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ARCHITECTURE & SUSTAINABLE DEVELOPMENT

Magali Bodart
Arnaud Evrard
Editors

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TABLE OF CONTENTS

(VOLUME 2)

DESIGN TOOLS AND METHODS

EXAMPLES OF SUSTAINABLE ARCHITECTURE AND URBAN DESIGN

RENEWAL/REFURBISHMENT

A sensitivity analysis approach: simulation tools as support at the early stages of low energy housing design

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ABSTRACT: The early stages of building design include a number of decisions, which have a strong influence on the performance of the building throughout the rest of the process. The sensitivity analysis approach was applied with the aim of analyzing the influence of technical parameters on the energy balance and building performances. The parameter values and assumptions of any model are subject to change and error. Sensitivity analysis (SA), broadly defined, is the investigation of these potential changes and errors and their impacts on conclusions to be drawn from the model. A case study of a residential building is presented as an example of the adequacy of timely analyses of building performances, based on a preliminary architectural design. A virtuous combination of a receptive building owner and a multidisciplinary design team, allowed a systematic methodology to be used, providing the opportunity for the consideration of several options for each class of constructive element and the possibility of choosing among the options for each case, based on quantitative results on the expected performance of the building. The options were analysed with the help of one dynamic simulation tool IDA ICE and one steady-state CENED PLUS, aiming at a comfortable and energy efficient building. Several parameters were used for enabling the sensitivity analyses, namely relating to wall and window frames U-value, percentage of opaque and transparent façade and HVAC system, etc.

Keywords: design, simulations, sensitivity analyses, energy balance

1. INTRODUCTION

The building sector accounts for 40% of the final energy consumption in EU countries. Housing, working and leisure places lightening, heating, cooling and water heating energy consumption is higher than in transport or even industrial sectors. Furthermore, this consumption continues to grow as well as buildings energy proportion in final consumption and CO_2 emission to environment increase [1]. The rapidly growing energy performance in buildings without compromising on comfort, performances, aesthetics and cost is leading to an ongoing development of technologies and innovations in the construction sector. At the same time the designers are faced with a variety of possible design options to realize low energy buildings, but often it is difficult to keep the right way. Choosing an appropriate combination of design options is now a complexity task and there is a risk of missing opportunities, which could have positive or negative effects if the design process is not properly informed. The objective of the paper is firstly to investigate the design theories and strategies used for the development of a method that can be used as an active design advisor in the early design stages and secondly to apply the sensitivity analyses (SA) method on a residential case study to demonstrate the importance of using it in the early stage. Moreover, the SA results help to clarify how design parameters will affect the energy performance and the quality of the indoor environment. The final outcome of the research is a series of indications on each strategy, which has to be taken into account from the early stage of building design.

2. METHOD

The general approach when it comes to the research in building design process is to divide the process into phases. This subdivision might be convenient to ensure progression in the development of design at the project management level, but it does not provide designer with any explicit support in making better decisions in the actual design situation [6]. A lot of design research is devoted to improving the ability of the designers [7]. One of the more recent and pragmatic outcomes is a paradigm called “performance-based design” formulated by Kalay [8].

One of the major advantages of the performance-based design is that is relatively easy to formalise as a practical workflow composed by the following main steps: performance requirements, design proposal, performance prediction and detailed design. From the proposal to the evaluation there is a loop called “design iteration”. Petersen et al. [6] considered this workflow ideal for the integration of building simulation tools to predict the energy performance and the quality of the indoor environment, but he emphasized the impossibility to provide any design advice in the case of undesirable performance, for this reason he proposed to had a new subtask called “parameter variation”. This subtask goes in the design iteration loop right after a potential rejection of a design proposal (Fig.1).

This final methodology configuration is which chosen for this work, being similar to sensitivity analyses presented in the introduction and furthermore because it minimizes trial and error analyses and should reduce the number of design iterations.

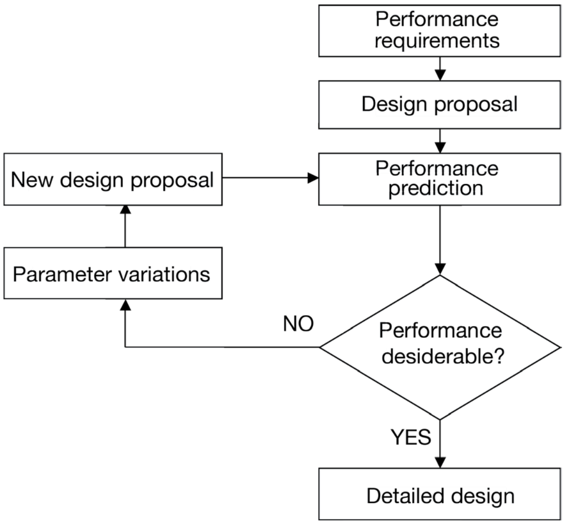

Figure 1: Petersen expansion version of the workflow of performance-based design

The approach used is informed by three key elements.

First, a multidisciplinary approach was used to gather together urban, architectural and technological aspects to keep an adequate compromise between sustainability, functionality, comfort and energy efficiency.

Second, comfort and energy performance of the building have been evaluated at the preliminary design stage in order to allow critical choices to be made before the final design work started.

Third, the main tool used was sensitivity analyses of the influence of each element's characteristics on the overall building performance.

The main steps and outcome were:

a. simulate the building under study on an hourly basis along the period of a whole year, exploring different configurations for the three levels: urban, architectural and technological;
b. considering the temperature range 20°C - 26°C as a settled normal thermal behaviour, assess the annual heating and cooling demands;
c. individuate the best configuration into the various analyzed with the SA.

3. CASE STUDY CHARACTERISTICS

3.1. Description of the building

The project is a residential complex located in Milan, Italy; it is focus on the idea of density to safe empty spaces in favour of the green area.

Three buildings compose the complex (Fig. 2): the north (the high-rise residential building), the west (along the street with parking function) and the east (the smallest residential ones).

The high-rise building has 17 floors and it is oriented north-south. The project foresees different types of flat: 2, 3 or 4 rooms.

The most common flat (3 rooms) is the object of the study (Fig. 3).

