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DYNAMIC SIMULATION OF BACS (BUILDING AUTOMATION AND CONTROL SYSTEMS) FOR THE ENERGY RETROFITTING OF A SECONDARY SCHOOL

Cristina Becchio[1], Paolo Cantamessa[1], Enrico Fabrizio[2], Pietro Florio[1], Valentina Monetti[1], Marco Filippi[1]
[1]DENERG, Politecnico di Torino, Torino, Italia
[2]DISAFA, University of Torino, Grugliasco (TO), Italia

ABSTRACT

School buildings in Italy are affected by large energy losses. Moreover, the energy efficiency market is growing, but it is not considering the entire potential of the building automation technologies yet (DIG, 2011). In order to test the relevance of these measures, a reference building was designed according to different references, as representative of the national stock of school buildings. It was simulated in order to obtain the energy requirements breakdown and select different technical upgrades with reference to the EN 15232 standard. The results, analysed for single measures and packages for two different HVAC system types (radiators and fan coils), showed reductions in the primary energy requirements up to 30% - 40%.

INTRODUCTION

Buildings account for around 40% of total energy consumption and 36% CO_2 emissions in Europe. Since 2007 the European Commission has been introducing energy efficiency goals, known as “20-20-20 set” (Commission of the European Communities, 2007); in 2010 the recast of Energy Performance of Buildings Directive – EPBD (The European Parliament and the Council of the European Union, 2010) defines the nearly zero energy building (nZEB) as the compulsory standard for new constructions after 2020.

Single passive measures (such as insulation increase) are often not performing enough to reach these efficiency objectives (Bayraktar et al., 2012). Improper scheduling and temperature setpoints may increase energy losses and occupant dissatisfaction, affecting the global efficiency of the building (Higgins, Robertson, 2012). Considering the installation cost and the larger need of maintenance due to a higher complexity of the HVAC system, a precise calibration of the electronic control based on the real use of the building is strictly needed to ensure their effectiveness. Building Automation and Control Systems solutions (BACS), interacting with building and technical system level, provide the exact energy need through the accurate measure of energy demand, in order to prevent energy losses and wastes. Compared to a small electric demand, they contribute to refine operational controls, both in new construction and in the retrofitting of existing buildings.

The challenge is important when considering that in the European Union more than 90% of the growing energy requirements in the tertiary sector is driven by the evolution of non residential buildings (Gaglia et al., 2007): but it is even more significant when dealing with public properties, which occupy about 12% by area of the EU region’s building stock (BPIE, 2011). The European Commission calls for the public sector to lead by example and helps to stimulate the market for energy-efficient products, practices, services and business models. An interesting survey on public buildings, including a large percentage of schools (Bull et al., 2012), can be found in the project Cyber Display ® (Display campaign, 2012), carried out in the 2001-2009 period. The efficiency campaign that involved the buildings attending the project has shown a general interest in improving the energy performance all around Europe, except for Italian registered buildings (Shukla, Bull, 2012).

In Italy, educational buildings are more than 60,000, generally affected by large energy losses, especially those built before 1980 (Rollino, 2012). This is partially due to the related Italian law, which dates 1996 but still refers to a Ministerial Decree of 18/12/1975 (Ministero dei Lavori Pubblici, 1975). Therefore, a deep action in this sector seems urgent.

In addition a view of the Italian school building stock can be found in a report produced by Politecnico di Torino concerning a sample of 103 schools in the Turin district (Corgnati et al., 2010). From the report, the mean primary energy consumption of the schools analyzed is approximately 129 kWh/m^2year, divided into 114 kWh/m^2year (88%) for space heating and 15 kWh/m^2year (12%) for lighting and electric equipment. In most cases, natural gas boilers with 0.85-0.90 efficiency are used to supply the heating energy, through a hot water loop with radiators, for a total mean capacity of 1000 - 1500 kW. Most schools (73%) are heated continuously without a specific control in the different rooms during incomplete occupation of the structure. This means that there is a great chance to improve the management efficiency through a better operation of the system, even with BAC components.

