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Reconciling Energy and Heritage: Retrofit of Heritage Buildings in Contexts of Energy Vulnerability

María Beatriz Piderit [1,*], Susan Agurto [2] and Laura Marín-Restrepo [2]

[1] Department of Design and Theory of Architecture, University of Bío-Bío, Concepción 4081112, Chile
[2] Faculty of Architecture, Construction and Design, University of Bío-Bío, Concepción 4081112, Chile; susan.agurto@gmail.com (S.A.); lmadim@gmail.com (L.M.-R.)
* Correspondence: mpiderit@ubiobio.cl; Tel.: +56-(41)-311-1120

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Abstract: Chile is a resilient country which has been struck by a series of natural disasters, affecting heritage areas whose inhabitants live under a great economic and energy vulnerability. Although there are some advances that have been made in the country to recover its heritage, these do not include energy efficiency parameters. In this context, intervention in heritage properties requires a specific, complementary treatment above and beyond what is currently applied. Consequently, this research aims to develop a methodology that balances heritage and energy in energy vulnerability contexts. The proposed methodology analyzes heritage and energy aspects separately through attribute matrices, as well as the building pathologies, to later integrate the results in a final matrix which allows defining an energy-heritage intervention plan. In this way, it includes the systematic identification of elements that require intervention because of pathological issues, as well as the type of intervention that would be acceptable given its heritage significance and whether they mean a possibility to optimize the energy performance. The methodology, for its validation, was applied in a heritage residential building inhabited by low-income occupants. The case study presents physical damages and is located in the city of Lota, an area with an outstanding cultural heritage from the mining era.

Keywords: energy retrofit; heritage buildings; assessment methodology; energy vulnerability; historical residential buildings

1. Introduction

During the last 12 years, Chile has aligned with global efforts to reduce energy requirements by generating its energy standards, namely the Thermal Regulation included in 2007 within the General Ordinance of Urbanism and Building (OGUC in Spanish) [1], along with policies that look to increase energy standards, like the National Urban Development Policy [2], the Sustainable Construction National Strategy [3], the Regional Urban Development Strategy [4], and other projects like the Housing Energy Rating System [5] and thermal conditioning programs for housing. Nevertheless, these do not address heritage buildings that often need to be restored, since they are affected by natural disasters.

Due to the great number of natural catastrophes which Chile experiences, 43% of which have occurred over the last 30 years [6], maintaining tangible heritage is a complex task. These events, in particular the earthquake of 27 February 2010, have made evident the vulnerability of the heritage buildings. According to [7], as a result of the aforementioned earthquake, 75 heritage buildings had severe damage, and 3 were completely destroyed. These precedents have led to policies that fostered the reconstruction and improvement of damaged heritage properties. The *Consejo de Monumentos Nacionales* or National Monuments Council (CMN), the Chilean public institution in charge of protecting national heritage, presented the General Guidelines for Reconstruction of Typical or Picturesque Areas [8] outlining the values and attributes to be preserved. There are also housing programs to add value of countryside heritage and post-earthquake improvement programs for heritage homes. However, these guidelines are rigid and inaccurate, lacking a methodology which allows an energy retrofit within a context of energy vulnerability, a frequent reality in Chilean heritage areas.

The energy vulnerability is defined by [9] as "the propensity of an individual to become incapable of securing a materially and socially needed level of energy service in home". According to [10], 15.7% of households in Chile are exposed to this situation. In this way, in a context framed by natural disasters and energy vulnerability, heritage buildings need to be resilient, as [11] stated. From the definition, they must resist and absorb, adapt and recover from natural disasters efficiently, integrating conservation and restoration as essential elements [12]. From a heritage conservation perspective, "protection of cultural heritage may help to strengthen the resilience of the community and reduce the impact of a catastrophe" [11], and this should include energy requirements, helping to revitalize heritage buildings.

Notwithstanding, there is a gap between energy and heritage initiatives in Chile. On the one hand, historic homes fall within energy vulnerability and segregation aspects, while having comfort condition deficiencies. On the other hand, the energy standard and housing improvement programs do not include heritage conservation criteria. At the same time, the heritage recovery programs do not have specific energy requirements.

In this sense, there is a lack of standards or guidelines that encourage overcoming energy vulnerability, while conserving and valuing heritage. For this reason, this work looks to develop a methodology that allows making energy and heritage values compatible to define an intervention plan that allows designing energy-heritage retrofitting solutions that apply to an energy vulnerability context. In this context, it is fundamental to balance heritage and energy values, as well as having an assertive process that allows identifying optimal strategies to have economic viability.

International Picture

The increasing global demands to reduce energy use have encouraged an ever-growing international interest to define methodologies that balance heritage and energy [13], particularly in the European Union, where at least 30% of its built stock are historic buildings [14,15]. Research and published papers have been concentrated in countries like Italy, Spain, the UK, Sweden and Portugal. They have identified energy retrofitting as a chance to recognize heritage [16], even when their legislation to reduce buildings energy requirements, including the Energy Performance Directive (2010/31/EU) and Energy Efficiency Directive (2012/27/EU), exclude the historic buildings [16–18]. In the same sense, considering the aforementioned exclusion, every country has had the option to implement their energy requirements for heritage buildings [17,19]. This has resulted in multiple projects like EFFESUS and 3ENCULT [20,21], as well as diverse procedures and methodologies [22–27] to integrate these two areas and to define common principles [19,28].

The European Standard, EN 16883:2017 [29], was recently published and presents a systematic methodology to choose measures which improve the energy performance of a building, acknowledging its heritage. The process proposed by the standard represents the main approach found in the literature to balance energy and heritage; selecting energy retrofitting measures depending on their impact on the heritage.

