INTERREG MED Programme

2014-2020

ESMARTCITY

Enabling Smarter City in the MED Area through Networking

(3MED17_1.1_M2_022)

Priority Axis 1. Promoting Mediterranean innovation capacities to develop smart and sustainable growth

Specific Objective 1.1 To increase transnational activity of innovative clusters and networks of key sectors of the MED area

WP3 – Testing

Activity 3.3 – Pilot Testing

Deliverable 3.3.1 – Pilot deployment – Partner PP7

Contractual Delivery Date: **xx.xx.2019**

Responsible Author: **Prof. Ferrarini Luca (PP7 – Politecnico di Milano)**

Project Coordinator : **Iris Flacco (LP – ABREG)**

Dissemination Level		
PU	Public	X
PP	Restricted to Programme Partners and MED Programme	
RE	Restricted to a Group defined by the Partnership and MED Programme	
CO	Confidential, only for members of the partnership and MED Programme	

Project co-financed by the European Regional Development Fund

Content

1 Introduction

In this document, the pilot deployment of Politecnico di Milano partner (PP7) is presented. The pilot at issue concerns the Building Energy Efficiency topic, in line with the Energy Efficiency main research topic of the last years of Politecnico's Daisy Lab. In particular, PP7 pilot intends to tackle the management of the building heating and cooling systems in order to decrease the overall energy consumption while maintaining the user-required level of comfort.

Through this pilot, it is intended to ease the permeation of the latest academic results into a broad applicative context. The possibility offered by such real pilot use case is thus exploited to evaluate the achievable advantages that multi-variable control strategies can yield. These advantages are carefully compared with a realistic and critical vision on the ease of implementation of such control strategies. In fact, PP7 pilot focuses on heating and cooling systems management strategies that can easily be replicated through a limited theoretical background. In this way, the presented solutions are chosen so to maximize the projected Building Energy Efficiency increase, which is the combination of the raw energy savings and the permeability of the solutions itself.

Concerning the structure of the presented document, an initial chapter is dedicated to the summary of the pilot itself. The pilot deployment site is briefly presented, highlighting the characteristics that make it fit to the presented study. Afterwards, the pilot main objectives and methodologies are presented in detail, together with a road map of the pilot deployment.

The following chapter presents the workflow and results for each pilot phase. The detail level and the chronological logic characterizing this chapter is meant to transmit some broad range guidelines to reply the research methodology applied in this pilot, since promoting an efficient research methodology is considered an efficient way to support the energy efficiency cause.

A final chapter is dedicated to a concise sum up of the results obtained through the pilot deployment phase. Such results are juxtaposed to a presentation of the future works, which will exploit the efforts conducted during the pilot deployment phase to strengthen the Building Energy Efficiency research.

2 Summary of the Pilot Deployment

The current chapter is dedicated to the detailed presentation of PP7 pilot deployment use case. In particular, in section 2.1 an overall presentation on the pilot objectives and philosophy is presented, together with the specific roadmap adopted for the pilot. In section 2.2 the pilot site is presented, with a specific detail to the relevance of such site with respect to the pilot objectives. The final section 2.3 is dedicated to the research methodologies exploited to optimally realize the pilot targets, in order to give a summarized insight over the theoretical tools applicable to the building energy efficiency in a control-oriented context.

2.1 Pilot presentation

PP7 pilot aims at developing an efficient and scalable control strategy to manage the heating and cooling systems for complex thermal networks. To this end, the pilot envisages the installation of a network sensor over an academic building of Politecnico di Milano named Building 25. The sampled data will be exploited to explore different modeling approaches for building thermal energy analysis, while several control solution will be deployed and tested in the context of classic to advance methods.

To guarantee a reliable simulation environment and to formulate energy-oriented advanced control strategies, an IoT sensor network is installed. This network sensor is meant to overcome the limitations imposed by the currently installed SCADA system of Building 25, which is a system dedicated to the control of the overall thermal network – i.e. all the components devoted to the manipulation of the building air temperature, humidity and CO2 levels – and, to some degree, to the data collection and historicization task.

Moreover, the multi-sensors constituting such IoT network are able to return a measurement of a highly-impacting disturbance on this building context: the people occupancy profile. Being the analyzed building subject to a massive people flux, the impact of such disturbance gains a relevant role in the energy-efficient control focus. The real occupancy measurement on the testing building will give us the opportunity of experiencing with the real operating condition, allowing the development of new modeling and control strategies for dealing with possible parametric and structural uncertainties.

The control strategies developed through the PP7 pilot will be developed considering the trade-off between control algorithm simplicity and efficacy. In fact, while the efficacy of the control algorithm is usually directly proportional to its complexity, by simplifying the final control algorithm it is possible to maximize its permeation in the widest range of real building management applications. By choosing a realistic level of complexity of such algorithms, PP7 pilot intends to encourage more and more energy management department to follow through the conclusions presented in the pilot and integrate such energy-efficient control algorithms.

2.1.1 Pilot motivation

Recent years has witnessed significant progress in innovative comfort control strategies for small and large buildings in order to increase the overall building energy efficiency and improve the comfort level of building occupants. Due to the fact that air conditioning systems contain a considerable portion of energy consumption in building sectors, a paramount importance lays on the improvement of the building structure and thermal devices efficiency in order to optimize the required energy for heating and cooling systems.

A multitude of advanced control strategies have successfully been developed in an academic context. Such advanced controls are encountering known problems in permeating a wide range of applicative case due to their complexity, which sometimes requires an excessive level of knowledge to be correctly implemented and managed by the interested client.

By exploiting the real data acquired from the building sensor network, a reliable simulation environment can be developed. Through such simulation environment it is possible to test a multitude of control strategies, so to identify the ones which are able to provide the highest level of energy-oriented benefits while maintaining an acceptable level of complexity, thus maximizing the probability of permeation of such control strategies in a wide range of real applications.

2.1.2 Pilot objectives

The main target of this proposal is to distillate advanced control strategies able to optimize the building energy consumption on a thermal point of view. As mentioned in the previous sections, such control strategies should be the result of a trade-off between efficacy and implementative simplicity so to encourage their implementation by the vastest energy management operators.

To this end, the pilot envisages experimenting different control techniques on energy efficiency scenarios based on a real PoliMi smart building. Such building is equipped with different heating and cooling systems, creating a vast range of control scenarios. By exploring this rich environment, it is possible to analyze the effectiveness of different plant algorithms on energy consumption and comfort level in building sectors.

To successfully exploit the control opportunities of this building, an efficient data acquisition architecture is required. In particular, this pilot intends to initially analyze the performances of the current SCADA system enrolled to the building thermal and air quality control and to the data acquisition and historicization. Then, the necessary IoT sensor network is implemented so to overcome the limitation of such pre-existing SCADA system and successfully model the building dynamic behavior under analysis. In such a way, a simulation environment dedicated to the development of the aforementioned advanced control strategies is set up. Energy-oriented control strategies are finally developed and evaluated according to both their performances and their overall implementation simplicity.

2.1.3 Pilot roadmap

PP7 pilot presentation has been divided in six operational phases – as presented in Figure 1 – so to ease its presentation.