All the schools considered do not include either a cooling plant or mechanical ventilation system.

The aim of this study is to demonstrate the relevance of BACS for the energy retrofitting in schools: due to their fine sensibility to environmental variables, a dynamic simulation is needed in order to obtain acceptable and detailed results. The interaction between climate, building envelope and HVAC system is taken into account, updating thermal variables every 15 minutes.

THE REFERENCE BUILDING

For the aims of this work, a school reference building was selected as a national sample concerning dimensions, uses, systems, as well as construction age and techniques. It represents a high school with scientific diploma, built from1960 to 1970, relevant for its frequency and average conditions over national scene.

The reference building was chosen among statistic samples of real existing schools, according to the national report of the project "Typology Approach for Building Stock Energy Assessment – TABULA" (Corrado et al., 2011). This report defines many types of reference buildings related with the methodological approach to the building features definition (Corgnati et al., 2013):

- Example building: real building selected by professional experience representing a construction category.
- Real building: real building selected by statistical analysis.
- Theoretical building: virtual building composed with statistically determined sample features.

In this case, an example building provided by Politecnico di Milano (Pagliano et al., 2010) is the main reference: missing data have been retrieved from manuals (Sole, 1995 and Stefanutti, 2007) and national standards (UNI 10339: 1995).The resulting building responds then to a theoretical reference type: its features are divided into four main categories, referring each to a particular data source, as shown in Figure 1.

It is assumed that 500 students are divided in 20 classrooms for 25 people. Every room has been sized according to the current law, DM 18/12/75.

The total surface of the reference school amounts at 6007 m^2, for a 19154 m^3 gross volume with an aspect ratio is 0.45 m^{-1}. The glazing surface, settled equally on the different sides of the building, reaches the value of 571 m^2 while the glazing/opaque ratio around the whole structure is 0.27. Windows of the example building have been resized in order to meet day lighting requirements (composed according to Rollino, 2012).

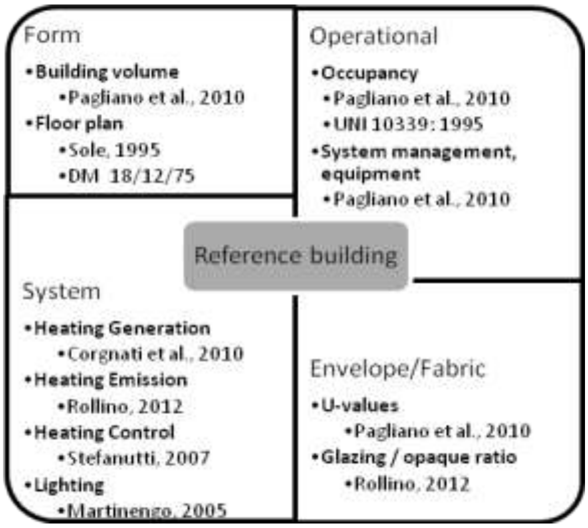

Figure 1 Main references divided in categories

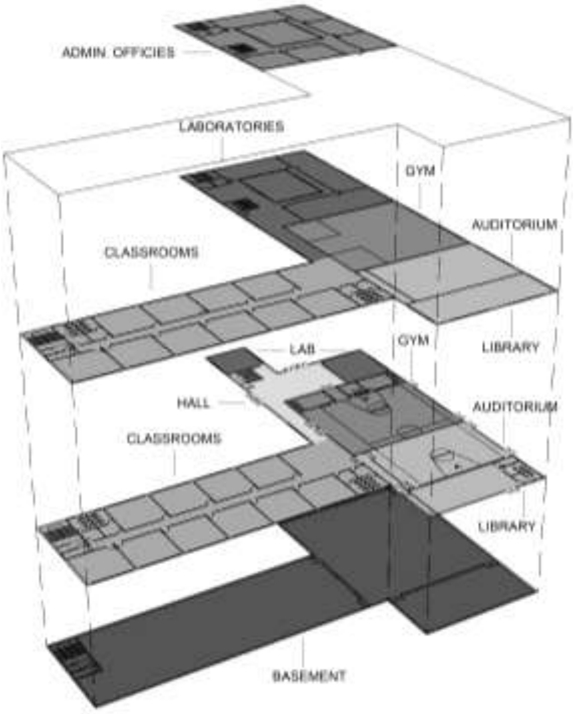

Figure 2 Exploded school model

As shown in Figure 2 the building is divided into 7 functional areas according to their main use (classrooms, laboratories, library, gym, administration, auditorium, hall).

