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Integrated urban regeneration for high-rise multi-family buildings by providing a multidimensional assessment model and decision support system

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ABSTRACT

Current urban challenges on promoting an integrated urban regeneration demand new decision support systems to adjust and optimise renovation strategies in the housing stock. This research aims to provide a multidimensional decision support system, specifically focused on high-rise multi-family buildings, which entails an added complexity in the design and decision-making stages of building renovation. The need to promote assessment protocols of key parameters that promote a viable and efficient renovation in high-rise multi-family buildings constitutes a research gap to be fulfilled in this study. This research contributes with an assessment and weighting model based on 12 indicators, both during and after renovation works, under 4 multidisciplinary dimensions: Technical; Social; Economic; and Environmental, in a -5 to 5 drawback-benefit index scale. An application procedure has been tested in two representative neighbourhoods in Argentina and Spain, identified by GIS resources, and demonstrating its operation and usefulness for vulnerable neighbourhoods due to global inflation. The implications of the graphic output of results, weighted for Mild, Moderate, Intense and Deep action strategies, allows us to identify drawbacks and benefits of each strategy independently, for each of the 12 indicators, visualising the trend, performance and variations between dimensions and strategies in large-scale buildings. Conclusions generate key recommendations and insights on decision-making patterns to urban policymakers by ensuring feasible and satisfactory renovation strategies in high-rise multi-family buildings.

1. Introduction

Managing the built environment efficiently has become one of the key challenges of the 21st century, according to global reports that follow the Sustainable Development Agenda or the European Agenda for Sustainable Buildings [1,2], which highlight the need to develop new assessment and decision-making mechanisms related to building renovation [3]. In recent years, integrating multiple disciplinary sectors in the assessment and diagnosis of existing buildings, especially in the housing stock, has proven highly useful in order to decide what renovation strategies are the most optimal to implement in a given environment context [4]. Thus, providing support from technical, social, economic and environmental requirements becomes even more important due to current socioeconomic

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Table 1
Main contribution, findings or gaps of related research on their subsequent topics.

Topic	Research paper	Contributions/Gaps
Housing renovation management – High-rise multi-family building	Timur et al. [25]	· Stated thermal retrofitting needs case-specific analyses and no generic solution · Final decision-making stage in renovation must consider thermal needs of users
	Serrano-Jiménez et al. [26]	· Provide an accessibility assessment model for social housing for elderly users · Decision support system after identifying the main risks and the optimal actions
	Liu & Rodriguez [22]	· Holistic approach to assess passive interventions and improve indoor quality · Based on a multi-objective optimization process in high-rise residential building
	Zhong et al. [23]	· Assessed energy and particular exposure in high-rise multi-family buildings · Control strategies with ventilation modes, filter efficiencies and ventilation rates
	Farsäter et al. [14]	· Evaluate how decisions are made in early stages of housing renovation projects · Show the need of a comprehensive analysis for all the viable aspects of concern
	Garrido & Mercader-Moyano [24]	· Multidisciplinary rating of eco-efficient actions for implementing in housing · Difficulties of including users' demands in the action proposal model
Multidisciplinary approach for building renovation	Love & Matthews [27]	· Assess the risk and uncertainty of rework from a multidisciplinary approach · Addressing by using the line of inquiry of sense-making from different disciplines
	Ge et al. [28]	· Combine experimental measurements and on-site surveys for reliable diagnosis · Propose multidisciplinary methods to identify efficient and sustainable solutions
	Mjörnell et al. [29]	· Sustainability and social awareness are moving up in proper renovation actions · Investigate how public and private housing owners deal with renovation levels
	Invidiata et al. [9]	· Multidisciplinary approach should be implemented to select design strategies · Highlight the need of using multi-criteria approaches to ensure right decisions
	Li et al. [30]	· Provide a comprehensive approach on the influence of stakeholders' factors · Users offer a better addressing for stakeholder concerns in urban renovation
Assessment model as decision support systems	Moghtadernejad et al. [31]	- Propose a decision-analysis methods to help identifying the best façade solution - Particularly focused on façades but interesting to extend to housing renovation
	Huang et al. [32]	· Assessed 3 supporting processes for optimising project management and costs · Decision-making as reducing capital cost barrier to extend sustainable renovation
	Giretti et al. [33]	· Stated decisions often are taken with limited knowledge in short time frames · Importance of developing tools for supporting fast and reliable assessments.
	Kamaruzzaman et al. [34]	· Incorporate weighting system for decision-making applied on many themes. · Exploratory study that gathers certain survey responses with reduced sample

(*continued on next page*)

Table 1 (*continued*)

Topic	Research paper	Contributions/Gaps
	Monzón & López-Mesa [35]	· Decision support system based on performance indicators to detect priorities · Provided a graphical output of results to facilitate decision-making in renovation

limitations caused by inflation [5].

Regarding the conservation status and the increasing obsolescence in the built environment, high-rise multi-family buildings are highly representative, as a the most prevalent type of building in the second half of the 20th century to meet the urgent needs of housing [6]. The high-rise consideration may vary according to different countries and regulatory requirements, so considering different fire protection regulations and accessibility limitations along with other socio-economic criteria provided by promoters, for this research purpose these high-rise buildings are established as those with 5 or more storeys [7]. In fact, according to European stats, this high-rise multi-family typology represents 37% of the existing buildings [8], which entails the need to develop more research advances towards innovative construction and their efficient renovation management [9].

This building category, both in linear and in tower typologies, involves an added complexity in the design and decision-making stages of building renovation, since the intervention costs, the technical difficulties of the works, and even the number of owners involved are higher compared to low-density construction [10]. Additionally, the expected drop in public funding to face urban regeneration, due to the limitations caused by inflation and population ageing [11], has become a major challenge in the design of an optimised tool for decision-making. Therefore, this research field currently demands a standardised system that could be adapted to the tower or linear model, which could allow for the visualization of both the improvements and drawbacks that different renovation strategies imply [12].

Given this context, there is currently a potential line of research that focuses on providing renovation guidelines on the assessment and decision-making in building renovation strategies, as Napoli et al. [13] or Farsäter et al. [14] focused on in their research. However, the specific literature review carried out in section 2 concludes what was highlighted by Ibarloza et al. [15], that there is a research gap on multi-criteria assessment systems specifically adapted to high-rise multi-family buildings to support the optimal decision-making of renovation strategies [16]. In addition, there is a lack of models that combine technical, social, economic and environmental perspectives, which would help to identify the advantages or disadvantages of each discipline and obtain an integral diagnosis according to each urban and socioeconomic context [17]. Thus, there is a need to promote protocols to decide which parameters are essential to cover in the high-rise multi-family building renovation process [18]. The fulfilment of this need would also comply with the Sustainable Development Goals and different national targets related to the built environment [19,20]. This would be accomplished by integrating more multidisciplinary factors and variables during the works, to promote feasible renovation strategies and appropriate retrofitting techniques [21].

This paper aims to design a multidisciplinary decision support system on housing renovation strategies whose originality is focused on high-rise multi-family buildings. As a key point regarding the novelty of this research, the provided approach fulfils the need to establish a multidisciplinary mechanism that integrates 4 dimensions: Technical, Social, Economic and Environmental, assessed from 12 identified parameters related to the during and after renovations works process. Consequently, this study expects to promote useful insights for decision-making through an assessment model that independently weights and shows the results by using data science, weighting and scoring a large amount of information, and GIS, for the identification and selection of the sample. The implications on the replicability of the model can allow us to optimise the renovation works in high-rise multi-family buildings and reduce the complexity of works.

As key contributions, this research gathers renovation guidelines adapted to high-rise multi-family buildings, develops an assessment model based on weighted indicators, and provides a decision support system from a multidisciplinary approach based on four dimensions through an original graphical output of results for the decision-making on different renovation alternatives. To follow this aim, the research identifies potential renovation factors, gathering their assessment parameters under specific criteria for high-rise buildings, and adjusts and tests the model in two pilot neighbourhoods in such a way as to exemplify the graphic results obtained. The application of this model would weight information on the impact and benefit of each renovation strategy both during and after the renovation works for a proper decision-making.

The following sections present a literature review of the research subtopics and relevant research gaps, thus defining and justifying the proposed multidisciplinary decision support system. Then, this model is applied and tested in two representative neighbourhoods from Argentina and Spain, countries with appropriate standards for the application of this model according to socioeconomic context and urban regeneration challenges. The main results and conclusions are finally discussed regarding its replicability and insights.

2. Literature review

This section aims to define a sample of the most influencing papers to consider in this literature review, that will serve to highlight the recent advances and to identify the research gap that needs to be fulfilled. Each paper represents important motivations for the design, adjustment and development of the multidisciplinary decision support system for high-rise multi-family buildings.

The documents broken down in Table 1 gather 3 main subtopics related to the goals of this research. There is a recent trend related to the management of housing renovation, as shown in the first subtopic, although there are very few studies that focus particularly on high-rise multi-family buildings, highlighting the approaches made by Liu and Rodríguez [22] along with Zhong et al. [23]. In this sense, the work developed by Farsater et al. [14] demonstrates the usefulness of establishing mechanisms that guarantee the success of renovation strategies, as well as the difficulty of addressing user demands in action protocols, as Garrido and Mercader-Moyano [24] or Timur et al. [25] concluded.

