Building and Environment 158 (2019) 260–280

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Implementing post-occupancy evaluation in social housing complemented with BIM: A case study in Chile

Alex Gonzalez-Caceres[a,c,*], Ariel Bobadilla[b], Jan Karlshøj[a]

[a] Department of Civil Engineering, Technical University of Denmark [1], Building 118, 2800, Kgs. Lyngby, Denmark
[b] Research Center of Construction Technologies CITEC, Bío-Bío University, Av. Casilla 5C, Collao, 1202, Concepción, Chile
[c] Department of Civil Engineering and Energy Technology, OsloMet – Oslo Metropolitan University, Postboks 4 St. Olav Plass, 0130, Oslo, Norway

ARTICLE INFO

Keywords:
Post-occupancy evaluation
BIM
Social housing
Indoor environment
Data
Building pathology

ABSTRACT

This study reports a Post Occupancy Evaluation performed on a social housing complex consisting of 400 apartments, in which symptoms and damage produced by high moisture levels needed investigation. The resulting knowledge is of special interest for other projects designed to be mass-produced such as social housing. Large costs for repairs can be reduced by applying measures to avoid moisture problems in indoor environments. The evaluation was performed over three stages, indicative, investigative and diagnostic. The process was mapped and the data stored using BIM standards so it can be used by stakeholders to take further actions. In the indicative stage, data was collected through questionnaires and surveys, and a quick evaluation was conducted of the affected units. In the investigative stage, an analysis of the entire building complex was conducted through simulation and tested against the building energy standards. In the diagnostic stage, *in-situ* and laboratory measurements were made and used for calculations. The results show that many factors were involved in the moisture damage, whose main causes were overcrowded spaces, inadequate thermal regulation for the local climate, poor apartment and complex design, and flaws and inconsistencies in the quality of construction.

1. Introduction

Among the most fundamental purposes in the design of a building is to provide a healthy and comfortable shelter for indoor activities that cannot be conducted in the natural environment. Considering that people spend 90% of their time indoors [1] and over 50% of that time is spent in residences [2], indoor environmental conditions in residential buildings are of great importance. If a healthy indoor environment is to be achieved, a number of factors need consideration: outdoor air quality, building regulations, design and construction quality, occupant behaviour, energy efficiency, etc. Despite efforts to regulate and standardise the work involved in the development of a project, negative results can still occur [3,4]. Some buildings all around the world have been poorly designed, affecting occupant well-being [5]. This is known in the literature as "sick building syndrome" (SBS). Sick buildings can have several negative impacts on occupants, resulting in absence from work, lower productivity, or remedial expenses, and they can force owners to increase building energy consumption and other operating costs [6] to maintain a healthy indoor environment.

Poor indoor environmental conditions are often linked to poor quality construction, inefficient heating systems, and low socioeconomic status, due to the economic struggle to afford adequate indoor temperature levels [7–10]. Poor quality construction and inadequate maintenance are often associated with hygrothermal pathologies, such as a lack of thermal comfort [11] and poor indoor air quality (IAQ), which are problems commonly reported in low standard social housing [12]. Although social housing is generally under-researched, issues related to health risks have been reported in both developed [8–10,13–15] and developing countries [16–20]. The definition of social housing is different in every country, but in general it refers to providing access to affordable housing for vulnerable people who cannot meet their housing needs in the market [21]. In Latin America, Africa and Asia, social housing is closely related to housing deficit problems [19], where governments have to decide between maximising the number of subsidies and lowering the standard of housing or maintaining the standard of housing but offering fewer subsidies [22]. The approach of producing large numbers of houses for low income populations has had negative effects in some countries. Construction issues in around 15,000 social housing units in Colombia might lead their demolition [19]. In Sri Lanka, the 'Hundred Thousand Houses Programme' has been criticised for the poor quality construction of the public housing built by contractors [20]. Similar problems can be seen

* Corresponding author. Department of Civil Engineering, Technical University of Denmark [1], Building 118, 2800, Kgs. Lyngby, Denmark.
E-mail address: aagc@byg.dtu.dk (A. Gonzalez-Caceres).

https://doi.org/10.1016/j.buildenv.2019.05.019
Received 17 January 2019; Received in revised form 19 April 2019; Accepted 9 May 2019
Available online 12 May 2019

in Mexico, where houses were identified as having industrialised, massive, and uniform designs [23]. The programme implemented in Brazil to overcome the housing deficit, "My House, My Life", has been criticised for making the same mistakes as in previous programmes, where standard poor quality units are provided for the poorest segment of the population [24].

Chile has made considerable progress in promoting access to affordable good-quality housing over the past two decades. One of the main objectives of the housing policy in Chile is to reduce the housing deficit for vulnerable groups [25]. By introducing ambitious housing policies, Chile has reduced its housing deficit from 30% in 1992 to 7% in 2017 [26,27], where half of the houses built in Chile are subsidised by the government [28]. However, these policies are strongly focused on quantity, not quality [26], which has led to severe problems in some residential projects, i.e. large expenses for the government for repairs. These can be attributed to three main causes. First, the current thermal regulations are not adequate in many local climates and critical factors, such as airtightness and thermal bridges, are not considered [29]. Secondly, low-income families tend to be large, and social housing is not designed for so many occupants [19,30]. Lastly, the strong influence of the housing prototypes and tabulated technical solutions used to reduce costs and construction time [31]. So, there are many factors that can simultaneously act to affect the performance of the buildings in many ways: increasing energy usage (poor thermal requirements), reducing indoor air quality (high levels of CO_2 from overcrowding), harmful materials in the building envelope (poor technical construction solutions), etc. On top of all this, there are the construction defects and failures to which the construction industry is prone, such as poor workmanship, work not done, inappropriate installations, deficient materials, inaccurate design of building elements, miscalculations, etc. A building has to be reviewed, inspected and approved by the authorities before, during, and after construction, yet many issues related to building performance can only be detected after it has been occupied. These are commonly known as latent defects [32,33].

Despite the complexity involved in determining causes, clear benefits in terms of costs and time would be provided by the elimination or reduction of defects in buildings and improvements in the construction process [32,34]. However, the most common method used by the construction industry (architects, construction companies and managers) to improve their practice is the single-loop learning (SLL) approach, which is intended to remove avoidable inefficiencies [35,36], such as the use of inadequate materials or its improper installation. In this way, SLL focuses on addressing the symptoms of problems [37], such as replacing damaged materials or components, instead of reflecting and diagnosing their root causes [38]. For example, one common practice in Chile is to use anti-fungal paints to treat mould issues instead of reducing the moisture levels. The appropriate lessons are documented and stored in organisational knowledge repositories, but no analysis is made of the underlying causes in the organisational context as a whole [39]. An indoor environment evaluation that only considers theoretical principles and occupant behaviour (questionnaires) is a problem, because indoor measurements are the most reliable and useful source of information [40]. The comparison of measurements with standards is a key element in assessing performance [41]. Measurement of indoor parameters and appropriate data analysis [42,43], combined with material and system performance-testing, can ensure construction quality [4].

The monitoring and evaluation of a project after the buildings are in use have the potential to test social housing designs, adapt them to different climate conditions, and to constantly improve them. Systematic evaluation is not a current practice in the construction industry in Chile. Architects and constructors do not have sufficient knowledge or the equipment to assess the indoor environment and the energy efficiency of their buildings. The monitoring and evaluation of a project are currently carried out by research institutions in order to find solutions and draw up guidelines and standards. However, if the stakeholders in the building industry were involved, several benefits could be obtained. Authorities would obtain more accurate statistical data through performance-tracking, which would enhance decision making on strength requirements to ensure good performance. Social housing developers would be able to apply the positive and negative lessons learned in future project designs, and construction companies could update their practice by introducing more efficient techniques and protocols to ensure that standards were met. These benefits are greatly needed: Chile's thermal regulations do not require windows to have minimal thermal transmittance; whole blocks of social housing used in climates unsuitable for their design have had to be demolished [19]; and the average airtightness in residential buildings at 50 Pa is 12.9 1/h, and for social housing 24.6 1/h. There really is a lot of room for improvement.

In Chile, the construction company's clients are not the final users but local authorities, and the prestige of the company is not visible or relevant to consumers, or even to some extent for the authorities, because the transparency system designed to award public projects is based on who can make the project with the lowest costs, while other aspects, such as quality and prestige, weigh much less. Construction companies are more concerned about avoiding delays, extra costs, and getting approval of their work. In the literature, the construction industry tends to focus on the successful completion of projects, ignoring the post-occupancy stages and missing long-term lessons [35,44]. Moreover, the standard practice in the building construction industry does not consider the concept of continual improvement [36] or a systematic evaluation process [45]. Nevertheless, a large number of systematic evaluation methods are available, including Post Occupancy Evaluation (POE). In practice, these research techniques are not used by the construction industry to apply continuous improvement, lessons learned, or to deliver quality projects based on evidence [46]. Instead they tend to be isolated experience from academic researchers and end up as recommendations in a report [47–49].

One way to tackle this is by the introduction of BIM into construction practices. This would give many attractive benefits for several stakeholders, such as policymakers, project bidders, researchers, architects, construction companies, etc. Benefits would be seen in all stages of the building process, from the initial concept through to completion and post-construction maintenance, including improved design, enhanced constructability, reduced net costs and risks, and improved productivity, coordination, and collaboration across multiple disciplines [50]. One of the most valuable BIM's capabilities is the storage of information at different level of resolution about the properties of building components, such as manufacturer, model, warranty, preventive maintenance, and so on [48]. This can be extended to energy efficiency and indoor environment parameters. An example of this can be found in Australia, where BIM is used to provide an automated code-checking tool that designers can use to check the code requirements at different stages of project design. Compliance consultants and building authorities get automated data from architects, as well as basic checking and building-code compliance tests [51].