Figure 2: Residential complex in Milan, Italy

In this case in fact not the entire building is considered, but the unique flat, being mandatory in Italy the energy certification for each housing unity. The gross floor area of the flat is 110 m^2, with two rooms, kitchen, living room and two bathrooms. It is located at the tenth floor of the building (Fig. 3).

Figure 3: Plan of the case study flat in Milan, Italy

3.2. Description of the simulation tools and model

Two kind of software were used for the SA: IDA ICE, a dynamic simulation tool and CENED+, a steady-state tool.

IDA Indoor Climate and Energy (IDA ICE) is a tool for building simulation of energy consumption, the indoor air quality and thermal comfort. It covers a large range of phenomena, such as the integrated airflow network and thermal models, CO_2 and moisture calculation, and vertical temperature gradients. IDA ICE [2] may be used for the most building types for the calculation of:

- the full zone heat and moisture balance;
- the solar influx through windows with a full 3D account of the local shading devices and those of surrounding buildings and other objects;
- air and surface temperatures;
- the operating temperature at multiple arbitrary occupant locations, e.g. in the proximity of hot or cold surfaces;
- comfort indices, PPD and PMV, at multiple arbitrary occupant locations;
- the daylight level at an arbitrary room location.

CENED, developed by ITC-CNR, is a tool simulation of monthly balance for energy certification of buildings, based on the calculation procedure approved by Regione Lombardia [3]. As a result of the publication of the norms UNI TS 11300 [4], Lombardia Region has supplied to the review of the algorithms of calculation for the determination of the energetic performance of systems building-system and it realized CENED+.

As the approach used is based on sensitivity analyses, a base case was needed, to play the role of a reference against which the alternatives could be assessed [5]. At the preliminary stage of design, choices have to be made according to plausible and good engineering judgment criteria: constructive solutions, materials and equipment, such as walls, windows quality and HVAC (heating, ventilation and air conditioning) systems. The company constructor of the building itself proposed the base case characteristics. The first 33 SA were done with IDA ICE in free floating only varying the parameters linked to the building itself, without the mechanical plant. The others SA, comprehensive of the mechanical plants, were investigated with CENED+.

The model obtained with IDA ICE (Fig. 4) considered also the building body of the high-rise building and for simplicity the flat has been considered as a unique thermal zone.

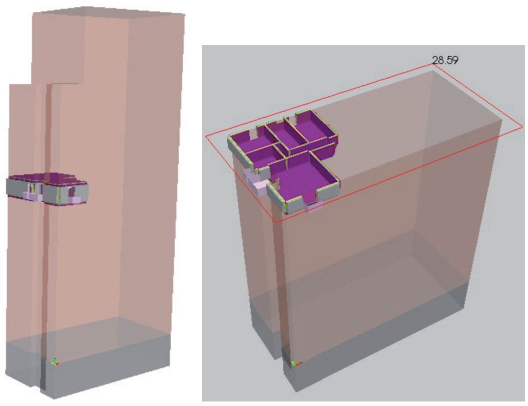

Figure 4: Simulation model of the flat in IDA ICE 4.0

3.3. Description of the base case

The base case (C-00), fixed by the construction company, has the following characteristics.

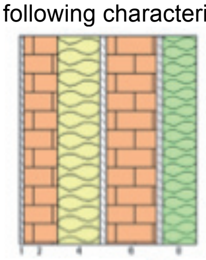

Figure 5: Base case: wall type Medium, U_w= 0,160 W/m^{2}K

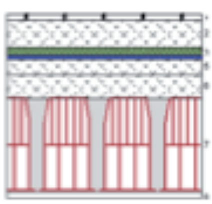

Figure 6: Base case: ceiling type Medium, U_w= 0,50 W/m^{2}K

The wall (Fig. 5) and the ceiling (Fig. 6) present a medium construction solution with a U-value that respects the limits of the Italian regulation.

The main orientation is east – west. The windows have a U-value equal to 1,59 W/m^{2}K and g value equal to 0,65 with internal shading devices.

The mechanical systems are composed by: a reversible heat pump coupled with radiant heating/cooling floor system and mechanical ventilation with heat recovery.

4. SA ON BUILDING PARAMETERS

The simulations were organized according to the purpose of identifying the influence on the building performance of particular changes imposed on constructive elements, devices or equipment, taking the base case as a reference, as requested by SA analyses, and aiming at the definition of the best configuration for an efficient final design.

4.1. Wall and Ceiling

The first ten simulations regarded the wall and ceiling construction (Table 1).

The medium wall construction solutions foresee a progress decrease of insulation (C-01 = 10 cm, C-02 = 8 cm) respect the base case (C-00 = 18 cm).

The heavy wall construction solutions are composed by different concrete thickness and a fixed insulation layer of 18 cm (C-03 = 25+18 cm, C-04 = 15+18 cm, C-05 = 10+18 cm).

Finally the light solutions are a typical dry assemble wall with a progress increase of insulation (C-06 = 5 cm, C-07 = 10 cm, C-08 = 15 cm).

The ceiling variations are only two the C-09 is a traditional concrete ceiling with 20 cm of concrete, while the C-10 is a dry assemble solution.

Table 1: SA variations on wall and ceiling

Conf. n°	Wall	U_w wall W/m^{2}K	Ceiling	U_w ceiling W/m^{2}K
C-00	Medium	0.16	Medium	0.50
C-01	Medium	0.26	= C-00	0.50
C-02	Medium	0.34	= C-00	0.50
C-03	Heavy	0.176	= C-00	0.50
C-04	Heavy	0.178	= C-00	0.50
C-05	Heavy	0.179	= C-00	0.50
C-06	Light	0.20	= C-00	0.50
C-07	Light	0.15	= C-00	0.50
C-08	Light	0.12	= C-00	0.50
C-09	= C-00	0.26	Heavy	0.46
C-10	= C-00	0.26	Light	0.42

4.2. Orientation

The simulations on the orientations were done considering the C-00 values for all the other parameters. Starting from the initial orientation East-West, three others were investigated in the C-11, C-12 and C-13 configurations (Table 2).