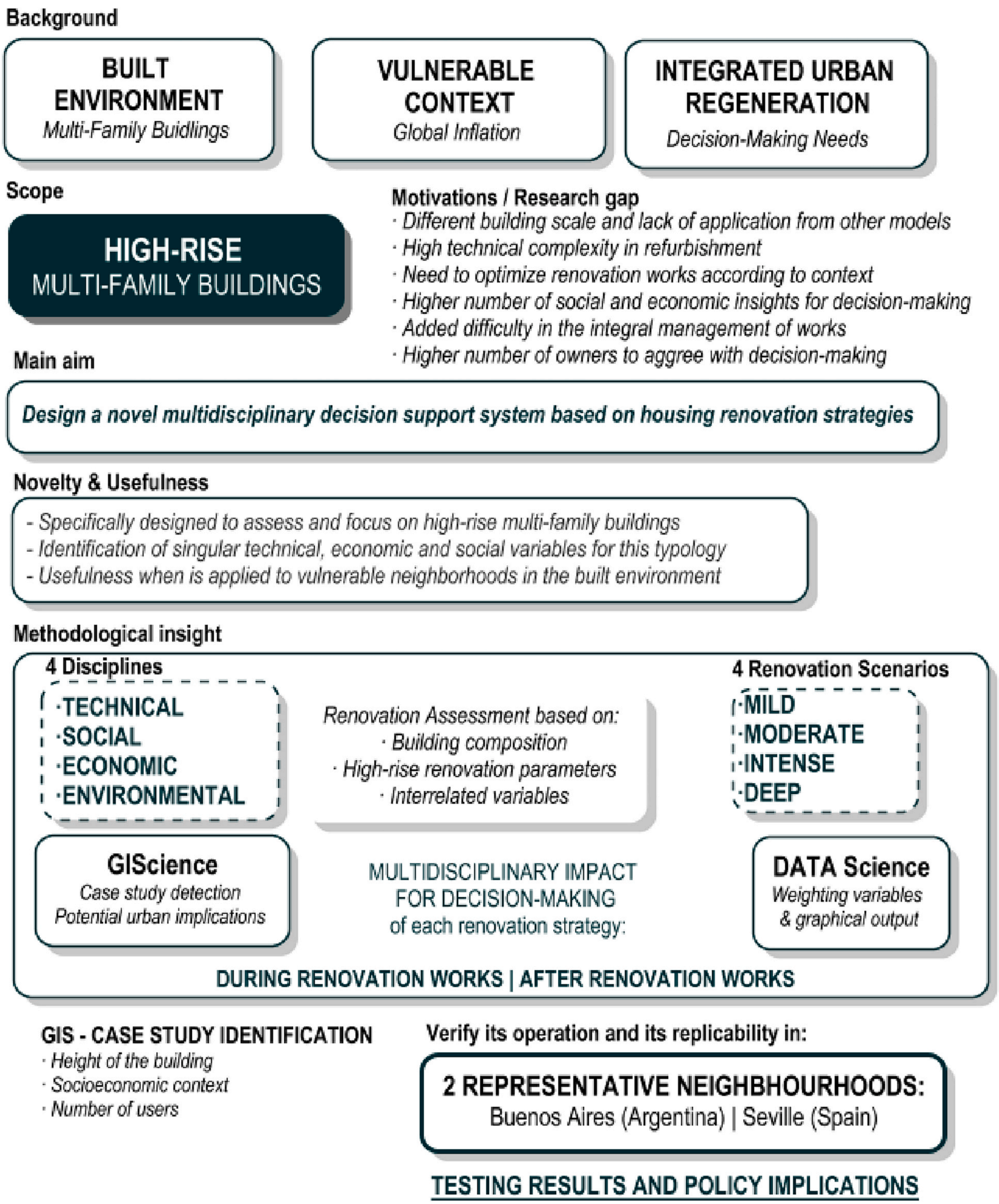


Fig. 1. General outline of the assessment and decision support system for high-rise multi-family buildings.

Regarding the following multidisciplinary subtopic, there is a research trend related to demonstrate the benefits of integrating social, economic and environmental dimensions of analysis into the technical discipline for promoting effective renovation works in the built environment, ensuring efficient and satisfactory interventions in the built environment [36]. In fact, recent studies have combined technical inspections of buildings, together with user questionnaires and environmental and economic simulations of renovation processes, which offered complete information to developers and public administrations, as Li et al. [30] demonstrated in their study.

Finally, the third subtopic covers many disciplinary sectors but remarks the importance of generating mechanisms as decision-making support systems. Regarding housing renovation, this is becoming increasingly useful given the complexities that exist during the works and anticipating certain results that the renovation proposals will entail, as suggested by Kamaruzzaman et al. [34]. In addition, numerous studies, such as the one developed by Monzón and López-Mesa [35], agree on the importance of designing an understandable and intuitive graphical output of results to quickly determine the advantages and disadvantages of each process. Thus, multiple studies have contributed with numerous assessment and decision-making models to effectively design the proposals, by analysing multiple parameters [37].

Beyond all the implications and limitations from each referenced study, the literature review highlights a research gap on the absence of studies that specifically focus on high-rise multi-family buildings, carrying out a special analysis on particularities and variations that exist in this scope. For all these reasons, this study fulfils this research gap and contribute original research to the literature review by providing a multidisciplinary assessment procedure to quantify multiple variables from different dimensions, in order to distribute public funds and adjust resources for a proper city-wide management in urban regeneration, as United Nations [19] and GBCE [2] stated.

3. Methodology

Aiming to design a multidisciplinary assessment model on housing renovation strategies, particularly focused on high-rise areas with a remarkable housing density, Fig. 1 presents a graphic outline of the different stages of the research, highlighting the scope and the corresponding motivations, providing the novelty and the insights and expected implications.

The operation procedure is based on two main methodological concepts that can allow us to conduct the appropriate decision-making process in high-rise multi-family buildings, following two key concepts provided by Cinelli et al. [38], and subsequently adapted to this research approach:

- Analytical Hierarchy Process (AHP), that compares and ranks different renovation alternatives according to quantitative and qualitative variables.
- Multi-attribute utility theory (MAUT), which quantifies multiple parameters in a weighted calculation through a standardised scale (-5 to 5).

The combination of these methodological concepts provide clear information for decision-making and graphical output of results regarding the advantageous and disadvantageous character for each index [39]. In fact, the use of these theoretical concepts is becoming a trend in recent research studies, seeking to structure different influencing factors and to develop a multidisciplinary quantification of 12 main identified variables, considered as key original elements in this model. Additionally, the corresponding variables are divided into 6, related to the impact generated during the works and another 6 related to the result. These 12 variables will be weighted independently from a multidisciplinary scale from 4 dimensions: Technical, Social, Economic and Environmental.

The methodology defined here complies with different scenarios to convert it into a standardised process, gathering technical information from inspections, and social demands from participatory surveys, that can be replicated in other urban and socio-economic contexts:

- 1. Carry out an integral diagnosis of the building typology.
- 2. Identify complexities, demands and requirements of high-rise multi-family building.
- 3. Design different renovation strategies according to the multidisciplinary diagnosis.
- 4. Data process and weighting in this preliminary assessment model on 12 key variables, quantifying in advance advantages and disadvantages during and after works.
- 5. Graph the results output and discuss through a sensitivity analysis for the correct decision-making from different dimensions to identify the most efficient and feasible actions.

To test the operation of this standardised procedure, this model is going to be applied in representative neighbourhoods in Argentina and in Spain, to verify the testing results and their corresponding implications.

Throughout the following subsections, the different stages of the proposed model will be broken down, defining the incorporated dimensions and the 12 key variables related to the process during and after the works, as well as their weighting parameters, which help to facilitate decision-making for owners, promoters and even government entities with useful policy-making insights.

Table 2
Variables, assessment parameters and weighting procedure of the multidisciplinary assessment.

Variable	Assessment Parameters	Weighting Procedure
1] Duration | Execution period *(During works)*	- Quantitative - Progressive range |*X*: [No. of weeks] *[Min.: 2 weeks | Max.: 156 weeks (3 years)]* · Limit between Benefits | Drawbacks: [Tec]:1 year; [Soc]:6 months; [Ec]:1 year; [En]:6 months ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$V1_{B\|D} = \pm\omega \frac{X_{B\|D}}{X_{\text{Range}B\,\|\,D}} * 5$
2] Scale | Scope of action *(During works)*	- Scale and intensity |*X*: [Item-Value] Outside (O); Common areas (C); Inside Apartm. (I): [0] Null [1]; Punctual [2]; Partial [3]; Total · Benefits | Drawbacks: [Tec]:I |O,C; [Soc]: O |I,C; [Ec]: I |O,C; [En]: I, C |O ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$x_{O,C,I} = \frac{\sum x * n_i}{x_{max} * n_t}$ $V2_{B\|D} = \pm\omega \frac{\sum (x_O, x_C, x_I)}{\sum x_t} * 5$
3] Construction system | Serialisation *(During works)*	- Elements, Techniques, Complexity |*X*: [Item-Value] - Elements: (A) Distribution and partitions; (B) Technical systems; (C) Vertical communication core; (D) Building envelope; (E) Structure and foundation; (F) Facilities - Techniques: [P] Prefabricated construction; [S] On-site components. - Complexity [1]: Low [2]; Medium [3]; High · Benefits | Drawbacks: P |S; 1| 2,3. [Tec]: A,B,F |C,D,E; [S]: B,D,F | A,C,E; [Ec]: A,B |C,D,E,F; [En]: B,C,F | A,D,E. ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$w_{A,B,C,D,E,F} = \frac{\sum x * n_i}{x_{max} * n_t}$ - - - - - - - - - - - - - - - $V3_{B\|D} =$ $\pm\omega \frac{\sum (w_{A,B,C,D,E,F})}{\sum w_t} * 5$
4] Concerns | Risks *(During works)*	- Risks, Concerns, Impact |*X*: [Item-Value] - Risks & Concerns: (A) Rent increase; (B) Quality of the information; (C) Organisation of the Renovation plan; (D) Nuisance; (E) Noise; (F) Dust. - Impact: [0] No impact - [5] High impact · Benefits | Drawbacks: [Tec]: B,C |E,F; [S]: B,C | A,D,E,F; [Ec]: C | A, F,D; [En]: C |D,E,F. ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$w_{A,B,C,D,E,F} = \frac{\sum x * n_i}{x_{max} * n_t}$ - - - - - - - - - - - - - - - $V4_{B\|D} =$ $\pm\omega \frac{\sum (w_{A,B,C,D,E,F})}{\sum w_t} * 5$
5] C&D | Waste *(During works)*	- Quantitative - Volume, Weight |*X*: [m^3 & Tonnes] - Volume (m^3): *[1 … 300 m^3]* - Weight (tonnes): *[1 … 300 tonnes]* · Limit between Benefits | Drawbacks: [Tec]: 40m^3 | 100t; [Soc]: 20m^3 | 70t; [Ec]: 20m^3 | 70t; [En]: 10m^3 | 30t ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$Vol. = \pm\omega \frac{x}{x_{max}} * 2.5$ $Weig. = \pm\omega \frac{x}{x_{max}} * 2.5$ $V5_{B\|D} = \pm Vol. \pm Weig.$
6] Relocation | Disablement *(During works)*	- Area | Restriction period |*X*: [Yes/No-Time] - Limitation: (A) Complete users' relocation; (B) Temporary restricted – apartments | rooms; (C) Temporary restricted – building envelope; (D) Temporary restricted – communal spaces; (E) Temporary restricted – facilities - Period: (0) No; (1) <1 week; (2) 1 week-1 month; (3) 1–3 months; (4) 3–6 months; (5) Over 6 months · Benefits | Drawbacks: [Tec; Soc; Ec; En]: No relocation | Limitations & Time ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	*Yes:* $V6_{B\|D} = -5 - 0 \rightarrow x = \pm\omega \cdot [time]$ *No:* $V6_{B\|D} = 0\text{-}5 \rightarrow \pm\,\omega \cdot \overline{x}[b, b, c, d, e]$
7] Liveability | Comfort *(After works)*	- Parameter, Impact, Frequency |*X*: [Item-Value] - Scope: (A) Distribution; (B) Thermal comfort; (C) Air quality; (D) Lighting - Impact: [0] No impact - [5] High impact - Frequency: (a) Occasional; (b) Seasonal; (c) Permanent · Benefits | Drawbacks: [Tec; Soc; Ec; En]: Benefit based on higher Impact & Permanence ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$V7_{B\|D} = \pm\omega \frac{\sum (x_A, x_B, x_C, x_D)}{\sum x_t} * 5$
8] Accessibility – Mobility *(After works)*	- Parameter, Impact, Frequency |*X*: [Item-Value] - Scope: (A) Accessibility common spaces; (B) Accessibility inside apartments; (C) Safety; (D) Mobility widths - Impact: [0] No impact - [5] High impact - Frequency: (a) Occasional; (b) Seasonal; (c) Permanent · Benefits | Drawbacks: [Tec; Soc; Ec; En]: Benefit based on Higher Impact & Permanence ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.]; 0.8 [5-6 storeys.]*	$V8_{B\|D} = \pm\omega \frac{\sum (x_A, x_B, x_C, x_D)}{\sum x_t} * 5$
9] Energy demand | Savings *(After works)*	- Quantitative - Reduction, % Saving |*X*: [kWh/m^2 & %] - Demand (kWh/m^2): *[1 … 100]* - Savings (%): *[1 … 80]*	$Dem. = \pm\omega \frac{x}{x_{max}} * 2.5$ $Sav. = \pm\omega \frac{x}{x_{max}} * 2.5$ $V9_{B\|D} = \pm Dem. \pm Sav.$

