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A tool for universal accessibility assessment in the interior of dwellings

Herramienta para la evaluación de la accesibilidad universal al interior de viviendas

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ABSTRACT

The present study proposes a tool for assessing universal accessibility in the interior of apartments, presenting a novel quantitative model for assessing the accessibility of buildings for buyers or tenants. For this, a multicriteria analysis for aggregating the assessment indicators with different units and scales is employed using a unique grade of accessibility according to four main pillars: Autonomy, Mobility, Comfort, and Safety. The assessment method has been applied in 35 show apartments in the urban area of Santiago in Chile. This work shows the application and results of 4 departments. The evaluation results are presented visually with a circular bar plot and a final grade in letter format from F to A. In general, it is observed that the four apartments proposed have a low degree of accessibility (letters F to D). And, the Autonomy pillar is clearly the lowest pillar in the selected apartments.

Keywords: disability; private housing; autonomy; user comfort; mobility; safety.

RESUMEN

El presente estudio propone una herramienta para evaluar la accesibilidad universal al interior de viviendas, presentando un novedoso modelo cuantitativo para evaluar la accesibilidad de edificios para compradores o arrendatarios. Para ello se emplea un análisis multicriterio que reagrupa indicadores con diferentes unidades y escalas utilizando un único grado de accesibilidad para cuatro principales pilares: Autonomía, Movilidad, Confort y Seguridad. El método de evaluación fue aplicado en 35 departamentos en venta en el casco urbano de Santiago de Chile. Este trabajo muestra la aplicación y resultados de 4 departamentos. Los resultados de la evaluación se presentan de forma visual con un gráfico de barras circulares y una calificación final en escala de letras de la F a la A. En general, se observa que los cuatro departamentos tienen un bajo grado de accesibilidad (letra F a la D). Y el pilar de Autonomía es claramente el pilar más bajo de los departamentos seleccionados.

Palabras clave*: discapacidad; vivienda privadas; autonomía; confort; movilidad; seguridad.*

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1. INTRODUCTION

The lack of accessible housing meeting the needs of people with disabilities is a worldwide issue. The inadequacy of accessible housing development is partially the result of diverging priorities vis-a-vis the realities and needs of people experiencing disabilities (PeD) in different areas such as health, support organizations for PeD, developers (real estate), architects, and occupational therapists. The increase of this type of housing has become one of the goals of the Sustainable Development Objectives 11.1 and 11.b (1).

Access to adequate housing is a basic human right and a health factor (2, 3). Housing should be inclusive and accessible, thus meeting all its users' needs at every stage of their lives. Simultaneously, it should not be a hindrance to the user's health (4, 5), their autonomy or independence (6). Furthermore, it should, at least, ensure the comfort and safety of its inhabitants (7-9).

The ageing population's growth poses a social challenge for accessible housing design as their limitations increase in both severity and frequency as they age (10). From a health perspective, physical inaccessibility at home leads to the need for long-term care with significant costs, but also negative health outcomes (11). According to Stineman, et al., (12) and Olivares-Tirado (4), housing accessibility changes over time as people encounter more difficulties in carrying out routine activities. Therefore, house renovations occur without there being any technical advice or the guidance of health care personnel. Some authors have shown that housing provides critical support to older people or PeD for keeping good health (13) or a certain degree of independence (14). Furthermore, as people grow older, they spend most of the day at home (15). Hence the need for accessible housing design for a healthy ageing process (16).

It is also worth mentioning that an accessible design will benefit PeD. According to World Health Organization (WHO), a disability is the interaction between a person with a health condition and personal and environmental factors (17). An estimated 1000 million people, 15.3% of the world population, had "moderate or severe disability", while 2.9% experienced "severe disability" (18). This number is expected to increase in the future, owing to an ageing population and increasing chronic health issues (19).

The universal design also can focus on the so-called "ageing-in-place" that allows the elderly to live in the community, maintaining a level of independence and autonomy (20), keeping the connection with social support services, and maximizing self-fulfillment and preferred lifestyle (21). This is relevant as older adults prefer to grow old at home and thus avoid having to live in institutional long-term care facilities (22).

On the other hand, many people with disabilities live in housing not adequate for their needs, especially those who acquired a disability later in life while living in a space that was not designed for accessibility (23). Thus, in developed countries such as Sweden, there is a high prevalence of physical barriers and considerable accessibility problems for senior citizens with functional limitations despite high housing standards in the housing stock and obligations to provide individual housing adaptation grants (16). Also, in the United Kingdom, 70% of people with muscle-wasting conditions live in houses that do not adapt to their mobility needs and lack enough adaptations to use the bathroom or kitchen (24).

The central studies addressing accessibility and housing approach the accessibility analysis "to" a place or places instead of "from" a place. The "to" mainly refers to the study of transport networks in urban areas (25, 26), accessibility assessment in housing exteriors (27), or accessibility analysis in common areas of a building (28). In "from" a place in housing, the principal analysis must focus on older adults (29, 30).

Regarding older people, some research examples include the research of Leung et al. (31) who studied the relationship between the indoor components of private housing and the quality of life of the elderly, and the research of Gracia and Olivera - Pueyo (32), who analyzed architectural barriers in community areas in the homes for elderly with hip fracture. Furthermore, some studies examined accessibility related to other disability situations. For example, Mostafa (33) analysed the spatial conditioning inside the house for autistic people. They assessed the adaptability of a unique house model to wheelchair users. The authors concluded that in that case, it is more appropriate to adapt the existing house of the person with a disability than design a new wheelchair-accessible house, as relocation can lead to isolating people from their existing social networks. While these studies deal with housing accessibility, they are mainly focused on assessing perception (34) or only one type of housing (32).

However, few studies are focused on the housing interior with appropriate safety standards and criteria, comfort, and mobility of its users. An apartment or a single-family house could have been conditioned for PeD. Still, the occupant will not be able to visit its neighbors if the other houses or apartments in the surroundings haven't been adapted as well. The type of housing that people occupy as they age is important to foster health and social well-being (35). It is necessary to have homes that consider accessibility issues to minimize the need for improvements or modifications once people age, becoming more flexible to adapt to each member's individual needs (10). In this regard, people need to make the best choice regarding their housing options, especially when they have any disability.

