Comparative LCA Evaluations between Conventional Interventions and Building Automation Systems for Energetic Requalification Activities

Alessandra Pierucci and Guido R. Dell'Osso

Polytechnic of Bari, DICATECh
Via Orabona 4, 70124 Bari, Italy
pieruccialex@gmail.com, dellosso@poliba.it

Abstract. The aim of the research is to investigate how the use of building automation and control systems could represent a valid tool for the achievement of a higher level of energy efficiency in the existing building panorama. The project develops a sustainability evaluation of an Italian dwelling with technological and typological features of sixties-seventies buildings; two alternative efficiency strategies were compared. The first one, more conventional, consisting in the application of walls' exterior thermal coat and substitution of existing windows; the second one, with the implementation of a specific building automation system for the management of existing components and building services. The results of the research, in terms of computer energy modeling and Life Cycle Assessment evaluations, have demonstrated, by using the second option, a higher potential in achieving a reduction in energy consumption during the use phase, together with a lower resources investment for the energy improvement goal.

Keywords: Building requalification, Energy efficiency, Automation, Life Cycle Assessment, Sustainability.

1 Introduction

Between all the available systems and technologies for the environmental parameters control, there are many features, for components' and equipments' management, that can be used to achieve a high level of building energy efficiency.

Several researches [1,2,3,4,5,6,7] concentrated in the last years to test which building automation (BA) system is the most effective in reducing building energy consumption, in increasing the comfort levels for occupants and at last in improving the balance between the performance of the building and user's requirements modification during the time. Therefore for several authors [8,9,10,11,12,13] the intelligent building is the integration of structures, system, services management strategies oriented to ensure a responsive and active control of the interchanges between external and internal environment, in a sustainable, adaptive and dynamic way.

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Recent studies enlarged the automation systems' application fields with regard to intervention on built heritage, for several reason including:

1) Low invasiveness and high reversibility, very important in the case of intervention on historical monuments;
2) high speed in execution and achievement of improvements, especially form an energetic point of view;
3) low cost intervention, also with reference to maintenance activities.

Furthermore, the increasing availability of wireless and low cost technologies is causing a higher diffusion of these systems, also in the residential sector. This is important to guarantee greater levels of comfort for the inhabitants and to partially contain the high energy consumption trend.

In Italy recent studies [14] found that, in the residential sector, about 80-90000 buildings already have a building automation system (0,7% of total available); in the next five years it is expected an implementation of those systems of 3-7%, for existing buildings, and of 10-20%, for new construction.

Regarding the change in consumption related to building automation opportunities, it is estimated that this will mean a potential electricity savings of 1,2 TWh and heat savings of 5,9 TWh.

These considerations, together with the growing need to implement a prompt energy efficiency upgrading for existing buildings, are making these systems more and more competitive in the construction industry, also with regards to other technologies more conventionally employed.

The aim of this study was to test the buildings' sustainability level, achievable, from a comparative prospective, with the use of building automation systems, during their whole lifecycle. Results have been achieved exclusively via simulation tools, both as regards the estimation of the energy consumption that the environmental impacts throughout the life cycle.

2 Calculation Models and Methods

2.1 Case Study

An application of the research methodology on a specific case study is here described. An existing dwelling located in Bari (41°7'7"32 N, 16°51'7"20 E) has been chosen; it is included in a multi-storey building built between 1960 and 1970. The dwelling has two bedrooms (2B, 2Bb), a living room (L), a kitchen (K), an office room (Of), a lumber-room (Lr) and a bathroom (WC), and a net residential floor area of 105 m2 (Fig. 1).

The building orientation is coherent with the construction period: the two free facades are south-east and north-west oriented, in order to assure an equal amount of solar radiation penetration in all areas, during the day. In fact the apartment has two balconies, the north-west one in front the master bedroom and the kitchen and the south-east one with exclusive access from the living room. All the other walls (north-east and south-west exposed), as well as the floor and the ceiling, partition the dwelling from other heated indoor spaces. Only the kitchen and the main entry constitute an exception, as they are adjacent to the unheated stairwell.