However, the strategies' selection criteria stated in the literature are, in most cases, subjective. Usually, they are addressed by a multidisciplinary group of experts, and in some cases, there are some decision-making tools to help to identify the best strategies and to remove unsuitable ones. These tools are mostly qualitative, like the risk-benefit table which the standard proposes, based on the research of [20,30], as well as the impact evaluation through matrices or charts like those suggested by [24,31]. Few studies have tried to develop a quantitative approach, as is the case of [32,33]. They propose an analytic hierarchy process and multi-objective optimization, using genetic algorithms, requiring specialized people to perform the process. Nevertheless, as stated by [34], the decision-making tools described above do not specify the theory that supports the methodology to evaluate the impacts on the heritage significance.

Similarly, the heritage significance definition is one of the aspects where there is no common ground [16]. It is, in most cases, a subjective decision without a theoretical background. The heritage significance is usually done through different methods that range from arbitrary decisions to multidisciplinary groups [20]. In all the reviewed methodologies, it is mentioned that this definition must be done, but it is not clear how to do it or which criteria have to be considered. In concordance with [13], in the literature, usually the definition of the heritage value is not described, and few studies analyze the theoretical framework for it.

Atkins, Emmanuel and Hermann (2018) propose the application of a "conservation statement" as a guide for the selection of strategies, a document which sets out what is significant along with the policies which are appropriate to guarantee this significance [35]. Eriksson et al. (2014) propose an identification system of the heritage significance in three aspects: Physical, visual and spatial, with this being one of the few studies which sets out a systematization in the definition of this aspect [36].

Concerning the energy efficiency measures, possible retrofitting strategies usually concur. They can be summarized as interior insulation, airtightness and moisture protection, windows improvement and shading, heat recovery ventilation, daylight and artificial lighting optimization, passive heating and cooling and integration of renewable energy sources [37,38]. Nevertheless, there is a general agreement that in heritage buildings the application of measures must be seen case by case, considering the particular impact on heritage [13]. Because of this, most studies are focused on the assessment and execution of the measures, that usually are appropriate only to the cases where they were applied [13].

Considering the above, neither the particular measures nor the methodologies developed in another context, could be applied in energy vulnerability contexts. Greater precision in the process is required, making assertive decisions that meet several criteria [39–41]. However, considering that at the international level efforts have been made to define a conceptual and procedural framework focused on energy rehabilitation of heritage buildings, this study starts from the general methodology but proposes a step with a different approach. It takes advantage of the fact that heritage recovery must intervene elements with pathologies and use them as a tool to select the energy efficiency measures objectively.

Therefore, the proposed methodology analyzes the heritage aspect and the energy aspect separately through attributes matrices, as well as the building pathologies, to later integrate the results in a final matrix which allows defining an energy-heritage intervention plan. This methodology is validated through the application in a building located in the city of *Lota*, an area with an outstanding cultural heritage from the mining era [42] where 20.1% of the population is in poverty [43] and faces energy vulnerability. The case study is a heritage residential building, inhabited by low-income and energy-vulnerable families, thus requiring a different approach for heritage conservation. The building dates from the start of the 20th century and presents physical damages, constituting a compelling case study.

2. Materials and Methods

The methodology proposed looks to balance energy and heritage in energy vulnerability contexts, through a shift in the usual approach. It is an evaluation of the building's components and the definition of elements with intervention potential, rather than the exclusion of strategies according to the impact of the energy measures on the heritage values. The proposed approach considers that in a context of energy vulnerability, where the resources for intervention are scarce, the aim is a rehabilitation process optimization. In that way, the necessary interventions because of building's damages are seen here as an opportunity for energy optimization.

Considering the above, an additional step, based on the constructive elements, is included in the general process presented in the EN 16883:2017 [29], as Figure 1 shows. This step, named the heritage-energy intervention plan, serves as a tool to make an objective selection of the energy retrofitting measures to be implemented. It includes the systematic identification of elements that require intervention because of pathological issues, as well as the type of intervention that would be acceptable given its heritage significance and whether they mean a possibility to optimize the energy performance.

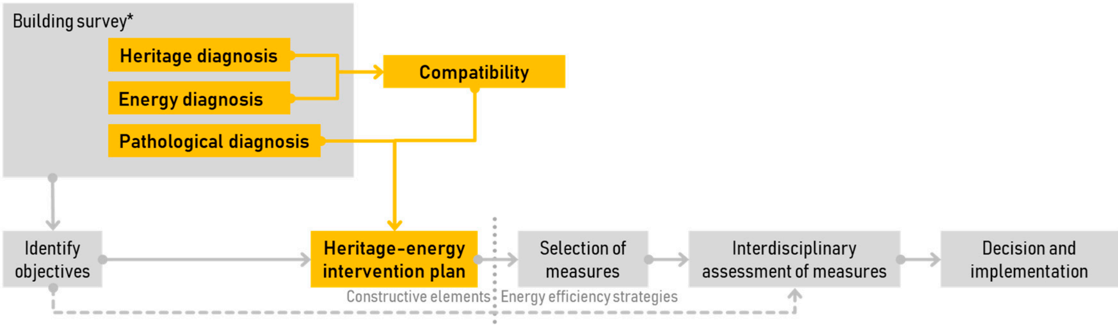

Figure 1. General procedure for energy retrofitting in heritage buildings, based on [29] and integrating the energy-heritage intervention plan.