BIM has been incorporated as an obligatory practice in the construction industry in many countries, and it will soon be included in Chile (2020), making BIM a mandatory requirement for public building developments [52,53]. Although it is not yet mandatory in Chile and does not currently cover social housing, it is expected that they will be included to guarantee that public investment is well spent, as has been done in other countries, such as Denmark and Norway. The purpose of the standard is to increase productivity and sustainability – social, economic and environmental – of the construction industry, securing the social profitability of projects and efficient use of government resources. Issues found that support the introduction of BIM include the lack of communication among stakeholders during design, construction and operation, and the lack of standards and the low quality of workmanship [54]. Information will be requested to comply with the current regulation "Terms of Reference for Standardised Environmental Control and Energy Efficiency", known as TDRe [55]. This limits energy consumption and sets requirements for thermal comfort in all types of public building. To prove compliance with the requirements during both the construction and the post-occupation stages, tests and measurements of various construction and environmental parameters are obligatory, such as airtightness, thermal transmittance, air flow rate, indoor temperature, relative humidity, etc.

POE is an expensive and laborious task, which is not expected to be performed by construction companies or designers, but by a trained group of experts. However, the cost of such study is marginal in comparison to the extra cost of repairing a large building complex. The results that can be obtained enable diverse stakeholders to take action based on reliable data, which can inform decisions and be applied in future projects to toughen requirements, develop standards, improve processes, and avoid mistakes. This research was therefore aimed at promoting the use of POE as a technique for improving decision-making in social housing based on repetitive projects. It was conducted by presenting a full POE project in a deficient social housing complex. The POE procedure and data exchange were detailed using BIM standards to enable data to be stored and used to plan, analyse and contribute to other projects.

1.1. Post-occupancy evaluation/building information modelling

There are many definitions of POE, because it can be used in a variety of ways [45]. However, for the purposes of this study, POE will refer to the systematic evaluation of the performance of building projects after their construction and occupation by users, with a view to gathering information about existing conditions, verifying expected results, finding solutions to any problems detected, highlighting what should be repeated and what should be avoided, and informing others regarding lessons learned by disseminating design guidelines to improve future projects. Relevant POE studies about the improvement of future buildings have been studied and are summarised in Table 1.

BIM is a tool that is already widely used in the Architecture, Engineering, and Construction (AEC) industry to design, document, and enhance communication among all project stakeholders throughout the life cycle of the building [64]. Incorporating POE into BIM facilitates the introduction of post-occupancy evaluation techniques into the industry, because BIM offers the best solution for data management and flow throughout a retrofit project from the survey to the building site [65].

Data exchange models have been developed and improved over time to transfer information to different BIM applications and share data between the various stakeholders involved, including third-party software. Current BIM versions can encapsulate all information related to a building throughout the entire building cycle of design, construction, and operation [66].

2. Methodology

A POE study was conducted in a social housing complex in combination with BIM. A complete picture of the building performance was captured as well as the interdisciplinary team interaction and data exchange process. The application of the systematic evaluation approach has the potential to combine data exchange and continual improvement, which is particularly important in social housing, which is known to have a poor indoor environment and is produced on a large scale repetitively. To achieve this, the methodology addressed two main tasks: First to fully detail how the POE research was planned and developed through three POE stages of analysis: indicative, investigative and diagnostic. Fig. 1 shows the process represented using IDM based on the ISO-29481 standard [67,68] and plotted based on ISO/IEC 19510 [69]. Secondly, the data obtained from testing and measurement was stored in a standardised way using IFC based on ISO 16739–1:2018 [70], and the requirement format of these information exchanges was

Table 1
POE research studies to improve indoor environment

Evaluation type	Authors	Building type	Climate	Period	Outcome	Aspects evaluated
Diagnose the outdoor air system performance through continual measurement and user satisfaction through questionnaire surveys [56]	Tang et al., 2019	inpatient buildings	hot and humid regions in China	30 days	Results can be used to design and retrofit other buildings	Air temperature, Relative humidity, Air velocity, PM2.5 level, TVOC level, CO2 level, Illumination, Noise intensity
Propose POE methods [57]	Choi & Lee. 2018	commercial office buildings	*moderate	4 months	Validates the usefulness of the POE method	Air temperature, Relative Humidity, CO2 level, Illuminance, UGR, dBA and total volatile organic compounds
Evaluate POE method and green building performance [58]	Geng et al., 2019	Green office buildings	3 climate zones in China	14 months	Evaluation of green building performance using long-term measurements	Air temperature, Relative humidity, CO2 level, PM2.5 level, Illuminance
Assess green building energy performance and occupant satisfaction [59]	Lin et al., 2016	Green office buildings	3 climate zones in China	8 months	Knowledge about design and performance gap	Air temperature, Relative humidity, Air velocity,
Compare a certified green building and a regular building [60]	Tham et al., 2015	Office buildings	*tropical rainforest	15 months	. Advantages of certified efficient buildings.	Air temperature, Relative humidity, Air velocity, sound pressures, PM2.5 level, TVOC level, CO2, CO, HCHO, smog, Illuminance, Noise intensity, SF6 and fungi and bacteria presence
Compare the predicted performance of energy efficient buildings with their actual performance [61]	Sodagar & Starkey. 2015	Social houses	*Oceanic climate	2 years	Knowledge of influential factors for energy use	U-Values, airtightness, infrared thermography, Air temperature, Relative humidity, CO2, utility metering for electricity, water and gas.
Analyse the effectiveness of regulation/labelling and design (architectural) choices in certified green buildings [62]	Pastore & Andersen. 2019	Office buildings	*Oceanic climate	4 weeks	User satisfaction issues from standards and norms	Air temperature, Relative humidity, CO2 level, Illuminance, luminance. Questionnaires and long-term survey to the occupants
Evaluation of social housing under different Code levels of performance [63]	Pretlove & Kade. 2015	Social houses	*Oceanic climate	One year	Verify whether code reduced resource consumption	Air temperature, Relative humidity, utility metering for electricity, water and gas

* Köppen climate classification estimated based on the location.

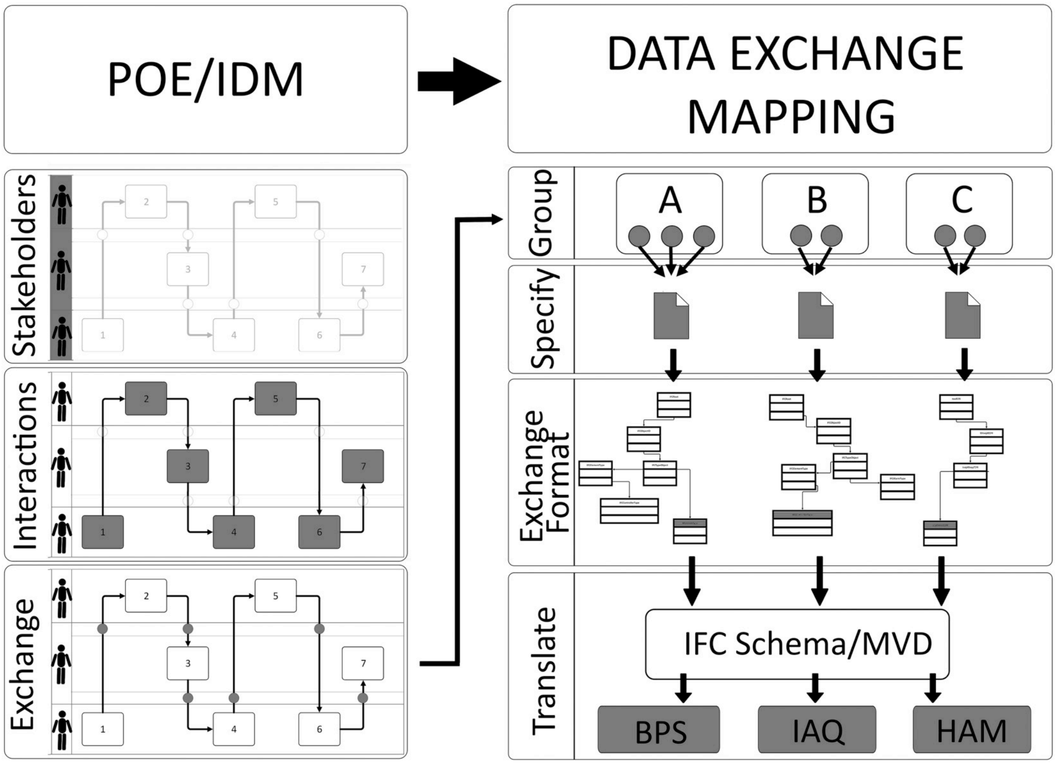


Fig. 1. Methodology used to identify data and store and export the most relevant results of the POE.

mapped so it could be utilised properly by the stakeholders for various purposes, including the Chilean standard for public buildings.

2.1. POE/IDM

In a social housing residential complex, the quality of the interior environment was compromised by pathologies whose causes were unknown. An interdisciplinary team took action in this case, initially by performing a POE. The flow of data exchange was planned, identifying the stakeholders involved and defining their roles and tasks. Subsequently, it became necessary to identify interactions between the stakeholders as the assessment progressed to prioritise the data that was required during the first research stages. Finally, data exchange requirements were identified for each interaction. The steps taken, the interactions, and the data acquired during the evaluation were plotted in the BPMN.

Stage 1 – Indicative POE: All the stakeholders were present at the same time during this evaluation, having previously reviewed the material about the building, such as architectural drawings, technical drawings, thermal properties of the envelope, and local climate. The walkthrough consisted of a tour around the building and into each affected apartment, where the stakeholders observed, recorded, and collected samples and testimonies regarding the most critical issues. This technique was used to conduct a quick evaluation and provide insights into the problems that might be affecting the building's performance and identifying items for future analysis where necessary. Given this information, a preliminary analysis was completed by each member of the team.

Data collected: During this stage, the main information available was obtained during the walkthrough. Surveys and questionnaires were used to gain insight into how the users behaved and used the installations. The data was collected through an inspection sheet developed by the Research Centre of Construction Technologies (CITEC UBB), as can be seen in the Appendix. The document contains two sections. The first contains a questionnaire to be filled in where there are at least two occupants. The main data collected were number of occupants, age (adults or children); occupation, and ventilation and heating schedules. The inspector fills in the second section, where damage and construction modifications have to described, measured, and located in the architectural plan of the apartment, together with the maintenance level of each window, exhaust ventilation (fans in kitchen and bathrooms), and passive ventilation (interior door vents).