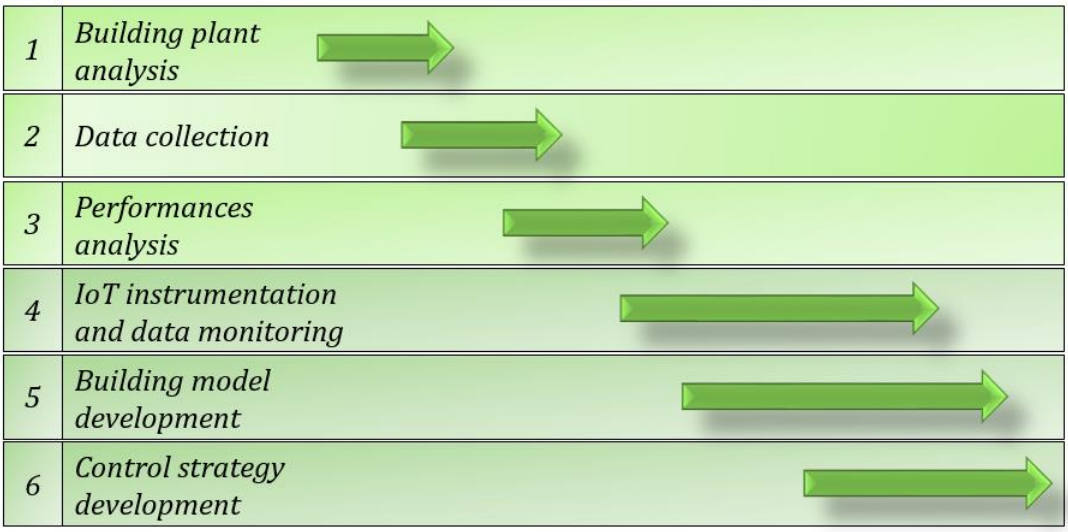

Figure 1: PP7 pilot phases

The pilot phases are presented in detail in the list below:

- ***Building plant analysis***
  By analyzing the technical sheets of the Building 25 thermal network, the overall functioning of the building control is analyzed. Such task provides the necessary insight on the functional capabilities of the building thermal network.

- ***Data collection***
  The current SCADA system is exploited to collect data from the building. In this phase, it is possible to observe the limitation characterizing an outdated sensor network. This analysis lays the foundation for the installation of the new IoT sensor network.

- ***Performance analysis***
  The data collected through the aforementioned SCADA is used for a control performance assessment over each room of Building 25, highlighting any inefficiency and reasoning about their nature.

- ***IoT instrumentation and data monitoring***
  The newly installed IoT sensor network is presented in detail, highlighting its technical specifications, communication protocols and installation logic.

- ***Building model development***
  According to the collected data, a model of the building thermo-dynamic and CO2 behavior is obtained. Such model is validated and used as a simulation environment for the next phase.

- ***Control strategy development***
  Exploiting the simulation environment obtained in the previous phase, different advanced control techniques are compared to the current ones. The control techniques are evaluated over their energy consumption, user comfort and overall implementation complexity.

2.2 Pilot site description

As mentioned in the PP7 pilot description, the pilot site is represented by an academic building of Politecnico di Milano, namely Building 25, located in the university quarter “Città Studi”.

This academic building is composed by 14 classrooms over 4 floors. A centralized thermal network composed by different thermal devices guarantees the control over each room temperature, humidity and CO2 levels. Each room is equipped with an air recirculation system and a fan coil system. The fan coil system is dedicated to the room temperature control, while the air recirculation system is dedicated to the humidity and CO2 control. The functioning details of such systems are presented in the first phase of the pilot deployment.

This building has been selected as pilot site for the following reasons:

- Building 25 is an academic building mainly composed by classrooms. For this reason, this building is overall subjected to a massive disturbance coming from the intensive people occupancy profile. In fact, the people flow highly affects many variables related to the people comfort requirements, such as the air temperature, humidity and CO2 levels. For this reason, a specific thermal network has been deployed to correctly compensate any disturbance and guarantee a correct user comfort.
  However, although the overall thermal network has been designed according to the expected disturbances caused by the impact of people occupancy, the control architecture reflects a classic strategy that does not consider people occupancy impact. The pilot is aiming at using the Building 25 as a test case to develop advanced control strategies able to effectively integrate the people occupancy disturbance, resulting in higher user comfort levels and lower energy consumption.

- As a result of previous renovation PoliMi projects, one of the recently built school building has been endowed with a complex network of thermal devices. This complexity allows the testing of different and innovative control strategies, which in turn could encourage the installation of particular thermal systems in different contexts.

- Building 25 is already equipped with a customized SCADA system, which is able to provide some preliminary data on the building control performances. In this way, it is possible to collect data for a preliminary performance analysis even before deploying the aforementioned IoT sensor network.

2.3 Research methodologies

In the current section, all the technical methodologies applied in the PP7 pilot are presented. This presentation is meant to give a clear insight on the suggested theoretical and practical instrument to carry out a control-oriented analysis on a building-size project. While the actual application of these instruments is presented in the description of each pilot phase, the present summary is meant to ease any future work related to the optimization of the energy consumption of a building thermal network. The objective of this section is then to spread a generic knowledge on the core aspects that should be considered when tackling a task related to the building energy control optimization on the thermal generation and management side.

The tools and techniques exploiting to carry out the pilot are presented in the following list:

- ***Technical sheets of the thermal network***
  Studying the thermal network installed in the analyzed building allows to understand the overall management of the thermal-related variables, such as the air temperature, humidity and CO_2 level. Usually, the main energivorous device through which these tasks are accomplished is represented by a heat pump. Through this heat pump it is possible to manipulate the temperature of a thermal vector, such as water. This thermal vector is then used by other devices (fan coils, air handling units, radiators etc…) to control the variables related to the user comfort, such as the rooms air temperature. Moreover, air handling units are used to control the air humidity and CO_2 levels. Such devices are usually fed by the thermal vector manipulated by the heat pump, allowing the control of the recirculated air temperature and humidity.

- ***Data acquisition system***
  The data acquisition task can be performed by an existing structure or by the installation of a new sensor network. In this pilot, the data acquisition is performed by exploiting both an existing customized SCADA system – to perform a preliminary performance analysis – and a new IoT sensor network.
  By acquiring data over the controlled building, it is possible to perform different tasks:
    - *Assess the current control performances*
      It is possible to define meaningful performance indexes related to the user comfort or the building energy consumption. Such indexes can typically suggest any intervention in the building thermal network equipment and/or in the control architecture.
    - *Data monitoring system*
      It is possible to represent the collected data through a data monitoring system, allowing the building energy manager to have a clear insight over the building

performances. This kind of monitoring is able to suggest both a real-time intervention or a structural investment over the building equipment.

- *Model identification*
  The collected data can be used to identify some representative models of the building key variables. In this way, it is possible to easily investigate any intervention over the structural aspects of the thermal network or over the control algorithms governing the building behavior.

- ***Model identification***
  As mentioned in the previous bullet point, data acquisition enables the development of dynamic (or static) models representing the building key variables. Such models can be obtained by exploiting the existing identification methodologies, for which a broad literature is already available. Summing up the model identification possibilities, it is possible to define three branches:
  - *White-box modeling*
    The models obtained are based exclusively on the known physical relationships among the key variables, tuned according to known design parameters of the building and thermal device parameters.
  - *Grey-box modeling*
    Starting from the physical relationships which allegedly govern the behavior of the building key variables, some tuning parameters are used to fit the measurements obtained by the data acquisition system with the final mathematical model. In this way, the model is tuned and validated over real data, while the equations constituting the model itself maintain their physical representativeness, thus easing the future model analysis and manipulation.
  - *Black-box modeling*
    It is possible to exploit a vast number of techniques which are able to find an analytical/numerical relationship among different building key variables without any preexisting knowledge over the physical relationships among them.

- ***Simulation tools***
  A wide variety of validated simulation tools are available on the market. Such tools are able to represent the energy-oriented building behavior under a vast range of building parameterization, installed equipment and external conditions. By tuning accordingly the precompiled model offered by these tools, it is possible to obtain a realistic behavior of the analyzed building. However, the model provided by these tools are not directly tunable according to the data measured on the real building.

- ***Control algorithms***

  Numerous control strategies have been developed in the automation and control field. For each context, usually some control strategy have resulted more suitable than others.
  For the specific case of building automation, usually a PID-based control structure is installed to guarantee a specific temperature and to respect the air quality limits. For example, Building 25 is currently using one PID controller for the temperature control and one PID controller for the CO2 control. However, such solution is widely adopted even in other applicative fields just because of its relative implementation simplicity.
  Although appreciable results are generically obtained by the application of a simple PID controller, more advanced control strategies can be implemented over this simple controller, as is presented in the pilot phase 6 presentation.

3 Pilot Implementation

Considering the pilot roadmap presented in the previous chapter, in this chapter each section is dedicated to a phase of the pilot deployment. In each section, all the results and the methodologies applied to fulfill each pilot deployment phase are described.

3.1 Building plant analysis

As presented in Chapter 2, the pilot deployment site is Building 25, an academic building of Politecnico di Milano. The first phase of the pilot deployment envisaged the study of the building itself. In particular, the building thermal network scheme was analyzed.