Traditional technical solutions are adopted for the definition of the school constructions. The envelope is composed by 12 cm - 8 cm plastered non-insulated hollow walls and 24 cm + 8 cm plastered non-insulated cement brick slabs. Only the basement structures are full concrete walls and floors. U-values of the main envelope components (Pagliano et al., 2010) are listed in Table 1.

Table 1
Construction elements U-values

CONSTRUCTION ELEMENT	U-VALUE $W/m^2 K$
Exterior walls	1.10
Slabs and walls facing the basement	2.78
Roof	1.41
Slab facing outward	1.39
Internal partitions (thickness 16 cm)	1.67
Internal partitions (thickness 12 cm)	1.85
Internal slab	1.30
Internal door	1.62
WINDOW ELEMENT	
Glass	5.8
Frame	7.00

Several modules (120 x 150 cm each) compose different window layouts, until 6 m long: a single pane clear glass (U_g = 5.8 W/m^2K) is combined with aluminium untreated frame (U_f = 7 W/m^2K); internal horizontal blinds are employed as manually activated shading devices. In most cases Italian schools have no mechanical ventilation system (Rollino, 2012) and air change is provided by natural ventilation. A manual operating window opening is then assumed in the reference building. Two types of HVAC systems were simulated. The first, based on radiators installed on the internal face of exterior walls, reflects the current prevailing condition in the Italian school building stock. The second, based on four pipes fan-coils, was analysed in coherence with law requirements of DM 18/12/1975, which already express the need of the mechanical ventilation and a cooling system in educational buildings. Unfortunately this aspect is still unattended in most of cases (Rollino, 2012). Anyway, in this survey, it was considered in a long-term perspective. Domestic hot water (DHW) production is not considered as relevant on the total energy demand so it was omitted for the present study.

MODELING ASSUMPTIONS

The simulation of the school energy performance was carried out by mean of the energy simulation program EnergyPlus version 7.0 (U.S. Department of Energy – DOE, EnergyPlus Energy Simulation Software, 2012).

Every single room was modelled as a thermal zone with its specific environmental properties, for the evaluation of a customized automatic control. A different weekly timetable for each room was created, including some activities during the afternoon.

Internal gains and ventilation

The classrooms are fully occupied only in the morning, according to their customized weekly timetable . Each area is also defined by a particular occupancy profile defined as a percentage of the maximum presence level (Figure 3). Holidays period comply with the typical Italian school calendar (summer holidays in July and August).

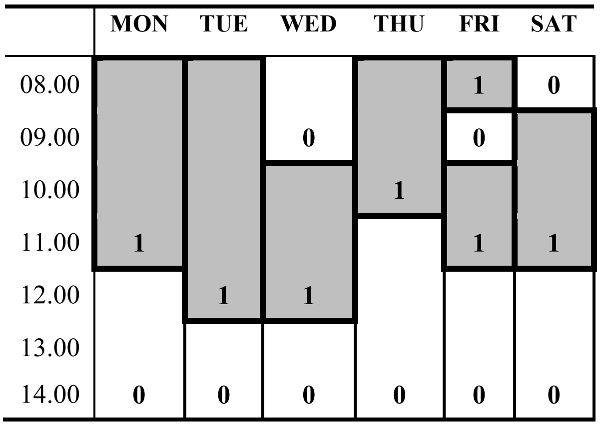

Figure 3 Weekly schedule of a typical classroom; 0 and 1 are the possible presence factors

Employees occupy the administration offices and some classes attend their lessons in the laboratories until late afternoon; external users (college teams, amateur practisers) train in the gym during the evening on weekdays.