Stage 2 – Investigative POE: During this stage, a deeper analysis was conducted because no definitive causes were determined during the previous stage. Before making any measurements, a hypothesis about the possible causes was put forward by the energy consultant and a proposed design for the second stage of the POE was provided to each research team, focusing on its role and its goal. Each team then organised how they wished to proceed. They first collected new information from the source and from other teams if necessary. The next procedure was to carry out calculations or measurements, which would be analysed later and summarised in a report sent to the energy consultants.

Data collected: Once it had been verified that the buildings comply with the local building regulations (by theoretical calculation based on Chilean standards), and particularly the thermal requirements, an analysis of the entire building complex was conducted using Ecotect building performance simulation software. The evaluation included orientation impact, shadow projection analysis, sun path and daylight hours, and the wind direction and velocity associated with rain penetration. At the apartment level, the most affected unit was simulated with standard inputs to obtain its energy consumption, thermal performance, and its calculated ventilation rate based on the Chilean standard NCh3309 [71]. Indoor monitoring also began at this point, recording indoor air temperature, humidity, and CO_2 concentration levels.

Stage 3 – Diagnostic POEs: Diagnostic POEs usually require several

Table 2
Main data collection and measurement.

Measurement	Parameter	Unit	Component	Method
Indoor environment	Indoor air temperature	°C		
	Interior surface temperature	°C	Space	
	Relative humidity	%		
	CO_2 concentration	Ppm		
Weather parameters	Air temperature	°C		Weather station
	Relative humidity	%		
	Wind speed	m/s	Climate	
	Wind direction	Degrees		
	Global solar radiation	kW/m^2		
Thermal transmittance	*In situ* heat flux in façade	$W/(m^2 K)$	Wall	ISO-9869 [74]
Thermal bridges	Superficial temperature	°C	Wall	ISO-6781 [75]
Condensing risks	Vapour pressure	Pa	Wall	NCh1973:2014 [76]
Airtightness	Air permeability at 50 Pa	Ach	Space	UNE-EN13829 [77]
	Air flow at 100 Pa	$m^3/(h·m^2)$	Window	NCh892:2001 [78]
Water penetration	Water penetration of façade	Pa	Wall	NCh2821: 2003 [79]
Thermal conductivity	Heat flow	W/(m K)	Material	NCh851:2008 [80]
Water vapour permeability	Water vapour transmission of materials	kg/(s m Pa)	Material	NCh2457:2014 [81]

months to one year or more to complete. During this stage, more advanced data-gathering techniques and sophisticated instruments were used [72]. At this point, no conclusive evidence was able to explain the symptoms in all the affected apartments, and new data needed to be obtained and integrated into the various calculations conducted by the various stakeholders in the study: measurements of material properties, airtightness, IAQ monitoring, simulations, etc. The apartments selected for the measurements were one apartment with no damage and five with a high level of damage, each representing a different floor, orientation, and block. Each team integrated this new and updated data into their calculations and analysis. This process was repeated several times, with new findings being integrated into other calculations. The results were analysed by the energy consultants to determine the causes and explain the problems observed. The results and recommendations derived from this level of the investigation were long-term and will serve as feedback not only for the complex involved but for the type of building [73].

Data collected: The third stage of the evaluation was when most measurements were taken, both on site and in the laboratory, as can be seen in Table 2. *In-situ* measurements were performed, such as blower-door tests, thermal transmittance of the exterior walls, and driving rain penetration of the façade. Tests on the airtightness of windows, thermal conductivity, and vapour permeability of materials were conducted in the laboratory.

2.2. Exchange requirements

Data exchange mapping concerns the data obtained during the various measurements and the monitoring performed in the apartments. The first step involved gathering the users' requirements, which were related to the tool used to process the data, e.g., building performance simulation software. The information collected was of different resolutions and units (fixed value, time, minute, etc.) and applied to different levels of housing (weather, zone, wall, etc.). All of the measurement results used with these post-processing tools were grouped, specifying the format in which the data were needed. The format exchange was completed using IFC, which makes it possible to hold and exchange relevant data between different software applications in a standardised way.

2.3. Description of the case-study complex

The POE study illustrates the methodology used to find solutions using various scientific techniques. The development of the methodology involved a multidisciplinary team and several tests.

The project was a residential complex built in 2013 comprising 25 blocks four storeys high, giving a total of 400 apartments, see Fig. 2. The complex is in an open area, exposed to the sea between bays, and approximately 140 m above sea level. The climate is characterised by high humidity and moderately low temperatures, see Fig. 3. The project addressed individual apartments of 57 m^2 each, in which the main space consists of an open area including a dining room, kitchen, and living room, and an independent laundry space (semi-open), three bedrooms, and a bathroom as independent zones, see Fig. 4.

2.4. Moisture and mould problems observed in the case-study complex

The apartment part of the study revealed several symptoms to various degrees, see Fig. 5, which can be summarised as high moisture, foul air, condensation on walls, mould behind furniture, etc. However, not all of the apartments had such problems, and there was no obvious occurrence pattern that might have identified clear causes. We verified by visual inspection that there had been no alteration in the original design, use of the apartments (e.g. to prepare food for commercial gain), number of occupants (only 20% of the apartments had more than six occupants), heating system (most of the heating systems found in the apartments were based on electricity; only 15 cases were based on gas or paraffin), or other installations (water boilers, water pipes).

We identified 76 affected apartments, distributed across most of the blocks, storeys, and orientations. Fig. 6 shows the random occurrence of the apartments affected on each storey in the complex. *A priori,* the lack of a relationship between the flats affected suggests that user behaviour could have been the cause of the problems. Although the construction details of the housing complex comply theoretically with the prescriptions of the Chilean building code [83], the energy code is much less strict than the recommended values based on the standard. The particular exposure conditions of the apartments on the site and the design and social housing construction characteristics might be contributing factors in the moisture problems. However, an in-depth study to identify the causes would be needed to provide a scientific diagnosis and definitive solutions.

3. Results

3.1. Stage 1: indicative POE

The abnormal presence of humidity was evident in the envelope of the apartments affected and in their interior environment. In the interior, the main findings were a bad smell and moisture on the walls and ceilings (bathrooms). Based on the visual characteristics of the

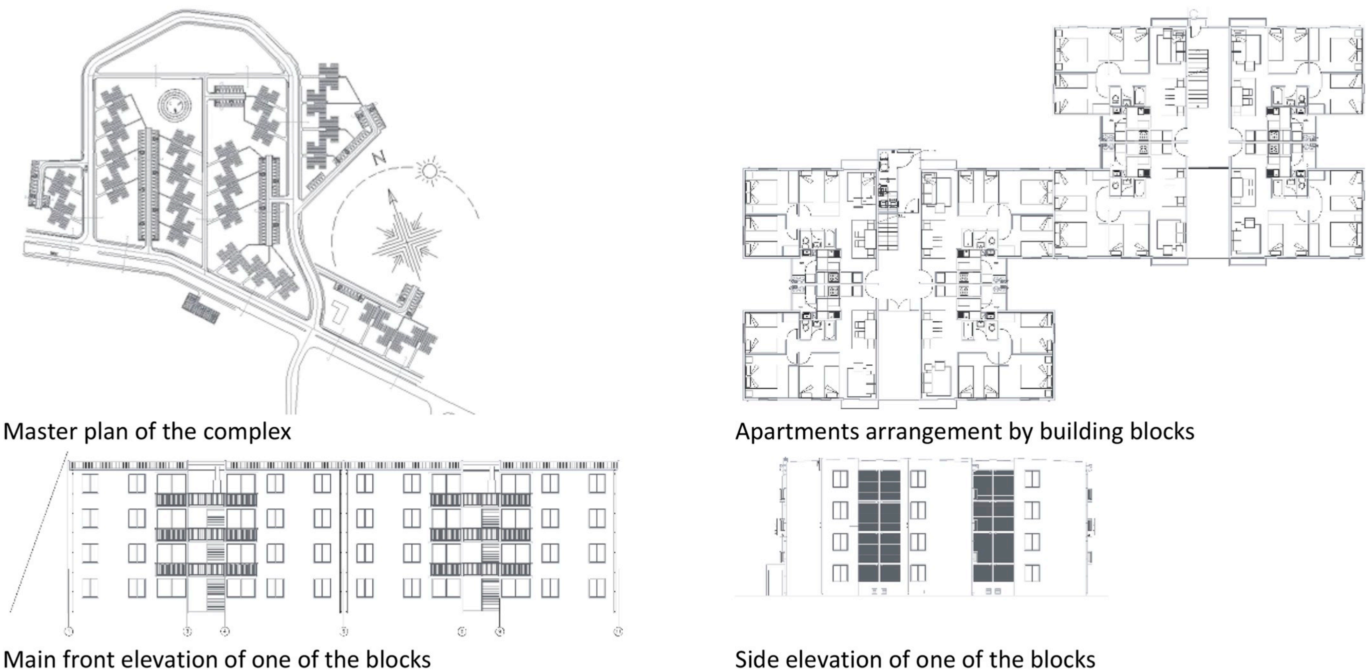
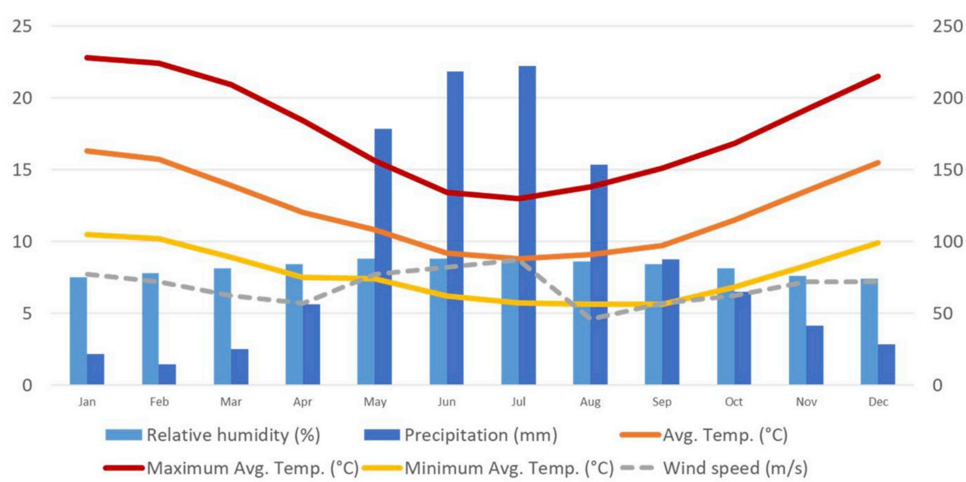