To help people identify houses designed to respond to the requirements of their inhabitants through all their life, following concepts of universal design or accessibility guidelines, some organizations have developed home certifications (36, 37). These certifications recognize the need for people to identify houses that are inclusive and help designers and builders include these concepts to differentiate their construction projects from the competition (38, 39).

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(40). In this regard, people need to make the best choice regarding their housing options, especially when they have any disability (41, 42). Nevertheless, no studies or tools insightfully assess the accessibility in the real estate market.

Shortage in the accessible housing offer is due, in part, to the complexity of developing accessible designs or decision-making about how to adapt them. It is mainly because implementing new accessibility policies is slow and the multiple building regulations that projects must meet. And although norms and rules exist, their inspection tools are scarce and not very functional (43).

Considering the above, this research proposes a tool for assessing universal design in the interior of apartments, presenting a novel quantitative model for assessing the accessibility of buildings for buyers or tenants. For this, a linear multicriteria analysis is employed for aggregating the assessment indicators with different units and scales by using a unique grade of accessibility according to four main pillars: Autonomy, mobility, comfort, and safety. This assessment tool delivers a simple, easy-to-understand visualization of accessibility performance through a letter grade mark and a colour scale. It also allows to deepen the analysis, disaggregating the global performance to the main pillars and each accessibility indicator.

The following sections of this article present the research methodology, followed by the leading research results, such as the final assessment model with all its constituent elements. Later, an example of how to use this instrument is shown, followed by the article's discussion and conclusion.

2. METHODOLOGICAL APPROACH

Complex decisions related to accessible housing design are often taken without early and significant consideration of the final user (44). Accordingly, various stakeholders (estate managers and architects) are mainly misinformed about the preferences and requirements of PeDs for suitable housing. Furthermore, they have the misconception that the final user must adapt to the limited choices open to them. This approach is less than optimal because the necessities of PeDs cannot be covered (45).

Consequently, this tool proposed to deliver an easy visualization of the level of fulfilment of accessible housing design according to many indicators gathered in four principal pillars of accessibility. These methods make it possible to identify the optimal combination of parameters according to a set of objectives (46). The literature offers many techniques. For example Nestico & Somma(47) compared four techniques: Analitic Hierarchy Process (AHP), ELimination Et Choix Traduisant la REalité (ELECTRE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Compromise Ranking Method (VIKOR) .Mardani et al., (48) reviewed the techniques presented by Nestico & Somma (47) with eight other techniques: the Hybrid fuzzy multi decision-making (FMCDM), ANP, PROMETHEE, ordered weighted averaging (OWA), DEMATEL, FWA or ENTROPY methods are analyzed. Muliticriteria analysis methods are used in various areas, such as building thermal modelling (49), evaluation of indoor environmental quality (50) or Climate Adaptation (51).

Many sectors of industry such as mechanics, chemicals, telecommunications, the environment, or transport are concerned by complex problems of large dimensions and multicriteria (financial costs, quality of services) for which decisions must be made optimally. The multicriteria analysis methods allow for comparisons of different design solutions based on multiple criteria (financial, social, cultural, and environmental), expressed through quantitative or qualitative indicators (52, 53).

To develop this tool, a linear multicriteria analysis method was chosen based on a weighted sum of normalized indicators according to four main pillars. The linear method was chosen to prevent a null evaluation of an indicator from prejudicing the result, since the main objective of the tool is to provide detailed information on the degree of accessibility and not just a design objective. Therefore, like an environmental certification, the linear method allows the intermediate and final scores to be the sum of the score of all its indicators.

The proposed assessment tool will deliver degrees of fulfilment at different levels of detail. It should help identify the gap between the actual design of an existing house or new project and a fully accessible house for PeDs. This tool must deliver a global performance index and disaggregate this global assessment in more detailed levels such as Safety, Comfort, Autonomy, and Mobility. The assessment must be thorough enough to ensure the user's confidence in the results. But the result visualization needs to be intuitive for all the profiles of potential users such as stakeholders, PeD and final customers. Finally, the tool should be applicable to existing buildings to assess accessibility in the sale of a house or before and after an adaptation project. It also should be used in the early stages of the design process of new buildings

2.1. Selection of indicators and associated ranges

Various evaluation schemes were studied to select the indicators and range to be included in the tool. The extensive lists were reduced to several indicators reasonable for this first version and an operational tool. According to the main international certifications and evaluations, the indicators and associated ranges of acceptability are defined through a detailed review of the indicators to be evaluated (37, 54-58). Although more than the selected indicators are available in the literature, priority was given to those that should be considered from the perspective of the design of an apartment. Therefore, their incorporation after construction implies a high cost or significant remodelling for the potential homebuyer (43). Considering this requirement, 19 indicators were selected.

Table 1 summarizes the main themes evaluated in different international certifications, evaluations, or regulations (marked with a tick), allowing the definition of the leading indicators and intervals used in our proposed method. The table also shows that most of the studied countries focus on accessibility requirements of Autonomy, mobility, and safety; however, few consider the indicators of comfort in their certification.

Table 1. Comparative summary of requirements for accessibility in housing.

Pillars	Room	Indicator	Unit	National regulations			Certification	Guides	
				Chile (54)	Canada (55)	Spain (56)	Australia (37)	Belgium (57)	USA (58)
Autonomy	Kitchen	height kitchen furniture	cm	70	-	70	-	85	69
	Bathroom	sink top height	cm	80	73.5	70	-	90	86
	Bathroom	the available area under sink cover	-	√	√	√	-	√	√
	Bathroom	toilet height	cm	46–48	-	45–50	46–48	50	38
	Bathroom	toilet transfer area	m²	0.8 × 1.2	-	≥80	-	1.10 × 1.5	107 to axis
	Bathroom	shower transfer area	m²	0.8 × 1.2	0.8 × 1.5	≥80	1.2 × 1.2	>90	0.91 × 1.22
	Bathroom	shower tray height	cm	0	-	0.02	-	-	0
Mobility	Living-dining room	wheelchair turning space	m	150	150	150	225	150	152
	Access	access door free width	cm	90	80–101	100	82	95	81
	throughout the apartment	hall width	cm	90	150	-	90	80–110	101
	throughout the apartment	interior doors free width	cm	80	90	90	82	85	81
Comfort	Bathroom and kitchen	Faucets (lever)	-	√	-	√	-	-	√
	throughout the apartment	Type opening doors (lever)	-	√	-	√	-	-	-
	In at least one room that the person in a wheelchair can access	Type of windows (lever and slide)	-	√	-	-	-	-	-
	throughout the apartment	Windowsill height	cm	60	-	-	100	-	-
Safety	Bathroom	shower area	m²	0.9 × 1.2	0.9 × 1.5	1.35 × 1.35	0.9 × 0.9	-	0.91 × 1.22
	throughout the apartment	opening mechanisms height	cm	90–120	-.	80–120	-.	80–110	122
	throughout the apartment	Switches height	cm	40–120	120	40–120	90-110	80–110	122
	throughout the apartment	Outlets height	cm	40–120	45	40–120	30	80–110	38