(*continued on next page*)

Table 2 (*continued*)

Variable	Assessment Parameters	Weighting Procedure
	· Limit between Benefits | Drawbacks: [Tec]: 20 kWh/m^2 | 15%; [Soc]: 10 kWh/m^2 | 10%; [Ec]: 10 kWh/m^2 | 10%; [En]: 30 kWh/m^2 | 20% ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.];* 0.8 *[5-6 storeys.]*	
10] Visual change | Aesthetics *(After works)*	- Parameter, Impact |*X*: [Item-Value] - Scope: (A) Outside visual change; (B) Inside visual change; (C) Aesthetic improv.; (D) Heritage protection - Impact: [0] No impact - [5] High impact · Benefits | Drawbacks: [Tec; Soc; Ec; En]: Benefit based on higher Impact [Tec]: D; [S]: A, B,C,D; [Ec]: A,B,C,D; [En]: A,B. ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.];* 0.8 *[5-6 storeys.]*	$V10_{B\|D} = \pm\omega \frac{\sum(x_A, x_B, x_C, x_D)}{\sum x_t} * 5$
11] Revaluation | Payback *(After works)*	- Quantitative - Revaluation, Payback |*X*: [Item-% Value] - Revaluation (% of increase): *[0 … 100]* - Payback (% of payback in 15 years): *[1 … 100]* · Benefits | Drawbacks: [Tec; Soc; Ec; En]: Benefit based on Higher Percentage ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.];* 0.8 *[5-6 storeys.]*	$Rev. = \pm\omega \frac{x}{x_{max}} * 2.5$ $Payb. = \pm\omega \frac{x}{x_{max}} * 2.5$ $V11_{B\|D} = \pm Rev. \pm Payb.$
12] Management | Maintenance *(After works)*	- Parameter, Impact, Frequency |*X*: [Item-Value] - Scope: (A) Management; (B) Maintenance; (C) Added services; (D) Permanent cost - Dependence: [0] None - [5] Essential - Frequency: (a) Occasional; (b) Seasonal; (c) Permanent · Benefits | Drawbacks: [Tec]: A, B |C; [Soc]: A |B,C,D; [Ec]: |B, C, D; [En]: A,B |C. ω: 1.2 *[>9 storeys.]; 1 [7-9 storeys.];* 0.8 *[5-6 storeys.]*	$V12_{B\|D} = \pm\omega \frac{\sum(x_A, x_B, x_C, x_D)}{\sum x_t} * 5$

3.1. High-rise multi-family building assessment model for decision-making

The usefulness of this multidisciplinary assessment model focuses on its particular approach on high-rise multi-family buildings, a representative building typology with particular complexities in the built environment. A combined model is presented that considers, according to calculations that are presented in Table 2, both the information from the technical diagnosis made by architects and engineers through inspection sheets, along with demands and other social parameters obtained from carrying out questionnaires and interviews with the residents.

The research establishes 4 main dimensions of assessment, highlighting the importance of a multidisciplinary approach as in recent studies such as Invidiata et al. [9] or Mercader-Moyano et al. [10], which allow us to quantify renovation parameters during and after the works, from different fields. Thus, the four dimensions are: 1. Technical; 2. Social; 3. Economic and 4. Environmental, in each of which the results of 12 parameters will be organised and quantified in their values taking the whole building into account, as well as enabling a discussion of the results according to the benefits and drawbacks of each renovation strategy. The definition is as follows:

- **Technical** (D_1) brings together the architectural, technological, and spatial patterns for the diagnosis of high-rise multi-family buildings. Each typology receives technical visits and inspections to carry out an evaluation regarding the materials, thermal and environmental performances, conservation status and other conditions related to complying with the habitability conditions and guaranteeing the comfort of users in housing environments. This dimension provides a quantification of the impact and benefits of the different renovation strategies proposed from parameters that meet the technical perspective.
- **Social** (D_2) represents a particular assessment of different parameters from the perceptions, reactions and benefits introduced towards the users in the built environment, measuring direct and indirect consequences of the way in which the works are carried out. Other subsequent aspects are considered, including their feasibility, management and other issues that contribute to improving the success of planning a renovation strategy. These are weighted based on preferences established in interviews, questionnaires and other community reports. As an original contribution, each of the selected parameters is considered from the social discipline, so as to ensure successful and satisfactory decided strategies.
- **Economic** (D_3) incorporates a financial vision to each one of the processes and stages of the high-rise multi-family building renovation, by considering investments, direct and indirect costs from the renovation works, maintenance fees and the subsequent increase in the valuation of the properties. This assessment allows for the decision-making to be adjusted in housing renovation strategies from a viable and defrayable guarantee of expenses both from the promoters and the homeowners. This evaluation provides important insights and variations from the economic perspective in each assessed variable, even more so in the case of large-scale buildings in which the number of properties and owners is too high to pay for certain common costs.
- **Environmental** (D_4) represents a particular assessment perspective based on a quantitative and qualitative perspective on sustainability and resource efficiency in the renovation process in high-rise residential buildings. This dimension focuses on environmental parameters in indoor/outdoor conditions, along with adding an environmental approach to the results outcomes including the optimization of resources, the adjustment of renovation mechanisms and other transversal patterns aimed towards achieving higher levels of efficiency during the works and its decision-making.

The design of this multi-criteria assessment system in housing renovation, specifically designed for high-rise multi-family buildings, introduces and breaks down as a novelty 12 assessment variables, organised into two types: 6 variables related to the development of the works, and 6 variables that value the result of the intervention for each renovation strategy. The criteria to identify and select 12 variables to be assessed from the 4 dimensions mentioned earlier (6 pertaining to the process of renovation works and the other 6 pertaining to the post-renovation process) follows basic housing principles established in world cities reports on the efficient management of the built environment [1,40]. The guidelines for selecting the variables are based on technical regulations, housing renovation patterns and other relevant demands from users and policy-makers [41,42].

These 12 variables are weighted independently from the 4 determined dimensions, and subsequently each variable is scaled in a range from -5 to 5, with negative values representing adversities and positive values representing benefits. When making decisions, this range allows for a much more visually comprehensible identification of what would be advantageous and disadvantageous, and a graphic output of results in which the benefits and downsides of a strategy can be seen with the visual guide of the X axis as a neutral contribution. The 12 variables are defined as follows:

V1] Duration | Execution period is the total time spent in carrying out the rehabilitation works, from its start to its delivery and set-up. The execution time is quantified in a progressive range through a number of weeks from the start of the works, weighing the different dimensions according to whether they are considered benefits or drawbacks.

V2] Scale | Scope of action focuses on the places where the works are carried out and correspondingly on the size and scale of said works, distinguishing between outside, the interior common spaces and the interior of the apartments, and subsequently distinguishing the level of intensity in each area.

V3] Construction system | Serialisation assesses the construction system, the elements of the building in which it works and the different construction techniques, taking into account the complexity of carrying out the works. It distinguishes the benefit that serialisation and precast elements entail in large-scale buildings, and the added complexity of certain buildings that highly exceed more than 5 storeys. An evaluation of the elements of the building, construction techniques and complexity are considered and a final weighted value (w_{f3}) is obtained.

V4] Concerns | Risk Relocation considers the perceptions, preferences and worries of users during the renovation works in order to facilitate the decision-making between renovation strategies and their impact on users. Possible effects of the works, noise, inconveniences and the frequency with which they are carried out, as well as other economic consequences along with other considerations, weighting a final value that includes the advantages and disadvantages of each strategy.

V5] C&D | Waste quantifies the generation of C&D waste during the works through two fundamental parameters, volume and weight, both equally weighted to obtain a final value. This variable allows us to visualise the optimization of resources according to each defined strategy. The weighting ranges chosen are based on specific databases and studies [43].