Table 2: SA variations on the orientation

Conf. n°	Orientation	U_w wall [W/m²K]	U_w ceiling [W/m²K]
C-00	East-West	0.16	0.50
C-11	North-South	= C-00	= C-00
C-12	South-West	= C-00	= C-00
C-13	South-East	= C-00	= C-00

4.3. Windows and g-value

The base case C-00 has a U-value of the window equal to 1.59 W/m^{2}K and a g value equal to 0.65.

Being already good values and considering the economic aspects only one variation was considered. C-14 with U-value of the window equal to 1.00 W/m^{2}K and a g value equal to 0.6.

Table 3: SA variations on the window quality

Conf. n°	Orientation	U_w window [W/m²K]	g value
C-00	East-West	1.59	0.65
C-14	= C-00	1.00	0.60

4.4. Natural ventilation

The natural ventilation parameters were investigated in the configurations C-15, C-16 and C-17. Considering the period June-September, the simulations were done with different time schedule as summarized in Table 3.

Table 4: SA variations on the natural ventilation

Conf. N°	Summer period	Natural ventilation (NV) Time schedule
C-00	-	Absent
C-15	01 Jun. – 01 Sept.	8 pm – 00 am
C-16	01 Jun. – 01 Sept.	00 am - 04 am
C-17	01 Jun. – 01 Sept.	10 pm – 02 am

4.5. Transparent/Opaque surface on South with shading devices and on West

The following SAs were done considering the same values of the base case C-00 for the variables: wall, ceiling, orientation and the C-15 conditions for the natural ventilation (24 pm – 06 am, 01 Jun.-01 Sept.). The inclusion of this optimization was defined after the higher cooling benefits registered in the previous SA and presented in the section 6.

The variables analyzed were linked to the opaque/transparent surface and the shading devices before considering the South façade (from C-18 to C-25 – Table 5) and then the same variations on the West façade (from C-26 to C-33 – Table 6).

Table 5: SA variations on the opaque/transparent south surface and shading devices

Conf. n°	% Transparent South façade	Shading devices (*)	Natural ventilation Time schedule
C-00	37% Transparent	Internal shading (IS)	Absent
C-18	50% T.	Internal shad.	= C-17
C-19	50% T.	Ext. shad.50%	= C-17
C-20	50% T.	Ext. shad.75%	= C-17
C-21	50% T.	Ext.shad.100%	= C-17
C-22	80% T.	Internal shad.	= C-17
C-23	80% T.	Ext. shad. 50%	= C-17
C-24	80% T.	Ext. shad. 75%	= C-17
C-25	80% T.	Ext.shad.100%	= C-17

(*) In case of external shadings (ES) the period considered for the simulations was from 01 May to 30 September.

Table 6: SA variations on the opaque/transparent west surface and shading devices

Conf. n°	% Transparent West façade	Shading devices (*)	Natural ventilation Time schedule
C-00	37% Transparent	Internal shading	Absent
C-26	50% T.	Internal shad.	= C-17
C-27	50% T.	Ext. shad.50%	= C-17
C-28	50% T.	Ext. shad.75%	= C-17
C-29	50% T.	Ext.shad.100%	= C-17
C-30	80% T.	Internal shad.	= C-17
C-31	80% T.	Ext. shad. 50%	= C-17
C-32	80% T.	Ext. shad. 75%	= C-17
C-33	80% T.	Ext.shad.100%	= C-17

(*) In case of external shadings the period considered for the simulations was from 01 May to 30 September.

5. SA ON MECHANICAL SYSTEM PLANT

These analyses were done with CENED+ considering all the building variables equal to the base case C-00.

The first simulation of this paragraph (C-34), done with CENED+ on the base case complete of mechanical system (reversible heat pump and mechanical ventilation with heat recovery), provided the following results: the primary energy for heating 40,44 kWh/m^2 and CO_2 emissions 8,04 Kg/m^2. These data correspond to the class B of energy building certification in Italy.

The last SA (Table 7) investigated the variation on the Energy class introducing renewable systems like photovoltaic (PV, C-38), solar collector (SC, C-36) or both solutions (C-37).

In this paragraph the aim was to check the class step reachable with each mechanical system and also together.

Table 7: SA variations on the mechanical system plants

Conf. n°	Reversible Heat Pump	MV+ HR	PV	SC
C-34	X	X	-	-
C-35	X	X	20 kWp	-
C-36	X	X	-	50 m^2
C-37	X	X	20 kWp	50 m^2

6. SIMULATION RESULTS

Before enter in details of SA results it is important to remark that the simulations from C-00 to C-33 were run in free floating during the whole year.

The results obtained are shown in terms of percentage of exceeding hours of comfort limits (20°C – 26°C) and compared to the base case (Table 8 and Table 9).

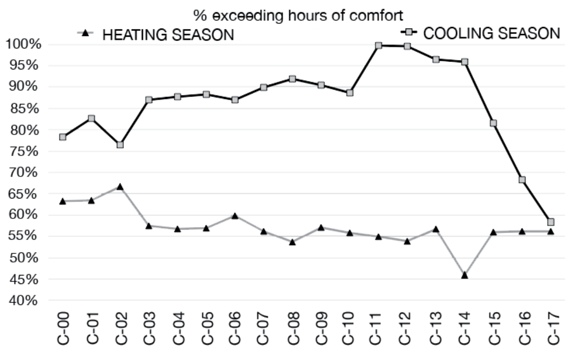

Figure 7: % exceeding hours of comfort from C-00 to C-17

In general the comfort level increases from the C-03 configuration for the heating season, while for the cooling season it is necessary the natural ventilation system (Figure 3).

It is evident the benefit of this passive cooling strategy (C-15, C-16 and C-17), but considering that users have specifics requests in a residential building, the authors decided to take into consideration for the next analyses the C-17 conditions (from 10 pm to 02 am).