The analysis of the thermal network of Building 25 allowed to identify the overall functioning of the heating and cooling system. A portion of the technical scheme analyzed is presented in Figure 2.

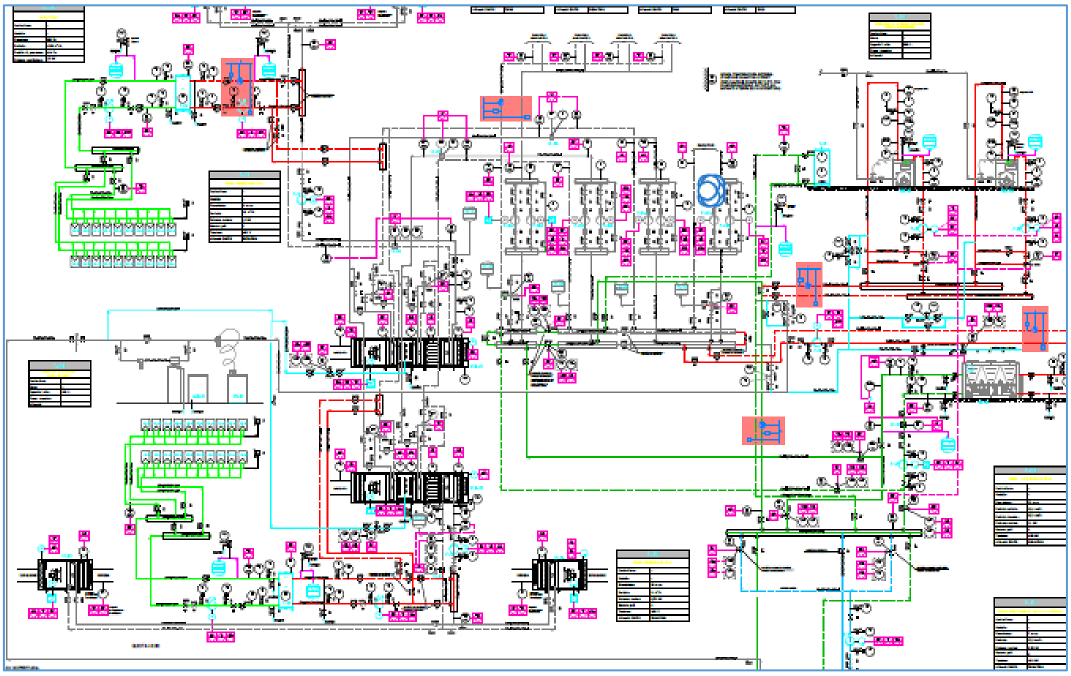

Figure 2: Section of Building 25 thermal network technical scheme

Through this first study phase, it was possible to gain a general insight of the thermal system under study. In particular, considering the objectives of the presented pilot, the development of a simplified block diagram structure was considered necessary. In fact, identifying the main components of this thermal network and their mutual relationship allowed the development of the next phases of the pilot deployment. The simplified block diagram of Building 25 thermal network is presented in Figure 3.

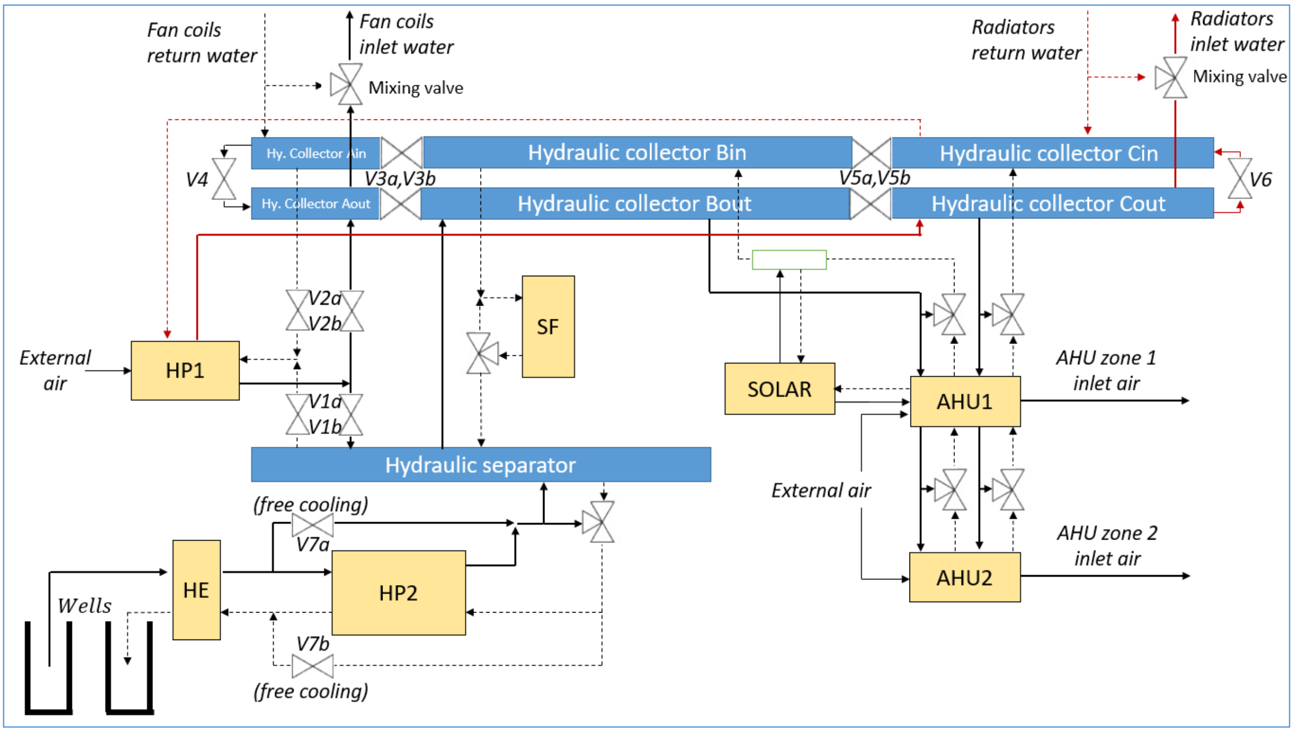

Figure 3: Building 25 thermal network block diagram

The thermal network presented in Figure 3 is meant to feed three different circuits:

- ***Fan coils circuit***
  This circuit is fed with a controlled temperature water so to provide the desired temperature in each room of the building. Each room is equipped with fan coils, which use the aforementioned circulated water to provide a cooling or heating action. In particular, in each room the speed of the fans of the fan coil devices is controlled so to provide the desired temperature set-point.
- ***Radiators circuit***
  This circuit is meant to fed the classic radiators installed to sustain the heating action of the fan coils during winter.
- ***Air treating circuit***
  Through the action of the two air handling units, the air quality – in terms of humidity and CO2 levels – is controlled in each room of the building. The treated air is sent to two different circuits (zone 1 and zone 2) so that each single room can control the quality of the air through its fan system.

Through the presented block diagram, it is possible to highlight the principal components of the thermal network, which are presented in the list below:

- ***HP2***
  This water-water heat pump is the principal thermal generator. It is an industrial-size heat pump characterized by a maximum electrical consumption of 92.4 kW and can produce up to 344 kW of refrigerating thermal power or 429 kW of heating thermal power. This heat pump is fed by water pumped up from underground wells. Its output is directed to the hydraulic separator, which will in turn be connected to the hydraulic collectors *Bin* and *Bout*.
- ***Hydraulic collectors (Ain – Aout – Bin – Bout – Cin – Cout)***
  Each hydraulic collector couple (in-out) is dedicated to a specific section of the thermal network:
  - *Collectors Ain – Aout:*
    These collectors are the interface with the fan coil circuit. In particular, they can be fed directly by the heat pump *HP1* or by the collectors *Bin* and *Bout* (which are fed by the main heat pump *HP2*).
  - *Collectors Bin – Bout:*
    These collectors are the interface with the main heat pump *HP2*. Moreover, these collectors feed the cooling coil of the two air handling units *AHU1* and *AHU2*.
  - *Collectors Cin – Cout:*
    These collectors are the interface with the radiator circuit. Moreover, these collectors feed the heating coil of the two air handling units *AHU1* and *AHU2*.