The acceptability ranges associated with the indicators should be defined according to the national regulations and certification. Nevertheless, Table 2 proposes a range of acceptability based on the values from the literature review summarized in Table 1. It describes the accessibility pillars, the room to be evaluated, and the indicators used for the evaluation. Besides, the units of measurement are detailed with the interval and type of the interpretation function used. The value refers to the acceptability functions presented in Figure 2.

2.2. Creation of accessibility pillars

The selected indicators are mainly related to people with reduced mobility. Subsequently, the indicators are gathered in the four pillars of accessibility: 1) Autonomy, 2) Mobility, 3) Comfort, and 4) Safety necessary to facilitate everyday life for those with reduced mobility. 1) The Autonomy pillar gathers the indicators that ensure the individual performs daily tasks, such as cooking or using the bathroom, independently. 2) The Mobility pillar gathers the indicators that allow a person with reduced mobility to move around the house and from one room to another without obstacles. 3) The Comfort pillar gathers house elements that allow the performance of daily tasks comfortably and straightforwardly. Finally, 4) the Safety pillar gathers all the indicators that ensure that a person with reduced mobility does not need to modify the pillar of stability, avoiding falls. Each accessibility pillar was considered equally important. Table 2 shows the range of acceptability for the study based on the literature review presented in Table 1. However, these limits can be discussed and set at a national level according to the existing regulations or certification.

This assessment model aims to aggregate multiple indicators with different units and their associated range of acceptability (maximum value, minimum value, or range) into four grades according to the four pillars of accessibility and then into a unique grade named global performance index (GPI). These grades are calculated on a scale from 0 to 1. Finally, they are also converted on a letter grade scale to communicate the results to the final user in an intelligible way (see Figure 1). This model is made up of three consecutive steps, as depicted in Figure 3: 1) the interpretation step, 2) the first aggregation step, and 3) the second aggregation step.

The interpretation step evaluates the degree of compliance according to each indicator and ensures the transformation of all objective functions according to an acceptability scale ranging from 0 to 1. Figure 2 shows the functions used to normalize the indicators according to the desired objective. For

Table 2. Comparative summary of requirements for accessibility in housing.

Pillars	Index	Room	Indicator	Unit	Function	Interval (SC or AC)
Autonomy	A1	Kitchen	height kitchen furniture	cm	Delimit	[70; 75; 75; 80]
	A2	Bathroom	sink top height	cm	Delimit	[70; 75; 75; 80]
	A3	Bathroom	the available area under sink cover	-	Maximize	[0–100]
	A4	Bathroom	toilet height	cm	Delimit	[46; 47; 47; 48]
	A5	Bathroom	toilet transfer area	m^2	Maximize	[0.96; 1.65]
	A6	Bathroom	shower transfer area	m^2	Maximize	[0.96; 1.44]
	A7	Bathroom	shower tray height	cm	Minimize	[0; 5]
Mobility	M1	Living-dining room	wheelchair turning space	m	Maximize	[1.5; 2.25]
	M2	Access	access door free width	cm	Maximize	[90; 101]
	M3	throughout the apartment	hall width	cm	Maximize	[90; 150]
	M4	throughout the apartment	interior doors free width	cm	Maximize	[80; 90]
Comfort	C1	Bathroom and kitchen	Faucets (lever)	-	Maximize	[0; 100]
	C2	throughout the apartment	Type opening doors (lever)	-	Maximize	[0; 100]
	C3	In at least one room that the person in a wheelchair can access	Type of windows (lever and slide)	-	Maximize	[0; 100]
	C4	throughout the apartment	Windowsill height	cm	Minimize	[0; 60]
Safety	S1	Bathroom	shower area	m^2	Maximize	[0.96; 1.82]
	S2	throughout the apartment	opening mechanisms height	cm	Delimit	[90; 100; 110; 120]
	S3	throughout the apartment	Switches height	cm	Delimit	[40; 66; 94; 120]
	S4	throughout the apartment	Outlets height	cm	Delimit	[40; 66; 94; 120]

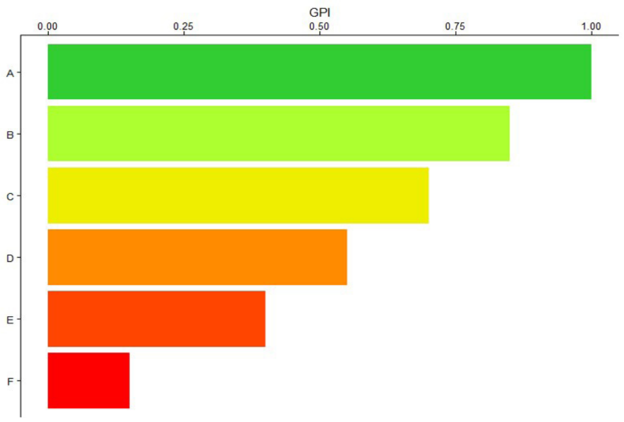

Figure 1. Color scale and letter grade according to the GPI.

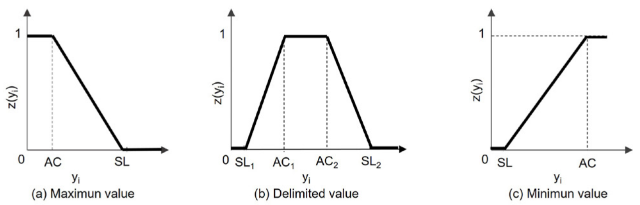

Figure 2. Acceptability functions used to normalize the indicators according to the desired objective.

example, when a) minimizing the height of a sill, b) delimiting the heights of plugs or switches, or c) maximizing the turning radius in a department room.