Fig. 2. Overview of the residential complex, from technical drawings.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Temp. (°C)	16.3	15.7	13.9	12	10.8	9.2	8.8	9.1	9.7	11.5	13.5	15.5
Maximum Avg. Temp. (°C)	22.8	22.4	20.9	18.4	15.6	13.4	13	13.8	15.1	16.8	19.2	21.5
Minimum Avg. Temp. (°C)	10.5	10.2	8.9	7.5	7.4	6.2	5.7	5.6	5.6	6.8	8.3	9.9
Relative humidity (%)	75	78	81	84	88	88	87	86	84	81	76	74
Precipitation (mm)	21.6	14.6	24.9	56	178.3	218.2	222.1	153.2	87.6	64.9	41.1	28.2
Wind speed (m/s)	7.7	7.2	6.2	5.7	7.7	8.2	8.7	4.6	5.7	6.2	7.2	7.2
Wind direction	SW	SW	SW	SW	N	N	N	SW	SW	SW	SW	SW

Fig. 3. Concepcion weather data from the Chilean standard NCh1079 [82].

Fig. 4. Layout of an apartment.

moisture damage, a classification of possible causes was completed. Characteristics such as location (under the window, wall, ceiling, etc.) and moisture spot shape, height, and size were used to determine possible causes, such as rainwater, thermal bridges, superficial condensation, etc. For the exterior, it is worth noting that we saw damage due to rainwater on the façades of north-facing walls, evidenced by the presence of mould and deteriorated paint. Part of the record is presented in Table 3.

According to the interviews with and questionnaires returned by the owners, there were some irregularities with the number of occupants. This is because the occupancy density was found to be higher than the apartment design value. However, this was the case in only 20% of the affected flats. Hours of occupation, ventilation, and moisture generation (from bathrooms, kitchens and clothes drying) accorded with conditions of use in most of cases, meaning that the exhaust ventilation was properly functioning and no clothes were being dried inside the apartments. However, in some of the apartments, the heating system was based on gas or paraffin. Although these heating systems generate a high degree of humidity in the air, they were only used for short periods of time and therefore were not considered as the main causes of the moisture issues even though they contributed to the excessive humidity.

During this stage of the study, we concluded that the causes of the moisture problems could not be attributed solely to user behaviour. Many of the apartments with high levels of moisture present low numbers of occupants with limited presence in the property and good maintenance, so we deduced that the moisture problems must be due to other causes.

3.2. Stage 2: investigative POE

The distribution of the apartment blocks and the gaps between them results in orientations that prevent the use of direct solar gains during a great part of the year, affecting passive thermal performance and the possibility drying of exterior walls after periods of rain, which affects

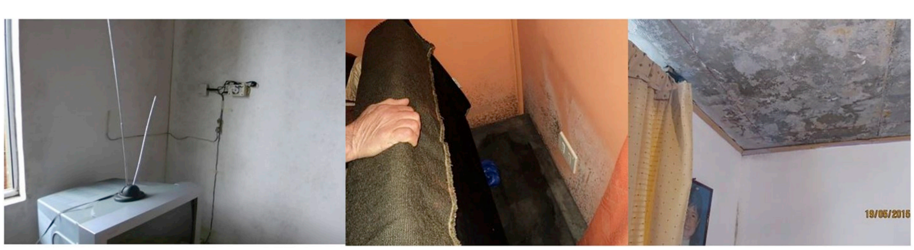


Fig. 5. Overview of the most common symptoms found in the apartments.

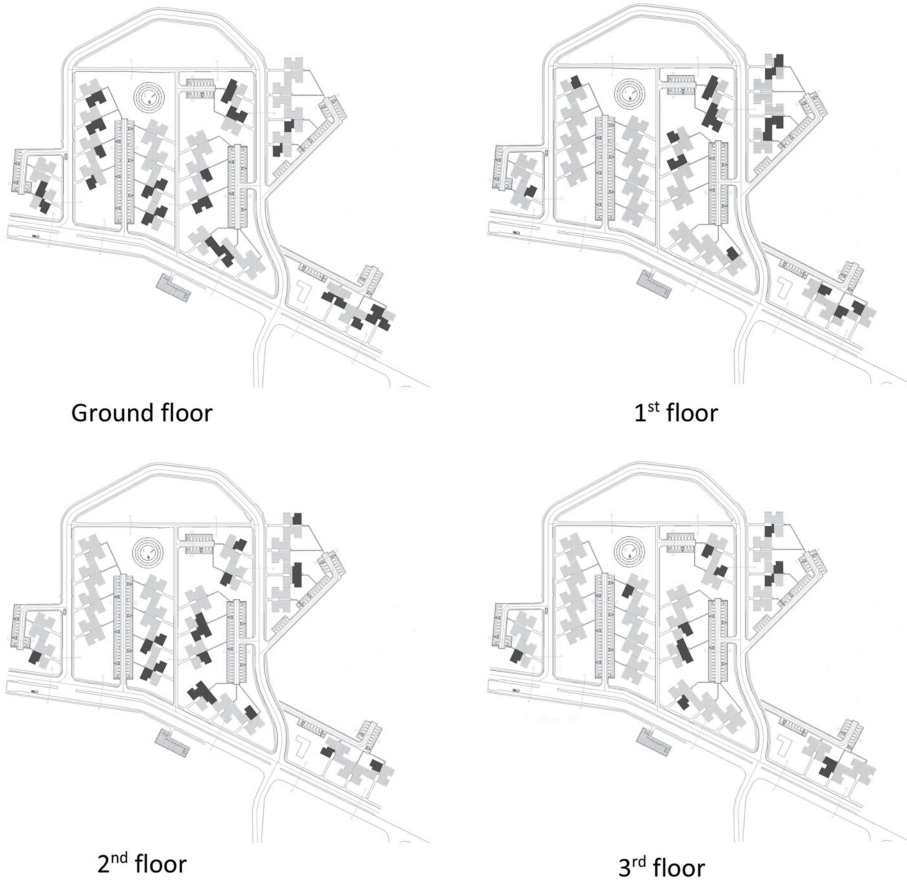


Fig. 6. Overview of the apartments affected, organised by block, storey, and orientation.

the thermal resistance of the insulation. The façades affected by shade are also subject to the effects of prevailing northerly winds during winter that often include rain. Another key point found in the assessment was the location of zones expected to produce high humidity, such as kitchens and bathrooms, facing the prevailing winds during the winter, which prevents the expulsion of excess moisture and moves it to the dry areas of the apartments. Moreover, none of the apartments had cross ventilation, so that the effectiveness of the displacement of indoor pollutants depended on the orientation of the façades.

However, the above-mentioned factors only had an impact on the apartments facing north, an orientation only present in less than one half of the total of the affected apartments. Moreover, even apartments

Table 3
Results from visual inspection in one apartment.

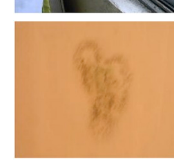
Wall orientation	Symptom	Affected area	Probable cause	Image
South	Fungus on window frames and the wall underneath	30% of the wall is affected (main bedroom)	Lack of maintenance of windows and condensation.	
South-East	Fungus and damp patches on the wall.	30% of the wall is affected	Condensation and rain water	
North-East	Fungus and moisture on windows and wall. Moisture in a vertical line.	40% of the walls (bedrooms) and corners	Condensation and rain water	

Table 4
Thermal transmittance results from in-situ measurement.

Source	Thermal transmittance (W/(m^2 K))						Wall description
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	
Requirement	1.7	1.7	1.7	1.7	1.7	1.7	Reinforced concrete wall e = 12 cm 2400 kg/m^3 (λ = 0.63 W/m·K), coating Poligyp interior (plasterboard e = 10 mm, 700 kg/m^3 (λ = 0.26 W/m·K) + polystyrene expanded e = 20 mm, 15 kg/m^3 (λ = 0.0413 W/m·K), exterior cladding paint
Calculated	1.30	1.30	1.30	1.30	1.30	1.30	
Measured	1.57	1.53	1.66	1.47	1.56	1.59	
Recommended [82]	0.5	0.5	0.5	0.5	0.5	0.5	

with good access to sunlight and without exposure to rainwater had the same problems. As a result, the evidence collected could not explain the moisture problems in all of the apartments.

3.3. Stage 3: diagnostic POEs

The in-situ measurements of the thermal transmittance of the exterior walls are shown in Table 4. The results show that measurement vales were some 20–30% higher than the theoretical U values. This is a consequence of the high moisture content in the walls, which was corroborated by measurements of moisture content at various points on the walls. We also performed a condensation risk analysis was performed using data from measurements and monitoring.

The measurements of the water penetration of the façade, which enabled the evaluation of walls exposed to wind pressure combined with rain, showed that one-half of the walls tested failed to maintain the minimum levels of water resistance. The inconsistent quality of the construction in the housing complex suggests phenomena such as subdensification by loss of grout through moulding joints and problems of quality in the concrete normally associated with failures in its compaction and/or dosage and/or size of aggregate, which have created an excessively porous structure. These results are shown in Table 5.

The airtightness tests performed exclude (sealed) devices intended for ventilation. They were carried out using the blower-door test (single fan). They provided a wide range of results, as can be seen in Table 6, ranging from 5.6 to 18.86 1/h at 50 Pa. They showed that the airtightness levels were below those recommended by Chilean standard NTM 011/3 2014, which is not ambitious compared to other countries, such as Austria, Germany, Lithuania and Slovenia (3 1/h at 50 Pa) or Norway (1.6 1/h at 50 Pa). The wide range in the sample group suggests that there was poor supervision of the construction work and low-quality workmanship, which explains the heterogeneity of the construction quality in the housing complex. This is in agreement with the results of the indoor environment monitoring, which showed that air infiltration flow rates were not able to reduce CO_2 levels. Based on the CO_2 concentrations, we calculated that unintentional air flows reached 0.5 1/h, which was insufficient to remove excess moisture.