The heritage-energy intervention plan is generated from the heritage, energy and pathological diagnosis. The heritage diagnosis determines the elements heritage significance, while the energy diagnosis identifies the elements which most affect the building's thermal balance. These two diagnoses are cross-checked in a matrix to define the compatibility between energy and heritage, looking for components with high saving potential and low heritage significance, since they allow major modifications. The heritage significance defines which type of intervention can be done. The matrix also ranks the elements, prioritizing those which have a high energy-heritage compatibility and have critical pathologies.

Since the general process follows the EN 16883:2017, this paper will focus on the methodology to generate the heritage-energy intervention plan, rather than the possible solutions to be implemented in heritage buildings. These solutions constitute the next step in the methodology and need to be developed carefully and in a specific way for each building, as [16] said.

The methodology, for its validation, was applied in a set of homes named "Pavilion 49", declared national historic heritage buildings. As previously mentioned, this paper presents the construction of the heritage-energy intervention plan for the case study, as a decision-making tool for the future selection of the best energy measures for its retrofit, a step beyond the scope of this article.

2.1. Case Study

Pavilion 49 is a set of collective mining homes located in the city of Lota (37°S, 73°W), an extremely poor mining area in the South of Chile. The city of Lota has been, at both a regional and national level, an example of Coal-Mining Industrial Heritage and attempts for its preservation. This coastal settlement grew as a result of the industry, and its urban planning and architectonic typeset correspond to foreign patterns, mainly English ones that have been adapted to the territory [42]. The sector of Lota Alto (High Lota) was declared a Heritage Zone in 2014, opening up an opportunity for the protection of its social, economic, urban and architectonic values.

The working-class Lota home, popularly known as "pavilions", is defined by a modular wood architecture, following the camp prototypes of English mines. In most cases, the first floor is built from masonry, while the second and third are built from wood [44]. Figure 2 presents the location of the case study, *Pavilion 49*, and images from its original conditions and current state (2017).

Location of Pavilion 49	Pavilion, Original Conditions	Image of Pavilion 49, from October 2017-Lota. (Photograph: Susan Agurto)

Figure 2. Case study location and images from original and 2017 conditions.

2.2. Building Survey

All the base information about the property being studied is collected in the building survey. For the property's diagnosis, field work to collect information must be considered. This includes the identification of pathologies, architectonic features, interviews with owners and the community, photographic records, as well as observing the use of the homes. Likewise, the specific architectonic and urban records must be studied, collecting administrative information, technical specifications and planimetry.

Moreover, it is necessary to study the place where the property being analyzed is located, performing a climatic characterization, including the type of climate, temperatures, relative humidity, prevailing winds, solar radiation, predominant skies and the rest of the information that allows understanding the location and its possible energy requirements and variations over time.

For the energy aspect, information must be collected about the property's current energy situation, looking to determine its energy requirements with an energy audit [45,46]. For this, a survey of the constructive elements must be made, considering materiality and its physical features, which are then compared with the applicable regional standard. Likewise, the property's energy demand must be known in terms of electricity, heating and cooling, if these exist. This information can be complemented with the building's current energy consumption, if the property is occupied and has these records, using electricity bills or another energy quantification option.

Likewise, where possible, a diagnosis of the building's thermal behavior must be made using Non-Destructive Testing (NDT) techniques [45]. These techniques allow identifying thermal bridges, defining transmittance values, identifying the air infiltration level, among other aspects. More detail about these techniques can be reviewed at [47,48]. Nevertheless, in some cases, particularly in low-income contexts, this may not be possible because of their costs and need of trained professionals. In those cases, a walk-through audit may be enough to identify deficiencies and broadly characterize the building's components. Although an accurate energy audit and performances could not be obtained in that way, the data can be used as a reference for comparisons and to identify the strategic elements to intervene.

2.3. Heritage Diagnosis

Heritage diagnosis implies an analysis of the property and its surrounding area, aiding to understand the heritage values of the building. Procedures and forms of the MINVU circular DDU 400:12-02-2018 [8] are taken as reference to carry out the general heritage valuation, before then analyzing the architectonic and constructive elements through a matrix which determines its heritage significance.

Information of the use and ownership is recorded through the diagnosis form of the Historic Conservation Property, alongside reviewing the property's values and attributes, as well as the morphological features and state of conservation and alteration of the building. The form also includes a summary of the attributes' score, which is then computed following the diagnosis table for the Historic Conservation Property. This table identifies the urban, architectonic, historic, economic and social heritage value of the property, by evaluating different attributes associated with each category. For further reference about the definition of values and attributes, please review Circular DDU 400 [8].

The valuation of each attribute is made on a scale of 0 to 2, where "2" is the highest score, corresponding to an attribute which highlights or contributes to the heritage value; "1" is the equivalent of an attribute which contributes or which does not affect the value, and "0" is an attribute which devalues or does not contribute heritage value. In this way, the maximum score that can be obtained is 24 points, with 10 being the minimum for the property to be considered a heritage property. The categories where the building has the highest heritage value can be established in this way, identifying whether the architectonic aspect is one of these, for a first approach to the degree of protection that the built space could end up having. Table 1 presents the application in the case study.

Table 1. General heritage valuation. Pavilion 49, Lota-Chile. Own preparation from [8,44].