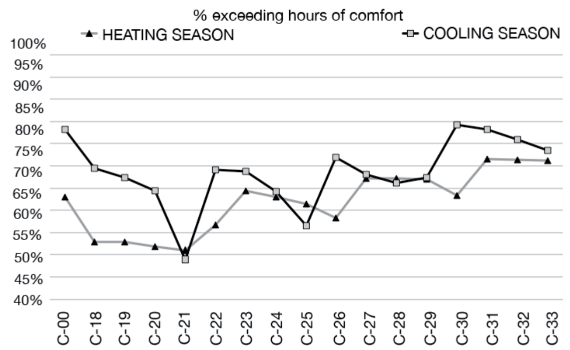

Figure 8: % exceeding hours of comfort from C-18 to C-33

The comfort during the heating season reached good results for the south façade with and adequate relation between openings and shadings (C-18 to C-21), while for the west façade the exceeding hours of comfort are higher than for the south. In fact in winter the south orientation is the best to reach solar gains.

In the cooling season the shading devices reduce the cooling demand proportionally to its percentage of shadow. However it is important to design them in comparison to the openings dimensions, in particular as seen before on the South façade, for both heating and cooling demand.

Nevertheless the results obtained with simulations (Table 8) are in line with what could be qualitatively expected.

Table 8: Exceeding hours of comfort in % for heating season (hs), and cooling season (cs).

Config. n°	hs (%)	cs (%)	SA
C-00	63.09	78.16	Base case
Config. n°	Δhs (%)	Δcs (%)	SA Parameter
C-01	+ 0.18%	+ 4.38%	Wall constr.
C-02	+ 3.64%	- 1.85%	Wall constr.
C-03	- 5.82%	+ 8.74%	Wall constr.
C-04	- 6.41%	+ 9.56%	Wall constr.
C-05	- 6.29%	+ 10.02%	Wall constr.
C-06	- 3.44%	+ 8.80%	Wall constr.
C-07	- 7.00%	+ 11.79%	Wall constr.
C-08	- 9.67%	+ 13.70%	Wall constr.
C-09	6.15%	+ 12.31%	Ceiling const.
C-10	- 7.39%	+ 10.43%	Ceiling const.
C-11	- 8.24%	+ 21.65%	Orientation
C-12	- 9.43%	+ 21.46%	Orientation
C-13	- 6.51%	+ 18.27%	Orientation
C-14	- 17.18%	+ 17.67%	Window
C-15	- 7.13%	+ 3.30%	Natural vent.
C-16	- 7.11%	- 38.07%	Natural vent.
C-17	- 7.11%	- 40.55%	Natural vent.
C-18	- 10.20%	- 8.61%	50%T South+NV+IS
C-19	- 10.26%	- 10.87%	50%T+NV+50%ES
C-20	- 11.30%	- 13.67%	50%T+NV+75%ES
C-21	-11.99%	- 29.17%	50%T+NV+100%ES
C-22	- 6.37%	- 9.04%	80%T South+NV+IS
C-23	+ 1.34%	- 9.40%	80%T+NV+50%ES
C-24	0.00%	- 13.89%	80%T+NV+75%ES
C-25	- 1.57%	- 21.57%	80%T+NV+100%ES
C-26	- 4.74%	- 6.15%	50%T West+NV+IS
C-27	+ 4.17%	- 10.02%	50%T+NV+50%ES
C-28	+ 4.07%	- 11.93%	50%T+NV+75%ES
C-29	+ 3.89%	- 10.87%	50%T+NV+100%ES
C-30	+ 0.22%	+ 1.20%	80%T West+NV+IS
C-31	+8.57%	+ 0.00%	80%T+NV+50%ES
C-32	+ 8.33%	- 2.23%	80%T+NV+75%ES
C-33	+ 8.18%	- 4.58%	80%T+NV+100%ES

The Figure 5 and 6 summarized the results of the building elements SA throughout the Δ percentage of exceeding hours of comfort compared to the base case C-00

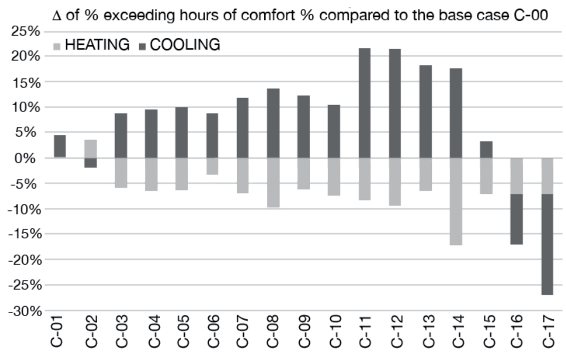

Figure 9: Δ percentage of exceeding hours of comfort compared to the base case C-00: from C-01 to C-17

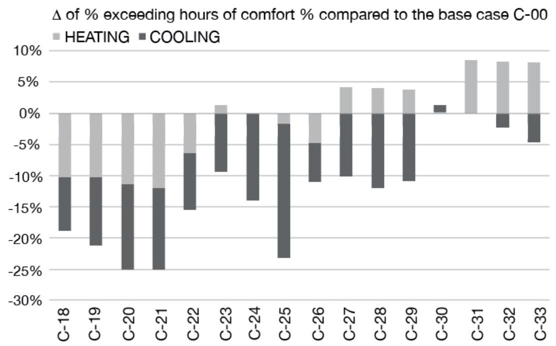

Figure 10: Δ percentage of exceeding hours of comfort compared to the base case C-00: from C-18 to C-33

The results of the last sensitivity analyses on the mechanical parameters are summarized in the graphics below (Figure 8).

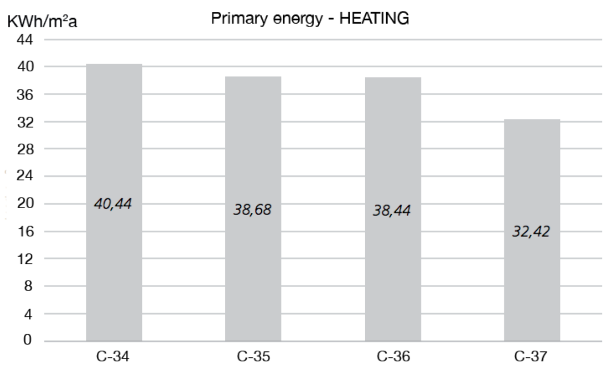

Figure 11: Primary energy heating demand for the SAs on the plant system (from C-34 to C-37)

The renewable energy system registered a small decrease of energy demand respect to the C-34, being constituted by a limited installed capacity. This is due to the restricted surfaces available on the roof of the building typology. The high-rise buildings or towers are, in fact, typologies very common in the density city where spaces are often limited.