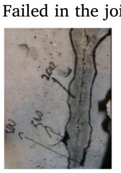
Table 6
Results from the airtightness measurement and recommended value for residential buildings.

Sample	Blower-door test (1/h 50 Pa)	Recommended (1/h 50 Pa)
Apartment 1	18.86	4.7 (in Chile)
Apartment 2	5.6	4.7 (in Chile)
Apartment 3	13.6	4.7 (in Chile)
Apartment 4	6.1	4.7 (in Chile)
Apartment 5	7.7	4.7 (in Chile)
Apartment 6	8.0	4.7 (in Chile)

Fig. 7 shows the thermographic assessment, which revealed the existence of thermal bridges in concrete structural elements such as columns, beams, and slabs. The insulation layer was installed on the inside of the flats (second layer from inside to outside). The images showed that there was at least 4 °C difference between the thermal bridge and the rest of the surface. The images from the inside revealed that thermal bridge temperatures were below the dew point (considering 80% relative humidity and 17 °C). This circumstance, in addition to the absence of adequate ventilation and high humidity levels, explains the occurrence of superficial condensation, resulting in the appearance of mould.

The indoor environmental monitoring during winter can be seen in Fig. 8. The results showed that HR was maintained between 75% and 92% for 95% of the time. The humidity load in Apartments 1,3–5 was between 0.002 and 0.004 kg/m3. According to standard NCh1073, this should be considered as humidity class 3, which is normal for residential buildings. However, the external relative humidity was constantly high during the measurements, and the combination of relatively high external temperatures (12–15 °C) with high absolute

Table 5
Results from the measurement of the water penetration of the building façade.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Wall orientation	South	South	Southwest	Southwest	Southeast	South
Result	Fail	Pass	Fail	Pass	Fail	Pass
Water tightness limit (Pa)	200	> 1000	200	> 1000	200	> 1000
Requirement (Pa)	600	600	600	600	600	600
Observation	Failed in the joint of mouldings	Did not fail	Failed homogeneously	Did not fail	Failed in the joint of mouldings	Did not fail
Record						

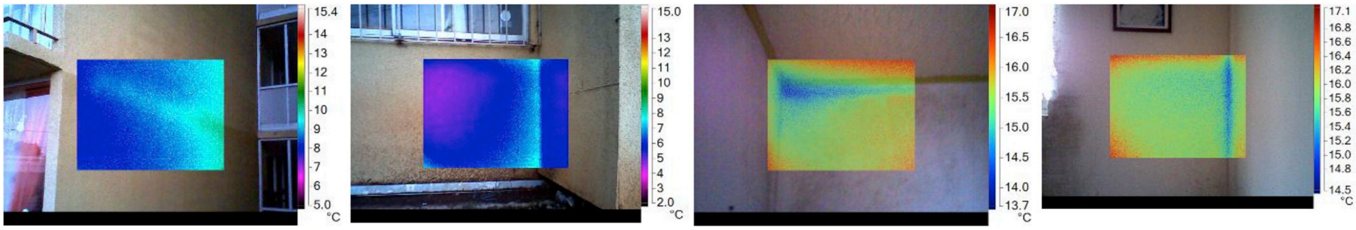


Fig. 7. Overview of some of the thermal bridges found during the thermographic assessment.

humidity made it easy for the air to saturate when it entered the indoor environment. Apartment 2 showed a much higher level of humidity, with more than 0.010 kg/m^3 water most of the time. This corresponds to internal humidity class 5, which is much higher than the standard for residential buildings.

We also carried out a condensation risk analysis using data from material property measurements and indoor environmental monitoring during winter, see Fig. 9. We verified the occurrence of interstitial condensation at the interfaces between the Poligyp-Polystyrene and the Polystyrene-Concrete layers in the apartments evaluated through calculation. The results indicate that the insulation was not sufficient in terms of its thickness or thermal conductivity; that vapour barriers are needed; and that fungus and stains on the wall can be attributed to the interstitial condensation. Even though the properties of the materials differed by 30% with respect to the theoretical values, see Table 7, the results were not considered critical for the local climate in the area.

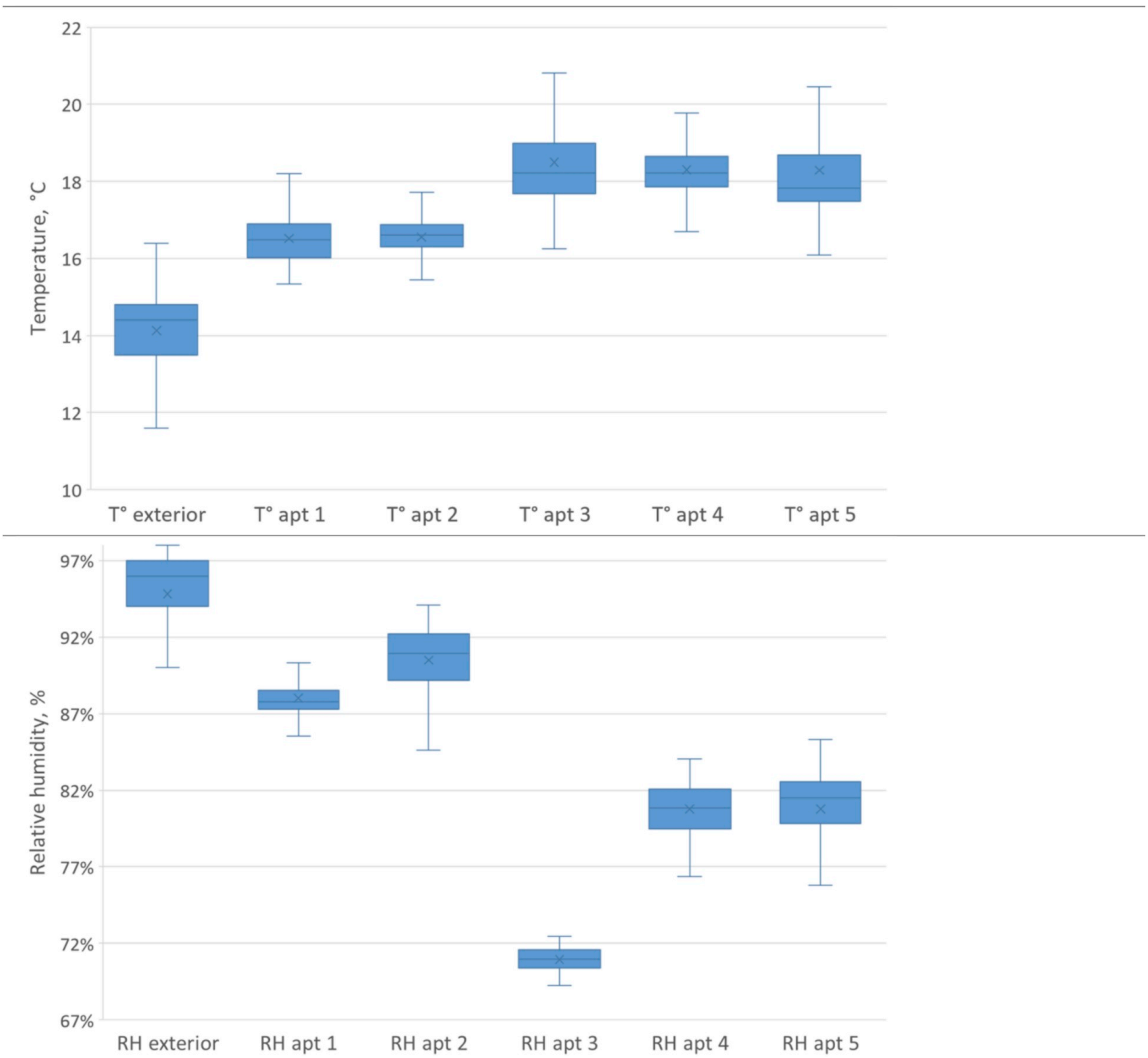
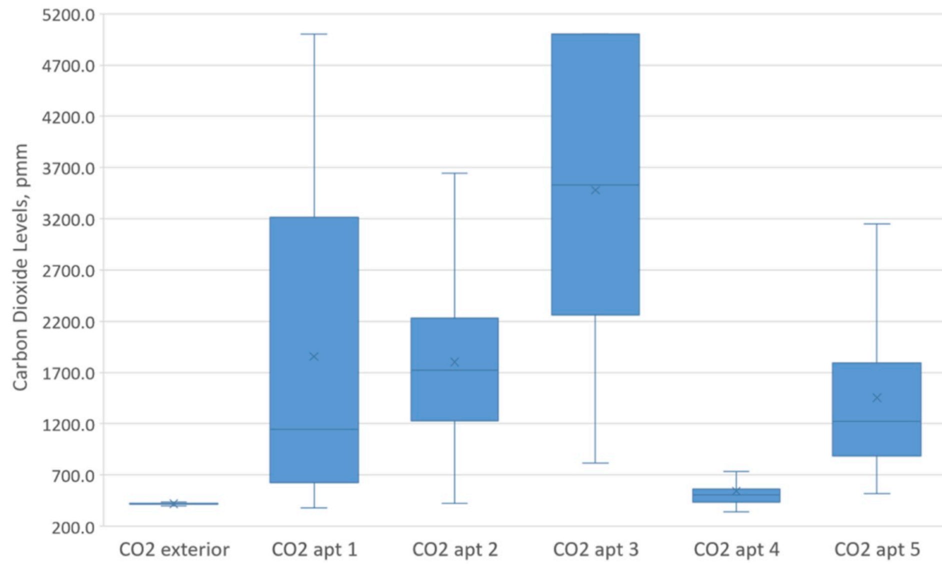


Fig. 8. Sample of indoor temperature, relative humidity and CO2 concentration monitoring in the main bedrooms of five apartments showing great differences mainly because the heating system type and operation hours.