Value	Description	Attributes			
		A	B	C	Points
Urban	This constitutes an urban typology with real originality and hierarchy that strengths the local landscape's heritage identity. It stands out as a consolidated formal unit, with high urban spatial quality and one which defines an area of the city around Carlos Cousiño road. The longitudinal spatiality of this road is reinforced by the pavilion's horizontal proportions. It adjoins urban heritage landmarks.	2	2	2	6
Architectonic	It has some singular constructive technological features. It represents a relatively rare architectonic typology corresponding to the collective Lota mining home with a corridor. This has some artistic quality elements like the balconies of the main facade and the corridor's pillar joints.	1	1	1	3
Historic	This is an exponent of a significant period of local social and urban development. It has been researched and published in specialist history or architecture books.	2	2	2	6
Economic	The pavilions have a regular state of conservation. Only some buildings have been retrofitted or restored.	2	1	-	3
Social	It has a strong recognition as local heritage by the community.	2	-	-	2
	TOTAL VALUE				20

Later, the emphasis is made on the property's architectonic and constructive elements, which are those that permit a physical intervention for energy improvement. The construction of a heritage target image must be made to define the elements of the property that must be preserved, identifying and categorizing the elements the architecture comprises as per their significance. The use of a table structured by aspects, criteria and features of the significant elements for the heritage to be safeguarded is suggested. Although the aspects and criteria may vary from project to project, Table 2 presents some guidelines, applied in the case study.

Table 2. Characterization of significant heritage elements—Pavilion 49, Lota-Chile. Own preparation.

Aspect	Criterion	Features to be Safeguarded
Surroundings	Integration with the environment	It integrates with the surroundings, as it fits the setting's local implementation patterns.
	Urban Landscape	The public space, the sidewalk, is part of the pavilions volume.
	Urban Morphology	It reinforces the linear configuration of Carlos Cousiño Street. Spatial linearity that the building forms.
	Outdoor paving	Originally cobbles through Lota Green's access corridor.
	Outdoor built elements	The old ovens are found on the pavilion's rear facade and were the place where food was cooked.

Table 2. *Cont.*

Aspect	Criterion	Features to be Safeguarded
Morphology	Shape/Volume	Solid and regular, 2-level horizontal parallelepiped.
	Height	All the pavilions have 2 floors and an average height of 6.8 m.
	Roofing	It has a hole made by the Chimney shaft and transoms in blind spaces on the home's second level. Gable roof with an average pitch.
	Other formal elements	The access space to the homes. Intermediate space between the city and home with a great spatial-functional view.
Formal expression	Rhythm of the facade	The design has been structured based on the minimum sizes in homes and on the total height. The height from floor to ceiling is 6.18 meters and the home's width is 3.5 to 4.1 meters.
	Composition of the facade	The openings maintain a vertical proportion versus the facade.
	Materiality	The flooring is placed horizontally, highlighting the horizontal proportion of the urban space formed by the pavilions and Carlos Cousiño Street. Masonry coated with stucco and wood on the second floor. Native wood doors and windows.
	Color	Originally the material's natural color.
Construction elements	Meeting of supporting beams and pillars along the corridor.	They are elements which have been kept despite some repairs.
	Wainscots	Finishing at each end of the mezzanine floor framing, over the access corridor.
	Struts	Bracing system of the pillars to the beams.
	Pillars	6″ × 6″ scantling frames on a metal base.
	Windows	The window is placed on its inner frame and is formed by a wooden frame, with simple glass and by a wooden shutter system. Closing is through a two-sheet folding system.
	Windowsills	These have an important role in the home's airtightness and highlight the set of windows.
	Chimneys	The chimneys stand out on the pavilion's roof volume. They also stand out, because the implementation of a heating system was not common for this type of home during the period.
Ornamental elements	Lamps	There are original forged iron coal lamps from the mining lighting system, known as *chonchón*.
	Window boxes	The main facade under the second-floor window considers an engraved wooden window box.

Heritage significance is determined following a professional criterion and must also include the appreciation of the community and users of the property in question. Qualitative information collection methods must be used to do this, such as surveys and interviews, looking to identify the aspects of the building that should be protected, depending on what the community values.

Once the features that define the architectonic heritage character have been discriminated, the heritage significance of the constructive elements is assessed using three criteria, adapted from [20,29,36]. These are the visual, associated with the aesthetic expression, the material, related to the materiality, and the spatial aspects, connected with the morphology and spatial proportions. This allows recognizing the aspects which define the heritage character of a certain element, which also allows differentiating the conditions that must be safeguarded and ones which are susceptible to intervention.

The heritage significance associated with the constructive elements susceptible to energy improvement is recorded in Table 3, identifying the aspects which give heritage value to the element. For this, the method proposed in the EFFESUS project [24,36] is taken as reference. This categorizes the heritage significance on a 5-point scale, as seen in Table 4, defining the level of heritage significance for each aspect. In addition, the table includes a column to select the maximum level registered in visual, material or spatial significance, as well as a column to make comments to differentiate the aspects which provide heritage character to the element.

Table 3. Construction elements heritage significance—Pavilion 49, Lota-Chile. Own preparation.

	Heritage Significance				
Element	**Visual**	**Material**	**Spatial**	***Maximum***	**Comments**
Walls (ext)	3	3	2	***3***	Flooring in machined wood
Windows	3	3	1	***3***	Proportion, decorative elements. Native wood
Roofs	1	2	2	***2***	Heights
Floors (first floor)	0	0	0	***0***	Floors are not original
Floors (mezzanine)	2	2	1	***2***	Structure and joints
Partitions (int)	0	0	1	***1***	Spatial layout
Doors	1	3	1	***3***	Native wood

The highlighted column is used in Table 8.

Table 4. Heritage significance levels. Adapted from [36].