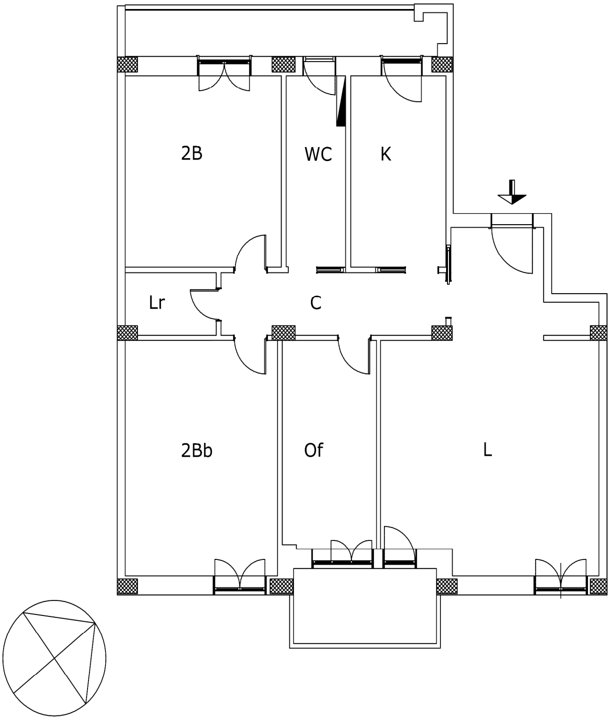

Fig. 1. Dwelling map

2.2 Thermal Proprieties and Specifications

For each dwelling of the existing building a heating system powered by conventional gas-fired boiler is installed and each room (with the exception of the corridor and the lumber-room) has a radiator as heating terminal. It is generally installed adjacent to the externally exposed wall.

A winter heating set-point temperature of 20°C is assumed and a heating period of 10 hours/day has been considered. All the rooms within the unit have the same set-point temperature, according with the hypothesis of a single chronothermostat installed. Before the heating period, no preheating strategy or mitigation action on the set-point temperature is considered, as the heating system is switched off.

The existing cooling system consists of two single air conditioners of 1 kW power each, located in two different rooms. For assessing the cooling energy consumptions, an operational period of both the two appliances of 4 hours/day over the 40 summer hottest days is assumed.

The external envelope's thermal properties have been calculated assuming the following existing stratigraphies:

- External walls consist of brick double layer (8 – 12 cm) with an interposed uninsulated 6 cm. air cavity and plaster finish on both sides (U = 1,1 W/m2K); internal partitions are made of hollow brick (thickness 8 cm) plastered on both sides;
- Floor and ceiling have a r.c. slab structure (30 cm lightened with hollow bricks), with ceramic tiles finishing the extrados and plaster finishing the intrados;
- The window has a 6 mm single glazing unit, and a 5 cm thick wood frame; a total U-value of 5,7 W/m2K has been considered. All the windows are equipped with a wood roller shutter, with the exception of the bathroom.

Moreover, in order to calculate the contribution, in terms of total energy requirements, related to heat transfer by ventilation, the following hypothesis have been assumed, during the heating and cooling periods:

- According to the UNI EN 12831:2006, a hourly rate of ventilation, n50, greater than 10 [1/h], has been considered for the infiltration model. It corresponds to a low degree of air tightness of the building envelope, essentially due to the window frames' quality. This is coherent with the assumption of an intervention on an existing building whose frames have, over the years, lost their air tightness. That means to consider an infiltration rate of 0,7 vol / h throughout the year;
- A natural ventilation air flow of 0,5 vol/ h rate of change has been considered, related to the rate of occupation of the rooms.

2.3 Climatic Data

The case studied is located in Bari (south of Italy) in a Mediterranean coastal area.
Summer temperatures are as follows: maximum average 28 °C and minimum average 17 °C, with absolute maximum temperature of 42 °C. During the winter maximum temperatures average is of 17 °C and minimum average of 5 °C, while an absolute minimum temperature of -4 °C has been registered. The relative humidity varies, throughout the year, between 64% - 78%. Precipitation concentrates during the autumn season and are totally lower than 600 mm/year; the predominant wind direction, during the summer, is north-west and the average wind speed is about 4,7 m/s (data source: weather station of Bari Palese).

2.4 Energy Upgrading Interventions' Hypothesis

In order to guarantee, for the above mentioned dwelling, a higher level of energy efficiency and sustainability, three interventions have been evaluated: a conventional one and two other with the use of building automation systems.