  Depending on the operating state of the thermal network, the valves connecting the collectors are opened or closed.
- ***HP1***
  Air-water heat pump fed by the external air. As *HP2*, his heat pump can work both for heating and cooling. Its output can be fed to three different locations, each one dedicated to a different function of the thermal network:
  - To the hydraulic collector, in case the *HP1* is working together with the *HP2* to provide the same action (heating or cooling).
  - Directly to collectors *Cin – Cout* to feed the radiator circuit and the air handling units heating coils with hot water.
  - Directly to collectors *Ain – Aout*, in case the control system wants to apply different control actions to *HP1* and *HP2*. In fact, it is possible to use *HP2* in heating mode to heat up the air treated by the air recirculation units *AHU1* and *AHU2* while using *HP1* in cooling mode to provide cold water to the fan coil circuit and vice-versa. This action could be useful in middle-seasons, for which a discontinuous functioning of the thermal control is recommended during a single day.

- ***AHU1 – AHU2***
  Two different air handling unit systems are installed. Each AHU feeds a specific zone of the building. Both the AHU share the same water used to manipulate both the temperature and the humidity of the air injected in the rooms. The AHU systems are meant to control the air quality of the rooms – both in terms of humidity and CO2 levels – while maintaining a reasonable air temperature so to avoid any negative interference with the room temperature control action imposed by the fan coil system. The heating coil is fed by the *Cin – Cout* collectors, while the cooling coil is fed by the *Bin – Bout* collectors. The solar cells system *SOLAR* is used to eventually pre-heat the external air before feeding it to the air handling units.
- ***SOLAR***
  This system is composed by a series of solar cells, which are able to heat up water and use it to pre-heat the external air entering the air handling units.
- ***HE***
  This heat exchanger is meant to optimize the functioning of the *HP2* by controlling the well-side of the heat pump circuit to maintain the correct working temperatures.
- ***SF***
  This tank is used to accumulate the refrigerated water so to optimize the functioning of *HP2*.

Although the pilot case presented focuses on the room-side of the network control, the current study is able to return a better insight towards the functioning of the whole system. Thanks to this analysis, it was possible to interface with the SCADA monitoring system currently used for the building. Moreover, the knowledge of the thermal network functioning resulted necessary to fully understand the logic behind the control strategies currently applied to the building, which marked the starting point of the pilot case. By fully understanding these control strategies, it was possible to conduct successfully a performance analysis of the current architecture and then develop more advanced control strategies. Finally, the knowledge of the thermal network of Building 25 can be exploited for future works concerning more advanced control techniques, which extend beyond the decentralized control of each room.

3.2 Data collection

After understanding and simplifying the overall structure of Building 25 thermal network, a SCADA was used to collect data of the building. For this purpose, the SCADA currently available in the building was exploited. Through such SCADA it was possible to programmatically retrieve data from the building relevant sensors and actuators.

The aforementioned SCADA presented, however, some technical limitations:

- *Low sampling frequency*
  Due to the communication protocols implemented in such SCADA, it was not possible to retrieve data with a sampling time lower than 30 minutes. In fact, by imposing a 30 minutes sampling time on the SCADA, the communication was saturated, since the average time needed by the SCADA to perform a complete cycle of data collection was, in fact, 30 minutes long.
  Unfortunately, the performances of any advanced control structure would suffer from this 30 minutes sampling time. Moreover, a 30 minutes sampling time is sufficiently low to identify the thermal dynamics of the building structure, but it is not sufficient to identify the dynamics of the air properties, such as temperature, humidity and CO2 levels. This is manly caused by the relevant impact of the people occupancy profile disturbance on the system, which is able to vary significantly those three quantities in just a few minutes.
- *Unsynchronized sampled data*
  Due to the SCADA cyclical data collection algorithm previously described, the data are not collected at the same time. This means that there is a time shift between the measurement of one sensor with respect to the measurement of another sensor which can vary from 0 minutes to 30 minutes. Each sensor measurement is then decoupled in time with respect to the other sensors measurements. An explanatory image is presented in Figure 4.

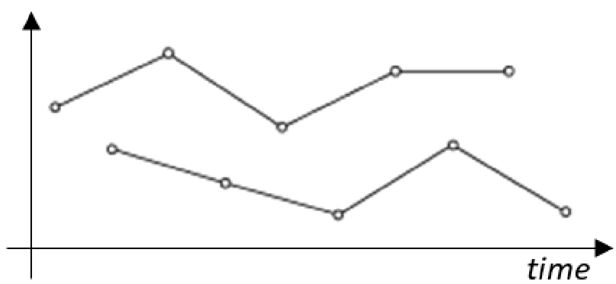

Figure 4: Example of unsynchronized sampled data

Because of this time shift on the measurements between different sensors, it is never possible to have a correct snapshot of the status of all the building in the same time. For this reason, it is not possible to compute effectively any performance index or any dynamic model that relies on more than one measurement at the time.

- *Inconsistent sampling frequency*
  As aforementioned, the time needed by the SCADA to perform the cyclical data collection is not constant. Because of this factor, the resulting sampling frequency is not constant. This factor, combined with the low value of the average sampling frequency, causes an incoherence between the sampled data and the model-predicted dynamics of the plant, which in turn lowers the expected performance of any advanced control technique.
- *Inability to provide a customized interface*
  Due to the proprietary nature of the software architecture enrolled to the building control, it is not able to enrich the current situation with additional features, such as an improved data monitoring system or some higher-level control strategies. This characteristic pose a massive limit to the potentiality of the overall building management, which is unable to effectively update to any current development in the building automation field.
- *Limited repeatability and scalability*
  As mentioned in the previous bullet point, the current software architecture is a closed unmodifiable structure. This means that this solution cannot be easily extended to a different context, since a specific customization has been carried on to configure such architecture.
- *Limited robustness*
  In addition to the poor data collection capabilities highlighted in the previous bullet points, the data gathered through the SCADA system presented a non-negligible failure rate, i.e. the system failed numerous times the task of data retrieval. The low robustness of the communication protocol is not up to date with the newer solutions presented by the IoT market, highlighting a wide difference between the current installation and the cutting-edge market-available technology.

In addition to the presented limitations of the current SCADA architecture, it is necessary to highlight the lack of a specific measurement: people counting. The measurement of such quantity can provide – as will be shown better in phase 6 of the pilot deployment – a great advantage on the building control efficiency. This is due to the impact of people in a context as the one here analyzed, i.e. a reality characterized by a people occupancy profile which is both highly variable and highly impactful.

The presented limitations have been tackled through the installation of a new sensor network. The detailed description of such new network is presented in the fourth phase of the pilot deployment.

3.3 Performance analysis

Exploiting the data collected through the existing SCADA system presented in the previous section, it was possible to conduct a performance analysis of the overall building control architecture.

Different performance indexes has been defined depending both on the available measurements and on the relevancy on the temperature and air quality control of Building 25. Such indexes are presented in the list below. All the following indexes have been computed for each one of the 13 monitored rooms and considering only the data collected during the active time of the building, i.e. between 7 a.m. to 7 p.m.:

- ***Average temperature*** $T_{av.}$
  The average of the measured temperatures.
  $$T_{av.} = \frac{\sum_{i=1}^{N} T(i)}{N} \qquad i = 1 \dots N \; measurements$$

- ***Overheating frequency*** $Freq_{Overheat}$
  This index, expressed as a percentage, represents the frequency by which an overheating phenomenon occurred, i.e. how many room temperature measurements have been registered over the room temperature desired set-point Sp_T with respect to the totality of the room temperature measurements.
  $$Freq_{Overheat} = \frac{M}{N} \qquad \begin{cases} N = total\; measurements \\ M = measurements\; with\; T > Sp_T \end{cases}$$

- ***Average overheating temperature*** $T_{Overheat,av.}$
  The average value of overheating registered, i.e. the average of the room temperature error (defined as the difference between the room temperature and its desired set-point Sp_T) when the room temperature is above its desired set-point.
  $$T_{Overheat,av.} = \frac{\sum_{i=1}^{M} \left(T(i) - Sp_T(i)\right)}{M} \qquad i = 1 \dots M \; measurements\; with\; T > Sp_T$$

- ***Maximum temperature*** $max(T)$
  Maximum registered temperature among all the temperature measurements.