Level	Heritage Significance	Description
0	Neutral or negative	Does not define the character of the property. Loss or damage would not be considered problematic and might even be considered beneficial
1	Minor	Slightly defines the character of the property. Loss and damage might be considered acceptable
2	Major	Defines part of the character of the property. Loss might be considered acceptable under special circumstances; damage should be minimized
3	Outstanding	Substantially defines the character of the property. Loss is considered unacceptable and damage should be kept to an absolute minimum
4	Exceptional outstanding	Exceptionally defines the character of the property. Any form of damage or loss is considered completely unacceptable

2.4. Energy Diagnosis

Table 5 is proposed to survey the constructive elements, identifying their material and thickness, as well as their thermal transmittance of U Values (w/m^{2}k). For an accurate assessment, the U values must be measured in the field with the corresponding technique. However, since this is not always possible and depends on the availability of equipment and trained professionals, in situations where there are not enough resources, the U values can be estimated according to the composition of the elements. In this case, the data will not be accurate, but would still allow identifying the elements with weak performance. The reference standard indicated in the table is the maximum value accepted by the current applicable standard, in the case of Chile, it is the OGUC Art. 4.1.10 [1]. The last column is the difference between the building elements' U value and the regulation reference. If this is positive, the element does not comply with the regulations and therefore has the potential for improvement.

Starting from Table 5, the elements that do not comply with the standard, or that have very high U values in comparison with reference levels, are identified, making them susceptible to energy optimization.

On the other hand, the analysis of the energy balance can be calculated through simulation software, either under seasonal or dynamic regimes. Depending on the goal of the retrofitting, the volume that will be analyzed, and that will be considered as the property's thermal envelope, must be defined. Likewise, the border conditions such as the orientation, occupation density, scheduling of the home's periods of use, metabolism of the people inhabiting the property, air infiltration, type of ventilation, must be decided. Regarding thermal comfort ranges, in the Chilean context and for naturally ventilated buildings, the use of adaptive thermal comfort is recommended. It must be considered that in energy vulnerability contexts, these ranges may respond to different variables, and in the Chilean case, it has been found that the lower limits could be lower than international regulations [41].

Table 5. Construction elements thermal transmittance—Pavilion 49, Lota-Chile. Own preparation.

Construction Element	Material	Thickness (cm)	U Value (w/m^{2}k)		
			Building Studied PAVILION 49	Reference Standard (OGUC Art. 4.1.10)	Building—Standard Difference
External wall	Masonry	30	1.61	1.7	−0.09
2 × 4 perimeter partition	Wooden flooring	14	1.18	1.7	−0.52
2 × 2 perimeter partition	Wooden flooring	11	1.26	1.7	−0.44
Roofing	Wood	27	1.06	0.38	0.68
Windows	simple glazing	0.33	6.25	2.56	3.69
Floor	Slabs + tiles	10	1.24	NA	-
Ventilated floor (mezzanine)	Wood	16	1.35	0.6	0.75

If the current energy consumption of the property is available, the model can be calibrated, as long as suitable border conditions are identified. EN 15603:2008 can be used as a reference. Otherwise, the simulation will only take this as reference to make comparisons and to determine the percentage of performance improvements.

The influence of the different construction elements in the energy balance must be set. For this, the Design Builder thermal balance tool can be used, under the free-cooling modality. This will indicate the gains or losses through construction elements like glazing, walls and ground, as well as through ventilation and the internal gains due to radiation, occupation, lighting, pieces of equipment and others. Likewise, the heating or cooling design can be simulated under a seasonal regime, to determine the elements that most affect the energy demand of these systems. The main opportunities for the energy retrofitting can be identified from this data.

The energy losses or gains that the different construction elements represent are identified through the Table 6, determining the degree of influence that they have on the energy balance through the proportion of the building's total losses that the element represents. The effect that an element has on the energy balance can be assimilated to an energy-saving potential since the element's intervention could reduce the losses in that proportion. In this way, depending on their percentage, the elements are classified according to their energy-saving potential. Considering the possible reduction when applying thermal regulation [1,49,50], a high saving potential is considered as over 30%, medium as between 5% and 30%, and low as less than 5%. This may vary depending on the project and the total percentage distribution. It is important to consider that this table is set up for a context where the highest energy requirement is through heating. Besides, the list of construction elements should be differentiated by orientation or areas according to the discrimination made in heritage significance or pathologies.

Depending on the type of problem identified, this impact can equate to higher heat losses in winter, representing a higher energy demand for heating, or gains not dissipated in summer, representing higher cooling demands. In the context of southern Chile, the challenge is often found in reducing the heating requirements but maintaining a balance which does not imply needing cooling in summer.

Table 6. Energy saving potential due to energy balance effect on Pavilion 49, Lota—Chile. Own preparation based on Design Builder simulation results.

Element	kWh/m²/year	% Total	Saving Potential
Walls	−90.9	67%	**High**
Windows/Glazing	−13.7	10%	**Medium**
Roofs	−3.2	2%	Low
Floors (first floor)	−0.5	0%	Low
Floors (mezzanine)	−2.9	2%	Low
Partitions (int)	0.0	0%	Low
External Infiltration	−20.5	15%	**Medium**
External Vent.	−3.9	3%	Low
Total losses	−135.6		

The highlighted column is used in Table 8.

On the other hand, considering that the homes in an energy vulnerability context must have the capacity to operate with passive strategies for as long as possible, it is suggested to make a diagnosis in terms of thermal, respiratory and light comfort, to identify problems and opportunities to optimize the performance of the home, reducing the energy requirement.

2.5. Pathological Diagnosis

Heritage buildings in energy vulnerability contexts which have been affected by natural events, normally have diverse pathologies that must be identified and considered for the retrofitting of the property. This must be done by an expert in the field, who recognizes the damages the property has (type of pathology), their possible causes and the risk level these involve.