Specific thermal gains are associated with different uses across the building rooms. Different sensible gain values are considered with regards to occupancy (Table 2, column 1) according to the main occupants activity. Occupancy factors (Table 2, column 2) are calculated according to the project, as a mean of different values proposed by different data sources (UNI 10339: 1995; Pagliano et al., 2010; DOE, 2004).

Artificial lighting is controlled in all rooms according to the 7 macro-zones activation profiles; lamps in bathrooms and circulation areas follow time-schedules. The standard fluorescent lamp is composed of 2 modules (36 W/each), for a mean electric power of 11.6 W/m^2 of lit surface (Martinengo, 2005). Internal blinds are activated for a solar radiance on window surface greater than 300 W/m^2. Windows are supposed to be opened by users for 15 minutes every 2 hours of occupation in all rooms. Incoming air volumes for natural ventilation are calculated according to “ASHRAE Handbook 2009”, as a combination of wind force and stack effect (American Society of Heating, Refrigerating and Air-conditioning Engineers – ASHRAE, 2009).

An example of natural ventilation air changes rate can be observed in Figure 4. Infiltrations across the hall (0.6 ACH) and the ventilated crawl space (0.15 ACH) are contemplated.

Table 2
Internal gains

ROOM TYPE	OCCUPANCY		ELECTRIC EQUIPMENT		ARTIFICIAL LIGHTING
U.M.	[W/person]	[persons/m^2]	[pieces of equipment]	[W]	[W/m^2]
Data source	Pagliano et al., 2010	UNI 10339: 1995; Pagliano et al., 2010; DOE, 2004	Pagliano et al., 2010	[Total]	DOE, 2004
Classrooms	100	0.52	-	-	15.06
Laboratories	100	0.35	60 computers (80 W/each) 2 printers (100 W/each) 2 servers (60 W/each) 2 copiers (500 W/each)	6120	15.06
Offices	105	0.10	12 computers (80 W/each) 5 printers (100 W/each) 1 server (60 W/each) 1 copier (500 W/each)	2020	11.84
Gym	300	0.08	-	-	15.06
Auditorium	100	1.00	-	-	9.68
Library	100	0.23	-	-	13.99
Hall, circulation areas	105	0.10	-	-	5.38
Toilets	100	0.01	-	-	9.68

The heating system

The radiative component of radiators heat transfer is distributed in different proportions to the facing construction elements, according to their view factor. The thermostat is a dual set point with dead band fixed at 20 °C (during occupation) and 15 °C (in absence of occupants), during the whole year. Circulation pumps installed on the heating loop work at constant speed in presence of heating load. Hot water set point of the heating loop is 70 °C (for radiators) and 82 °C (for fan coils) with no compensation based on external temperature. Boiler efficiency, as asserted by Politecnico di Torino report (Corgnati et al., 2010), is 0.85, with a partial load ratio (PLR) between 0 and 1.

The cooling system

The cooling system is set only for the fan coil system case. The thermostat, during the whole year as well, is a dual set point with dead band fixed at 26 °C (during occupation), 45 °C (in absence of occupants), to allow the free temperature floating. Circulation pumps in chilled water loop have the same characteristics of heating system. The chilled water set point is 7 °C. The condensed water set point is 29 °C. A single speed cooling tower is installed for condensing purposes. The chiller coefficient of performance (COP) is 3.2, with a PLR between 0 and 1.

Weather conditions

The reference building is simulated in Turin (45° 22' N, 7° 39' E, 287 m above sea level) with a typical meteorological year (TMY) data (World Meteorological Organization, 2012).