2.3. Tool operation

In the first step, the interpretation model normalizes the selected indicators with different scales and units into a dimensionless numerical value through three possible acceptability functions: maximum value (Figure 2a), range (Figure 2b), and minimum value (Figure 2c). These functions presented in Table 2 evaluate the degree of compliance according to each criterion and ensure the transformation of all objective functions according to an acceptability scale ranging from 0 to 1. Acceptability functions are parametrized by soft limits (SL) and absolute constraints (AC). AC should be the values determined by the national regulations because the minimum grade of 0 should be assigned for houses which do not comply with the law. Regarding SL, the values might be defined at national scale by national experts or using the scientific literature.

The selection of an acceptability function depends on the acceptability range of the indicator being respectively a maximum value, a minimum value, or an interval. For example, when 1) a maximum value for the height of a sill, 2) delimiting the heights of plugs or switches, or 3) maximizing the turning radius in a department room.

Values of SL and AC presented in Table 2 are defined based on the literature review.

The maximum value function assigns the maximum score of 1 is below the lower limit of the interval

The second step of the methodology is the "aggregation" model, which aggregates the individual evaluations of each indicator in the accessibility pillar through an aggregation function (design objective index, DOI). The aggregation function proposed by Scott and Antonsson (59) was used in two steps (Formula. [1]) First, the indicators are aggregated according to four DOIs of accessibility: Autonomy, mobility, comfort, and safety. Then, the DOIs are aggregated into a unique global performance index. Among the several aggregation strategies proposed through Scott and Antonsson (59) function, we used the weighted arithmetic mean of all the interpretation values associated with computing the DOIs and GPI. It was selected to equally weigh the interpretation variables to calculate the DOIs as follows:

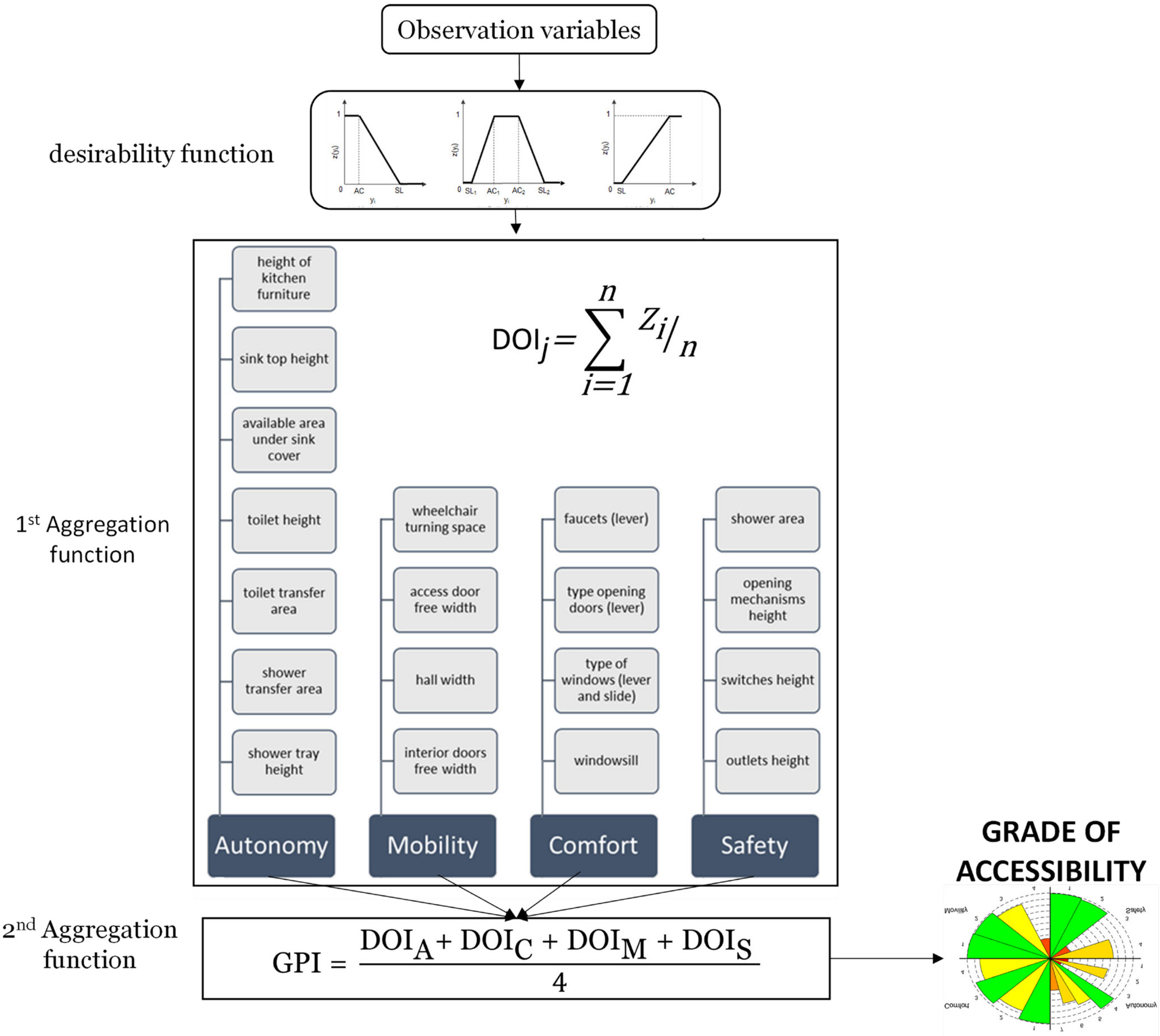

Figure 3. Different elements and steps composing the multicriteria analysis model.

$$[1] \quad DOI_j = \sum_{i=1}^{n} \frac{z_i}{n}$$

where j is the pillar of autonomy (A), comfort (C), mobility (M), or safety (S); and n is the number of indicators included in each pillar.

Then, the GPI of the house was calculated, weighting each DOI by the number of indicators included in the accessibility pillar to ensure an equal weight among indicators (Formula [2]):

$$[2] \quad GPI = \frac{DOI_A + DOI_C + DOI_M + DOI_S}{4}$$

The weight of indicators and pillars can be modified based on surveys to experts of the field and PeD. The Figure 3 outlines and summarizes the steps of the method.