The pathology risk levels may be critical, moderate or minimal. Based on the definitions from [51], the first one includes pathologies that can cause damage to the health and safety of the users and surroundings, like an excessive loss of performance of the building's elements or impossibility of use, increasing operation costs and significantly depreciating the property. On the other hand, a moderate risk involves pathologies that can cause the loss of functionality without interrupting the property's operation and imply small performance losses, which can be recovered on a one-off basis and that represent a minor depreciation of the property. Pathologies which mainly affect the building's aesthetics, not compromising its stability or functionality and that can mean a minor depreciation of the property belong to the minimum risk. The recording of the information gathering is made in Table 7.

Table 7. Pathology diagnosis—Pavilion 49, Lota-Chile. Own preparation based on [52]. For an extended version with images, please see Appendix A.

Element	Type of Pathology	Pathology Risk	Probable Cause	Comments
Masonry external walls	Cracking	**Moderate**	Natural event (Earthquake 27/2/2010)	The cracks mainly appear on the home's external walls.
Wooden external walls	Out-of-plumb	**Minimal**	Execution	Concentrated on the edges of the pavilion.
	Attack of xylophagous insects	**Moderate**	Maintenance	The wood has damages on the boarding.
Roof	Broken roof	**Critical**	Natural event (Earthquake 27/2/2010)	The breakage is concentrated around the chimney.
	Rotting	**Moderate**	Maintenance/ Execution	Humidity damage on the second-floor ceiling caused by rainwater seeping through the roof.
	Attack of xylophagous insects	**Moderate**	Maintenance	The wood holding up the roof has damage.

Table 7. *Cont.*

Element	Type of Pathology	Pathology Risk	Probable Cause	Comments
Mezzanine	Loose supporting beams	**Critical**	Natural event (Earthquake 27/2/2010)	The main problem is concentrated on the beams visible in the access corridor.
	Deformations	**Moderate**	Use	Resulting from the fatigue of the mezzanine beams due to age.
Interior walls	Humidity	**Moderate**	Project/ Maintenance	Signs of humidity due to condensation.

The highlighted column is used in Table 8.

2.6. Heritage-Energy Intervention Plan

To integrate heritage values and energy requirements in a scenario that is compatible with both aspects, an "Energy-Heritage Compatibility Matrix" has been designed, where the results of both evaluations for the construction elements are recorded and integrated. This matrix, presented in Table 8, is linked to the highlighted columns of Tables 3, 6 and 7, so the features of each element can be seen with regard to their energy saving potential, heritage significance and if they have pathologies. At the same time, the heritage-energy intervention plan is proposed.

Table 8. Compatibility matrix and intervention plan—Pavilion 49, Lota-Chile. Own preparation.

	Diagnosis			Heritage-Energy Intervention Plan		
Element	**Heritage Significance [max]**	**Energy Saving Potential**	**Pathology Risk**	**Heritage-Energy Compatibility**	**Probable Intervention Type**	**Ranking**
Walls	Outstanding	High	Moderate	Medium	Controlled	2
Windows	Outstanding	Medium	Non-existent	Medium	Controlled	3
Roofs	Major	Medium	Critical	Medium	Controlled	1
Floors (ground)	Neutral	Low	Non-existent	Low	Major	5
Floors (mezzanine)	Major	Medium	Critical	Medium	Controlled	1
Partitions (int)	Minor	Low	Moderate	Low	Major	4

The highlighted columns are extracted from Tables 3, 6 and 7 respectively.

The list of the constructive elements considers the list where the most differentiated elements are. The heritage significance considers the maximum level recorded in all the types in Table 3. This may be essential, important, major, minor or negative/neutral depending on Table 4. The energy saving potential may be high, medium or low, corresponding with Table 6. The pathology risk corresponds to Table 7 and may be critical, moderate, minimal or non-existent if the element does not have an associated pathology. If the element has more than one pathology, the most critical one should be chosen. The column ranking prioritizes compatibility between energy and heritage and the risk of the pathology.

The compatibility between heritage and energy is defined as the relationship between the element's heritage significance and its energy-saving potential. The ideal compatibility is determined as one where the saving potential is high and the significance is minor or neutral, given that the element can be intervened to the maximum level to optimize energy performance, without affecting the building's heritage value. Table 9 is considered as a reference.

The type of intervention that the construction element admits may be major, controlled or just recovery, depending on the heritage significance, following the definitions in Table 10. The probable intervention in Table 8 is a general guide to make the intervention plan and as a supply of sorts for an initial strategy selection stage. Once the strategies have been chosen, they must be assessed according to their impact on each type of heritage significance for their final selection, given that the type of intervention may vary depending on the solution being applied. For this reason, it is suggested to apply the impact assessment methodology proposed in [24], which can be directly cross-checked with the data of Table 3.

Table 9. Compatibility between savings potential and heritage significance. Own preparation.

Compatibility	Description	Heritage Significance	Energy Saving Potential
High	High energy savings potential. The element must not be protected	Neutral/negative or Minor	High
Medium	High energy savings potential. The element must be slightly protected	Major or Outstanding	High
	Medium energy savings potential. The element must not be protected or must be slightly protected	Neutral/negative, Minor, Major or Outstanding	Medium
Low	Regardless of the savings potential, this is an element that must be protected, and no intervention is accepted	Exceptional outstanding	High, medium or low
	Regardless of the heritage significance, this is an element that does not have energy savings	Neutral/negative, Minor, Major, Outstanding or Exceptional outstanding	Low

Table 10. Type of possible intervention depending on heritage significance. Own preparation.