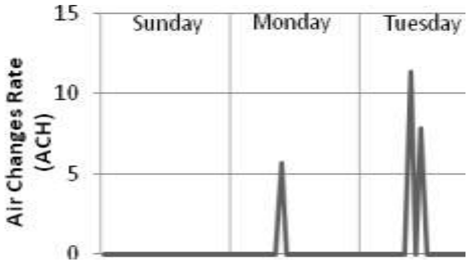

Figure 4 air changes rate per hour in a typical classroom

BACS

BACS are related both with the operational level and the systems (heating, cooling, generation, mechanical ventilation and DHW production) as well as with the electrical devices (for lighting and equipment). In Europe there is a standard, EN15232:2007, that defines and describes the BACS solutions. Different technical installations are listed for each of the possible uses of electronic control in the building system. The standard outlines also a classification of automatic control efficiency, for residential and non-residential buildings. Four classes are stated from "D – non-energy efficient" to "A – high energy performance". Each solution described in the standard is identified by one of these classes. The implementation of every solution marked with a certain class is needed to determine the global performance class of the building. In Table 3, an example of the control function steps for a thermostatic valve is reported.

Table 3
Control function analysis of a BAC solution (thermostatic valve)

	TYPE	VARIABLE
SENSOR	- Thermistor	- Indoor temperature (T)
CONTROLLER	- DDC - On-off	- T < 20°C → on - T > 20°C → off
CONTROLLED DEVICE	- 2 positions - Valve	- Radiator on-off

PLAN OF THE SIMULATIONS

In absence of any automatic control the reference building can be matched with a "D" class. On this "base case" different BACS upgrades were implemented. These were chosen between the different applications in the building systems (excluding mechanical ventilation that is absent).

The types of components implemented in the model were selected from the list of the standard EN15232: 2007 (after being analysed as in Table 4), according to criteria of responsiveness to the functional needs of the school. In particular, seven different solutions were simulated one by one and subsequently joint together in application packages.

Auxiliary system

The auxiliary system includes both the circulation pumps installed on the heating / cooling / condensing loop and the fans as components of the fan coil group. These fans do not supply primary air changes but just trigger the convective recirculation of internal air.

1. Intermittent pumps and fans according to heating/cooling load (INT AUX): the auxiliary system is activated just in presence of heating/cooling load measured for each time step, while in the "base case" it works continuously all day long (7:30-22:00). This solution can be realised by linking the pump engine with a thermostat set point.
2. Variable flow pumps and variable speed fans (VAR AUX): a variable speed engine can be implemented to improve the auxiliary system response. It adjusts the pump/fan flow according to the heating /cooling load by keeping constant the differential pressure at the pump/fan heads. This can be achieved through the installation of an inverter and a heating/cooling load detector.

HVAC system

3. Climatic compensation of supply water temperature based on external temperature (CLIM): this solution cuts down the thermal dissipation across the water loop, minimizes the air speed and allows a lower and more stable temperature in order to reach comfort.

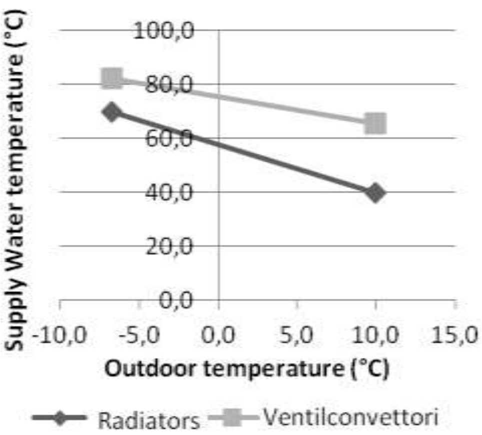

Figure 5 Heating compensation function

It is composed by one or more external air thermometers linked with the supply water temperature sensor through an electronic controller. This controller drives a modulating three - way valve that mixes the supply water with the return water to reach the correct temperature set point of the water going to the water loop. The supply water temperature is then a function of the external air temperature. As result, the boiler/ chiller is released by a certain part of the load, when the external air temperature is reasonably mild. The compensation is activated for 24 hours a day, following a linear algorithm. The one for the heating is shown in Figure 5.