V6] Relocation | Disablement considers the impact generated in the different dimensions by the possibility of relocating users during the works, either completely to another dwelling, or by limiting the use of certain spaces or basic services and supplies for a certain period of time. This variable distinguishes between the capping frequency, which causes the variation towards higher drawbacks the longer the caps and relocations are.

V7] Liveability | Comfort evaluates the impact generated after the rehabilitation works by each strategy regarding design and distribution parameters, thermal comfort, lighting, and air quality and subsequently quantifying the impact generated in each of these areas. The final weighting considers the improvement of the user's standards as well as whether the benefits of the renewal are permanent, seasonal or occasional according to the service, the use and the day-to-day operation of the users.

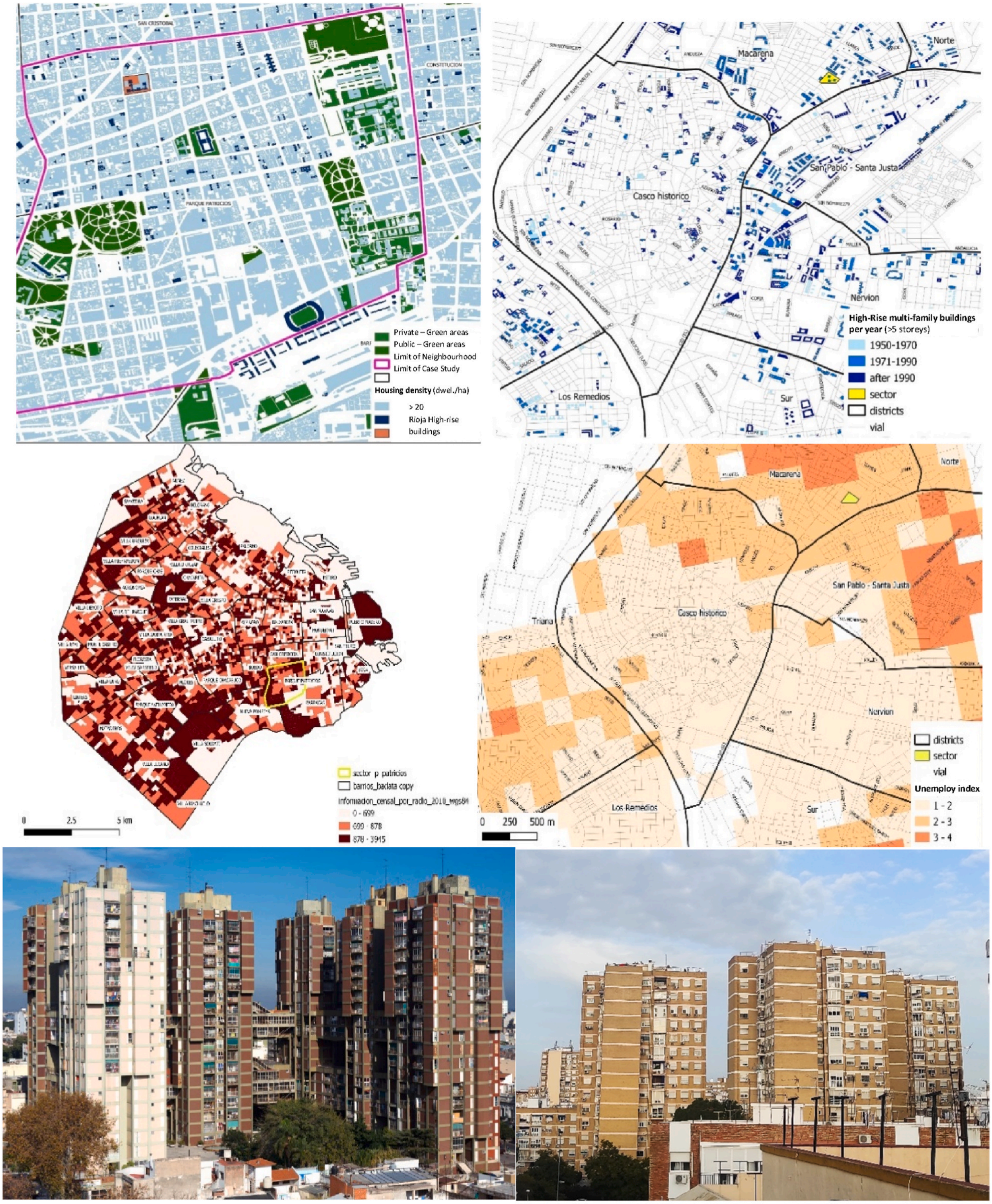
V8] Accessibility | Mobility assesses the improvement, or the impact generated by the works regarding mobility and accessibility conditions, both in the common spaces of the building and inside the apartments, as well as regarding safety conditions and risks in the face of accidents and falls. Being a specific tool for high-rise buildings, the guarantee of accessibility conditions must be evaluated with essential and fundamental criteria. The final value considers the impact generated in each of the highlighted areas as well as the frequency with which they are perceived from the different perspectives.

V9] Energy Demand | Savings quantifies the reduction in energy demand and the percentage of energy and economic savings that the rehabilitation works entail according to each action strategy. For these energy calculations, the original state and the calculation of the demand after rehabilitation are compared and percentages of demand and savings in consumption are obtained by "DOE2" engine [44], which are equally weighted according to the ranges established below.

V10] Visual change | Aesthetics focuses on assessing the visual changes to the building (pertaining to the design and its aesthetics) after the renovation works, both indoors and outdoors, as well as its possible impact on its heritage value. This parameter provides information on the quality of the final result, even more so in large-scale buildings, and the acceptance when making decisions between strategies. The quantification of this factor may be positive (benefit) or negative (drawback) depending on the final result, the type of changes, and the patrimonial protection of the building.

V11] Revaluation | Payback quantifies the revaluation values of the property after the selected renovation strategy, through percentages, allowing for the incorporated benefit or drawback to be verified from different dimensions, as well as considering the possible defrayment of the costs of the works in a period of 15 years, either through energy savings, revaluation or amortization of costs.

V12] Management | Maintenance considers the weighting of the benefits and drawbacks that the renovation strategy introduces in terms of management, maintenance, additional services to be contracted and other costs and expenses in rates and fees incurred by the rehabilitation works. This variable considers the dependence of the works and their necessity, from none to essential, as well as the frequency with which they occur, which may be benefits or drawbacks according to the different assessment perspectives.



A) "Rioja" Buenos Aires (Argentina)

B) "Ordás" Seville (Spain)

Fig. 2. Urban and socioeconomic GIS maps for the selection of cases A) Argentina and B) Spain. Source: Authors.

Table 2 presents the assessment parameters of each variable and provides the weighting procedure for obtaining normalised values in a -5 to 5 range. The calculations are defined independently in the last column and are mainly based on assigning a score for each variable (x) in relation to its possible maximum score (x_{max}) and other subsequent parameters according to each variable in the 4 established dimensions. Additionally, another cross-sectional parameter (ω) arises which adjusts the weighted values of each variable based on the height and number of apartments of the building, distinguishing between a higher benefit or drawbacks of certain parameters in buildings with higher number of storeys, and a smaller variation in lower buildings.

The table gathers the definition of the evaluation parameters of each variable, often combining qualitative and quantitative data through item-values or through percentages or absolute amounts. In order to obtain independent and standardised values for each variable, a weighting system is used that is based on normalised means, as followed by Vafaei et al. [45], that allows us to regulate the scores of all the variables on the same scale to be discussed and compared. This model also incorporates an evaluation system for each variable according to areas, elements, degree of impact, or quantitative limits, among others, being weighted independently for each variable in a range of $\pm$ 5 to show benefit or drawbacks.

The implications of establishing these variables entails aspects directly related to the status and design of the building, both indoor and outdoor, the habitability conditions it offers, the way of carrying out the different works, duration, scale, construction techniques or serialisation attributes. Additionally, it takes into account implications that also generate an impact, such as possible relocations, economic revaluations and other tasks derived from maintenance and management. It incorporates certain variables that were used in the design of previous assessment models from referenced works, such as the one developed by Delmastro et al. [46] or Díaz-López et al. [47]. Therefore, the obtained results vary depending on the technical, social, economic and environmental dimensions to identify the best renovation strategies in high-rise multi-family buildings, providing a sensitivity analysis and a graphical output of results to discuss the partial and overall performance, in order to decide the most appropriate strategy.

3.2. Scope of application

The originality of the paper lies in the particular approach that this research proposes to high-rise multi-family buildings, providing useful insights for the decision-making in residential areas with high population density in social neighbourhoods. The related parameters to apply this research focus on multi-family buildings, higher than 5 storeys, thereby involving multiple apartments, correspondingly with numerous different owners who face the costs of global renovation in the building.

Regarding the year of construction, the model is planned for buildings built before 1980, with more than 40 years of use, and whose conservation status is obsolete and deteriorated, along with having numerous regulatory non-compliances in terms of habitability, accessibility, safety and comfort [29]. Furthermore, it is important to consider high-density residential areas with low socioeconomic levels, which under vulnerable conditions seek to adjust and choose the most optimal renovation strategies in these residential areas [48].

This study incorporates the use of GIS Geographic Information Systems as a resource that supports sample selection, allowing us to efficiently and intuitively cross the parameters of building height, the year of construction, number of occupants and socioeconomic levels of the population, and allowing us to draw maps of representative buildings in the city with potential to apply this model [12, 49]. Thus, GIS is the support tool to detect and identify neighbourhoods that would be suitable for this research, when it comes to detecting opportunities for policymakers, developers, construction firms and owners to promote urban regeneration. In addition, this resource serves to identify added vulnerabilities in the corresponding areas of action, thus not only having implications for this study, but for the replicability of the model in other housing environments and cities.

Beyond defining the scope of application patterns and the GIS technological resources (open software “QGIS”) to identify potential areas of application, this subsection aims to test and verify the operation of the assessment model and decision support system. Within a framework of international cooperation between researchers, a city from South America, Buenos Aires (Argentina), and a European city, Seville (Spain), have been selected to develop a GIS preliminary analysis. Both countries have suffered significant economic and urban consequences due to inflation, 7.5% in Spain and a remarkable 48.4% in Argentina in 2021 [11], with a direct impact on payback times and increasing the costs of renovation, which has increased the limitations to address an effective renovation of housing stock [50]. The identification of the selected neighbourhoods in each city has been developed after obtaining different analyses of building height, age, and the socioeconomic context of its inhabitants, as depicted in selected maps of Fig. 2.