Type of Intervention	Description	Heritage Significance
Recovery	Elements which define significant visual, material and spatial features of the property that cannot be removed or subjected to any action that modifies their original form.	Exceptional outstanding
Controlled	Elements which define significant visual, material or spatial characteristics of the property, but that can be intervened in a controlled manner, depending on the type of relevance involved.	Major or Outstanding
Major	Elements which are not significant in the definition of the property's heritage characteristics and that, therefore, can bear major modifications.	Neutral/negative or Minor

The ranking for the intervention plan is defined depending on the compatibility between heritage and energy with the risk of the pathologies. This prioritizes the elements that have high compatibility and critical pathologies, ranking depending on the level of compatibility and pathology risk, with the elements with low compatibility and without pathologies coming last. This follows the logic that the elements with critical pathologies must be intervened whatever the case may be and it would be ideal to do so using energy efficiency criteria, if possible. Therefore, the priority level an element has can be identified with this table, depending on their contribution to the energy retrofit and heritage recovery. The same is right for the type of intervention that can be done, defining an energy-heritage intervention plan, so that the definition of the strategies matches the compatibility and the intervention budget.

3. Results

3.1. Heritage Diagnosis

Table 1 presents general heritage valuations for Pavilion 49, prepared from the definitions of [8]. Lota's Pavilion 49 scored 20 out of 24 points, which evidences its high heritage value. It can also be seen that the high value is found in the urban and historic contribution that it generates in the city, followed by the architectonic and economic value and finally the social value. Therefore, the architectonic aspect is not the aspect which contributes most to the property's heritage valuation, which would allow for certain modifications for its energy retrofitting.

In Table 2, it can be seen that in Lota's Pavilion 49, the elements with highest architectonic heritage value are concentrated on the pavilion's main facade, through urban spatial, ornamental and constructive elements like the access corridors, struts, wainscots on windows and the facade's unitary composition. The building's morphological situation on the rear facade is not homogeneous, given the great diversity and amount of interventions that owners have made to improve habitability and the quality of the spaces in the home. This implies that this facade could have greater modifications made without altering the heritage values identified at the property.

On the other hand, Table 3 presents the type of heritage significance of the architectonic/constructive elements susceptible to investment for the energy improvement of pavilion 49. It was found that external walls, windows and doors have an outstanding significance. The first two being particularly significant due to their visual and material importance, by defining the property's character.

3.2. Energy Diagnosis

Lota's climate is mainly characterized by its heating requirements. Cooling demands are not important in this climate as they can be easily controlled by natural ventilation by opening windows and with solar protection. The envelope is a significant parameter for Lota as heating demands, which are the most important demands for this weather condition, can be considerably reduced by the design or improvement of an efficient envelope. On the other hand, the most important features to consider for buildings in Lota, which affect interior environmental comfort are infiltration, orientation, glazed surface, and the envelope. Table 5 presents the thermal transmittance values for the construction elements of pavilion 49 and the comparison with the normative reference. It can be seen that the roof, windows and mezzanine do not comply with the norm, which immediately makes them elements that should be improved and that have the potential to affect the property's energy performance.

Upon structuring the energy balance results Table 6 was obtained, showing that the walls are the construction elements with the greater saving potential, followed by the windows and the roof. It is also clear that the external infiltration represents considerable losses for the home.

3.3. Pathological Diagnosis

Regarding the pathologies, a summarized version of the survey is presented in Table 7. The complete version can be found in Appendix A, including the photographs of the pathologies. The main issue detected is the wear of the construction elements, due to lack of maintenance, and construction deficiencies, as the original construction did not include insulation. On the other hand, sea salt was included in the construction technique in the masonry and stucco which, due to its composition, still generates condensation and humidity issues in the homes. The critical risk of the roof and mezzanine stand out.

3.4. Heritage-Energy Intervention Plan

The compatibility matrix Table 8 is built with the information collated in Tables 3, 6 and 7. It is seen that the roof and the mezzanine are the elements with the highest potential for energy intervention. There is also medium compatibility between energy and heritage, which suggests that the property allows optimizing energy performance if intervened in a controlled way. In addition, these elements present critical pathologies and as such their intervention is a priority.

The external walls may also be subject to intervention, since even though they have heritage significance, their energy saving potential is high, which means medium compatibility with controlled intervention. Strategies can be defined which respect the heritage but that, at the same time, optimize the performance and correspond to the moderate pathology. In this case, it is essential to know the types of heritage significance the element has, to later be able to assess the impact of the strategies on each one of these.

Taking this matrix and the heritage-energy intervention plan as a decision-making tool, it is possible to objectively select the solutions that integrate the identified elements. Multiple solutions could be proposed based on the characteristics of the elements.

4. Discussion

The improvement criteria of heritage buildings that are currently implemented in Chile do not include the concept of Retrofitting, and even though these allow generating internal and external improvements along with extensions of protected properties, there are no specific energy requirements to retrofit heritage buildings.

Heritage retrofitting in Chile is currently limited by the investment levels the interventions required. Therefore, it is necessary to propose management and simplification measures of the economic incentives and procedures for investors like bonuses or exemptions of payments, while including higher investment subsidies for heritage energy renewal. A multidisciplinary process is also needed with citizen participation, including a wide range of options in the solution decision-making process. This must include the owner or owners, the citizenry, along with the regulation institutions for heritage interventions.