2.4.1 Conventional Energy Efficiency Intervention

The first strategy (subsequently named C 2.3) aims to improve the house's performance through the implementation of walls' exterior thermal insulation and substitution of existing windows with new ones. Components and materials for these interventions have been chosen in relation to the typical constructive practice for this kind of refurbishment activities. These are able to confer lower levels of envelope's components transmittance (less than or at last equal to those imposed by law for the climatic zone of the city of Bari).

For the external walls, a 8 cm expanded polystyrene insulation panel has been chosen, in order to achieve a combined U-value of 0,32 W/m2K.

New windows are characterized by double-glazed low emissivity units (4.16.4) and 5 cm wood frame (U= 2,08 W/m2K). In this way the infiltration rate through the envelope, n50, has been considered (according to the UNI EN 12831:2006) lower than 4 [1/h].

This means consider in calculating an infiltration rate of 0.25 vol/h throughout the year. However the air flow for natural ventilation, as well as all the assumptions relating to the operation of the heating, cooling, lighting and production of hot water are unchanged in comparison to the existing case (subsequently named C 2).

2.4.2 Implementation of Building Automation and Control System

In this case (subsequently named C 11.2), differently from what indicated in the preceding paragraph, it has been assumed to equip the dwelling with a network of sensors (wireless low-power) and actuators. The predicted benefits are related to a reduction of energy loads yearly by implementing natural ventilation strategies and managing existing windows' shading in summer, as well as controlling the heating system in winter. This approach was assumed in order to test if, using the BA system, was possible to achieve the energy efficiency' upgrading of the dwelling without generate, from a life cycle assessment point of view, an additional flow of materials and energy in input (production and use of polystyrene and new windows) and output (for maintenance and dismantling activities of components used for the conventional intervention).

Particularly the automation system is composed as follow (Fig. 2):

- N.7 internal temperature/humidity sensors (one for each room, except for lumber-room);
- N.2 external temperature/humidity sensors (one on each facing);
- N.6 solar radiation sensors (one for each frame with shading);
- N.8 presence detectors (one for each room);
- N.7 motors for the opening of the windows;
- N.6 motors for the control of existing rolling shading;
- N.8 switching actuators for lights (on/off);
- N.7 solenoid valve connected to temperature/humidity sensor (one for each room with radiator);
- N.1 control unit;
- N.1 software for building automation system management and control.