Fig. 2 represents a visualization of the two selected neighbourhoods, as well as a series of analysis maps obtained in GIS to fulfil the scope patterns and show their representativeness. The application of the model in two neighbourhoods from different countries has made it possible to verify the variations and necessary adjustments in the 12 main factors, from the four dimensions. Thus, the selection of the following pilot cases demonstrates its operation, adjustment to the design phase, and helps create a numerical and graphical output of results to enhance the usefulness of the model, promoting more effective actions in urban planning and policymaking. Last but not least, this application of the model shows public and private entities, promoters and policymakers the need to adjust feasible and more sustainable renovation proposals in the built environment, also allowing for a comparison and discussion between both cases and their results, according to the resulting performance from technicians and users in different variables and dimensions.

The two case studies are further defined below:

A) **RIOJA, Buenos Aires,** (Argentina). Vulnerable and deteriorated multi-family housing complex situated in one of the worst planned districts of Buenos Aires: Parque Patricios. These six high-rise residential buildings were built between 1969 and 1973, standing out among the low-rise buildings that surround them without any integration into the predominant urban environment. The building typology is isolated towers, all of which connected by a ground platform with commercial spaces, with 22 storeys. Buildings are highly deteriorated and open common spaces are poorly maintained. The apartments are owned by their occupants (apart from those that are rented by tenants). Some apartments have been refurbished in recent years, mainly renovating the facilities and air-conditioning, but no general renovation action has been developed, mainly because most residents cannot afford the refurbishment of common spaces and facades. This case study represents a medium-low socio-economic index, which will also allow us to compare the performance of the assessment method in social neighbourhoods with intermediate socioeconomic levels [51].

B) **ORDÁS**, **Sevilla**, (Spain). Case study predominantly composed of 4 high-rise multi-family housing in the urban extension of the city, in southern Spain, whose construction period was from 1978 to 1981. The building typology is isolated towers with 14 storeys, so accessibility must be ensured by sufficient number of capable elevators. The state of conservation in the facilities is generally obsolete, and the building envelope and indoor common areas show some damage, which requires certain repair measures in different parts of the building [52]. The apartments are owned by their occupants (apart from those that are rented by tenants). Some apartments have been refurbished or moderately refurbished on an ad hoc basis in recent years, mainly in terms of renovating the distribution, facilities and other services, but no communal renovation action has been developed due to the owner's economic condition. The urban morphology is more regular, with wider streets, green areas and common spaces between the buildings. This case study represents a medium socioeconomic index in the city, whose results will be assessed and compared with other lower o higher socioeconomic levels [53].

Following the procedure detailed in subsection 2.1. of the methodology, a technical diagnosis of the state of conservation of these pilot cases has been obtained through technical visits and inspections in both countries. The architects in charge of these inspections have gathered data on the buildings based on the 12 defined variables (based on both their current state and in the accounting for the improvements that the different renovation strategies would entail). Additionally, information provided by residents on the operation of the building, deficiencies and demands has also been included. Tables 3 and 4 describe a summary of the main diagnosis obtained by each of the pilot cases, which will serve to adjust the weighting exposed in each of the 12 variables and to determine the design of each of the action strategies with which to carry out the study.

According to the diagnosis obtained in each of the high-rise multi-family buildings, the criteria ranges to be followed to define the renovation strategies have been determined by the urban and socioeconomic context of both countries, following corresponding databases updated in 2022 [13,54]. The different ranges according to the defined parameters of each strategy and country are:

Mild. Consider renovation proposals with total costs for the building of less than 200,000 € or 150€/m^2 per apartment. Interventions are generally from the outside, both in common areas and from outside, and can be partial. This strategy does not involve actions that interfere with the normal use of the apartment, except for partial disturbances, or local relocations, without being very long over time.

Moderate. covers renovation proposals with total costs for the building between 200,000 € and 500,000 € or between 150€/m^2 and 300€/m^2 per apartment. Works are mostly conducted on external surfaces of the buildings, both in common and private areas, partially or totally, although it does consider some specific interventions inside. This strategy may involve actions that interfere with the normal use by the apartment's residents, generating partial disturbances, or local relocations, and can have a considerable duration over time, normally less than 6 months.

Intense. renovation strategy that covers a total cost for the building between 500,000€ and 1,000,000€ or between 300€/m^2 and 600€/m^2 per apartment. Works are both from external, in global operations on the façade of the building, as well as in common

Table 3
Basic data, characterisation, and diagnosis of a representative building of Case A "Rioja" in Argentina.

Tower High-rise	Year of construction	Apartments (per reference building)	Storeys	% of occupied apartments (aprox.)	Initial property value (ratio; 2021)	Surface area per apartment (average)	Initial energy Demand (Heating/ Cooling)
Case 1	1972	88	22	78%	1270 €/m^2 *341,245 Peso/m^2*	64m^2	226 kWh/m^2

Envelope	Systems
Façade: Prefabricated concrete panel, air cavity, insulation, interior gypsum board. Roof: Galvanised metal sheet, insulation, mortar slope formation, concrete slab. Floor: Concrete slab, ceramic flooring bonded with cement mortar. Interior partitions: Lightweight walls with gypsum boarding.	Heating: No central heating. Local heating suppliers in each apartment Windows: Wood frames, without thermal break and single glazing. Ventilation: Passive ventilation. Domestic hot water: Local heating pump – Gas heater

DIAGNOSIS	
Technical status	Facade is in deteriorated condition. Numerous cracks and fissures and detachment of materials. Facilities lack regulatory compliance and are in need of renovation.
Distribution and layout	Small rooms, with particularly small and inaccessible kitchen and bathroom.
Outdoor and indoor accessibility	Limited access to the entrance. Reduced space in common areas. Inadequate accessibility conditions inside the apartments.
Thermal performance	The transmittance values and the energy demand are very high compared to the energy requirements, mainly due to poor energy performance of the building envelope
Maintenance	During the last 15 years, hardly any communal action has been taken. There is a lack of maintenance.
High-rise Particularities	Important changes between apartments on different floors, with different distributions and a large number of treatments on balconies and windows.

Table 4
Basic data, characterisation, and diagnosis of a representative building of Case B "Ordás" in Spain.

Tower High-rise	Year of construction	Apartments (per reference building)	Storeys	% of occupied apartments (aprox.)	Initial property value (ratio; 2021)	Surface area per apartment (average)	Initial energy Demand (Heating/ Cooling)
Case 2	1979	56	14	82%	2420 €/m^2	72 m^2	182 kWh/m^2

CHARACTERISATION	
Envelope	Systems
Façade: Solid brick wall, air cavity, insulation, interior brick partition, and gypsum board. Roof: Ceramic tile cover, cement mortar layer, insulation, mortar slope formation, concrete slab. Floor: Concrete slab, ceramic flooring bonded with cement mortar. Interior partitions: Hollow brick partition with gypsum boarding.	Heating: Central heating and water radiators. Windows: Aluminium frames, without thermal break and single glazing. Ventilation: Passive natural ventilation. Domestic hot water: Local heating pump – Gas heater

DIAGNOSIS	
Technical status	Building with an acceptable technical status. There are certain damages in the facade that are not important for aesthetic visualization.
Distribution and layout	The size of bathrooms and kitchen is especially small. The apartments are highly subdivided (3 bedrooms and living room).
Outdoor and indoor accessibility	There are a few problems in accessing to the entrance and the use of certain rooms, such as the kitchen and bathroom due to the reduced indoor spaces.
Thermal performance	Although the thermal performance of the envelope materials is acceptable, regulatory requirements continue to be breached in windows, roof and facades.
Maintenance	The roof and façade were slightly renovated around 18 years ago.
High-rise Particularities	Without significant variations among apartments' layout, favourable shape of the building for scaffolding placement; open ground floor.

spaces or inside the apartments, partially or totally. This strategy may involve actions that notably interfere with the normal use of the residents in the apartment, generating total inconvenience, or even temporary relocation of certain spaces in the home, having a considerable duration over time, even exceeding 6 months.

Deep. renovation strategy that encompasses a total cost for the building of more than 1,000,000 € or more than 600€/m^2 per apartment. Works are both from external, in global operations on the façade of the building, installations and other basic systems, as well as in common spaces or completely inside the apartments. This strategy implies actions that interfere with the normal use of the residents in the apartment, generating total inconvenience and a total relocation of the apartment for a certain period of time.

4. Results and discussion

This section presents the application of the multidisciplinary assessment model for high-rise multi-family buildings in the two selected pilot neighbourhoods, aiming to demonstrate its operation and replicability in diverse urban and socioeconomic contexts. The results have been obtained after following the procedure described in subsection 3.1., particularly in Table 2, where the assessment parameters of each of the 12 variables have been defined.

Table 5 brings together the main results of the parameters obtained, according to each renovation strategy, particularised for each variable and independently weighted, for both case studies A) Rioja and B) Ordás. This table is organised by following the procedure established in Table 2, defining the weighted values for each variable according to each of the four dimensions. As expressed in the methodology section, the results have been quantified in a negative and positive range between -5 and 5, which correspondingly means drawbacks and benefits. This results format will then allow to be graphed so as to show the drawbacks and benefits that they would entail in each technical, social, economic and environmental field.

The weighted values of each of the 12 variables show the performance of each discipline according to each strategy in each neighbourhood, giving a comprehensive view of the suitability of each strategy to be followed in each parameter for the current requirements and demands. The results are wide and varied, so they require a deep level of discussion and analysis, obtaining values from -4.9 (drawbacks) to +5.0 (benefits). In addition, important variations between case studies are appreciated, for the different strategies, which also demonstrates the adaptability of the model to each architectural and socioeconomic context.

The multi-criteria decision-making model implies the illustration of the results in global schemes that will in turn allow for the visualization and facilitate the identification of the most optimal strategies to implement. As practical implementation of the outcome, the methodological process will provide promoters, public administrations and construction firms, among others, with a graphical output of results that directs towards an effective process of sensitivity analysis to aid with the decision-making process.

Table 5
Multi-criteria assessment of renovation strategies of both pilot neighbourhoods according to Table 2.