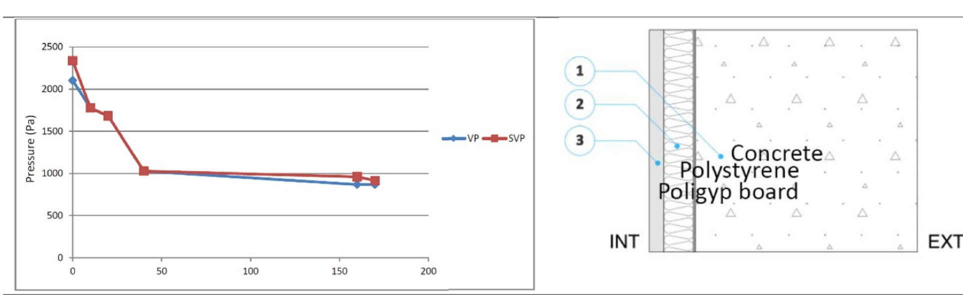


Sample	Nº of occupant	Heating system type/Hours per day	Observations
Apartment 1	Two adults	Gas / Less than 4 hours	It presents moisture damage
Apartment 2	Two adults	Electric / Less than 4 hours	It presents moisture damage
Apartment 3	Two seniors	Electric /Continuously	It presents moisture damage
Apartment 4	Two adults	Electric / Less than 4 hours	It presents moisture damage, bedroom door semi-open
Apartment 5	Two adults	Paraffin / Less than 4 hours	It presents moisture damage
Apartment 6	Empty	Empty	Without visual moisture damage

Fig. 8. (*continued*)

During this stage, we concluded that the results of the measurements, in combination with the theoretical calculations and simulations, showed that numerous factors simultaneously contributed to the poor quality of the indoor environment. The low performance presented in several measurements and the assessment conducted provided clear indications of poor construction and a lack of hygrometric and ventilation solutions.

Fig. 10 shows the BPMN diagram of the interaction between the different stakeholders involved in the POEs, as well as the information generated and its dissemination. It summarises the different stages of



Node	Location	Temperature (°C)	VP (Pa)	SVP (Pa)
Inside	-	20	2103	2337
Node 1	Inside surface-Poligyp board	15.6	1775	1775
Node2	Poligyp board-Polystyrene	14.8	1682	1682
Node 3	Polystyrene-Concrete	7.4	1028	1028
Node 4	Concrete-External surface	6.4	869	961
External	-	5.7	869	915

Fig. 9. Results of the condensation risk analysis.

Table 7
Results of the tests conducted in the laboratory for the determination of material properties. Official values refers to the Chilean standard NCh853 [80].

	Thermal conductivity λ (W/(m K))		Diffusion resistance factors (μ)	
	Official value	Measured	Official value	Measured
Concrete	1.63	2.12	13	15
Expanded polystyrene	0.04	0.047	37	32
Gypsum board	0.16	0.20	10	19

the research, the main exchanges between the participants, and the process of determining and verifying the causes of the issues.

3.4. Data exchange

BIM technology is used to store the data collected, so that improvements can be made based on data that reflects the real conditions under which the buildings were constructed (the quality of the construction process), how apartments are used (user behaviour), and their energy performance (design and materials). Low levels of airtightness may indicate that more air barriers are needed, or there has been poor-quality workmanship, or poor-quality sealing materials. Measurements *in situ* may not match the design thermal transmittance: for example, the insulation may have been poorly installed, or the moisture may have reduced the insulation value. The moisture may have originated from rain soaking the insulation before it was installed, poor protection against driving rain penetration of the wall, interstitial condensation, etc.

3.4.1. Grouping and specification of requirements

Although there are many measurements that can be made in a POE of a building complex, some information may not have to be exchanged because it is not related to future projects. It is necessary to screen out what the stakeholders need to know and specify how these data should be stored. Grouping the data by the resolution of the element observed typically starts with identifying the data in terms of high-level data, such as weather, zone, wall, material, etc. This is an effective procedure for organising the exchange data from raw data to IFC open standard data.

3.4.2. Exchange requirements

An exchange requirement is a set of information that has to be exchanged to support a particular business requirement during a particular stage of a project. In this case, the purpose was to store the measurements performed using the source format, so that the information can be used by designers or engineers to improve the original model. Table 8 illustrates this task, and shows all the requirements for the data to be stored in the format originating from the source, while

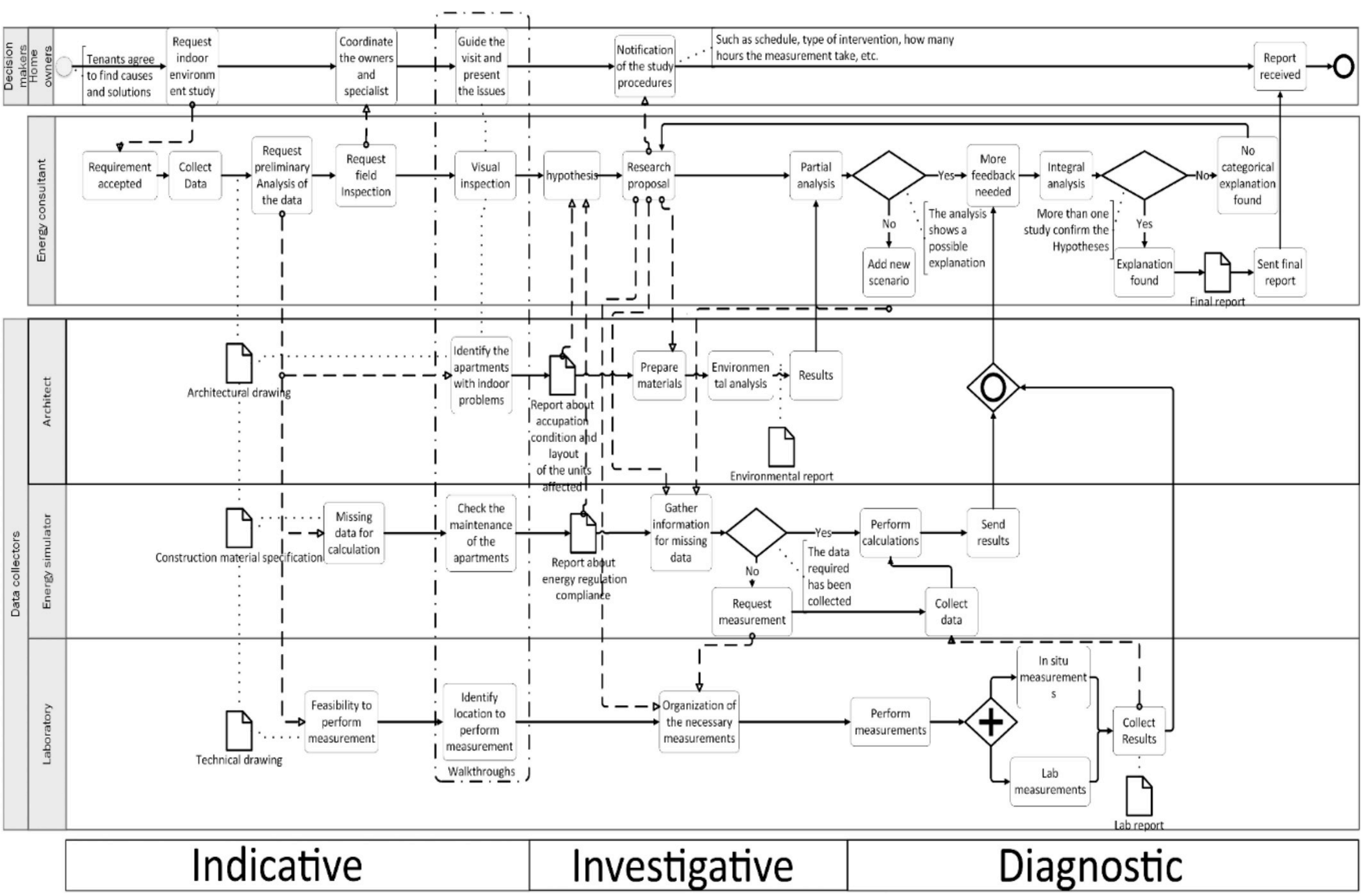


Fig. 10. BPMN diagram showing the POE process map.

Table 8
IFC properties required by each measurement.

Weather parameters	**PropertySet Name: Pset_SiteCommon**		
	Name	**Property Type**	**Data Type**
	Dry bulb temperature	P_REFERENCEVALUE	IfcTimeSeries/IfcThermodynamicTemperatureMeasure
	Humidity	P_REFERENCEVALUE	IfcTimeSeries/IfcThermodynamicTemperatureMeasure
	Wind speed	P_REFERENCEVALUE	IfcTimeSeries/IfcNormalisedRatioMeasure
	Wind direction	P_REFERENCEVALUE	IfcTimeSeries/IfcLinearVelocityMeasure
	Global solar radiation	P_REFERENCEVALUE	IfcTimeSeries/IfcHeatFluxDensityMeasure
Zone level	**PropertySet Name: Pset_SpaceThermalRequirements**		
	Name	**Property Type**	**Data Type**
	SpaceTemperature	P_SSINGLEVALUE	IfcThermodynamicTemperatureMeasure
	SpaceTemperatureMax	P_SSINGLEVALUE	IfcThermodynamicTemperatureMeasure
	Infiltration	P_SSINGLEVALUE	IfcThermodynamicTemperatureMeasure
	SpaceHumidity	P_SSINGLEVALUE	IfcRatioMeasure
	NaturalVentilationRate	P_SSINGLEVALUE	IfcCountMeasure
	MechanicalVentilationRate	P_SSINGLEVALUE	IfcCountMeasure
Windows and wall level	**PropertySet Name:Pset_WindowCommon**		
	Name	**Property Type**	**Data Type**
	ThermalTransmittance	IfcPropertySingleValue	IfcThermalTransmittanceMeasure
	Infiltration	IfcPropertySingleValue	IfcVolumetricFlowRateMeasure
	WaterTightnessRating	IfcPropertySingleValue	IfcLabel
Material level	**PropertySet Name: Pset_MaterialHygroscopic**		
	Name	**Property Type**	**Data Type**
	ThermalTransmittance	IfcPropertySingleValue	IfcThermalTransmittanceMeasure
	VaporPermeability	P_SINGLEVALUE	IfcVaporPermeabilityMeasure
	MoistureDiffusivity	P_SINGLEVALUE	IfcMoistureDiffusivityMeasure
	PropertySet Name: Pset_MaterialThermal		
	Name	**Property Type**	**Data Type**
	ThermalConductivity	P_SINGLEVALUE	IfcThermalConductivityMeasure

Fig. 11 shows a visualization of the data using third-party software.