3. VERIFICATION OF THE ASSESSMENT TOOL'S APPLICABILITY

The assessment method has been applied in 35 show apartments in the urban area of the Grand Santiago in the Metropolitan Region of Chile. The results of GPI vary from 0.15 (F) to 0.54 (D), which show that the assessment method can clearly discriminate against the quality of accessibility inside the apartments. Four apartments are selected to detail the results visualization and analysis. Table 3 shows the main characteristics of the four chosen apartments to evaluate their accessibility performances.

Figure 4 presents the visual summary of the performance of each four apartments detailed in Table 3. Figure 4 is composed of a circular bar plot of the assessment indicators grouped by accessibility pillars. Finally, a circular stamp is in the centre with the grade letter of GPI with the associated colour (See Figure 1).

Although the performance of these four apartments is different, Autonomy is clearly the lower pillar in the set of selected apartments, including apartment 4, which offers the larger surface area with 239 m² and the higher sale price by far. Five indicators in the Autonomy pillar get the minimum grade in all four apartments, which are A1 (height of the kitchen

Table 3. Characteristics of the selected apartments.

Apartment Index				**1**	**2**	**3**	**4**
Sale Price		(USD)		123 850	308 700	536 476	971346
Floor area		(m²)		71	79	133	239
Configuration		N° bedrooms (D) N° bathrooms (B)		3D-2B	2D-2B	3D-3B	4D-4B
Pillars	Index	Indicator					
Autonomy	A1	Kitchen	height kitchen furniture	85	86	94	90
	A2	Bathroom	sink top height	54	85	87	88
	A3	Bathroom	available area under sink cover	0	0	0	0
	A4	Bathroom	toilet height	38	38	42	43
	A5	Bathroom	toilet transfer area	0.60	1.10	0.50	0.5
	A6	Bathroom	shower transfer area	0.60		0.50	1.7
	A7	Bathroom	shower tray height	47	35	29	5
Mobility	M1	Living-dining room	wheelchair turning space	2.1	1.3	1.8	2.7
	M2	Access	access door free width	87	89	88	110
	M3	throughout the apartment	hall width	89	110	88	97
	M4	throughout the apartment	interior doors free width	64	90	69	87
Comfort	C1	Bathroom and kitchen	Faucets (lever)	100	100	100	100
	C2	throughout the apartment	Type opening doors (lever)	0	100	100	100
	C3	In at least one room	Type of windows (lever and slide)	0	100	100	100
	C4	throughout the apartment	Windowsill height	47	32	40	55
Safety	S1	Bathroom	shower area	0.98	1.04	1.12	1.68
	S2	throughout the apartment	opening mechanisms height	92	96	90	98
	S3	throughout the apartment	Switches height	127	112	108	105
	S4	throughout the apartment	Outlets height	45	35	32	35

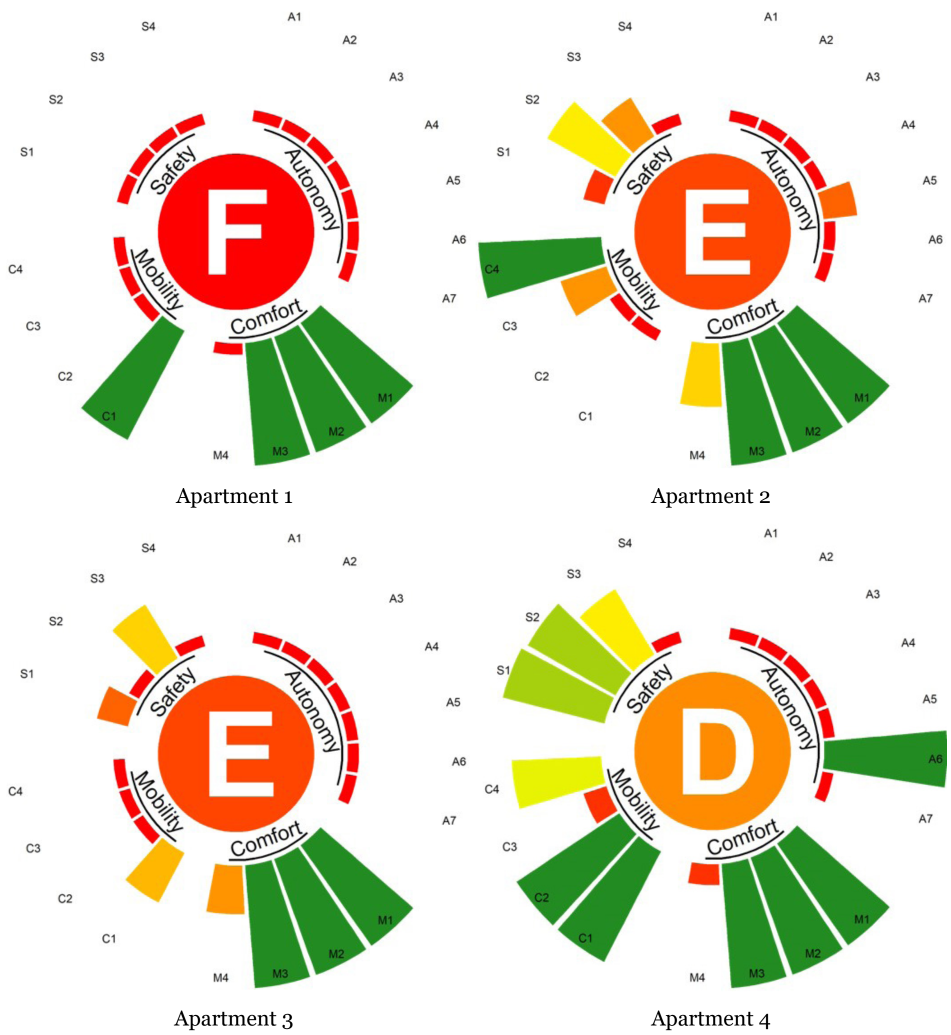

Figure 4. Accessibility compass of apartments 1, 2, 3, and 4.

furniture), A2 (height of bathroom sink top), A3 (available space under the bathroom sink cover), A4 (toilet height) and A7 (shower tray height). Figure 5 reveals the problem of the lack of free space under the bathroom sink in apartment 2 because a storage cabinet under the sink blocks the access with a wheelchair.

Figure 5. available space under the bathroom sink cover in apartment 2 (the best rated).