7. CONCLUSION

Building design has better results when, in general, a multidisciplinary team is active right from the beginning. The use of simulation tools is a key factor to support the design from the early phase. a systematic approach, as shown in this paper, to the consideration of the main aspects influencing building performance has a high potential of providing adequate answers at a low labour cost.

The wall construction has to be validated through a life cycle cost analysis in the final stage, after the energy evaluation with the sensitivity analyses of the preliminary architectural design.

For the openings, a satisfactory compromise between direct gains in winter and an acceptable intensity of heat exchange with the environment may be achieved by using double-glazing with thermal break and external shading with automation control.

Natural ventilation and mechanical ventilation must be simulated together in order to assess the most adequate compromise in terms of energy consumptions.

The integration of renewable energy system doesn’t reveal high differences on the high-rise building roof. The solution suggested to the designer is the integration of mechanical system into the façade. The authors will discuss this aspect in detail in a future work.

8. ACKNOWLEDGMENT

Thanks to Greenway construction company that provides the case study project for this research.

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Development of Innovative Bioclimatic Strategies:

Method, Experimental procedure and Results

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ABSTRACT: One of the main goals of nowadays is the development of a new concept of social housing that could improve occupant comfort through decisive design choices based on high-quality, sustainability and environmental impact awareness. These challenges for future dwellings mean an approach to current bioclimatic strategies through its implementation in constructive systems that could involve a notable reduction in the corresponding budget. The present paper focuses on the methodology applied to a four-year research project that aimed to improve the energy efficient performance of social housing through low-cost flexible designs based on sustainability, innovation and open industrialization during the global process of construction. Taking into account a previous research on existing bioclimatic strategies, related results led to the final development of innovative constructive systems, whose patents are currently in progress. Computer simulations and monitoring procedures in experimental buildings constituted significant phases of the research project. The results demonstrated that the selected strategies had considerable lower embodied energy levels in comparison to conventional housing prototypes as well as relevant features so as to implement comfort conditions and energy efficiency in buildings.

Keywords: sustainable construction, bioclimatic design, energy efficiency, research methodology, open industrialization.

1. INTRODUCTION

During the last fifty years, systems and procedures of construction in Spain have hardly been modified. Consequently, this situation has made the development of the building sector conditional on an obsolete framework with both low efficiency and index of rationalization. The majority of 'in situ' techniques in housing buildings are based on a wide-spread use of unskilled labor. This fact usually implies the demolition of building units, which could be just completed [1]. In addition to the obvious amount of rubble produced, other consequences regarding this context are the technical impoverishment of the construction sector, significant cases concerning building pathology as well as an inevitable increase in the final product cost [2]. Historically, the implementation of industrialized systems in traditional construction was developed in a partial way without considering the process in its entirety [3]. Several EU co-financed projects like ManuBuild Project [4] shows the current interest in achieving efficiency and competitiveness in housing production with criteria based on sustainability and open industrialization.

Thinking in terms of simplicity means thinking in terms of constructive logic so as to achieve higher effectiveness regarding building energy optimization. As health and comfort of occupants are indirectly associated to housing performance [5], it is important taking into account implementing bioclimatic strategies to control indoor environment (noise, hydrothermal factors, lighting or moisture). Giving contemporary occupants the chance of living 'healthy' their lives also implies thinking out more flexible and varied housing designs according to house hold structure and life styles [6].

1.1. INVISO Project

The singular and strategic INVISO (Spanish acronym for 'Industrialization of sustainable housing') project constituted a 4-year research project founded by the Spanish Ministry of Science and Innovation. From its beginning in 2006, the project was conceived as a tool to give response to detected deficiencies within social housing and construction sector in Spain. The singular feature of the project resided in the objectives and multidisciplinary entities (commercial entities, universities, research centres and manufacturers). The research work developed by participants aimed to improve sustainability on dwellings through global energy efficient performance and the use of low embodied energy materials. In addition to the construction sector as beneficiary of results from the present research, the project was based on the conception of housing as a final industrialized and sustainable product with high-quality and comfort parameters as main benefits for the occupant. The whole research was organized from a strategic local approach as a result of a global plan that focused on optimizing all the phases of housing production by industrializing materials and systems. The project consisted of ten subprojects (SP) that were organized according to particular aims: sustainability in housing (SP3-Sustainable energy generation in housing; SP9-Design and experimentation of innovative technical solutions; SP10-Systems for the optimization of energy efficient housing performance) and industrializing the project (SP2-Design of typologies of rationalized solutions; SP5-Optimization of industrialization in housing construction; SP6-Automating construction; SP7-Development of software tools).

2. RESEARCH OBJECTIVES

The present paper focuses on SP10 subproject, 'Systems for the optimization of energy efficient housing performance'. SP10 subproject aimed to develop sustainable and innovative bioclimatic strategies so as to improve the energy efficiency performance of low-cost dwellings. This objective implied studying the optimum conditions of habitability: health and environmental comfort, ventilation with low energy waste and compatibility between acoustic conditions and natural ventilation systems. Sustainability, as second objective, aimed to achieve a responsible consumption of resources through the conservation of energy generated or captured indoors (ventilation control systems), the use of renewable energies and materials, water management (toilet and bath water, irrigation water) as well as energy management regarding thermal comfort (heating and cooling systems), lighting and sanitary hot water.

2.1. Open industrialization

The housing production process was conceived as a global process which included particular requirements according to the phases of the project, from its previous design until the end of its construction. Hence, the work flow was based on the incorporation of systematized design processes based on the concept of open industrialization [8], which involved the manufacture of materials and components of installation and the implementation of the constructive systems.

2.2. Social housing implementation

Another important issue of the subproject was the cost-effectiveness of the constructive solutions proposed according to its implementation in social housing. The challenge of introducing the obtained results on a large scale implied providing high-energy efficient solutions without considerable influence on the final building budget [9].