International methods start by defining strategies and removing them depending on whether they meet heritage conservation criteria or not. In most cases, what is suggested is choosing energy optimization strategies following their impact on the heritage. This article proposes a shift of approach, starting by identifying elements that need intervention, their potential energy saving and heritage significance, considering them as a tool to choose the strategies and final measures to be implemented. It is important to note that the strategies are finite, but the measures can be varied. For this reason, the proposal is made to define the viability of intervening a building's component from an initial stage. A cost-effective approach is necessary for the solution's selection [53] after this step.

The methodology proposed to identify elements that are susceptible to energy heritage retrofitting interventions becomes the first step in an energy retrofitting process with heritage valuation, upon ranking following heritage significance and giving priority considering the property's physical-constructive pathologies. This given that if the energy retrofitting is compatible with the conservation requirements or, for example, with obligatory actions to improve the structural behavior and safety, then the strategies can be applied [54]. A similar approach is proposed by [23,55,56], focusing on structural and seismic retrofits. This is particularly relevant in the context of energy vulnerability, where resources are limited.

Heritage valuation allows using the architectonic aspect, through a detailed and flexible procedure, to assess the building's construction elements to define the intervention without losing the property's character. Each retrofit is individual and follows a specific diagnosis. Therefore, the interventions must be ranked following their goals or the framework identified in the proposed methodology. It must be considered that the results are subject to uncontrollable modifications since, on dealing with a heritage recovery and conservation project, the real status of the structures will be seen when these are dismantled. The means of addressing energy heritage retrofitting requires integrated action which safeguards not just the energy performance, but also the other conditioning factors, like the practical use and living behavior of the user of each property analyzed. In coherence with the environmental comfort concepts, it is necessary to consider local adaptive comfort ranges, considering the resilience of the inhabitants under energy vulnerability contexts.

The article speaks solely of energy saving potential through the optimization of the envelope, however other aspects like the occupant's behavior must be considered just as [57] suggests.

There is also a fledgling awareness of the energy vulnerability heritage properties have, which opens up a focal point for intervention and research, allowing for improving the quality of life while considering heritage and energy values. To move forward in these areas, it is necessary to promote awareness of Chilean heritage value, promoting heritage energy retrofitting, socializing the potential for this with the authorities who must then approve this type of project through the Chilean National Monuments Council, Municipal Works Directions, Ministry of Housing and Urbanism, Chilean Chamber of Construction, among others, to generate changes in Chilean regulations and policies. Changes which consider the project's technical standardization, emphasizing treatment of the envelope and roof, as well as the integration of NCRE to contribute to the primary energy demand, before finally in the context of vulnerability, providing financing to retrofit the homes.

5. Conclusions

Just like in other research, this article shows that it is possible to make heritage and energy compatible through a systematic process. However, it is focused on energy vulnerability and low-income contexts; therefore, it proposes starting from the identification of the elements that need to be intervened because they had pathologies and take advantage of that for energy optimization. At the same time, it balances energy and heritage quantitatively, by proposing a system for evaluating heritage significance and the potential for energy savings based on categories and the constructive elements, rather than the measures or strategies. This is a shift in the conventional approach since most of the proposed methodologies evaluate the impact of the energy strategies on heritage, mostly in a qualitative way that make it difficult in the objective selection of them.

Recovering heritage is an arduous task, but it must include energy efficiency criteria whenever possible, so that this is also valued, on improving the habitability conditions and energy performance.

Integration and compatibility of heritage and energy values require first recognizing and defining each one of the aspects that these comprise in existing buildings to then determine the degree of compatibility between them. In the case of existing protected buildings related to the standards, this recognition is even more complex as it involves a multifactorial analysis comprising mainly historical, environmental, social, economic, urban and architectonic aspects along with the user's needs and behavior. Therefore, the methodology designed generates a detailed and flexible procedure which allows addressing and valuing these aspects of the building, defining what to improve and how to do so without losing its character. In this sense, it is fundamental to consider a multidisciplinary process and citizen participation from the early stages of the project, including a broad range of opinions in the heritage-character definition.

With regards to Chile, valuation of heritage properties is rising, through different plans and programs that have been implemented since 2007 and that have been strengthened by the catastrophes over the last 8 years. As such, energy retrofitting in this type of building is becoming more and more pertinent, given that it provides a sustainable approach to interventions, contributing to the harmony and balance of the setting, preserving historic values, contributing towards overcoming energy vulnerability through energy savings produced via the property's construction quality.

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Appendix A

Table A1. Pathology diagnosis—Pavilion 49, Lota-Chile. Own preparation based on [52]. Full table including images.

Element	Image	Type of Pathology	Pathology Risk	Probable Cause	Comments
Masonry external walls		Cracking	Moderate	Natural event (Earthquake 27/2/2010)	The cracks mainly appear on the home's external walls.
Wooden external walls		Out-of-plumb	Minimal	Execution	Concentrated on the edges of the pavilion.
		Attack of xylophagous insects	Moderate	Maintenance	The wood has damages on the boarding
Roof		Broken roof	Critical	Natural event (Earthquake 27/2/2010)	The breakage is concentrated around the chimney.
		Rotting	Moderate	Maintenance/ Execution	Humidity damage on the second-floor ceiling caused by rainwater seeping through the roof

Table A1. *Cont.*

Element	Image	Type of Pathology	Pathology Risk	Probable Cause	Comments
		Attack of xylophagous insects	Moderate	Maintenance	The wood holding up the roof has damage
Mezzanine		Loose supporting beams	Critical	Natural event (Earthquake 27/2/2010)	The main problem is concentrated on the beams visible in the access corridor.
		Deformations	Moderate	Use	Resulting from the fatigue of the mezzanine beams due to age.
Interior walls		Humidity	Moderate	Project/ Maintenance	Signs of humidity due to condensation.

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