TEC.: SOC.: ECON.: ENV.:		MILD		MODERATE		INTENSE		DEEP	
		A) Rioja (Argentina)	B) Ordás (Spain)	A) Rioja (Argentina)	B) Ordás (Spain)	A) Rioja (Argentina)	B) Ordás (Spain)	A) Rioja (Argentina)	B) Ordás (Spain)
1] Duration | Execution period		**12 weeks**	**7 weeks**	**28 weeks**	**22 weeks**	**78 weeks**	**64 weeks**	**132 weeks**	**112 weeks**
	T.	*3,2*	*3,1*	*2.5*	*2.4*	*-1.0*	*-1.7*	*-3.9*	*-3.1*
	S.	*4.6*	*4.8*	*2.3*	*3.2*	*-2.8*	*-2.1*	*-4.7*	*-4.0*
	Ec.	*4.0*	*4.2*	*1.1*	*1.6*	*-2.2*	*-2.9*	*-4.4*	*-4.4*
	En	*3.6*	*3.6*	*0.2*	*1.1*	*-1.6*	*-0.9*	*-2.9*	*-2.6*
2] Scale | Scope of action		**O:2 C:1 I:0**	**O:1 C:2 I:0**	**O:2 C:2 I:1**	**O:2 C:2 I:1**	**O:3 C:3 I:2**	**O:3 C:2 I:2**	**O:3 C:3 I:3**	**O:3 C:3 I:3**
	T.	*2.8*	*2.2*	*-3.6*	*-1.9*	*-4.5*	*-3.7*	*-4.6*	*-4.4*
	S.	*4.2*	*4.3*	*0.9*	*1.3*	*-3.3*	*-2.3*	*-4.8*	*-4.7*
	Ec.	*3.1*	*1.5*	*-0.4*	*-1.6*	*-4.2*	*-2.7*	*-4.4*	*-3.9*
	En.	*2.0*	*1,8*	*-2.6*	*-0.6*	*-2.9*	*-1.8*	*-4.0*	*-4.1*
3] Construction system | Serialisation		**A:0 B:2S C:1P D:2S E:0 F:0**	**A:0 B:1S C:2P D:1S E:0 F:0**	**A:1S B:2S C:2P D:2S E:1S F:2**	**A:1P B:1S C:2P D:2P E:0 F:1**	**A:2S B:2S C:2P D:2S E:1S F:3**	**A:2P B:2S C:2P D:3P E:1S F:2**	**A:3S B:3S C:3S D:2S E:2S F:3**	**A:3P B:3S C:1P D:3P E:2S F:3**
	T.	*2.9*	*2.6*	*2.2*	*1.1*	*-1.9*	*1.2*	*-3.2*	*-2.6*
	S.	*1.4*	*0.9*	*0.3*	*-0.7*	*-2.4*	*-1.9*	*-3.6*	*-3.3*
	Ec.	*1.6*	*1.7*	*-2.9*	*-2.3*	*-3.7*	*-3.1*	*-4.8*	*-4.5*
	En	*0.9*	*1.9*	*1.6*	*0.2*	*-0.6*	*0.3*	*-2.8*	*-2.1*
4] Concerns | Risks		**A:0 B:1 C:1 D:1 E:2 F:1**	**A:0 B:1 C:0 D:1 E:1 F:0**	**A:2 B:2 C:3 D:3 E:2 F:2**	**A:1 B:1 C:1 D:2 E:1 F:1**	**A:3 B:3 C:3 D:4 E:3 F:4**	**A:2 B:2 C:2 D:3 E:2 F:3**	**A:4 B:4 C:4 D:5 E:3 F:5**	**A:3 B:3 C:3 D:5 E:3 F:3**
	T.	*2.7*	*3.2*	*1.3*	*2.4*	*-3.6*	*-0.6*	*-4.3*	*-3.4*
	S.	*4.4*	*4.3*	*0.9*	*1.3*	*-3.9*	*-3.7*	*-4.8*	*-4.3*
	Ec.	*3.7*	*4.0*	*-0.5*	*0.3*	*-3.1*	*-2.6*	*-3.5*	*-3.8*
	En	*3.0*	*3.6*	*-0.2*	*1.1*	*-2.5*	*-2.0*	*-3.8*	*-3.6*
5] C&D | Waste		**V:35 m^3 W:15t**	**V:25 m^3 W:10t**	**V:60 m^3 W:40t**	**V:50 m^3 W:25t**	**V:160 m^3 W:120t**	**V:130 m^3 W:100t**	**V:200 m^3 W:160t**	**V:160 m^3 W:95t**
	T.	*3.2*	*3.7*	*0.6*	*1.1*	*-3.1*	*-2.5*	*-4.0*	*-3.6*
	S.	*3.6*	*4.1*	*-0.3*	*0.6*	*-3.8*	*-3.2*	*-4.4*	*-3.8*
	Ec.	*4.1*	*4.5*	*1.4*	*1.9*	*-2.1*	*-1.2*	*-3.5*	*-3.2*
	En	*1.8*	*2.3*	*-2.4*	*-2.1*	*-2.6*	*-3.9*	*-4.8*	*-4.3*
6] Relocation | Disablements		**A:0 B:0 C:3 D:2 E:1**	**A:0 B:0 C:2 D:1 E:1**	**A:0 B:2 C:3 D:3 E:2**	**A:0 B:1 C:2 D:3 E:2**	**A:0 B:3 C:4 D:4 E:4**	**A:0 B:2 C:3 D:4 E:4**	**A:4 B:5 C:5 D:5 E:5**	**A:3 B:4 C:4 D:4 E:5**
	T.	*3.5*	*3.9*	*1.2*	*1.8*	*-3.1*	*-2.7*	*-4.3*	*-4.1*
	S.	*2.6*	*2.4*	*2.4*	*0.4*	*-2.6*	*-2.0*	*-4.9*	*-4.6*
	Ec.	*4.3*	*4.1*	*1.5*	*2.2*	*-3.3*	*-2.9*	*-4.9*	*-4.7*
	En	*3.1*	*3.6*	*0.4*	*-0,7*	*-2.4*	*-1.9*	*-3.9*	*-3.7*
7] Liveability | Comfort		**A:0 B:1c C:1b D:1c**	**A:0 B:1c C:2b D:1c**	**A:1a B:3c C:2b D:1c**	**A:1a B:3c C:2b D:1c**	**A:3c B:4c C:2c D:3c**	**A:3c B:4c C:3c D:3c**	**A:5c B:4c C:3c D:3c**	**A:5c B:5c C:4c D:3c**
	T.	*-3.3*	*-3.5*	*1.7*	*1.2*	*4.3*	*3.2*	*4.4*	*4.0*
	S.	*-4.6*	*-4.4*	*3.1*	*2.0*	*3.9*	*3.4*	*4.6*	*4.4*
	Ec.	*-3.7*	*-4.0*	*1.4*	*1.5*	*3.0*	*2.9*	*3.7*	*2.8*
	En	*-2.4*	*-2.7*	*2.8*	*2.6*	*3.3*	*2.7*	*4.4*	*3.9*
8] Accessibility | Mobility		**A:3b B:0 C:2a D:2c**	**A:2c B:0 C:2a D:2c**	**A:4c B:2b C:3b D:3b**	**A:4c B:3b C:3b D:3b**	**A:5c B:3c C:3c D:4c**	**A:5c B:4c C:4c D:4c**	**A:5c B:4c C:4c D:4c**	**A:5c B:5c C:4c D:5c**
	T.	*-2.1*	*-3.9*	*1.7*	*0.9*	*3.4*	*2.7*	*4.0*	*3.8*
	S.	*-0.6*	*-1.9*	*2.6*	*2.3*	*4.1*	*3.9*	*5.0*	*4.7*
	Ec.	*-1.6*	*-3.5*	*1.2*	*1.5*	*3.1*	*2.8*	*3.9*	*2.5*
	En	*-2.9*	*-3.0*	*-0.3*	*0.7*	*2.6*	*2.4*	*3.7*	*3.4*
9] Energy demand | Savings		**D: 10 kWh/ m^2 S: 4%**	**D: 5 kWh/ m^2 S: 3%**	**D: 22 kWh/ m^2 S: 12%**	**D: 18 kWh/m^2 S: 10%**	**D: 45 kWh/ m^2 S: 26%**	**D: 38 kWh/m^2 S: 22%**	**D: 58 kWh/ m^2 S: 29%**	**D: 52 kWh/m^2 S: 25%**
	T.	*-1.5*	*-4.3*	*-1.2*	*-1.6*	*3.1*	*2.6*	*4.2*	*4.0*
	S.	*-2.0*	*-2.2*	*0.6*	*-0.7*	*3.7*	*3.3*	*3.8*	*4.2*
	Ec.	*-0.6*	*-4.5*	*-1.8*	*-2.1*	*1.9*	*1.6*	*3.8*	*3.3*

(continued on next page)

Table 5 (*continued*)