3. RESEARCH METHODOLOGY

3.1. Technology and innovation in the scientific method

The procedure applied was based on a scientific method of research and development that included technology and innovation as highlighted features in all its phases. An inventory of those bioclimatic strategies that might influence on housing energy performance was drawn up through a classification and qualitative description in accordance with sustainability indicators. Depending on the aim of each phase, results were collected in different file models ('Document 1', 'Document 2') that would afterwards facilitate the information required for the design and construction of the constructive solutions. Computer simulations, monitoring procedures and other experimental experiences complemented the research. Related results led to the final development of innovative constructive systems, whose patents are currently in progress

3.2. Review and characterization of conventional passive strategies

Inventory of bioclimatic strategies

The first step of the methodology consisted on the development of an inventory of conventional passive strategies [10] that would permit systemizing the existing bioclimatic solutions. A total of 1021 strategies were characterized according to technical criteria [11] and classified as follows: winter conditions, summer conditions, hygienic ventilation, energy accumulation, natural lighting and water management. The strategies were also divided into several categories. When certain strategies were considered equivalent ones, the same strategy could appear in different categories.

Characterization of strategies

Once the inventory was completed, collected information from the inventory was organized into a Microsoft Access data base according to a file model ('Document 1'), which included a detailed characterization of each bioclimatic strategy. As this software facilitates the search of data by any filter criteria, it was possible to gather easily those strategies required depending on necessary cases throughout the research phases. Moreover, the computer program permitted changing the structure of 'Document 1' without modifying the content of those model files already generated. This document provided information from each strategy according to the following topics: characteristics (components description, benefits, disadvantages, strategy sketches); implementation depending on climate (hot, cold, warm); use (residential, tertiary, non-residential) and building type (closed block, block, detached house); estimated budget; Life Cycle Assessment (from existing data about the strategy); regulation statement; manufacturers and commercial entities; equivalent strategies; indicator of implementation in social housing; cost average; industrialization indicator; efficiency indicator; etc.

3.3. Selection process

The last section of 'Document 1' aimed to be an assessment of each strategy by means of an indicator system that provided a numerical estimation of the strategies, which could be easily arranged according to the highest effectiveness. The systems consisted of ten indicators: two exclusive and eight grade level indicators. Indicators of industrialization and implementation in social housing were the two exclusive ones. If the strategy did not reach as far as minimum values, it was dismissed. On the contrary, when there was a positive assessment regarding aforementioned indicators, subsequent criteria based on innovation, sustainability and functionality was carried out. This assessment criterion was weighted according to the previous objectives of the project as global results underlined those strategies that showed more interest to be developed in next research phases. Since the assessment system was based on grade level indicators (Table 1), the application of these indicators made possible the comparison among strategies. Obtaining a maximum punctuation in each category meant a mark of 100%.

Criteria	Assessment	Percentage
INNOVATION	Yes/No	30% MAX.
SUSTAINABILITY		50% MAX.
Effectiveness	0-1-2-3-4	20%
Energy consumption	yes/no	10%
Reusable	0-1-2	10%
Recyclable	0-1-2	10%
FUNCTIONALITY		20% MAX.
Multi-conceptuality	Yes/No	8%
Service life	Yes/No	6%
Maintenance	0-1-2	6%

Table 1: Grade level indicators.

3.4. Statistical analysis

The use of indicators permitted selecting those strategies to be developed in following research phases. According to the classification and characterization of the strategies, a statistical analysis was carried out. It is worth emphasizing that only 606 bioclimatic strategies (from a total of 1021 strategies studied) went beyond a high level of industrialization and implementation in social housing. Hence, these ones passed to a more detailed level of assessment and development. Following the study of these 606 strategies, nearly the half of them obtained a total punctuation higher than the 50%. The next study regarding the development of innovative strategies was based on this second group of strategies. The statistics analysis was formulated according to global criteria without leaving out each category. Significant results from each category are detailed bellow (Fig. 1).

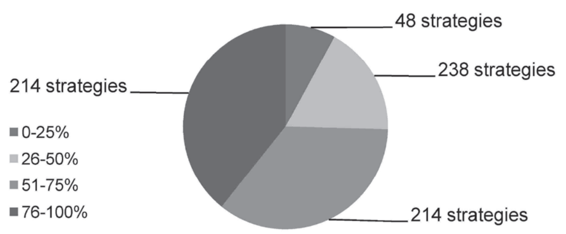

Figure 1: Total punctuation of the 606 strategies selected.

Winter conditions

The majority of the strategies has an overall mark lower than 50%. This result shows that the solar radiation use is not total due to determining factors that influence on the effectiveness of the strategies. However, the 71 % of the strategies are muticonceptual (feasible in different uses). As a result of inverting air-flow direction through natural or forced-air systems inside rooms, walls and roofs, many winter strategies could become heat extractors by convection or radiation. Hence, it is possible its application as summer strategies. Nearly the 96% of the strategies do not require important additional energy contributions to work, since they are based on simple physical laws related to thermal and pressure differences and characteristics of materials.

Summer conditions

Although over 76% of the strategies needs a medium-low maintenance, only the 30% has a service life equivalent to the building's. The majority of them constitutes delicate strategies as its components and materials are installed outside the building. Once the strategy is dismantled, the 60% could be partially reusable in other situation.

Hygienic ventilation

Almost the majority of the strategies presents an innovative feature owing to the incorporation of new materials such as Phase Change Materials and new systems like heat recuperators. All the strategies consisted of metal or plastic materials that are partially recyclable.

Energy accumulation

The service life of 91% of the strategies is equivalent or higher when compared with the building's. This fact shows that the replacement of the strategies during its service life is not necessary (30 years of estimated service life). Over 50% of the strategies is partially reusable and made from 100% recycled materials. Once its service life ends, materials could be introduced in the manufacture of new elements as raw material. The implementation of almost the whole strategies does not imply significant energy consumptions. Regarding multiconceptuality, the strategies work as building enclosures and instruments of hygrothermal control.

Natural lighting

More than half of the strategies represents innovative solutions since new concepts regarding technological, functional and constructive features were incorporated. Some of them constitute an optimization of existing systems that incorporates new functions and output improvements. Nearly the 60% requires a low-maintenance as its components consisted of materials that do not regularly need an exhaustive care regarding durability extension or protection measures against agents that could modify its function.