- ***Average CO2 levels*** $CO2_{av}$
  The average of the measured CO2 levels.
  $$CO2_{av.} = \frac{\sum_{i=1}^{N} CO2(i)}{N} \qquad i = 1 \dots N \; measurements$$

- ***Excessive CO2 frequency*** $Freq_{HighCO2}$
  This index, expressed as a percentage, represents the frequency by which an excessive level of CO2 is detected, i.e. how many CO2 level measurements have been registered over the room CO2 maximum level $CO2_{max}$ with respect to the totality of the CO2 level measurements.

$$Freq_{HighCO2} = \frac{M}{N} \quad \begin{cases} N = total\ measurements \\ M = measurements\ with\ CO2 > CO2_{max} \end{cases}$$

- ***Average excessive CO2*** $CO2_{HighCO2,av.}$
  The average value of CO2 excess registered, i.e. the average of the CO2 level error (defined as the difference between the measured CO2 level and its maximum acceptable value $CO2_{max}$) when the CO2 level is above its maximum value.

$$CO2_{HighCO2,av.} = \frac{\sum_{i=1}^{M}\left(CO2(i) - CO2_{max}(i)\right)}{M} \quad i = 1 \dots M\ measurements\ with\ CO2 > CO2_{max}$$

- ***Maximum CO2 level*** $max(CO2)$
  Maximum registered CO2 level among all its measurements.

- ***Thermal energy injected by fan coils*** $E_{Thermal}$
  Measurement of the thermal energy injected by the fan coils measured in KWh. This index is obtained by combining:
    - The measurement of the fan coil command;
    - The measurement of the hot water temperature recirculating in the fan coil circuit;
    - The data sheet declared thermal power adjusted with the current hot water temperature measurement and integrated over the SCADA sampling time.

In Table 1 the presented performance indexes are presented considering the whole March month. Consider that the temperature set-point (Sp_T) for each room is set to 22°C, while the maximum acceptable value for the CO2 ($CO2_{max}$) is set to 20 PPMx100.

Table 1: Performance indexes over March

Performance Index	D01	D02	D04	D11	D21	D22	D23	D24	D25	D26	D31	D32	D33	Av.
$T_{av.}$ [°C]	22,3	22,1	23,4	22,7	23,7	22,1	22,7	24,2	24,9	24,7	23,3	24,5	24,9	23,5
$Freq_{Overheat}$ [%]	86%	85%	80%	63%	90%	59%	80%	98%	98%	97%	82%	94%	98%	85%
$T_{Overheat,av.}$ [°C]	2,7	2,4	2,4	2,8	1,9	1,3	0,9	2,2	3,0	2,8	1,7	2,6	2,9	2,2
$Max(T)$ [°C]	26,2	25,6	27,6	26,9	26,1	25,2	24,8	26,7	29,5	28,4	27,1	28,1	29,0	27,0
$CO2_{av.}$ [PPMx100]	41,2	38,0	35,7	ND	31,7	ND	29,7	33,4	27,7	ND	31,5	39,9	34,1	34,3
$Freq_{HighCO2,av.}$ [%]	53%	50%	43%	ND	44%	ND	38%	46%	54%	ND	19%	33%	53%	46%
$CO2_{HighCO2,av.}$ [PPMx100]	28,3	27,5	21,8	ND	14,5	ND	16,5	17,4	16,4	ND	21,6	29,2	13,8	20,7
$Max(CO2)$ [PPMx100]	99,2	91,9	99,8	ND	86,5	ND	76,2	76,3	99,5	ND	95,9	99,6	99,0	92,4
$E_{Thermal}$ [KWh]	126	150	160	276	151	330	218	28	0	43	179	38	0	134

Multiple conclusions can be drawn from such performance indexes:

- Some rooms – for example D25 and D33 – have registered an elevated average temperature over the analyzed month.
- An elevated frequency of overheating has been registered over all the monitored rooms, with some peaks that are dangerously close to 100%. The rooms associated with a higher overheating frequency are correlated with the rooms associated to a higher average temperature.
- Some rooms have reached an excessively high value of maximum temperature reached.
- Three rooms – D11, D22 and D26 – have shown a complete failure of the CO2 monitoring system, since it was not possible to record any measurement related to the CO2 level control. The corresponding indexes have been assigned to “ND” (not defined).
- As for the temperature-side analysis, the general behavior of the CO2 level control has shown poor performances over many rooms, with a frequency of excessive CO2 levels around 50% and CO2 level peaks almost close to 100 PPMx100.
- Concerning the combination of the thermal energy index and the overheating frequency index, it is possible to deduce that a smarter control strategy would have minimized the activation of the fan coil system. In fact, the overheating caused by the combination of the fan coil system and the impact of the people occupancy profile could be avoided by preventively deactivating the fan coil system when a relevant people occupancy profile is detected.

An example of the behavior of the room temperature and the CO2 levels is presented in Figure 5, where it is possible to appreciate graphically the results presented in the performance indexes table.

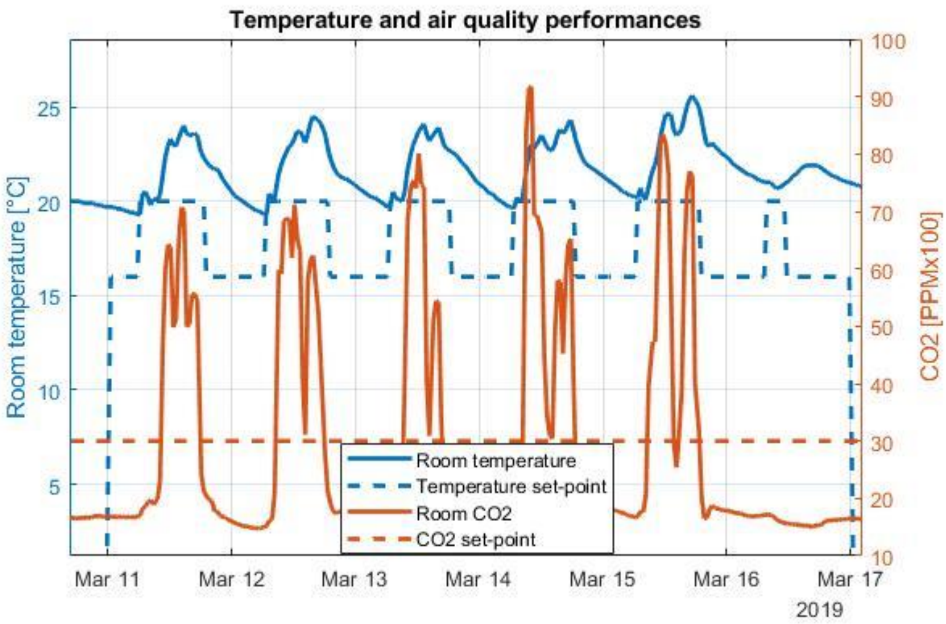

Figure 5: Temperature and CO2 level performance example on room D24

By analyzing the CO2 level profile, an intensive people occupancy profile can be deduced. The impact of the people occupancy profile is reflected even on the temperature side, which suffers from an almost constant overheating phenomenon. This phenomenon could have been mitigated by avoiding the use of the fan coil system in the first hours of each day. In the pilot phase 6, advanced control strategies will be presented to minimize the occurrence of inefficient use of the heating systems.

Following the previous conclusions, a dangerously high level of inefficiency of the current control architecture has been highlighted. Moreover, the presented indexes have been computed over March because of the malfunctioning of the heating system over February and the malfunctioning of the existing data collection system over April and May. Adding this inefficiency to the presented control performance, the introduction of a reliable sensor network – presented in the next section – and the study of more advanced control strategies – presented in the pilot phase 6 – is recommended.

3.4 IoT instrumentation and data monitoring

In this section, the deployment of a new network sensor is presented. The new network sensor is meant to overcome the limitations of the current SCADA system presented in the pilot phase 2.