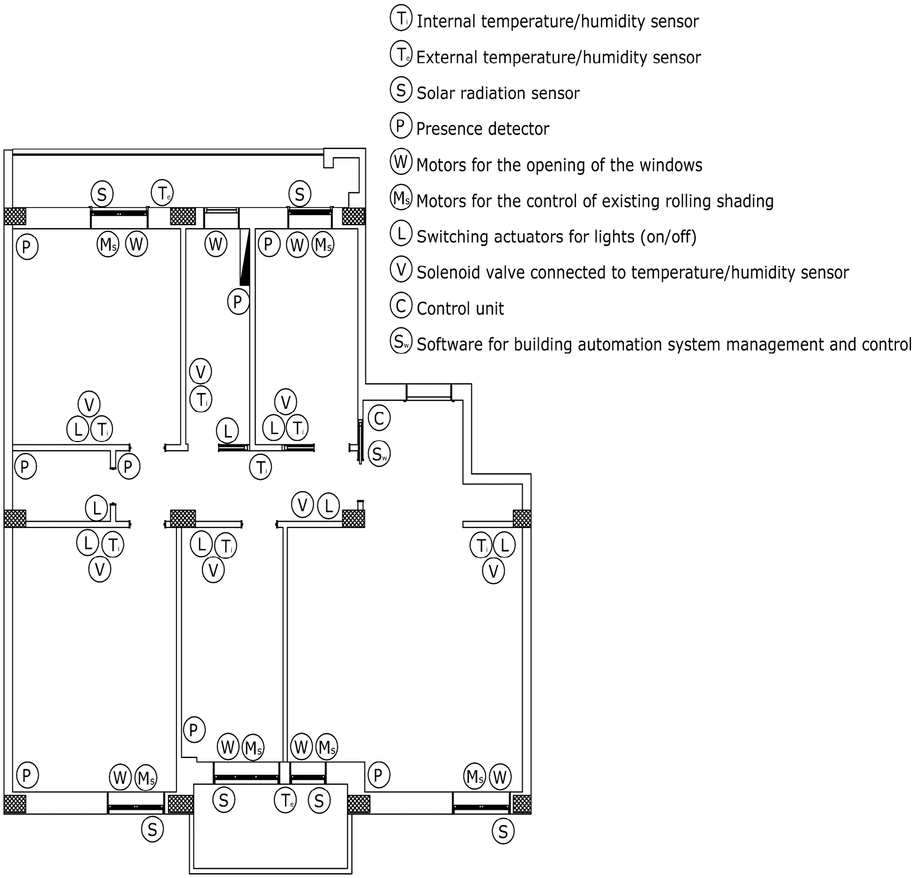

Fig. 2. Building Automation System scheme

For all sensor and actuators specific operation strategies have been studied, as follow:

- Shading :

  Closure during the night;

  Closure during the summer day when the solar radiation value exceeds the set-point of 120 W/m2, in order to contain the overheating of the internal rooms and the consequent need for cooling;

- Natural ventilation :

  Natural ventilation, related to the orientation of the building and external climate parameters (wind pressure coefficient = 0,2), was scheduled to be operational only in summer conditions and when there is a Tint> 22 °C. This value, however, is further related with the external environment characteristics in order to coordinate the windows opening as follow:

  a. the maximum percentage of window that can be opened for natural ventilation strategies has been set of 15% (2B), 20% (2Bb), and 50% (other rooms);

b. when Tint -Tout = 15 °C the opening of the fixture is 1% of the maximum opening possible whereas is the 100% when Tin-Tout = 2 ° and intermediate when Tin-Tout is intermediate between the limits imposed. This allows to contain the entry of hot air for natural ventilation in summer conditions, contributing to increase the effectiveness of the passive cooling strategy.

The maximum air flow rate of change was set of 2,5 vol/h for bedrooms and 6 vol/h for others rooms and the air speed was set to ensure a rate of air flow area of 1,95 cm /s m2 .

- Heating :

  The BA system provides the management of window openings in relation to the temperature difference between inside and outside. This control allows, for example, to close the windows in the presence of heating on, containing the relative heat loss.

  Moreover, using thermostatic valves connected to the sensors of temperature and humidity in each room is possible to implement a differentiation of the heating set-point temperature as follows: Bedrooms and Kitchen: 18 ° C, corridors and WC: 19 ° C, Living Room and Office room: 20 ° C.

  In this case, after 10 hours of operation, the heating system was reported at an attenuation temperature of 17 ° C. The same temperature of attenuation was maintained, thanks to the BA system, during winter weekends. For other days, the heating was off.
- Lighting :

  Lighting system was linked to the occupation level of the rooms: the automation system switches off lights in the absence of people.

2.4.3 Enhancing Natural Ventilation with BA System

In this case (subsequently named C 11.3), in addition to all strategies above mentioned, the outcome of potentiation of natural ventilation strategies was tested by increasing the quantity of the air flow rate of exchange (according to [15]) as follows:

- For bedrooms (2B and 2Bb), from 2,5 to 6 vol/h;
- For other rooms, from 6 to 10 vol/h.

3 Sustainability Assessment Tools

3.1 Energy Simulation

In order to compare the effect of the three different alternative strategies, several energy simulation models were developed; Design Builder software was used to achieve this goal, especially in order to assess the contribution of the building automation system in reducing energy consumption levels of the dwelling. This strategy allowed to articulate specific algorithms, energy efficiency oriented, for the management of natural ventilation flows, shadings and building services.

3.2 Life Cycle Assessment

For the above mentioned simulation cases, comparative Life Cycle Assessment evaluation was developed (according to [16] and [17]) in order to estimate the effect that different energy efficiency improvement strategies have within the whole building lifecycle's impact and in relation to different system boundaries specifications.

The following cases have been compared by the LCA evaluation: C2, C 2.3, C 11.3. SimaPro 7.1.8 software applications were used as supporting tool in order to implement the LCA model and carry out the assessment (IMPACT 2002+ method).

3.2.1 System Boundaries

Five different lifecycles were hypothesized for LCA evaluations; they were built in order to represent resources and energy flows (in input and output) of different time spans for energy improvement interventions: every 5, 15, 30, 40 and 60 years.