Water management

The current framework of water management systems is quite developed despite the lack of real application in many Spanish cities. Nearly one third of the strategies involves energy consumption. The majority of passive strategies are related to rain water accumulation and permeable pavements. Even so, strategies of grey water reuse and water depuration treatments constitute the ones with more additional energy requirements to work. Over 50% of the strategies requires a high maintenance due to the compliance of necessary quality controls regarding accumulated or treated water by grey-water reuse systems and residual water depuration.

3.5. Development of constructive solutions

After the analysis of results obtained from weighted percentages, 15 bioclimatic strategies were selected to be developed. The design of the constructive systems, the selection of the components of each prototype and consequent adjustments were made according to previous research on existing industrialization processes. Conclusions were collected through specific work files (‘Document 2’), in which the necessary phases of the subsequent construction process were detailed. ‘Document 2’ included extended information from ‘Document 1’ and also incorporated new general topics for instance contextual statements; constructive and assembly details of the industrialized process and the components of the system in its entirety and technical statements (measuring process, results from simulations and other experimental procedures). Next the constructive systems designed regarding the bioclimatic strategies selected are specified:

Winter conditions

Pneumatic modular roof. Unit that consisted of three cushions (two mobile and one fixed). While the movement of the mobile ones permits the climate regulation of covered spaces, the fixed one permits keeping proper distances between the mobile cushions. This way the mobile ones adjust to optimum inclinations for solar energy capture, without casting shadows on each other.

Solar wall. System to capture solar energy at façades. This energy is stored in the layers of a subsystem. Physical phenomena involved in heat transfer are radiation, conduction and convection.

Summer conditions

Ceramic material of evaporative cooling. Trombe wall that integrates an evaporative cooling system based on porous ceramics. A double functionality is achieved: wall to capture radiation in winter and evaporative cooling wall in summer.

Modular prevegetated green tank roof in PVC. System designed for flat roof installations that integrates rainwater tank.

Vegetal gabion façade. System that consists of making panels with rectangular wire mesh baskets filled with a mixture of rocks and plants. This rectangular prism is made by electrowelded meshes with a galvanized fort and a high resistance.

Vegetated shutter as solar protection. Mobile solar protection device for façade openings. Its main role is to shade the frontage through the incorporation of climbing plants.

Indoor green wall. Prefabricated panel of wood structure with vegetation on one or both surfaces to be incorporated in indoor spaces.

Hygienic ventilation

Hybrid hygienic ventilation grille with heat exchanger. The strategy combines, within the same element, a ventilation grille and an air-liquid heat exchanger to pretreat the air.

Natural cooling through buried concrete air ducts distributed in comb. System that harnesses the ground temperature through buried concrete pipes by circulating a quantity of air during time enough to reach the ground temperature. This air is driven inside the building and can get cold by a fan at a stable speed. Its distribution as comb shaped means a large conduit that distributes the air into small ones that finally end up in the building in an individual way.

Energy accumulation

Gypsum and plastic fibre panels with PCM additions. System that consists of gypsum plasterboards with a wide thermal mass on the inner face of brickwork façades. The thermal mass is concentrated in a mixture of wax and paraffin microencapsulated in polymers which absorbs heat generated during the whole day, at a phase change temperature and releases it when temperature drops.

PCM capsules for energy storing in raised technical floors. System to increase energy efficiency through passive heat use, which is accomplished with the use of PCM which are architecturally integrated into stone pavements or similar ones

Natural lighting

Enclosed balcony unit. Unit to create gaps in façades. Enclosed balcony that is transformed through a manual or motorized system, depending on space necessities required by users. The strategy consisted of a double layer that protects from outside temperature changes.

Modular window. System to capture and distribute natural light in an optimum way. Besides providing outside views, it protects from the excess of sunshine and reduces heat losses.

Water management

Industrialized reedbed-macrophytes-floating system for greywater reuse. Phytodepuration time optimization by the design of a prefabricated system which determines the way the greywater flows through prefabricated modules where macrophytes in flotation grow up. Depurated water will be reused for gardening and flushing WC.

Modular and technical wall for ventilation, natural lighting and greywater treatment in bathrooms. Bahtroom optimization by the design of a technical wall which provides ventilation, natural lighting through a solar tube and a compact system for greywater treatment to reuse WC-flushing.

3.6. Computer simulations

The performance of the prototypes designed was analyzed through dynamic software (Energy Plus, Design Builder) from virtual models of the experimental buildings. Simulations aimed to collect data regarding the energy savings obtained. This research phase made possible a subsequent quantification of the pay-back periods and the environmental benefits associated to each strategy before installing in the experimental buildings.

3.7. Experimental buildings and monitoring procedures

The constructive systems were installed in real experimental buildings (Fig. 2) in different locations throughout Spain so as to check the assembly feasibility of the solutions and start standardized experimental procedures according to national and international regulations. After months of data gathering, conclusions regarding the implemented strategies were drawn in terms of sustainability and efficiency. Afterwards, collected monitoring data were compared with results previously obtained from simulations. In certain cases, important differences in the aforementioned data were noticeable as a consequence of several deficiencies in the computer model. Based on experimental results collected, a research on the implementation of different computer models is currently being developed.

3.8. Economic and environmental sustainability: pay-back time and LCA

Once enough data to determine the strategies performance were obtained, corresponding pay-back time assessments were developed. The systainability factor of the constructive systems was analysed through Life Cycle Assessments (LCA), which permitted to study the amount of energy required to manufacture. In some cases, the lack of information about existing components in the market hindered this research phase. On the contrary, the development of experimental procedures regarding some constructive solutions like the green roof systems provided more precise data for its LCA.