On the other hand, Figure 4 shows the indicator A5 (toilet transfer area) as an indicator that discriminates the accessibility performance according to the autonomy pillar (wheelchair users). For example, Figures 6a and 6b show the toilet transfer area of the best and worst rated apartments, respectively.

Figure 6a. Indicator A5 for apartment 2, the best rated.

Figure 6b. Indicator A5 for apartment 1, the worst rated.

Finally, M4 (interior doors free width) is also another discriminating indicator. Indeed Figure 7 shows the thickness of the door leaf. Also, the door stop reduce the free space to pass through the door with a wheelchair.

Figure 7. example of a problem in the free width of the door that is limited by the thickness of the panel and the door stopper.

Some indicators reach the maximum grade in all four apartments such as M1 (wheelchair turning space in the living room), M2 (free space of the entrance door), M3 (Entrance Hall width), C1 (type of door openings), C2 (type of window openings), S2 (height of opening mechanism), and S3 (switch heights).

4. DISCUSSION

The tool is easy and fast to apply already in the early stages of a design process, in existing buildings or even to evaluate purchase options. It provides a labelling system, which can be implemented at the national level, regulation, or complement the certification program.

Although the application of the presented method is limited to the small geographical area of the metropolitan region of Chile, it can be applied at an international level using the same indicators and associated intervals or adapting them to the national context and regulation. Furthermore, the range of indicators can be easily modified and extended, including external accessibility in the building and the neighborhood, which also make it possible to apply the presented method to other types of infrastructure such as public buildings, schools, or public transport. Finally, decision-makers or users can modify the weighting of accessibility pillars according to the degree to which objectives they want to emphasize.

The proposed tool can be used by different profiles of users thanks to its various levels of disaggregation. The GPI and the four pillars can be used to inform the final customer about the accessibility performance of an existing or new apartment. An architect will quickly identify which indicators need to be improved to reach a fully accessible apartment at an early stage of the design process. Its purpose is to promote dialogue between consultants and building owners or developers and PeDs and their caregivers.

The design patterns of real-estate companies used in existing projects should change to include concepts of universal accessibility from the very early stages to make apartments more inclusive to the whole population, including those with reduced mobility or a temporary or permanent disability from ageing. In this regard, it is crucial to consider the size and distribution of all interior spaces to meet the minimum requirements of accessibility. The lack of such consideration shows how uninformed design professionals are regarding the real needs and requirements in living spaces for persons with disabilities. Additionally, dwelling designs should also incorporate the concept of adaptability, either for versatility or convertibility. As such, living spaces should be designed and built to respond to the ever-changing needs of their inhabitants, not limiting their design exclusively to the specific modifications required by persons with a disability. At the very least, these houses and apartments should include elements of spatial design or optional fixed furniture that would allow for easy and safe use of all spaces, reducing physical obstacles that these areas may present over time and satisfying the changing needs of the occupants, regardless of the stage in the life of the family: single, with young children, teenagers, elderly, or persons with disabilities. The presented assessment tool should be implemented in software using building information modelling (BIM) to facilitate an iterative evaluation of universal accessibility during all stages of building design.

Finally, the application of this methodology at a large scale might be helpful to identify the gap between the current built heritage and a fully accessible built environment. Consequently, the analysis of the results should guide policymakers to implement new public policies and regulations.

5. CONCLUSIONS

The presented tool can assess holistically the accessibility performance inside houses. The assessment is based on many indicators distributed in four pillars: Autonomy, Mobility, Safety and Comfort. Although the assessment is focused on people with reduced mobility in houses, the evaluation method should be easily extended to other building typologies and disabilities, including new indicators.

On the other hand, we chose to equally weight the four pillars used to gather the indicators. However, the weighting should be modified in the future based on surveys to experts in the field, stakeholders, PeDs and caregivers.

The visualization through a circular bar plot with the GPI as a letter grade appears to be an efficient way to communicate because it can be used for the different profiles of users from the final customer to the architect.

Future works should focus on incorporating new indicators with associated ranges of acceptability and weightings to consider other disabilities such as visual impairment or intellectual disability. Finally, the assessment method implementation in BIM software should be developed considering the real-time feedback on accessibility performance during the design process as a priority.

REFERENCES

(1) Organización de las Naciones Unidas - ONU (2015). *Objetivo 11: Lograr que las ciudades sean más inclusivas, seguras, resilientes y sostenibles*. Retrieved form https://www.un.org/sustainabledevelopment/es/cities/ [Acceso marzo 2022].
(2) United Nations General Assembly (1948). *Universal declaration of human rights*.
(3) Roessler, R. T., Gitchel, W. D., &y Bishop, M. (2013). Housing satisfaction: An additive predictor of QOL for adults with MS? *Journal of Vocational Rehabilitation*, 39(2), 101-109. https://doi.org/10.3233/JVR-130648.
(4) Olivares-Tirado P (2006). *Documento de trabajo: Perfil Epidemiológico del Adulto Mayor en Chile*. Superintendencia de Salud – Gobierno de Chile. 20pp.
(5) Lakhani, A., y Zeeman, H. (2016). Analytic hierarchy process to inform disability housing development: Two applications. Presented at the International Symposium on the Analytic Hierarchy Process, in London, UK, August 4-7, 2016.
(6) Huete García, A. (2019). *Autonomía e inclusión de las personas con discapacidad en el ámbito de protección social*. Banco Interamericano de Desarrollo (BID). 55pp.
(7) D'Alençon R., Justiniano C, Marquez F. y Valderrama C. (2011). Habitability parameters and standards in dwellings. Contesting technical objectivity in the context of slum management and housing provision in Chile. Lateinamerikanische Städte im Wandel: zwischen lokaler Stadtgesellschaft und globalem Einfluss, 16, 121.
(8) Ferrada X., Valderrama C., Serpell A., Alcayaga C. y Rubio M. (2016). Capítulo IV. Mejorando la accesibilidad y habitabilidad de la vivienda para personas en situación de discapacidad. Centro de Políticas Públicas UC. pp 113. Chile Ed.: Pontificia Universidad Católica de Chile - ISBN 978-956-14-1721-2.
(9) World Health Organization -WHO (2018). *WHO Housing and Health Guidelines* Retrieved form https://www.who.int/publications/i/item/9789241550376 [Acceso febrero 2022].
(10) Caffaro, F., Galati, D., Loureda, M. V. Z., y Roccato, M. (2019). Housing-related subjective well-being in Turin (Italy) and Havana (Cuba): dimensions and prediction. *Applied Research in Quality of Life*, 14(1), 273-285, 3–285. https://doi.org/10.1007/s11482-018-9592-5.
(11) Iwarsson, S., Horstmann, V., y Slaug, B. (2007). Housing matters in very old age—yet differently due to ADL dependence level differences. *Scandinavian Journal of Occupational Therapy*, 14(1), 3-15. https://doi.org/10.1080/11038120601094732.