4. Heating / cooling interlock (ILOCK): a control function, related with a calendar, prevents the simultaneous generation of hot and cold water. The system based on fan coils is characterized both by a heating and a cooling season, which are independent. The system based on radiators is defined just by the heating season. The Presidential Decree 412/1993 (Presidenza della Repubblica, 1993) describes the heating season, reduced in comparison with the "base case", that admits the heating system activation during the whole year. This solution modifies directly the energy need profiles with a relevant impact on energy requirements.
5. Night cooling with mechanized opening of windows (NCOOL): free cooling measures are usually applied in presence of mechanical ventilation. A mechanical opening of the windows, based on the detections of an outdoor and of an indoor thermometer, has been installed anyway. The activation of the night cooling is

possible if these conditions are verified simultaneously:

- Operating time is between 00:00 and 08:00;
- The indoor temperature is higher than 23 °C;
- The outdoor temperature is higher than 15 °C;
- The difference between indoor and outdoor temperature is higher than 2 °C.

As a result, the chiller is released by a certain part of the load. This measure has been applied as well to the system based on radiators, even if there is no cooling generation, in order to improve the internal comfort.

Lighting system

The following solutions are already spread on the nationwide market due to their easy installation and low costs.

6. Automatic presence switch (PRES): an infrared or ultrasound sensor is linked with a switch to turn off the artificial lighting in absence of occupants. The 7 macro-zones activation profiles are then reduced according to effective occupation.
7. Lamps dimmer and blind control compared with day lighting levels (DAYL): a photoelectric sensor detects the day lighting level at a certain point and reduces the artificial lighting through a dimmer. These instructions are used as well to control the internal blinds.

Intervention packages

A. Thermal package (TH PACK): it includes the variable auxiliaries (2), the climatic compensation (3), the interlock (4) and the night cooling (5).
B. Lighting package (L PACK): it includes the presence switch (6) and the day lighting control (7).
C. Combined package (COMB PACK): it includes the two previous packages.

For every simulation the system has been sized during the design days in order to meet internal comfort in the most critical conditions. A simulation test are launched first in 5 rooms for a 3 days benchmark period in every season (January, April, June, October). To evaluate any condition of HVAC plants the chosen period goes from Sunday (all systems down) to Tuesday (mid-week run). Environmental variables (such as temperature), system variables (PLR), IAQ variables (air change rate) are assessed, checked in order to meet comfort requirements. Once completed the coherence review, the simulation run period is extended to a complete year, (from January 1st to December 31st).

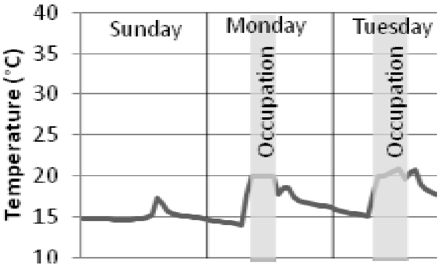

Figure 6 Indoor temperature in a room

RESULTS

The "base case" – radiators

In the "base case" with radiators as heating system, the maximum heating load measured during the simulated sizing period is 1479 kW, generating a nominal boiler capacity of 1695 kW (with a 0.85 boiler efficiency). The energy sources considered are natural gas (for the heating system) and electricity (for the cooling and lighting system), respectively with a primary energy conversion factor of 1 and 2.17 for the electricity. The heating system is activated for the whole school year (10th September – 20th June). The global primary energy performance rate is 155 kWh/m^2 year, divided in the different end uses as represented in Figure 7. This base case model does not refer for the calibrating process, to the Politecnico report previously cited, above a sample of 100 schools (Corgnati et al., 2010).

The "base case" – fan coils

As a result of the sizing period, in this case the nominal boiler capacity is 1662 kW, while concerning the cooling system the nominal capacity is 262 kW for the chiller and 374 kW for the cooling towers. The global primary energy performance rate is 200 kWh/m^2 year. The increase of energy requirements can be explained with the introduction of cooling and of auxiliary fans as part of the fan coil units. On the other hand the indoor thermal comfort is more stable and reached faster, as verified during the summer test period.