The most limited lifecycles (5-15 years) were representative of the impact of an anticipated dismissing of the requalification strategy (conventional or with building automation one) as a result of accelerated functional or technological obsolescence phenomena.

On the contrary, in order to get a cradle-to-grave LCA evaluation, in the largest lifecycles (40-60 years) the impact related to the maintenance activities of components set up for the efficiency of the existing case (maintenance of wall coat every 25 years, of new windows every 35, etc.) was evaluated.

Inventory data for building materials were retrieved from ETH-ESU 96 System Processes, IDEMAT 2001 and Ecoinvent System Processes databases and from producers' collected information and declarations.

For the calculation of energy consumption, database items relating to the Italian energy mix were used.

As regards to transportation, all on the road, distances were calculated as the nearest suppliers of building material was chosen in relation to the building site in Bari.

In the LCA evaluation the following items were not considered:

- consumption for the production of sanitary hot water and for the use of equipment;
- electricity consumption for feeding the building automation system (omitted because assumed completely negligible, in comparison to other energy flows);
- impacts associated with construction, maintenance, dismantling of the existing building (the same for all cases);
- impacts associated with the production, maintenance and disposal of sensors and actuators (as explained in the next paragraph).

Considered processes for the inventory analysis are explained in the Table 1.

Table 1. Considered processes for the life cycle inventory

Life span	**C 2**	**C 2.3**	**C 11.3**
5 years	Consumption for heating, cooling (related to two single-air conditioners) and lighting	Existing window removal Installation of new windows External wall coat application Consumption for heating, cooling (related to two single-air conditioners) and lighting New window removal (at the end of the predicted lifecycle, 5 years in this case) External wall coat removal (at the end of the predicted lifecycle, 5 years in this case)	Consumption for heating and lighting (no use of two single-air conditioners)
15 years	Consumption for heating, cooling and lighting	Existing window removal Installation of new windows External wall coat application Consumption for heating, cooling and lighting New window removal External wall coat removal	Consumption for heating and lighting
30 years	Consumption for heating, cooling and lighting	Existing window removal Installation of new windows External wall coat application Consumption for heating, cooling and lighting External wall coat maintenance every 25 years (1 time) New window removal External wall coat removal	Consumption for heating and lighting
40 years	Consumption for heating, cooling and lighting	Existing window removal Installation of new windows External wall coat application Consumption for heating, cooling and lighting External wall coat maintenance every 25 years (1 time) Window maintenance every 35 years (1 time) New window removal External wall coat removal	Consumption for heating and lighting
60 years	Consumption for heating, cooling and lighting	Existing window removal Installation of new windows External wall coat application Consumption for heating, cooling and lighting External wall coat maintenance every 25 years (2 times) Window maintenance every 35 years (1 time) New window removal External wall coat removal	Consumption for heating and lighting

3.2.2 Consideration about Developing LCA Evaluations on Components of the BA System

The integration between the architecture and the automation field could be considered, even today, particularly slow due to a variety of problems including the strong specialism of the electronic field that precludes the architect from looking at automation systems as component parts of his project.

Automation is perceived from designers, who are great experts of specificities and problems of the construction process and building systems, as an application field unrelated to their skills and therefore often delegated to others for a possible implementation. This dichotomy reflexes Life Cycle Assessment evaluations difficulties in quantifying the impacts of building automation systems in the life cycle of building structures.

In particular, in the present study, these impacts were neglected in relation to the following considerations: first of all the compactness and miniaturization of the constituting elements of the home automation system (with respect to the scale of building components) makes possible to assume a low investment of resources and energy in their production.

These products, also, largely composed of disassemblable parts and metallic electrical components, may be subject to a qualified treatment at their end of life. This suggests that the impact associated with their disposal is particularly modest.

In confirmation to these considerations, it should be noted that some studies in the automation field [18] showed in lighting application that the environmental impacts of the intelligent lighting system could be 18 to 344 times smaller than those of the conventional lighting system.

