out the economic analysis, as it varies the costs of each building solution or package of solutions. However, contractors and government agents responsible for the inspection of quality standards must show a degree of technical competence, construction activity planning and knowledge of relevant regulations. Currently, improvement proposals in the area are supported by thermal improvement subsidies from the government's Housing and Urban Planning Service (SERVIU) through the Social Housing Management Entity (EGIS). The ideas studied for the energy rehabilitation of housing involve proposals for improving the envelope with external insulation in semi-detached and detached dwellings. Investments range from $3,950 to $8,000 USD and comply with the standard for envelope, window, roof, ceiling and floor improvements. In walls, the enhancement involves exterior cladding systems on the market. In the south-central area of Chile, the proposed solutions focus on design weaknesses prior to the implementation of the Thermal Regulations [5] due to a lack of attention to technical specifications. For example, the relationship between the ceiling insulation and roof height, and the ventilation system and its air chamber, where thermal bridges are generated.

Furthermore, considering the occupants or users in evaluating improvements has significant value, since the purpose of the improvements is to raise the standards of the dwelling and quality of life of its inhabitants. Upon analyzing the case study surveys, it was demonstrated that there was a change in environmental parameters within the dwelling which are perceived positively by users.

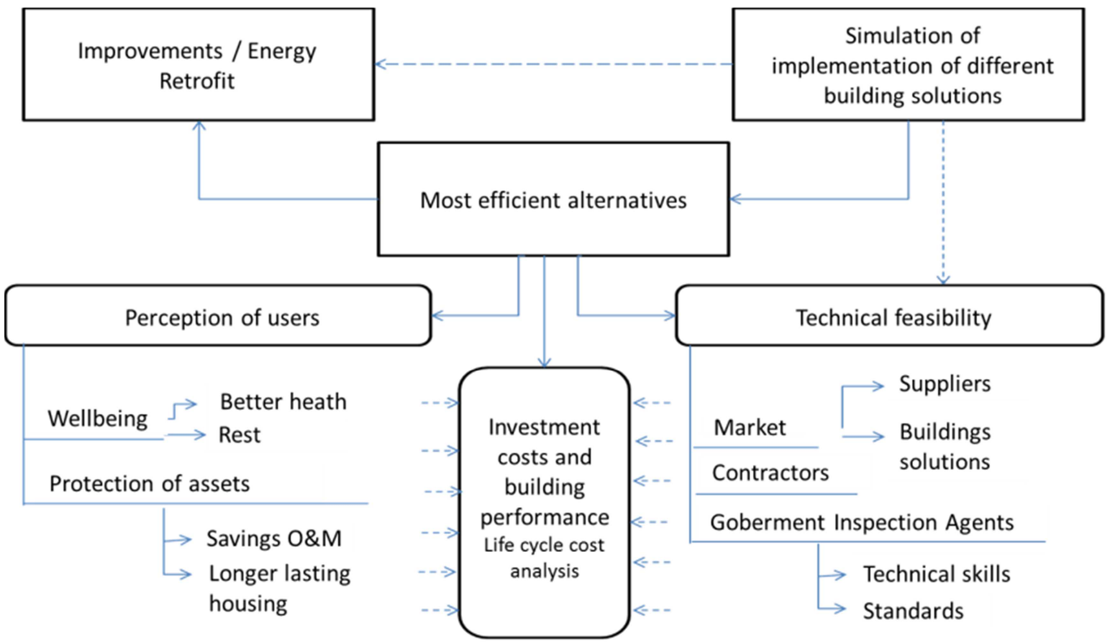

Fig. 2. Study methodology for the efficient improvement of housing. Source: Author.

This proposal also focuses on taking advantage of the power of improving information on energy use in dwellings, and user habits and perception to develop more effective analysis criteria over time. For example, family groups were interviewed as part of a thermal improvement program currently being carried out in 158 dwellings in the Municipality of Chiguayante and information from previous government analyses [15] was reviewed. It was observed that there are instances of public monitoring of user perception and analysis of results of improvement programs, but that the indirect benefits and lower costs are not recorded in relation to energy savings. Improved quality of life conditions, such as acoustic insulation, lower indoor humidity, decreased health costs and psychological wellbeing are factors that translate into benefits for dwelling inhabitants. In the case study, similar opinions were recorded, but prolonged monitoring over time is required to obtain conclusive criteria regarding family habits and the benefits resulting from energy retrofitting.

5. Conclusions

The process of housing improvement is evolving from its current perspective of status development and is affected by the dynamics of the construction industry.

Subsidies for housing improvement in Chile, which encourage energy retrofitting, are an effective measure that helps protect family assets and enables the reduction of energy consumption in the country's dwellings. From the perspective of financing, the opportunity exists to develop strategies for credit at lower rates than traditional banks in order to promote an increase in the improvement of middle-class dwellings.

Improvement packages for energy retrofitting can include modifications in design or mechanical systems, the optimization of which requires the participation of qualified construction professionals and building occupants. In addition, this could be more structured in the package implementation evaluation process, as shown in Fig. 2. The methodology can be used in large-scale retrofitting or construction programs, particularly in programs of Latin American governments, which are similar to this topic.

The proposed methodology connects knowledge of architectural simulation and energy efficiency technologies to finance a strong search for effective returns on investment in housing improvements. The investment in improvement is not paid for only by energy savings, but rather depends on several important factors such as the discount rate, period of analysis and fuel price escalation rate. Also, indirect costs occurring during the housing life cycle due to energy retrofitting, related to aspects of inhabitant health and building appraisal should be considered among others.

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