3.4.1 Multi-sensors

The new sensor network envisages the installation of 12 multi-sensors in 8 rooms. The data collected by these multi-sensors are routed to a central data storage, where the data is formatted and stored in a database. Moreover, an initial graphical interface has been deployed which is able to monitor the profile of the measured quantities of each multi-sensor. The multi-sensor exploited for this purpose is the EnviSense Smart multi-sensor depicted in Figure 6.

Figure 6: EnviSense multi-sensor

This multi-sensor is able to collect plurality of measurements. The main measurements exploited for this pilot are presented in the list below together with their functional ranges and declared accuracy:

- ***Temperature***
  Range [-10 , +85]°C
  Accuracy ±0.4°C

- ***Humidity (relative)***
  Range [0 , 80]%
  Accuracy ±3%

- ***Luminosity***
  Range [0 128]klx
  Resolution <100mlx

- ***Presence***
  Movement detection angle: 82°
  Movement detection range: 5m

- ***Air quality***
  - *CO2*
    Range [400 , 5000]ppm
  - *VOC*
    Range [0 , 1000]ppb

The multi-sensor is able to provide the following additional features:

- ***Smoke detection***
- ***Seismic vibration detection***
- ***Acoustic noise measurement***
- ***Mini-thermal camera for:***
  - *People counting*
  - *People tracking*
  - *Surveillance function*
  - *Fire detection*
  - *Health assistance*

Among the additional features presented, the “People counting” function will play a crucial role in the development of advanced control strategies.

3.4.2 Network protocols

The previously presented multi-sensors are connected in through a mesh network. The mesh network is a network composed by non-hierarchical nodes which are able to connect dynamically so to create an efficient connection to the requiring clients. In this way, mesh network are able to dynamically self-configure and reorganize so to guarantee an optimal data flow, allowing the following advantages:

- The automatic configuration of the mesh network reduces significantly the overall installation overhead;
- Any fault occurring to a sensor can be compensated by the dynamic rearrangement of the network itself, which is able – when possible – to re-configure so to guarantee the connection of all the functioning sensors to the requiring client;
- The mesh network can be equipped with a dynamic distribution of workloads, so to optimally manage the data flow over the network.

In the current pilot, the Thread network protocol has been applied to the mesh network. Thread protocol is an IPv6-based networking protocol designed for low-power IoT devices in an IEEE 802.15.4-2006 wireless mesh network. Through this protocol, each node is associated to a specific role, while the structure of the network remains dynamic according to the aforementioned non-hierarchical structure of the mesh network. In Figure 7 a scheme of the thread-based mesh network is presented.

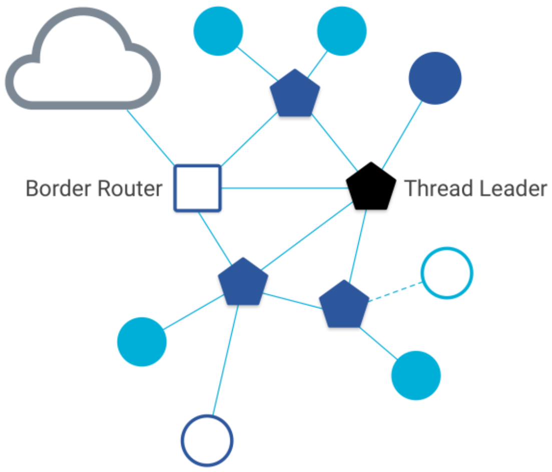

Figure 7: Thread-based mesh network

3.4.3 Sensors deployment

The multi-sensors presented have been deployed in building 25. In particular, 12 sensors were deployed in 8 rooms. Each room is equipped with a multi-sensor – for a total of 8 multi-sensors – dedicated to the measurement of the room temperature, humidity and air quality. Such sensors are installed at 1.6m from the ground, so to collect air-related measurements that are relevant in terms of user comfort.

Moreover, two rooms have been chosen to install the remaining 4 multi-sensors. This 4 devices have been equipped with the people-counting function so to monitor the people occupancy profile. The impact of such profile represents the most variable and influential disturbance on the room temperature, humidity and air quality. For this reason, these people-counting devices have been installed in the two rooms on average suffering from the highest levels of people occupancy. These multi-sensors are installed on the top of the rooms entrance doors so to correctly perform the people counting function, while also monitoring the room temperature, humidity and air quality levels. Thanks to the multiple measurement of the air-related variables in these two rooms, it is possible to study two phenomena:

- The stratification effect on the room temperature, humidity and air quality by comparing the measurements of the two people-counting devices (installed on the ceiling) with the measurements of the other device;
- The measurements overall reliability and coherence by comparing the measurements of the two people-counting devices.

In Figure 8 is presented the location of the installation of the 12 multi-sensors.

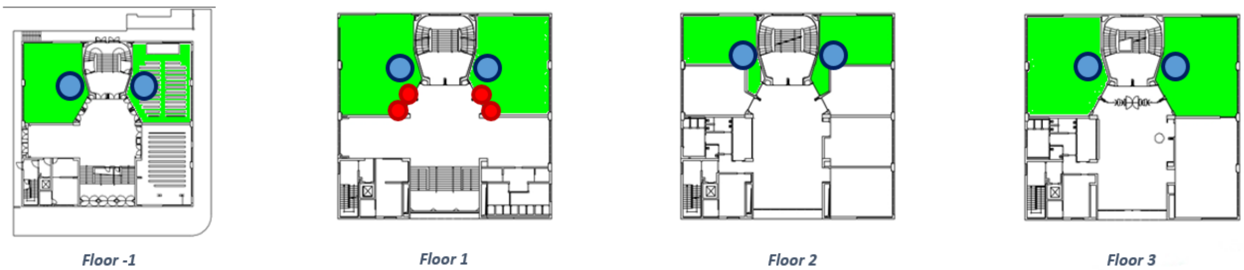

Figure 8: Multi-sensors installation location
(Blue: temperature, humidity and air quality; Red: temperature, humidity, air quality and people counting)

3.5 Building model development

The models developed in this pilot phase lay the foundation of the pilot phase 6 work, i.e. the development and test of advanced control strategies. Through the development and validation of the building dynamic models, a verified simulation test is available for any control performance tests. Consequently, in phase 6 the model developed in this phase will be exploited to test the most suitable advanced control strategies in terms of efficiency and implementative difficulty.

Moreover, this model is suitable for any investment analysis concerning the building structural parameters and/or the devices involved in the dynamic behavior of the described variables. In fact, the developed model maintains a strong physical representativeness with respect to the usual building structural parameters (thermal volumes capacitance and transmittance…) and the devices thermal characteristics (air mass flow, thermal exchange efficiency…). In this way, it is possible to easily study the impact of a variation of these structural parameters and devices in a long term window, so to economically evaluate the feasibility of such investments.

To develop such models, the following information were used:

- ***Building 25 collected data***
  The data collected through the preexisting SCADA system presented in pilot phase 2 has been used to develop the building model. Despite this SCADA disadvantages highlighted in pilot phase 2, it was possible to select some data that could be used to correctly identify and validate the building model. The SCADA data was used instead of the data collected by the IoT sensors to develop the building model as soon as possible. The data collected by the IoT sensors are meant to be used for future validation or adjustment of the developed building model. Moreover, the IoT sensors data collected will enable the development of new mathematical models, which will be able to correlate more relevant building variables by exploiting the new available measurements.
  Exploiting the byproduct of pilot phase 2, real data was collected on the following quantities:
  - *Air temperature of each room*
    One temperature sensor for each room [°C];
  - *CO2 levels of each room*
    One CO2 sensor for each room [PPMx100];
  - *Fan coil system command on each room*
    A discrete command assigned to all the fan coil systems in the room – the command is assigned to 0 (OFF), 1 (low speed), 2 (medium speed) or 3 (high speed);

- *Air recirculation command on each room*
  A continuous command assigned to the fans dedicated to the air recirculation – the command is assigned as percentage from 0% (OFF) to 100% (maximum speed);
- *Water temperature of the fan coil circuit*
  Temperature of the inlet water entering the fan coil circuit from the hydraulic collector Ain presented in pilot phase 1;
- *External air temperature*
  The average of four different sensors used to measure the temperature of the external air [°C];
- *Recirculated air temperature*
  Temperature of the air leaving the two air handling units AHU1 and AHU2 [°C].