Table 2. Impact details for the case C11.3 with and without the automation system

	LCA Code	**Considered processes**	**yrs**	**Impact (Pt)**	**Impact of BA system**
A	C 11.3_lifecycle 5 yrs	Consumption for heating and lighting	5	1,950	
B	C 11.3+ BA_ 5 yrs	Consumption for heating and lighting. Production and dismission of BA system	5	1,952	+ 0,09 %
C	C 11.3_lifecycle 15 yrs	Consumption for heating and lighting	15	5,850	
D	C11.3+ BA_ 15 yrs	Consumption for heating and lighting. Production and dismission of BA system	15	5,852	+ 0,03 %
E	C 11.3_lifecycle 30 yrs	Consumption for heating and lighting	30	11,701	
F	C 11.3+ BA_30 yrs	Consumption for heating and lighting. Production, maintenance and dismission of BA system	30	11,705	+ 0,03 %
G	C 11.3_lifecycle 40 yrs	Consumption for heating and lighting	40	15,602	
H	C 11.3+ BA_ 40 yrs	Consumption for heating and lighting. Production, maintenance and dismission of BA system	40	15,607	+ 0,03 %
I	C 11.3_lifecycle 60 yrs	Consumption for heating and lighting	60	23,403	
L	C 11.3+ BA_ 60 yrs	Consumption for heating and lighting. Production, maintenance and dismission of BA system	60	23,410	+ 0,03 %

Analyzing in our case, from a LCA point of view, the impact of the wireless network components it's possible to further confirm these considerations.

As shown in Table 2, during all of the life spans considered (5,15,30,40, 60 years), the impact of the case C 11.3 does not vary in relation to the building automation system presence or absence. In fact, is confirmed that this environmental impact could be higher than the solution without the BA system, between a variable rate of 0,09% and 0,03%.

Inventory data for cases B, D, F, H, L include: materials flows for the production of PWB (Printed Wiring Board), energy consumption for dismantling, transport to further treatment at their end of life (assuming that metal pieces are recycled, plastic parts incinerated, and PWB recycled) and maintenance activities every 15 years.

4 Results and Discussion

4.1 Energy Simulations Results

According to the Energy Plus simulations Fig. 3 summarizes the achieved results of heating and cooling consumption related to different energy improvement strategies above mentioned of the dwelling studied.

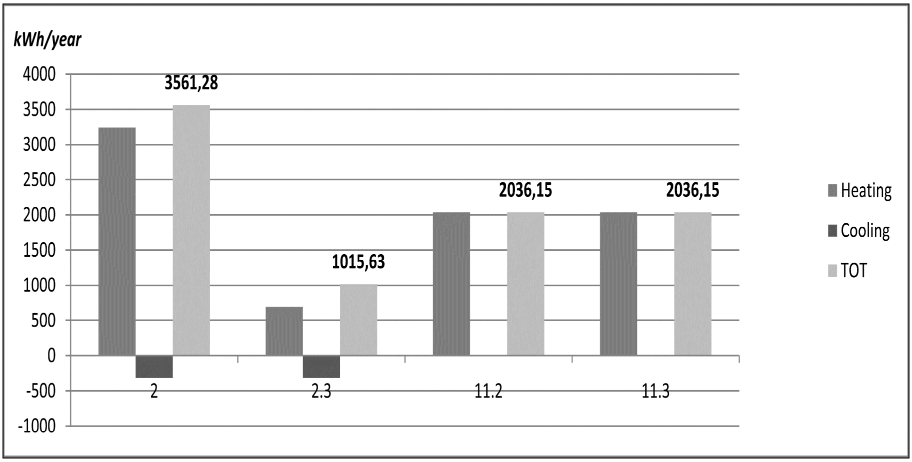

Fig. 3. Heating and Cooling consumption

Results reveal that the implementation of conventional efficiency improvement strategies (C 2.3) generates a reduction in fuel consumption for heating of about 78,5%, compared to the existing case (C 2).

Through the implementation of the automation system (C 11.2 and C 11.3) this reduction amounted to 37,2% approximately. Looking at the total values, percentages become 71,5% for the C 2.3 case and 42,8% for cases 11.2 and 11.3, also in relation to the lower incidence of automation strategies in consuming fuel for cooling operation.

In order to understand the contribution of different strategies to the improving comfort levels during the summer, the internal room temperatures were investigated for a reference week, from 27th July to 2nd August. In such period the cooling system of cases C 2 e C 2.3 (two single air conditioners) was considered switched off, while natural ventilation control strategies and shading management, provided in the cases 11.2 and 11.3, were considered active. Fig. 4 shows results achieved for the simulated summer week.