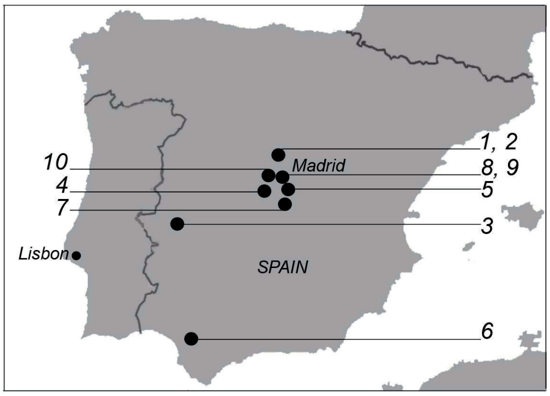

Figure 2: Experimental buildings location map.1)Colmenar Viejo I; 2) Colmenar Viejo II; 3) Cáceres; 4) Móstoles; 5) Rivas Vaciamadrid; 6) Las Cabezas de San Juan; 7)Tembleque; 8) Madrid I; 9) Madrid II; 10) Pozuelo.

4. CASE STUDY. VEGETAL SHUTTER

According to conclusions from summer conditions strategies, the vegetal sliding shutter was selected as an innovative solar protection device for façade openings (Fig. 3). It consists of a mobile outer panel which main role is to shade the building frontage through the incorporation of climbing plants. Its bioclimatic response depends on the vegetal species selected.

Figure 3: Vegetal sliding shutter system.

As a sliding shutter, a metal-grid framed panel moves parallel to the enclosure through horizontal guides. A sheet of planter-pot, folded as a box and pierced on its base, is installed in the panel bottom. Substrate is contained in drainage cells, stuffed and wrapped with felt. Being conceived as a façade input, the system is applied easily in new building and existing ones due to its light industrialized design that could be hung up directly in its entirety on façades.

The system was installed in two experimental buildings (Fig. 4) where dynamic simulations were developed: 'Madrid I' (system installed in a North façade opening of one-story office building in Solar Decathlon Europe 2010) and 'Cáceres' (system installed in a South façade opening of a two-story detached house).

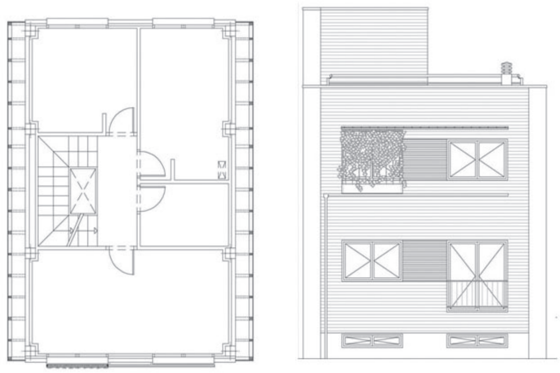

Figure 4: Experimental building nº3-Cáceres.

In order to analyze the building cooling demand, the thermal and solar-radiation performance of the system was processed by Design Builder software in hot summer conditions for a transitional regime. The ventilation rates considered (Table 2) were according to minimum values established in the Spanish Building Code. Regarding internal loads, it was considered 3.40 W/m^2 for lighting and 0.02 person/m^2 for occupation. Solar gains are calculated directly with the program according to the orientation, the dimensions of windows, typology of materials and shading elements in working order. Temperature in working order considered for heating systems was 20℃ during the period November-April and 26℃ regarding cooling systems.

Building space	Ventilation rate (ach)
Ground floor – Toilet	7.7
Ground floor – Kitchen	2.3
Ground floor – Living room	2
First floor – Bathroom	7
First floor – Bedroom 1	0.7
First floor – Bedroom 2	1.3
First floor – Bedroom 3	1

Table 2: Simulations conditions.Ventilation rates

The methodology was based on comparing the cooling demands, which the experimental building required without the strategy, with demands once the vegetal shutter was installed. This analysis confirmed energy savings from power-cooling systems over 38% (Fig. 5).

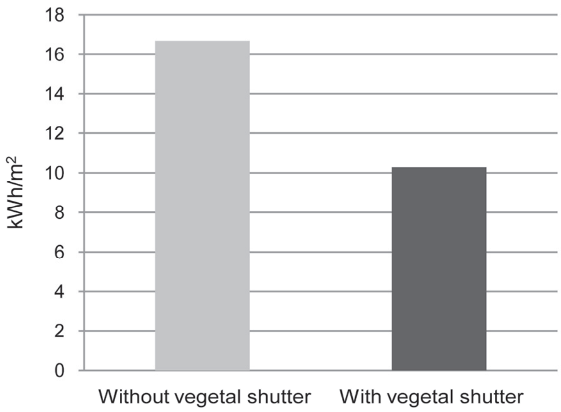

Figure 5: Comparison between cooling demands with and without the vegetal shutter. Simulations period 1/01 – 31/12.

Once results from simulations were obtained, an environmental impact assessment regarding manufacture and the use of the vegetal sliding shutter was developed. Results from this Life Cycle Assessment showed that the avoided impact from energy savings of the use phase noticeably exceeded energy contribution from manufacture phase. Results from this last phase compared with those from the use phase could be negligible in all the categories of the methods applied (Ecoindicator 99, CML 2000). Monitoring procedures are currently being carried out. However, conclusions are not yet drawn up as a longer period to collect data will be considered.

5. CONCLUSIONS

The implementation of the selected strategies in experimental buildings and the subsequent monitoring procedure made possible the verification of a previous objective: the validity of open industrialization as a constructive method that facilitates rationalization of housing construction process and hence, global cost reduction and quality and comfort improvements in dwellings. Indeed, the results led to apply for patents based on the constructive solutions developed.

In addition, the coordination and interaction among the multidisciplinary participants and subprojects within INVISO Project proved the feasibility and efficiency of implementing open industrialization procedures in the real framework of the Spanish construction sector.

In the majority of cases, the constructive systems developed did not imply additional cost regarding the building budget. Although this fact achieved the feasibility of implementing in social housing, some selected solutions implied unsatisfactory results regarding LCA. In order to improve the solutions before its implementation in the real prototypes, a deep analysis of materials regarding the sources and the whole manufacturing process was developed.

On the other hand, existing simulations programs do not plan, in some cases, the possibility of introducing innovative elements in the studied strategies. Consequently, another phase of research is nowadays being developed in collaboration with software teams to improve these programs.

6. ACKNOWLEDGEMENTS

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