(12) Stineman, M. G., Ross, R. N., Maislin, G., y Gray, D. (2007). Population-based study of home accessibility features and the activities of daily living: Clinical and policy implications. *Disability and Rehabilitation*, 29(15), 1165–1175. https://doi.org/10.1080/09638280600976145.
(13) Fänge, A., y Ivanoff, S. D. (2009). The home is the hub of health in very old age: Findings from the ENABLE-AGE Project. *Archives of Gerontology and Geriatrics*, 48(3), 340–345. https://doi.org/10.1016/j.archger.2008.02.015.
(14) Wahl, H.W., Fänge, A., Oswald F., Gitlin, L.N. y Iwarsson, S. (2009). The home environment and disability-related outcomes in aging individuals: what is the empirical evidence? *Gerontologist*. 49(3). 355-67. https://doi.org/10.1093/geront/gnp056.
(15) Heyl, V., Wahl, H.-W., y Mollenkopf, H. (2007). Affective well-being in old age: The role of tenacious goal pursuit and flexible goal adjustment. *European Psychologist*, 12(2), 119–129. https://doi.org/10.1027/1016-9040.12.2.119.
(16) Jonsson, O., Frögren, J., Haak, M., Slaug, B., y Iwarsson, S. (2021). Understanding the wicked problem of providing accessible housing for the ageing population in Sweden. *International Journal of Environmental Research and Public Health*, 18(3), 1–21. https://doi.org/10.3390/ijerph18031169.
(17) World Health Organization – WHO (2021). Disability and health. Retrieved form https://www.who.int/news-room/fact-sheets/detail/disability-and-health.
(18) World Health Organization – WHO & The World Bank (2011). *World report on disability*. 350 pp. Retrieved form https://www.who.int/disabilities/world_report/2011/report.pdf.
(19) Cieza, A., Causey, K., Kamenov, K., Hanson, S. W., Chatterji, S., y Vos, T. (2020). Global estimates of the need for rehabilitation based on the Global Burden of Disease study 2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, 396(10267), 2006-2017. https://doi.org/10.1016/S0140-6736(20)32340-0.
(20) Siltanen, S., Rantanen, T., Portegijs, E., Tourunen, A., Poranen-Clark, T., Eronen, J., y Saajanaho, M. (2019). Association of tenacious goal pursuit and flexible goal adjustment with out-of-home mobility among community-dwelling older people. *Aging clinical and experimental research*, 31(9), 1249-1256. 9) 31:1249–1256. https://doi.org/10.1007/s40520-018-1074-y.
(21) Sánchez-González, D., Rojo-Pérez, F., Rodríguez-Rodríguez, V., y Fernández-Mayoralas, G. (2020). Environmental and psychosocial interventions in age-friendly communities and active ageing: a systematic review. *International journal of environmental research and public health*, 17(22), 8305. https://doi.org/10.3390/ijerph17228305.
(22) Liu, L., Stroulia, E., Nikolaidis, I., Miguel-Cruz, A., y Rincon, A. R. (2016). Smart homes and home health monitoring technologies for older adults: A systematic review. *International journal of medical informatics*, 91, 44-59. https://doi.org/10.1016/j.ijmedinf.2016.04.007.
(23) Heylighen, Van der Linden y Van Steenwinkel (2017). Ten questions concerning inclusive design of the built environment. *Building and Environment*. 114: 507-517. https://doi.org/10.1016/j.buildenv.2016.12.008.
(24) Muscular Dystrophy United Kingdom (2015). *Breaking point: The crisis in accessible housing and adaptations*
(25) Jiron & Mancilla (2013). Atravesando la espesura de la ciudad: vida cotidiana y barreras de accesibilidad de los habitantes de la periferia urbana de Santiago de Chile. *Revista de geografía Norte Grande*. 56: 53-74. http://doi.org/10.4067/S0718-34022013000300004.
(26) Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Chen, Q., y Weston, L. (2000). *Urban accessibility index: literature review*. Center of Transportation Research, University of Texas at Austin, Springfield.
(27) Olivera Poll, A. (2013). Discapacidad, accesibilidad y espacio excluyente. Una perspectiva desde la Geografía Social Urbana. *Treballs de la Societat Catalana de Geografía*. 61-62. 326-343.
(28) Leung, M. Y., y Liang, Q. (2019). Developing structural facilities management–quality of life models for the elderly in the common areas of public and subsidized housings. *Habitat International*, 94, 102067. https://doi.org/10.1016/j.habitatint.2019.102067.
(29) Oswald, F., Wahl, H.W., Schilling, O., Nygren, C., Fänge, A., Sixsmith, A., Sixsmith, J., Szeman, Z., Tomsone, S. y Iwarsson, S. (2007). Relationships Between Housing and Healthy Aging in Very Old Age. *Gerontologist*, 47(1), 96–107. https://doi.org/10.1093/geront/47.1.96.
(30) Nygren, C., Oswald, F., Iwarsson, S., Fänge, A., Sixsmith, J., Schilling, O., Sixsmith, A., Szeman, Z., Tomsone, S. y Wahl, H.W. (2007). Relationships Between Objective and Perceived Housing in Very Old Age. *Gerontologist*, 47(1), 85–95. https://doi.org/10.1093/geront/47.1.85.
(31) Leung, M., Famakin, I., y Kwok, T. (2017). Relationships between indoor facilities management components and elderly people's quality of life: A study of private domestic buildings. *Habitat International*, 66, 13–23. https://doi.org/10.1016/j.habitatint.2017.05.002.
(32) Gracia, A. S. y Olivera Pueyo, F. J. (2005). Estudio de la accesibilidad a los domicilios en ancianos con fractura de cadera. *Rehabilitación*, 39(5), 207–214. https://doi.org/10.1016/S0048-7120(05)74350-4.
(33) Mostafa, M. (2010). Housing adaptation for adults with autistic spectrum disorder- ProQuest. Open house International, 35(1), 37–48. https://doi.org/10.1108/OHI-01-2010-B0004.
(34) Frain, J. P. y Carr, P. H. (1996). Is the typical modern house designed for future adaptation for disabled older people? *Age Ageing*, 25(5), 398–401. https://doi.org/10.1093/ageing/25.5.398.
(35) Orrell, A., McKee, K., Torrington, J., Barnes, S., Darton, R., Netten, A., y Lewis, A. (2013). The relationship between building design and residents' quality of life in extra care housing schemes. *Health & Place*, 21, 52-64. https://doi.org/10.1016/j.healthplace.2012.12.004.
(36) Lifetime Design Limited (2016). *Lifemark Design Standards Handbook version 2*. Lifetime Design Limited, Auckland, New Zealand.
(37) Livable Housing Australia (2015). *Livable Housing Design. Livable Housing Australia*, Sydney, Australia.
(38) Yavari, F., Khajehzadeh, I., y Vale, B. (2018). Design options for an ageing New Zealand population: A life cycle energy (LCE) analysis. *Energy and Buildings*, 166, 1-22. https://doi.org/10.1016/j.enbuild.2018.01.027.