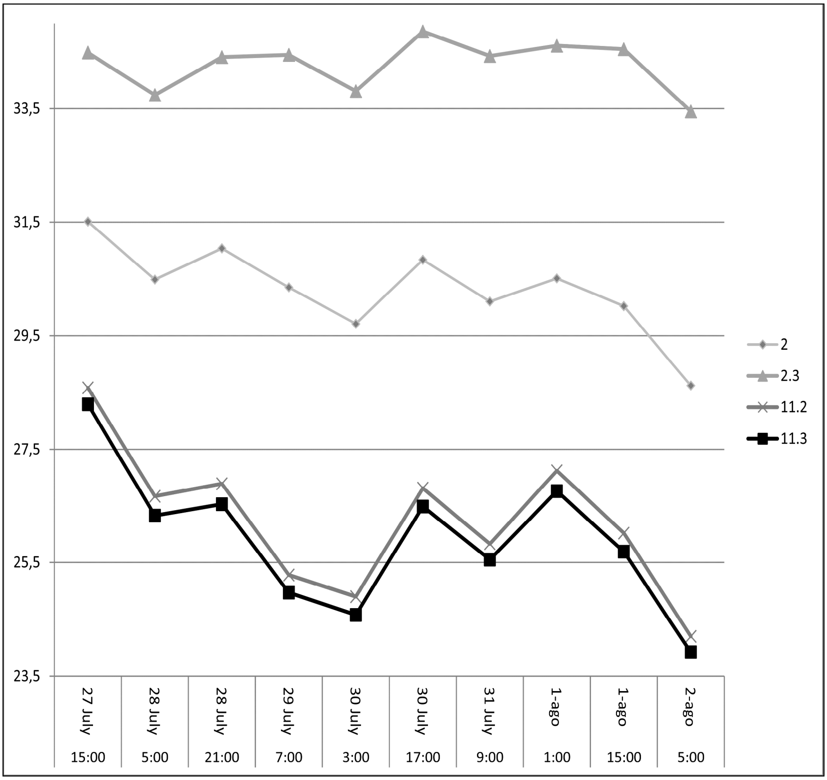

Fig. 4. Internal temperatures during the summer week

In first place, the simulation showed that conventional efficiency technologies not combined with passive cooling strategies causes an increase of internal temperatures, with considerable discomfort of the occupants.

On the other hand, the automatic management of windows and shadings' opening (C 11.2), compared to the existing case (C 2), contributes in reducing the internal temperatures from a minimum of about 2,9 °C to a maximum of about 5,1 °C. This range growths in case of enhancement of natural ventilation strategies (C 11.3) from a minimum of 3,2 °C to a maximum of about 5,4 °C.

4.2 LCA Results

According to the ISO 14040 and 14044 standards, Fig. 5 summarizes the achieved LCA results of the dwelling, considering different life spans for energy improvement interventions (every 5, 15,30, 40 and 60 years).

Each triplet of values, corresponding to the relative reference period, represents the impact due to input and output flows of resources and energy for the specific case, as above explained in Table 1.