TEC.: SOC.: ECON.: ENV.:		MILD		MODERATE		INTENSE		DEEP	
		A) Rioja (Argentina)	B) Ordás (Spain)	A) Rioja (Argentina)	B) Ordás (Spain)	A) Rioja (Argentina)	B) Ordás (Spain)	A) Rioja (Argentina)	B) Ordás (Spain)
	En	*-2.4*	*-4.0*	*-0.9*	*-1.1*	*4.2*	*3.1*	*4.5*	*4.3*
10] Visual change | Aesthetics		**A:3 B:0 C:2 D:2**	**A:2 B:0 C:1 D:1**	**A:4 B:2 C:3 D:2**	**A:3 B:2 C:2 D:2**	**A:5 B:4 C:4 D:2**	**A:5 B:4 C:3 D:2**	**A:5 B:5 C:4 D:2**	**A:5 B:5 C:3 D:2**
	T.	*-2.5*	*-3.0*	*1.6*	*0.8*	*3.8*	*3.1*	*4.3*	*3.9*
	S.	*1.4*	*0.7*	*2.3*	*1.6*	*4.2*	*3.5*	*4.6*	*4.3*
	Ec.	*-2.1*	*-1.8*	*1.9*	*-0.2*	*3.3*	*4.1*	*3.9*	*3.2*
	En	*-3.1*	*-3.3*	*0.9*	*-0.6*	*2.6*	*3.0*	*3.6*	*3.7*
11] Revaluation | Payback		**Rev.: 5% Pay.: 3%**	**Rev.: 4% Pay.: 2%**	**Rev.: 12% Pay.: 8%**	**Rev.: 9% Pay.: 6%**	**Rev.: 28% Pay.: 19%**	**Rev.: 26% Pay.: 17%**	**Rev.: 35% Pay.: 23%**	**Rev.: 33% Pay.: 20%**
	T.	*-3.2*	*-3.7*	*0.8*	*0.3*	*3.6*	*3.3*	*4.2*	*3.9*
	S.	*-1.7*	*-2.1*	*1.2*	*1.4*	*3.4*	*3.6*	*3.8*	*4.2*
	Ec.	*-0.9*	*-1.4*	*2.2*	*1.9*	*3.9*	*3.6*	*4.7*	*4.8*
	En	*-2.9*	*-3.4*	*-0.3*	*0.8*	*2.9*	*2.6*	*2.8*	*3.2*
12] Managem. | Maintenance		**A:2a B:1a C:0 D:0**	**A:1a B:1a C:1c D:0**	**A:3b B:3b C:2c D:2b**	**A:2b B:2c C:3b D:2b**	**A:4c B:4c C:3c D:4c**	**A:3c B:3c C:4b D:4c**	**A:5c B:4c C:4c D:4c**	**A:4c B:4c C:4b D:4c**
	T.	*3.2*	*4.3*	*0.4*	*1.1*	*-1.8*	*-1.3*	*-2.9*	*-2.6*
	S.	*3.6*	*3.4*	*1.1*	*0.7*	*-0.9*	*-1.6*	*-4.1*	*-3.4*
	Ec.	*3.9*	*4.0*	*0.7*	*0.4*	*-2.4*	*-2.8*	*-3.4*	*-3.9*
	En	*2.6*	*2.7*	*1.6*	*1.3*	*-1.5*	*-1.4*	*-1.8*	*-2.0*

The following Figs. 3–6 present the visualization of weighted results for each strategy: mild, moderate, intense and deep, correspondingly. These results are graphed in such a way so as to allow for a comparison and visualization of the level of drawbacks and benefits for each variable, independently for each of the dimensions, providing insights when identifying coincidences and deviations between different assessments. As a mechanism that facilitates the understanding of the users of the model, each assessment from each discipline is represented by a symbol on a vertical scale between -5 and 5, with a horizontal line marked on the balance 0, allowing for the identification of coincidence or deviation between dimensions and each of the 12 defined variables, during and after the renovation works.

From a general discussion, the provided results show a similar evolution in the performance of each of the variables with respect to the 4 strategies, clearly identifying that in the mild strategy, beneficial parameters are obtained during works and, after works, higher drawbacks are obtained, mainly for not having implemented sufficient improvements. Focusing on a more detailed analysis by strategy, the Mild strategy, in Fig. 3, represents benefits during the works, mostly highlighted in the social discipline of users in both study pilot cases, reaching remarkable values in 1]Duration, 2]Scale, or 4]Concerns. In other variables such as 3]Construction system, the benefits are lower because, being a high-rise building, any retrofitting intervention from the building envelope supposes a higher technical and consequently economic complexity, due to the cost of scaffolding and auxiliary machinery, site equipment and tools for working at height. On the other hand, results obtained after works show benefits 12]Management-maintenance, mainly because this strategy involves specific operations that do not require care or supervision. However, there are numerous drawbacks in variables such as 7]Liveability, 8]Accessibility, or 9]Energy demand, for not incorporating improvement in the established requirements and not constituting operations that improve residents' quality of life, especially negative in case study B. Finally, there are parameters such as 5]C&D-waste or 10]Visual change–Aesthetics in which the assessment valuation between dimensions is contrasted, reaching a difference of more than 4.5 points, which demonstrates the usefulness of this multidisciplinary fragmentation.

Regarding the Moderate strategy, in Fig. 4, the results show a higher balance between the impact generated during the works and the subsequent benefits. Although in the large majority of weighted values turn out to be positive, which shows that betting on intermediate strategies are much more effective in the global computation than the mild strategy. Introducing more benefits in 7]Liveability-Comfort, 8]Accessibility-Mobility and 10]Visual change-Aesthetics are aspects that quantify the quality improvements of the building after the renovation. In addition, regarding the feasibility of actions, the moderate strategy guarantees that the 11]Revaluation-Payback turns out to be positive, so they are actions that are worth carrying out from a multidisciplinary view. On the other hand, regarding the variables during the works, there are notable differences between the values obtained for the same variable, for example 2]Scale (+0.9 Technical vs. -3.9 Social) fundamentally due to the polarity of the results when integrating relative aspects to works in large-scale and high-rise buildings, with numerous apartments. In any case, both case studies show that the moderate strategy obtains advisable and intermediate values that guarantee the effectiveness, viability and improvement of the building in the short and medium term.

Finally, considering the Intense and Deep strategies together, in Figs. 5 and 6, the multi-criteria assessment model offers an inversion of the results previously discussed in Mild, with a very negative generalised impact during the works. Even more pronounced and led to extreme in the Deep strategy, while the consequences after the works are very beneficial, only with certain drawbacks regarding management and maintenance charges. As such, committing to an intense strategy implies clear benefits in 7]Liveability-Comfort, 8]Accessibility-Mobility, 9]Energy demand-savings, 10]Visual Changes-Aesthetics and 11]Revaluation-Payback, with

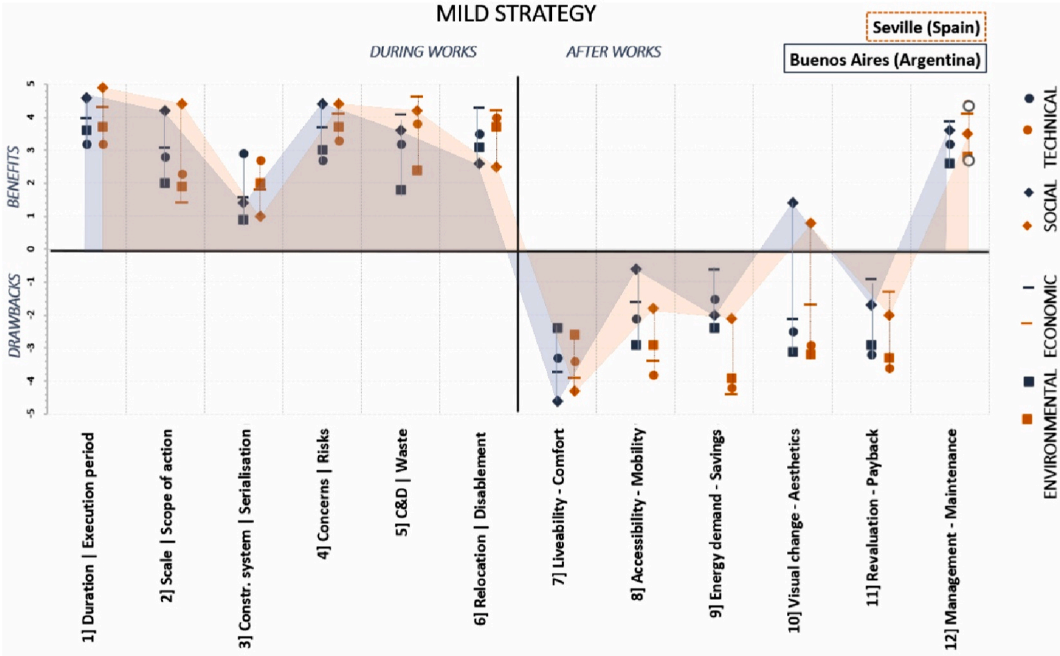


Fig. 3. Results on the multidisciplinary decision-making tool according to a mild strategy.

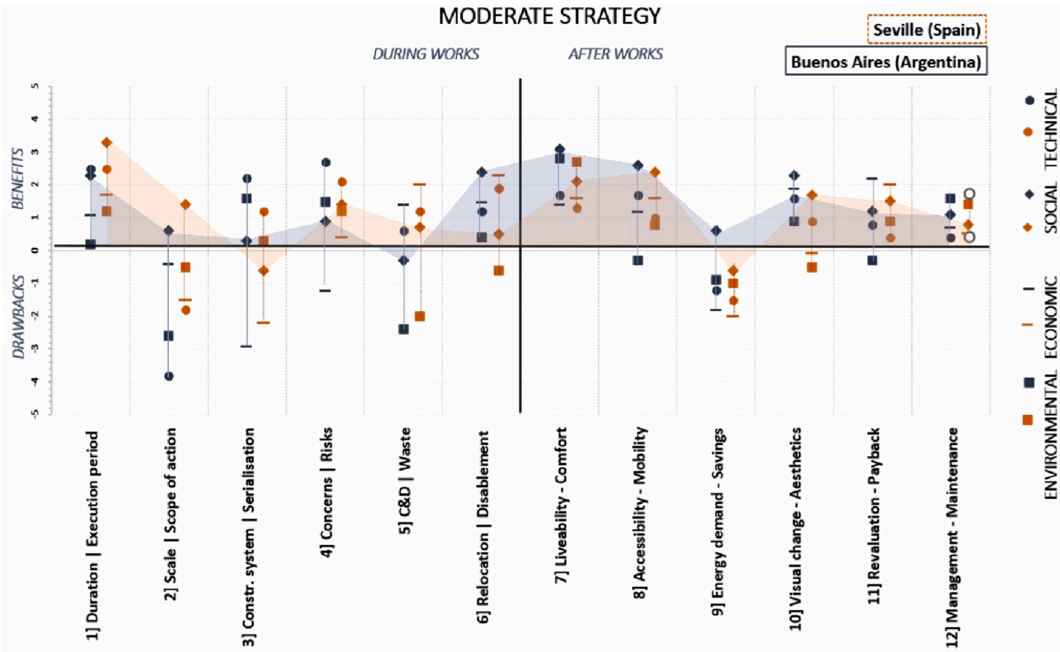


Fig. 4. Results on the multidisciplinary decision-making tool according to a moderate strategy.

close values between the different dimensions, which shows that it is worth betting on this type of strategy to provide high profits to the building. However, it is true that the added drawbacks involved in choosing the Deep strategy do not translate into a notable increase in benefits after the works, so the Deep strategy does not turn out to be as good as the intense strategy in this regard, mainly due to the relocation of tenants for a certain period of time during the works.