The stakeholders may use specialised software to evaluate the model using the measurements as input, but this software may use different units or simple conversions; so, it is best to keep the data in its original form.

4. Discussion

The combination of POE and BIM could be an effective approach. In 2020, Chile will start using it for all public building financed by the government, so the next step might be to use it for social housing construction. In fact, POE/BIM can be used by the authorities and construction companies even now. Once the authorities know the quality and issues present in the social housing sector, they will be able to apply the information to address national housing needs and improve social housing performance [86]. Construction companies are already implementing BIM in their practice, but they do not find the incorporation of self-assessment of construction quality attractive because of the cost such study involves and because the benefits, such as prestige and improving construction practices and technologies, will not be reflected in the tenders to award social housing projects. An obligation to verify quality by measurements would trigger the use of systematic evaluations and the use of the data collected in future projects to avoid extra costs and create continuous improvement.

POE: Many studies have shown that a poor indoor environment in residential buildings is strongly related to occupant behaviour. However, they have not always been very scientific; often surveys and interviews are the main source of data on which conclusions are based [72,87–89]. This study shows the importance of using measurements instead of assumptions to scientifically determine causes. The method presented has a stronger focus on building pathology than on users' satisfaction, due to the difficulties in transferring users' satisfaction data through BIM. Many of the data collection procedures can be carried out before the buildings are occupied. This method is known as Post Construction Evaluation (PCE), e.g. blower-door tests, *in situ* thermal transmittance measurements, and thermal bridge detection can be used to verify construction quality and material performance. This approach could avoid indoor environment issues before a building is occupied.

BIM: The incorporation of BIM can be an effective complement to POE during all the stages, from the planning of the assessment to result analysis, by exporting the data stored into the formats required by third-party software. However, not everything is working fluently, some aspects demand additional tasks and others represent challenges, as can be seen in Fig. 12. Without BIM, data would have to be shared manually between the different stages, and to interpret and translate information from reports for different stakeholders and software. The Chilean standard does not require BPMN to plot process plans, and instead uses tables for information describing stakeholders, roles, responsibilities, standards to apply, and procedures to follow. By not mapping the process, many steps and data can be missed, which BPMN avoids by anticipating interactions, exchange requirements, and data processing flow.

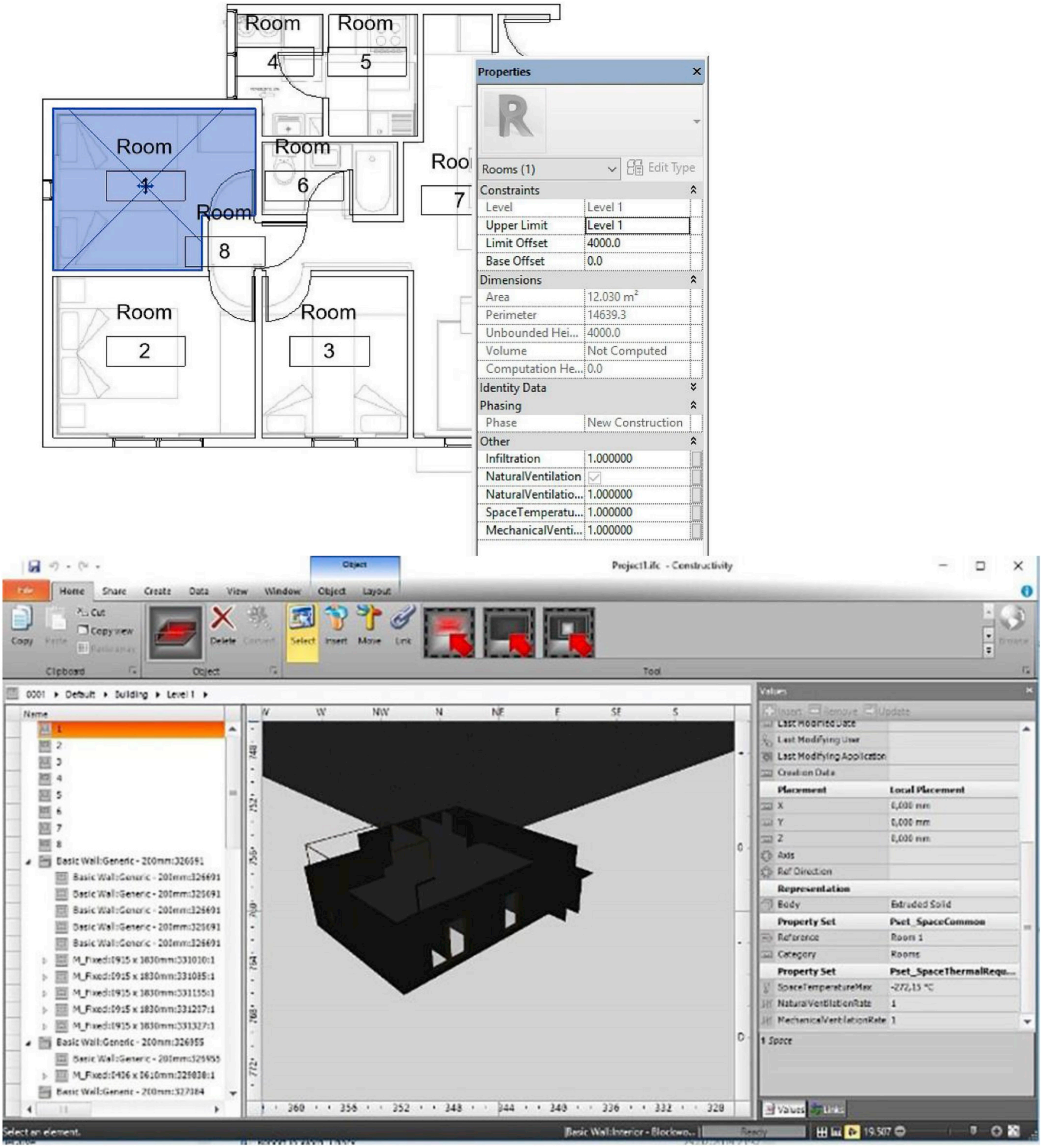


Fig. 11. Shows a visualization of the data storage using Revit, Constructivity, and IFC File Analyzer (NIST).

5. Conclusion

In a social housing building complex, the quality of the interior environment was compromised by pathologies whose causes were unknown. The POE presented involved the collaboration of an interdisciplinary team, which is a common scenario during a POE. The evaluation was performed over three stages, each using specific techniques and tools for the level of detail that was required during the

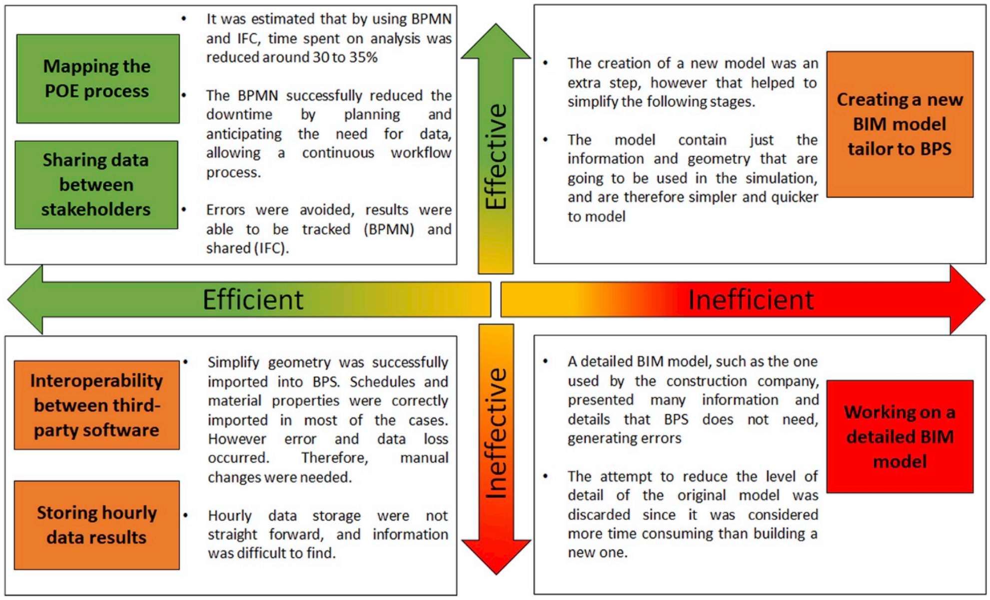


Fig. 12. Summarised the benefits and challenges of using BIM found during this research.

different phases of the study. The measurements and post analysis of the data collected indicated that the problems of the interior environment of the apartments were mainly due to the low quality of the construction and the design of the complex. Although the behaviour of the occupants contributed in some cases to the high humidity levels in the apartments, its impact was low in comparison to other causes. The main conclusions can be summarised as follows:

- Moisture problems cannot be solely attributed to the user behaviour. Many of the apartments that had high levels of moisture had low numbers of occupants with limited presence in the property, which was also well maintained.
- Measurement of the water penetration of the façade showed that one-half of the walls tested failed to maintain minimum levels of water resistance. The inconsistent quality of the construction in the housing complex suggests phenomena such as sub-densification by loss of grout through moulding joints and problems of quality in the concrete.
- The airtightness tests performed showed inconsistent construction quality in the tested apartments, with the results varying from 5.1 up to 18.86 1/h at 50 Pa.
- The thermographic assessment revealed the existence of thermal bridges in the concrete structural elements. The images showed that there was at least 4 °C difference between the thermal bridge and the rest of the surfaces. Temperatures were below the dew point, causing superficial condensation.
- The results from the monitoring and construction material measurements used for a condensation risk analysis confirmed interstitial condensation at the interfaces between the Poligyp-Polystyrene and Polystyrene-Concrete layers in the apartments evaluated, which was due to high levels of external humidity, insufficient thermal conductivity (or thickness) of the insulation layer, and a lack of vapour barriers.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

Acknowledgments

The authors wish to acknowledge the help provided by the CITEC UBB Research Centre during this research work.