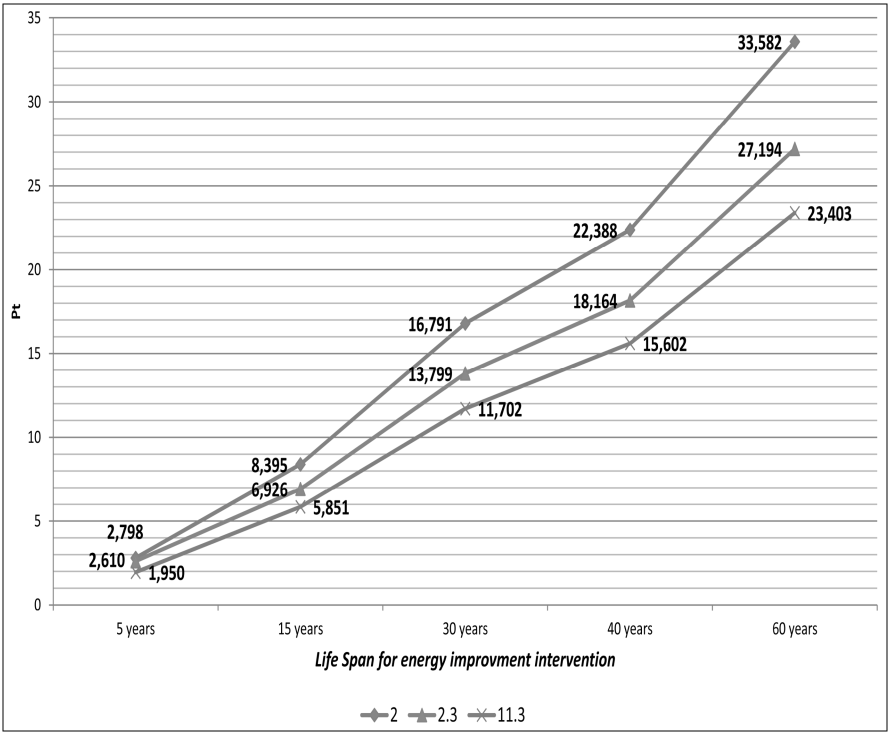

Fig. 5. Impacts for different energy improvement strategies

The graph shows that the reduction of the overall impact of the case studied with the BA system, is greater (30,3%) than conventional strategies, in all lifecycles analyzed. This result that Building Automation systems can ensure a greater saving of resources and energy that can be invested for the efficiency improvement of existing buildings, even after a very limited duration of time (such as for 5 years) .

Furthermore, the difference between the impact of the two solutions (with building automation or conventional one) increases with the lifecycle of reference; this shows, also, the contribution - achievable with the first type of intervention - in reducing input and output flows for maintenance activities (such as the replacement of the coat and windows), required in longer time frames.

4.3 Considerations about Results

In this study, we simulated a conventional energy improvement intervention through the installation of a coat insulation made of EPS. This choice had a negative impact on the final comparative simulations both with regard to the poor sustainability content of the selected product, from a LCA perspective, but also with reference to its inadequate performance in summer conditions. Further studies will analyze how the impact of the C 2.3 case could be improved by the use of wall coat materials with higher standards of sustainability and breathability.

At the same time it should be underlined that BA systems, if contributes to greatly improve the internal comfort conditions in summer, could not ensure, during winter conditions, the same goals. This is true especially in comparison with the realization of the wall coat, which is more effective in the correction of thermal bridges and the overall envelope performance. With reference to the non quantification of automation components' impacts - however negligible - in LCA evaluations, we hope that further researches regarding the production, transportation, installation, maintenance and disposal of BA technologies would consolidate the achieved results and suggest future ideas in this research field.

5 Conclusion

The present research showed, from a LCA point of view, the achievable benefits resulted implementing building automation systems for the components and services management of existing building.

Regarding the BA system, it is important to underline the sensible reduction of the consumption during summer and winter periods. In fact, during the winter season, a reduction in fuel consumption (in kWh/year) up to about 43%, compared to the existing case without BA system, is achievable.

In the summer the intelligent management of natural cooling and overheating protection reduces the internal air temperature up to a maximum of 5 °C. This contributes to reduce the demand of air conditioning systems, as well as the consumptions for cooling.

Compared to conventional strategies, Building Automation technologies show greater levels of sustainability of interventions, in Life Cycle Assessment perspective, with a total impact reduction of 30,3 %.

Two reasons can be found: the first one the use of wireless low power devices, with a low impact on wired connections. The second one, a more rational control of energy to contain consumptions during winter and summer due to strengthening of passive cooling strategies. Starting from these initial results, it is evident the need to expand the simulations to other types of buildings/dwellings, eventually located in different latitudes, in order to test the response of BA systems and the achievable savings.

Another element of interest lies in the economic savings achievable with the use of BA systems for the energy efficiency intervention, in the whole building life cycle and, therefore, in a logic of Life Cycle Costing. The recent rapid market spread of low cost technologies can certainly help in increasing the competitiveness of these systems.

Further research in this field will be needed to test the variability of the achieved results, both with regard to the building characteristics (different site, envelope and services) that to the BA technologies and logics.

In fact, as proved by several researches [19, 20], particular attention must be given to the analysis of the contraction of the lifecycle of electronic devices, that, in short time spans, could make their replacing more convenient than their maintenance. In such sense, the use of LCA evaluations could promote the development of specific algorithms to estimate the impacts' variation, in relation to different kind and rhythms of obsolescence of building's systems with respect to automation ones.

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