- ***Fan coil data sheet***
  By identifying the correct model of the fan coil devices installed in Building 25, it was possible to retrieve the specific data sheet about its thermal behavior. In particular, the data sheet presented certificated values about the thermal power discharged in the ambient air (under some given conditions) and the air mass flow imposed by the fan coil device. From this information, it was possible to fit an equation describing the impact of each fan coil device on the room air temperature, which will be presented later in more detail.

- ***Air recirculation system project design parameters***
  From the project design parameters it was possible to retrieve the recirculated air mass flow imposed by the air recirculation system for each room. In particular, the air recirculation system is designed to recycle 2 volumes of air each hour for each room at maximum capacity.

- ***Building structural parameters***
  The building structural parameters gave an insight over the expected thermal behavior of the building itself. In fact, the initial values assigned to the dimensions and thermal characteristics of each room structural elements (volume of air, walls, pavement etc…) were assigned according to the building structural parameters. Then, as will be presented later in detail, the model tuning corrected these initial parameters according to the measured data in order to fit the measured thermal behavior of the building.

3.5.1 Model presentation

The model development phase of PP7 pilot resulted in a model describing the behavior of a single building room, which is then extended to the behavior of any other building room just by re-parameterizing the model according to the structure of each room. A dynamic model was adopted to describe the behavior of each room temperature and CO2 levels. This model is presented in the following equation:

$$\begin{cases} C_Z\dot{T}_Z = P_{FC} + U_{DISP}(T_W - T_Z) + \#_{PPL} * P_{INT} + u_R * nV_{TOT} * c_{p,air} * (T_{air} - T_Z) \\ C_W\dot{T}_W = U_{DISP}(T_Z - T_W) + U_{DISP}(T_{EXT} - T_W) \\ \dot{V}_{CO2} = \#_{PPL} * P_{CO2} - \frac{V_{CO2}}{V_{TOT}} * u_R * (nV_{TOT}) \end{cases}$$

The details of such model are presented in the following list:

- ***Model states***
    - T_Z: Internal room volumes air temperature – i.e. the thermal volumes not dispersing heat towards the external environment, such as the room air, pavements, ceiling and internal walls;
    - T_W: External room volumes temperature – i.e. the thermal volumes dispersing heat, such as the walls facing the external environment and the windows;
    - V_{CO2}: Room volume of CO2.
- ***Model inputs***
    - P_{FC}: Thermal power delivered by the room fan coil devices, computed as:
      $$P_{FC} = \beta_{FC}\#_{FC}\dot{w}_{air}(FC_{cmd})\rho_{air}c_{p,air}(T_M - T_Z)$$
      with:
        - $\dot{w}_{air}(FC_{cmd})$: air mass flow governed by the digital command {0,1,2,3} sent to the room fan coil devices;
        - $\#_{FC}$: number of fan coil devices in the room;
        - T_M: temperature of the water in the fan coil circuit;
        - ρ_{air}: air density;
        - β_{FC}: heat exchange efficiency, identified as 0.75 by fitting the presented equation with the certified information provided in the fan coil data sheet;
    - $\#_{PPL}$: Number of people occupying the room;
    - u_R: Continuous command [0 , 100]% sent to the air recirculation fan system;
    - T_{air}: Temperature of the recirculation air coming from the AHU devices;
    - T_{EXT}: External air temperature.

- ***Model parameters***
  - C_Z and C_W: thermal capacity of the internal room volumes and the external room volumes;
  - U_{DISP}: thermal convective transmittance of the external room volumes;
  - P_{INT}: Average thermal power produced by a person;
  - P_{CO2}: Average CO2 production rate of a person;
  - V_{TOT}: Room air volume;
  - $c_{p,air}$: Air specific heat capacity;
  - n: Number of room air volumes recycled when the air recirculation system is working at full capacity.

In the following list, an explanatory description of the presented mathematical model is given:

- ***Room air temperature equation (T_Z)***
  The variation of the room air temperature is associated to the impact of four factors:
  - *Thermal power coming from the fan coil devices* P_{FC}
    As presented before, the fan coil devices force a convective exchange between the room air and the tubes containing the water of the fan coil circulation pipeline;
  - *Heat dispersion towards the external room volumes* $U_{DISP}(T_W - T_Z)$
    Such heat dispersion is modeled as a well-known convective heat exchange between the room air and the external room volumes;
  - *People internal gain* $\#_{PPL} * P_{INT}$
    This term represents the heating action coming from the thermal power produced by each person occupying the room;
  - *Thermal power from the air recirculation system* $u_R * nV_{TOT} * c_{p,air} * (T_{air} - T_Z)$
    This term is proportional to the product of different factors, such as the temperature difference between the room air and the recirculated air, the speed of the air recirculation fans and the total volume of air recirculated at full speed, all multiplied by the air specific heat capacity.

  The heat exchange of the room air temperature with the near rooms is neglected so to simplify the model. In fact, it is assumed that the near rooms are always characterized by a temperature sufficiently close to the one of the modeled room, thus preventing any relevant heat flow among the rooms.
- ***External room volumes temperature equation (T_W)***
  This thermal volume is associated only to the convective heat exchange between the external room volumes and the internal room volumes ($U_{DISP}(T_Z - T_W)$) and the convective heat exchange between the external room volumes and the external environment ($U_{DISP}(T_{EXT} - T_W)$). The solar radiation has been neglected because of the unavailability of its measurement.

- ***Room volume of CO2 (V_{CO2})***
  The variation of the room volume of CO2 is due to the impact of two phenomena:
  - *CO2 produced by people* $\#_{PPL} * P_{CO2}$;
  - *CO2 removed by the air recirculation system* $\frac{V_{CO2}}{V_{TOT}} * u_R * (nV_{TOT})$
    The CO2 removed by the air recirculation system has been defined as proportional to the fraction of CO2 in the room, the speed of the air recirculation fans and the total volume recycled at maximum capacity.

As mentioned in the previous section, the model parameters were initially set according to the building structural parameters. In the following section, the variation of these parameters imposed in the model tuning phase are presented.

3.5.2 Model tuning and validation

The model parameters presented in the previous section were initially assigned based on the information retrieved by the building structural parameters, fan coil devices data sheet and air recirculation system project design parameters. As will soon be presented, the computation of the model parameters is specified by maintaining the highest level of physical representativeness, so to ease any possible adaptation of this model to other studies.

The parameters computation and initial value (before the model tuning phase) are reported in the following list. As an example, the reported parameters initial value is relative to room D02, which is the room used for the model identification. The reasons behind the choice of room D02 are presented later:

- *Room dimensions*
  - Room width $w_{room} = 12m$, length $l_{room} = 10m$ and height $h_{room} = 2.5m$;
  - Windows width $w_{wind} = 9m$ and height $h_{wind} = 2m$;
  - Internal walls thickness $t_{intWalls} = 0.25m$;
  - External walls thickness $t_{extWalls} = 0.35m$;
  - Pavement and ceiling thickness $t_{pav} = 0.45m$.

- *Materials thermo-physical characteristics*
  - Air density $\rho_{air} = 1.2\ \frac{kg}{m^3}$ and specific heat capacity $c_{air} = 1000 \frac{J}{kg\ K}$;
  - Walls density $\rho_{walls} = 1800\ \frac{kg}{m^3}$ and specific heat capacity $c_{walls} = 800 \frac{J}{kg\ K}$;

- Pavement and ceiling density $\rho_{pav} = 1800 \frac{kg}{m^3}$ and specific heat capacity $c_{pav} = 800 \frac{J}{kg\ K}$;
- External walls conductivity $u_{walls} = 0.26 \frac{W}{m^2\ K}$;
- Windows conductivity $u_{wind} = 3 \frac{W}{m^2\ K}$.