Excluding the night cooling measure, that only introduces comfort benefits and no energy saving because cooling is absent, the first result in a growing performance scale is related with the auxiliaries, which account for 2-5% of total primary energy requirements. Primary energy variations by end uses are listed in Table 4. In particular the variable auxiliaries cut the electricity needs for water circulation up to 96%. On the other side they increase the heating demand for 1-3%, deducting their internal gain. The lighting measures introduce a primary energy saving between 6% and 11%, with a growing heating demand between 2% and 3%. In this case the best performing solution is the day lighting control.

The system upgrades – radiators

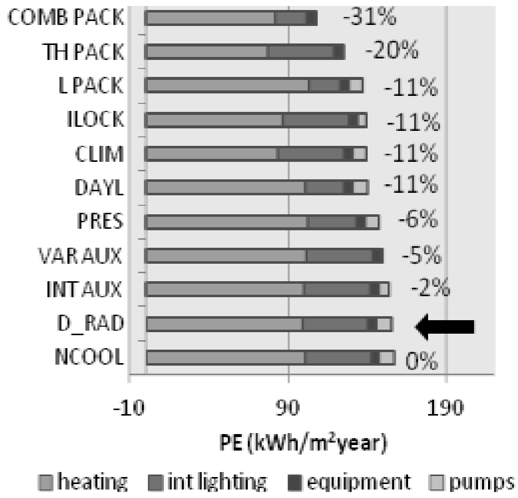

Figure 7 Primary energy requirements of the radiators base case and system upgrades

Concerning HVAC solutions, both the climatic compensation and the interlock reduce of 11% the primary energy requirements, underlining the importance of a correct system management. In particular the interlock, with the modification of the energy need profiles, combines a relevant primary energy reduction for heating (12%) with an auxiliary system cut-off (42%). Combining the effect of different measures the lighting package is the least effective (11% reduction) due to the lower internal gains. The mix with the thermal package cuts the energy requirements up to 31%, thanks to a better integration between HVAC and lighting systems.

Table 4
Primary energy variations by end uses for radiators system and fan coils system

	Heating		Cooling		Int lighting		Equipment		Fans		Pump	
	Radiators	**Fan coils**	**Radiators**	**Fan coils**	**Radiators**	**Fan coils**	**Radiators**	**Fan coils**	**Radiators**	**Fan coils**	**Radiators**	**Fan coils**
COMB	-17%	5%	-	-80%	-52%	-52%	0%	0%	-	-94%	-98%	-85%
TH PACK	-22%	-3%	-	-74%	0%	0%	0%	0%	-	-93%	-98%	-81%
L PACK	4%	9%	-	-9%	-52%	-52%	0%	0%	-	0%	0%	-3%
ILOCK	-12%	-7%	-	-78%	0%	0%	0%	0%	-	-21%	-42%	-57%
CLIM	-15%	-6%	-	-15%	0%	0%	0%	0%	-	0%	0%	-3%
DAYL	2%	10%	-	-44%	-41%	-45%	0%	0%	-	0%	0%	-18%
PRES	3%	5%	-	-2%	-26%	-26%	0%	0%	-	0%	0%	-1%
VAR AUX	3%	14%	-	-53%	0%	0%	0%	0%	-	-96%	-96%	-72%
INT AUX	1%	4%	-	-53%	0%	0%	0%	0%	-	-42%	-26%	-40%
NCOOL	2%	0%	-	-27%	0%	0%	0%	0%	-	0%	0%	-11%

The system upgrades – fan coils

Due to the presence of cooling system and fans the results change. Total primary energy savings are pictured in Figure 9, while primary energy variations on each end use are listed in Table 4. The first result in a growing performance scale is the presence switch followed by the climatic compensation (5% and 6% reduction of primary energy requirements). The relative ineffectiveness of climatic compensation can be improved by a more accurate compensation function. The maximum primary energy saved quota, that accounts for 45%, can be achieved with the combined package of measures, as drawn in Figure 8.