(39) Ward, M., Franz, J., y Adkins, B. (2014). Livable housing design: The voluntary provision of inclusive housing in Australia. *Journal of Social Inclusion*, 5(1), 43-60.
(40) Kim, J. (2020). Housing accessibility for seniors with mobility and grasping disabilities: lessons from the American Housing Survey. *Housing Studies*, 1-26. https://doi.org/10.1080/02673037.2020.1729963.
(41) Askar, R., Bragança, L., y Gervásio, H. (2021). Adaptability of buildings: a critical review on the concept evolution. *Applied Sciences*, 11(10), 4483. https://doi.org/10.3390/app11104483.
(42) Tucker, R., Kelly, D., Johnson, L., de Jong. U. y Watchorn, V. (2021). Housing at the fulcrum: a systems approach to uncovering built environment obstacles to city scale accessibility and inclusion. *Journal of Housing and the Built Environment*.1-19. https://doi.org/10.1007/s10901-021-09881-6.
(43) Ferrada, X., Valderrama, C., y Fuentes-Contreras, C. (2020). Economic and technical analysis of universal accessibility in social and private housing in Chile. *IOP Conference Series: Earth and Environmental Science*, 503(1), 1-10, https://doi.org/10.1088/1755-1315/503/1/012003.
(44) Wright, C. J., Muenchberger, H., y Whitty, J. A. (2015). The choice agenda in the Australian supported housing context: A timely reflection. *Disability & Society*, 30(6), 834–848. https://doi.org/10.1080/09687599.2015.1038336.
(45) Imrie, R. (2003). Housing quality and the provision of accessible homes. *Housing Studies*, 18(3), 387–408. https://doi.org/10.1080/02673030304240.
(46) Odu, G. O., y Charles-Owaba, O. E. (2013). Review of multi-criteria optimization methods–theory and applications. *IOSR Journal of Engineering*, 3(10), 28-37.
(47) Nesticò, A., y Somma, P. (2019). Comparative analysis of multi-criteria methods for the enhancement of historical buildings. *Sustainability*, 11(17), 4526. https://doi.org/10.3390/su11174526.
(48) Mardani, A., Jusoh, A., y Zavadskas, E. K. (2015). Fuzzy multiple criteria decision-making techniques and applications–Two decades review from 1994 to 2014. *Expert systems with Applications*, 42(8), 4126-4148. https://doi.org/10.1016/j.eswa.2015.01.003.
(49) Sahu, M., Bhattacharjee, B., y Kaushik, S. C. (2012). Thermal design of air-conditioned building for tropical climate using admittance method and genetic algorithm. *Energy and Buildings*, 53, 1-6. https://doi.org/10.1016/j.enbuild.2012.06.003
(50) Larsen, T. S., Rohde, L., Jønsson, K. T., Rasmussen, B., Jensen, R. L., Knudsen, H. N., y Bekö, G. (2020). IEQ-Compass–A tool for holistic evaluation of potential indoor environmental quality. *Building and Environment*, 172, 106707. https://doi.org/10.1016/j.buildenv.2020.106707.
(51) Haque, A. N. (2016). Application of multi-criteria analysis on climate adaptation assessment in the context of least developed countries. *Journal of Multi-Criteria Decision Analysis*, 23(5-6), 210-224. https://doi.org/10.1002/mcda.1571.
(52) Caballero-Moreno, W., Alegre, I., Armengou-Orús, J., y Aguado, A. (2019). Self-construction in informal settlements: a multiple-criteria decision-making method for assessing sustainability of floor slabs in Bucaramanga, Colombia. *Journal of Housing and the Built Environment*, 34(1), 195-217. https://doi.org/10.1007/s10901-018-9606-5.
(53) Canales, P., Valderrama-Ulloa, C., y Ferrada, X. (2021). Hospitales sustentables: partidas críticas para su construcción y el rol de la inspección técnica. *Hábitat Sustentable*, 11(2), 22-33. https://doi.org/10.22320/07190700.2021.11.02.02.
(54) Ministerio de Vivienda y Urbanismo - Gobierno de Chile (1992). Ordenanza general de urbanismo y construcciones. Modificado 2017.
(55) Office of Housing and Construction standards (2006). *The building access handbook: building requirements for persons disabilities from British Columbia Building Code*. Canada.
(56) Ministerio de Vivienda – Gobierno de España (2010). *Real Decreto 173/2010, por el que se modifica el Código Técnico de la Edificación, en materia de accesibilidad y no discriminación de las personas con discapacidad.*
(57) 57 Confédération Construction Wallone (2008). *Guide d'aide à la conception d'un logement adaptable*.58 U S Department of Housing and Urban Development Office of Fair Housing and Equal Opportunity Office of Housing. (1998). *Fair Housing act design manual: A manual to assist designers and builders in meeting the accessibility requirements of the fair housing act*. North Carolina: Raleigh.
(58) Scott, M. J. y Antonsson, E. K. (1998). Aggregation functions for engineering design trade-offs. *Fuzzy Sets System*, 99(3), 253–264. https://doi.org/10.1016/S0165-0114(97)00032-8.