In a particular discussion between case studies, there are differences that vary in certain situations between A) Rioja and B) Ordás. On the one hand, due to the more vulnerable and deteriorated situation of the A) Rioja building, each action represents higher values, closer to the benefit after the works, while, due to the larger scale of the building, they represent more negative values or drawbacks,

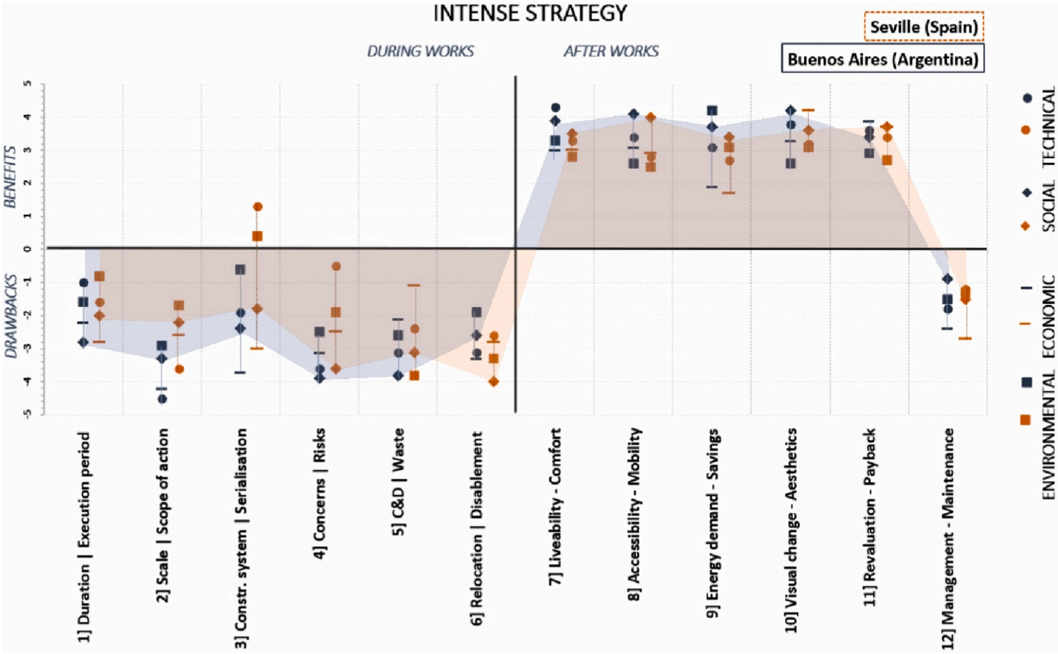


Fig. 5. Results on the multidisciplinary decision-making tool according to an intense strategy.

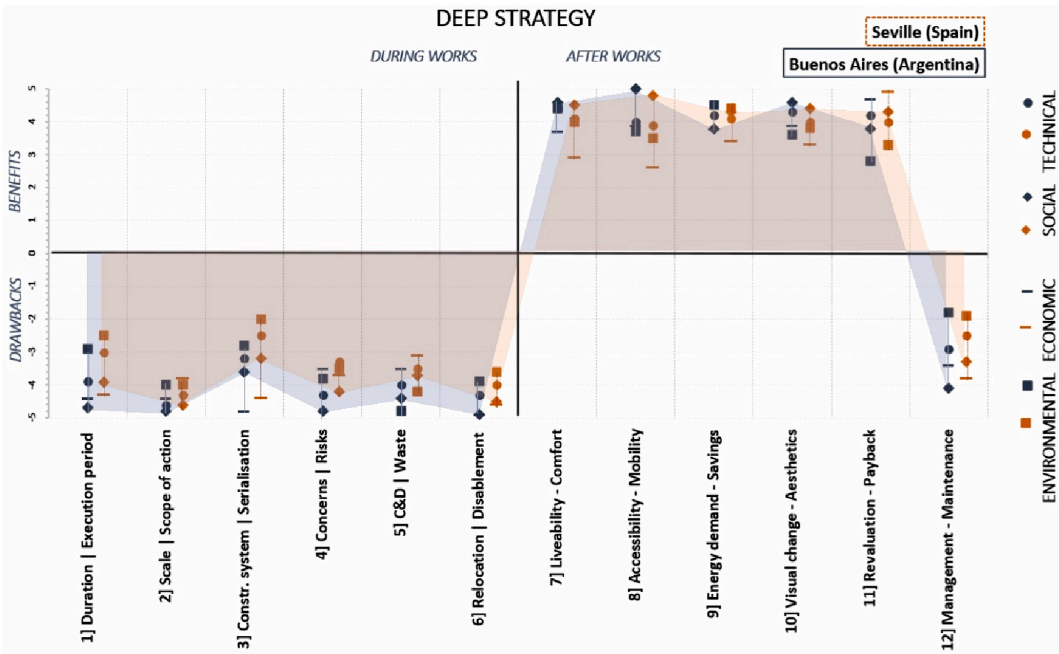


Fig. 6. Results on the multidisciplinary decision-making tool according to a deep strategy.

during said works, due to the complexity in undertaking them. These variations and adjustments represent the usefulness and operability of the model designed in high-rise multi-family buildings, in such a way that small movements between dimensions and variables can be visualised in the different case studies applied by developers, public administrators or policymakers.

The usefulness of showing the results on this scale and the graphic style is based on visualising the trend, variation and jumps between strategies and values for the same variable. These graphic results allow for the decision-making in high-rise buildings to be adjusted and renovation to be redirected from a multidisciplinary vision to guarantee the effective management of the built environment, as demanded by Riera et al. [55] in their study. This graphic output lets us visualise the prevalent variable among the ones suggested, and the degree of benefits/drawbacks when establishing the selected renovation strategies, in line with the goals of the Sustainable Development Agenda or the European Agenda for Sustainable Buildings and concluded as a research gap in the review article developed by Nielsen et al. [56].

Lastly, the testing procedure of this multidisciplinary decision support system in both neighbourhoods from Argentina and Spain, demonstrates the operation of the assessment model for vulnerable multi-family housing, with large scale and densely occupied. This application procedure displays the weighted results between different dimensions for each of the during and after variables, thereby filling the research gap highlighted towards ensuring the decision-making and proper renovation guidelines in high-rise multi-family buildings, which was demanded by Bolis et al. [57] and Moghtadernejad et al. [58] in their research studies.

5. Conclusions

This paper presents an original multidisciplinary decision support system especially focused on high-rise multi-family buildings, which supports the fulfilment of an identified lack of assessment and weighting mechanisms for the set of variables and dimensions involved when deciding which strategy or level of renovation is the most appropriate. This study also satisfies the global challenges of optimising the management of the built environment, especially demanded in high-rise multi-family buildings, considering the urban, architectural, environmental and socio-economic conditions of the building and also the increasing vulnerability scenario due to global inflation.

The research contributes with a renovation assessment model that independently weights 12 variables specifically related to high-rise multi-family buildings, as scope of action, classified into 6 variables linked to the process during and 6 variables linked to the process after the renovation works. The corresponding valuation parameters are based in Data Science resources, using weighting expressions to obtain normalised ranges between -5 and 5 index values. Furthermore, the originality of the model is also based on the design patterns incorporated in the graphical output of results, which allows promoters, construction firms or policy makers to visualise and identify which renovation strategy is the most optimised and viable according to the different circumstances. Additionally, the graphic output of results permit to develop a sensitivity analysis to distinguish results between the 4 established dimensions: Technical, Social, Economic and Environmental.

The value of the methodological proposals is based on filling a research gap in which there are no evaluation, weighting and support mechanisms for decision-making in the urban regeneration of high-rise buildings, considering the scale of construction and the number of owners. This decision support system establishes a new way of quantifying all these variables through a particular weighting procedure for obtaining multidisciplinary indexes through 12 variables from 4 dimensions, in order to ensure a feasible and proper decision-making of different renovation proposals. In fact, the graphical output of results is already considered one of the key outcomes of this assessment model since it allows us to detect drawbacks and benefits according to dimensions and strategies.

The application and testing of the model designed in 2 representative neighbourhoods with high-rise multi-family buildings, in Argentina and Spain, has generated important results outcomes that demonstrate the usefulness of the research and the validity of the model to obtain diverse, adapted and visual results, which facilitate decision-making in urban regeneration. The results have shown trends in benefits and drawbacks according to the chosen strategy in each case, and have varied, in some cases by up to 5 points of difference, between the different variables, both during and after the works, depending on the study and state of conservation of the buildings in question. As insights from the use of this model, it allows us to adequately adjust and determine the optimal cost for rehabilitation strategies, ensuring a holistic management of the built environment with application to vulnerable areas.

Based on the obtained results, as the proposed intensity of the works increases, the drawbacks-benefits relationship is inverted, with an established balance in moderate strategies, and a progressive and absolute inversion in intense and deep strategies correspondingly (higher drawbacks are obtained while maximum benefits are obtained at the same time). This new assessment model and decision support system introduces important implications for policymaking in housing renovation, especially in highly occupied buildings, aiming to ensure a higher satisfaction and feasibility in the selected renovation works. As overall implications, the incorporation of this decision support system for urban administration entities, promoters and homeowners would entail important insights towards a viable, sustainable and satisfactory management of high-rise multi-family buildings.

As for its limitations and future developments, this research presents and tests a model that still lacks a systematised mechanism, through digital tools or applications, that allows for the promotion of urban regeneration. However, this presents an opportunity to convert this mechanism into a digital tool that can sequence said process. This future development would also imply a mechanisation of the graphic output of results, to allow for a global use, given the flexible and open nature of the outlined methodological patterns. In addition, it would be an object of a particular study to focus more on other different types of buildings, adjust the omega (ω) parameter in a more exhaustive valuation study on the impact of this parameter, varying not linearly from 5 to n number of storeys, or specify different economic management models according to other ownership models and inflation rate per year for each country.

Author statement

Pilar Mercader-Moyano (Corresponding author): Conceptualization, Investigation, Funding acquisition, Project Administration, Supervision, Validation, Writing – Review & Editing. Patricia Camporeale: Resources, Investigation, Writing – Review & Editing. Antonio Serrano-Jiménez: Conceptualization, Investigation, Methodology, Data curation, Software, Formal analysis, Validation, Visualization, Writing - Original draft, Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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