Appendix

The following is the Inspection sheet used in this study.

1	General information			
	Type of residence			
	Address			
	Attended by the	Owner ☐ Tenant ☐ Other ☐	Name	
	Inspector			
	Date			
	Time			
	Have repairs been made?	Yes ☐	No ☐	Quantity:

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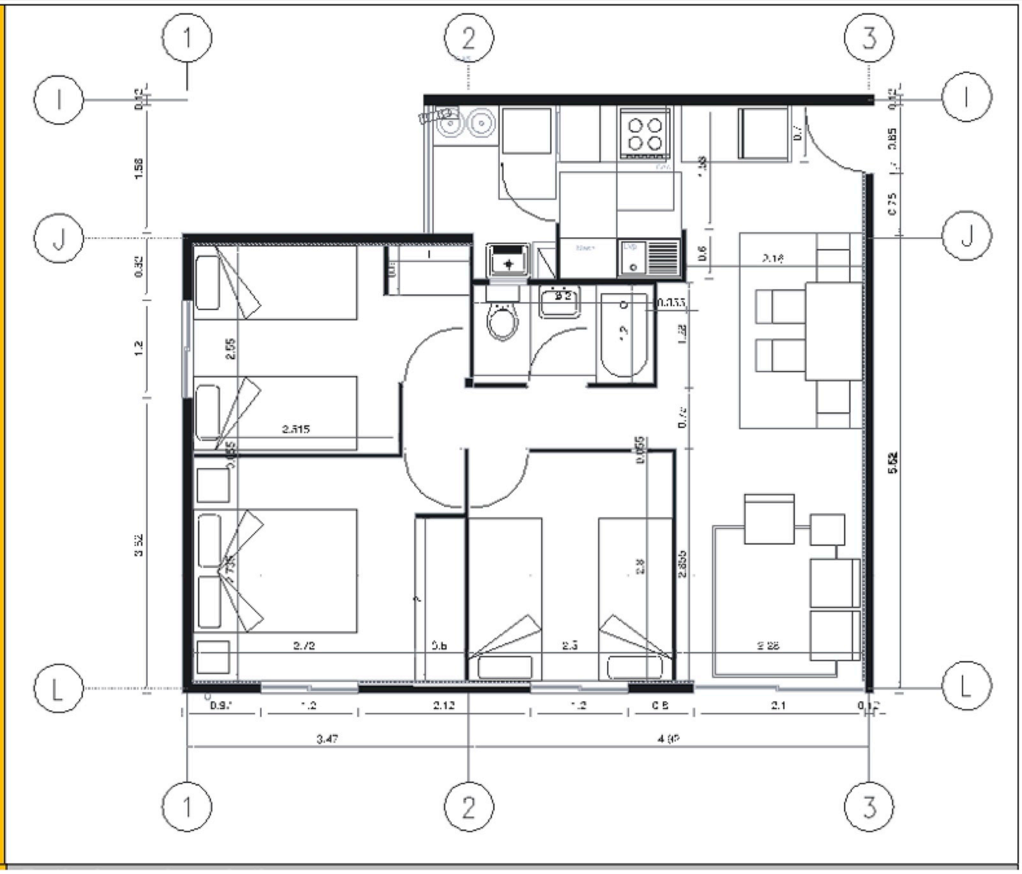
2	Occupants									
	Inhabitants numbers	1	2	3	4	5	6	Adults:	Kids:	
	Heating system		Electric	Gas	Firewood	Paraffin	Other:			

3	Occupation time													
	Week	Schedule												
	Monday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Tuesday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Wednesday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Thursday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Friday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Saturday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Sunday	Day	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
		Night	18:00	19:00	20:00	21:00	22:00	23:00	24:00	01:00	02:00	03:00	04:00	05:00
	Observations													

4	Building characteristics
	Floor plans

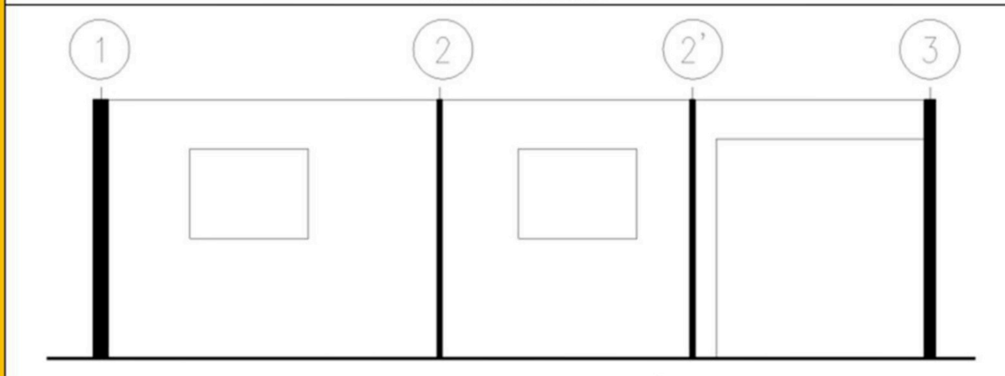
5	Selected unit
	Floor plans



6

Pathology description

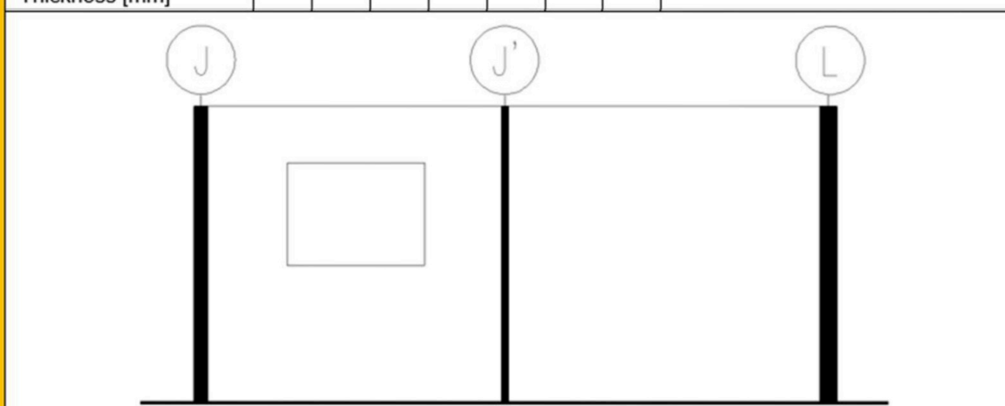
Cross sections



Characterization of damages							
Level							
Pathology enumeration (nº)							
Distance x_i [cm]							
Distance y_i [cm]							
Distance x_f [cm]							
Distance y_f [cm]							
Length [cm]							
Thickness [mm]							

Pathology Characterization

- Presence of mold ☐
- Surface condensation ☐
- Surface damage ☐
- Others: ☐
- Observation:



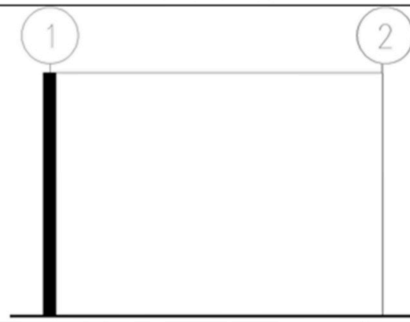
Characterization of damages							
Level							
Pathology enumeration (nº)							
Distance x_i [cm]							
Distance y_i [cm]							
Distance x_f [cm]							
Distance y_f [cm]							
Length [cm]							
Thickness [mm]							

Pathology Characterization

- Presence of mold ☐
- Surface condensation ☐
- Surface damage ☐
- Others: ☐
- Observation:

Pathology description

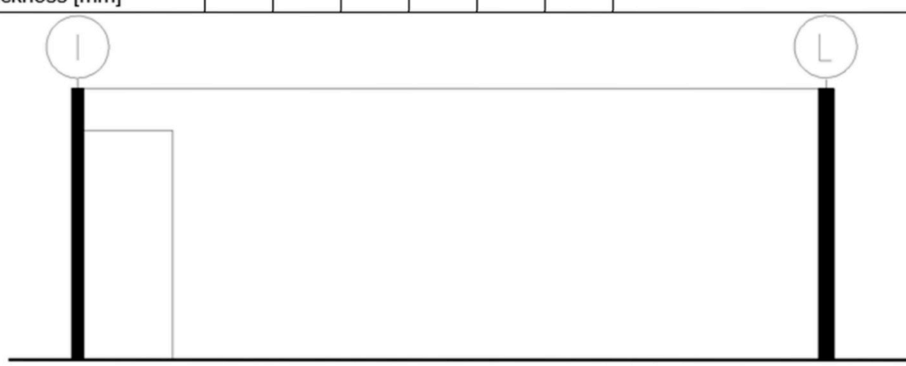
Cross section



Characterization of damages						
Level						
Pathology enumeration (nº)						
Distance x_i [cm]						
Distance y_i [cm]						
Distance x_f [cm]						
Distance y_f [cm]						
Length [cm]						
Thickness [mm]						

Pathology Characterization

- Presence of mold ☐
- Surface condensation ☐
- Surface damage ☐
- Others: ☐
- Observation:



Characterization of damages						
Level						
Pathology enumeration (nº)						
Distance x_i [cm]						
Distance y_i [cm]						
Distance x_f [cm]						
Distance y_f [cm]						
Length [cm]						
Thickness [mm]						

Pathology Characterization

- Presence of mold ☐
- Surface condensation ☐
- Surface damage ☐
- Others: ☐
- Observation:

Received by:

Name: ______________________________

Signature: ______________________________

Inspected by:

Name: ______________________________

Signature: ______________________________

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