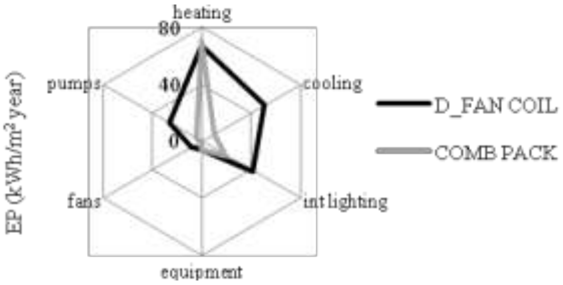

Figure 8 Spider graph of the end uses. Fan coils base case compared with fan coils combined package

The night cooling cuts both the cooling load and the electricity need for water circulation for a total primary energy saving of 8%. The auxiliary system measures can save up to 23% of the final demand, with a combined action on the water circulation electricity need and on the cooling load, due to fewer thermal losses. The day lighting solution introduces a 20% total saving. The interlock operates on all the end uses of energy for a 30% reduction. As seen before the lighting package of interventions is not so convenient in comparison with the thermal package, which allows a 34% cut-off. Assuming a standard unitary energy cost as listed in Table 5 (Autorità per l'energia elettrica e il gas, 2011), a rough evaluation of the expenditure in the different measure sets can be done. As a result, almost 20,000 € can be saved in the radiators case and more than 30,000 € are preserved in the fan coil case.

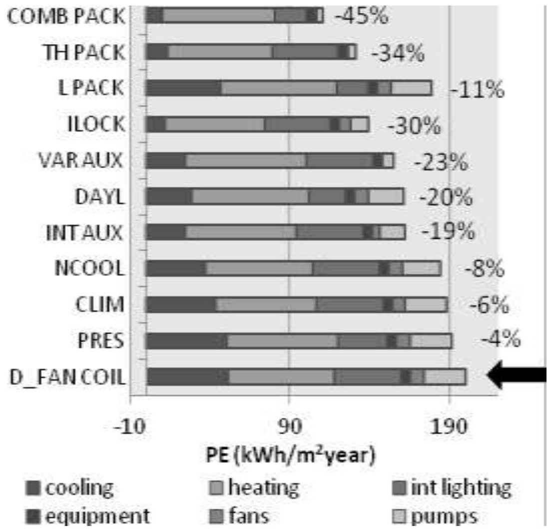

Figure 9 Primary energy requirements of the fan coils base case and system upgrades

Table 5
Energy expenditure.

LHV natural gas	8.79	kWh th/m3
natural gas cost	0.10	€/kWh th
elecrtricity cost	0.20	€/kWh el
	FAN COIL	**RADIATORS**
measure	annual erergy cost	annual erergy cost
BASE CASE	€ 76,555	€ 60,681
PRES	€ 73,404	€ 57,971
CLIM	€ 71,930	€ 54,560
NCOOL	€ 70,403	€ 60,681
INT AUX	€ 62,410	€ 60,292
DAYL	€ 62,068	€ 55,193
VAR AUX	€ 60,055	€ 58,624
ILOCK	€ 53,733	€ 54,448
L PACK	€ 68,752	€ 54,279
TH PACK	€ 50,853	€ 48,672
COMB PACK	€ 43,296	€ 42,485

CONCLUSIONS

The combined application of different measures shows the significant equality of the final results concerning the different HVAC system types: 107 kWh/m^2 year for radiators and 111 kWh/m^2 year for fan coils, considering the greater comfort of the second solution. The thermal control is generally more effective than the lighting control on the final primary energy breakdown. This can be explained by a spread inaccurate management of HVAC systems and by great thermal losses due to the building envelope. In Italy BACS are not so widespread in the local culture and on the national market because other measures are more pressing and requested by the law, such as thermal insulation, HVAC system renovation (Dipartimento di Ingegneria Gestionale – DIG, 2011). However a primary energy saving of 30% – 40% shows the relevance of these solutions. For specific aspects like the ventilation effectiveness, however, the sole dynamic building simulation is not sufficient to analyze the problem under investigation, and coupled numerical approaches (Ascione et al., 2013) that merge Building Energy Performance Simulation with Computational Fluid Dynamics may be necessary.

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