- $V_{TOT} = 300m^3$.
- $C_Z = \sum_{i=1}^{N_{Int.Vol.}} C_i = 2.52 * 10^7 \frac{J}{K}$ and $C_W = \sum_{i=1}^{N_{Ext.Vol.}} C_i = 8.28 * 10^7 \frac{J}{K}$ with:
    - $C_i = V_i * \rho_i * c_i =$ Thermal capacitance of the i-th thermal volume;
    - $N_{Int.Vol.} =$ Number of internal volumes;
    - $N_{Ext.Vol.} =$ Number of external volumes.
- $U_{DISP} = S_{ExtWalls} * u_{walls} + S_{wind} * u_{wind} = 192.2 \frac{J}{K}$.
- $P_{INT} = 63W$ for each person.
- $P_{CO2} = 0.0052 \frac{L}{s}$ for each person.
- $n = 2$.

Subsequently, the model was fitted on the real data collected from Building 25 by tuning the parameters that are subjected to well-known uncertainties, which are the material thermo-physical characteristics. In fact, for this pilot, the initial value assigned to such parameters relies only on the average value deduced from literature referring to a generic high energy class building. The data block used for the model fitting task has been selected among the SCADA collected data by respecting the following criteria:

- Sufficient continuity in the data collected by the SCADA system, which was not always guaranteed due to the basic unreliability of the SCADA data collection function.
- Correct functioning of the heating system, since a malfunctioning on the building control system resulted in a deactivation of the heat pumps heating function, thus leaving the room temperatures uncontrolled.
- Minimization of the people occupancy profile impact. Since the people presence was not yet monitored, it was necessary to select a room and a time window in which the people occupancy could be considered negligible. To deduce the impact of people presence on the room measured temperature, the variation of the measured CO2 level was analyzed. In particular, the lowest amount of people occupancy could be related to the lowest amount of CO2 level perturbations. Moreover, such selecting a data set characterized by a small variation of CO2 levels is associated to a negligible recirculation air command, which allows to neglect the impact of the air recirculation action on the temperature.

To respect these criteria, a time window of two days over a specific room has been identified. In particular, as mentioned before, the room D02 has been selected as representative of the tuning phase. The model fitting was then performed over a 2-days time window on room D02.

The following variations to the room thermo-physical parameters resulted from the model fitting procedure:

- $C_Z = C_Z(0) * 0.5 = 1.26 * 10^7 \frac{J}{K}$;
- $U_{DISP} = U_{DISP}(0) * 3.2 = 610 \frac{J}{K}$;
- $C_W = C_W(0) * 2 = 16.53 * 10^7 \frac{J}{K}$.

The fitting results of the room model with respect to the data selected for the model fitting phase are reported in Figure 9.

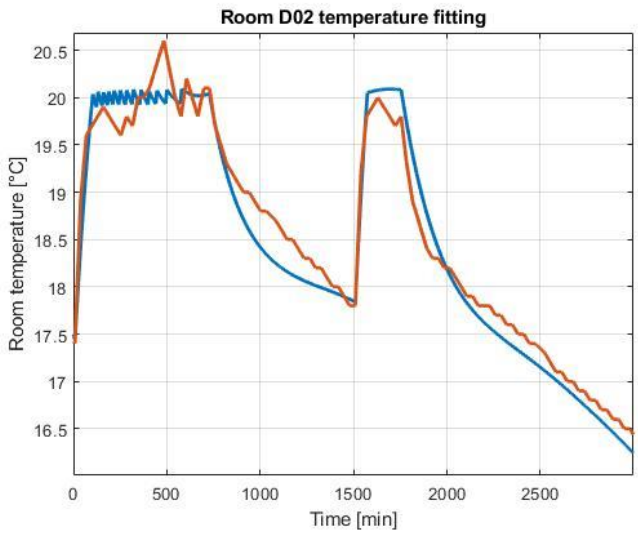

Figure 9: Room temperature model fitting

As it can be seen, the thermal behavior of the obtained model shows a sufficiently high degree of fidelity with respect to the measured data.

In the validation phase, the occupancy profile of the modeled room was manually measured. Then, after collecting the real data through the SCADA, it was possible to validate both the thermal and the CO2 dynamics of the previously developed model. The results of the model validation are presented in Figure 10.

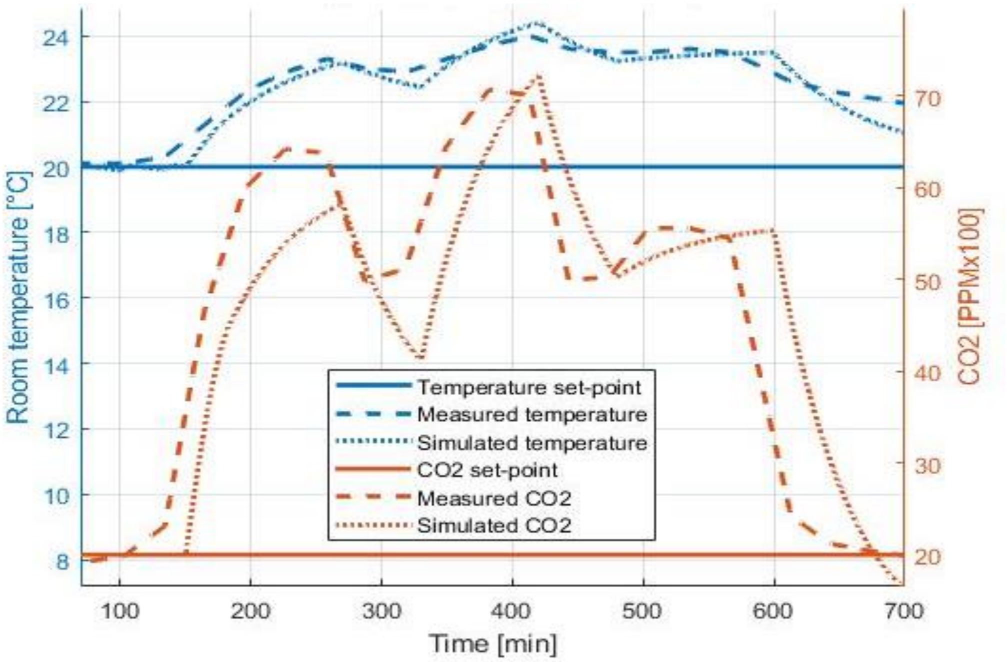

Figure 10: Room temperature and CO2 level model validation

An appreciable level of fitting over the air temperature and the CO2 level dynamics is shown, thus confirming the capability of the developed model in representing the thermal and CO2 dynamics of a building room. This model can be replicated and re-parameterized to model the behavior of the other building rooms, thus obtaining a multi-room model. Such multi-room model has actually been developed and used in the last phase of PP7 pilot to effectively test the new control strategies subject of this study.

3.6 Control strategy development

This final section presents the final results obtained by PP7 pilot case. The advanced control strategies which were found to be most suitable for the pilot purposes are presented in detail, together with a comparative performance analysis with respect to the baseline control strategy currently implemented in Building 25.

As it will be shown later, these control strategies strongly rely on a measurement introduced thanks to the newly implemented IoT sensor network, i.e. the people occupancy measurement. It will be shown the energy-saving advantages obtainable through the integration of such measurement in the new proposed control strategies.

To present an effective comparison between the current control strategy and the new proposed ones, a first sub-section is dedicated to the presentation of the current control strategy, which is based on PID controllers.

3.6.1 Current control strategy

By analyzing the available SCADA system currently controlling Building 25, it was possible to identify the current control strategy. Such PID-based control strategy will be used in the following sub-sections as comparison to show the performance increase allowed by the newly developed advanced control strategies subject of PP7 pilot case.

As aforementioned, the current control strategy is based on the usage of PID controllers. Specifically, the derivative action of the PID controller is not used. This choice is common in the building control field, since the derivative action is known to provide some undesired behavior once the measurement of its controlled variable is subjected to a slow dynamic and/or excessive measurement noise. The generic control law governing the PID controller is presented in the equation below – following the previous considerations, the derivative part of the PID controller is neglected:

$$u(t) = P * \left(e(t) + I * \int_0^t e(t)dt \right)$$

where $u(t)$ is the PID computed control action, $e(t)$ is the difference between the controlled variable desired set-point and its actual measurement, P and I are the controller tunable parameters and $\int_0^t e(t)dt$ is the integral over time of the error $e(t)$.

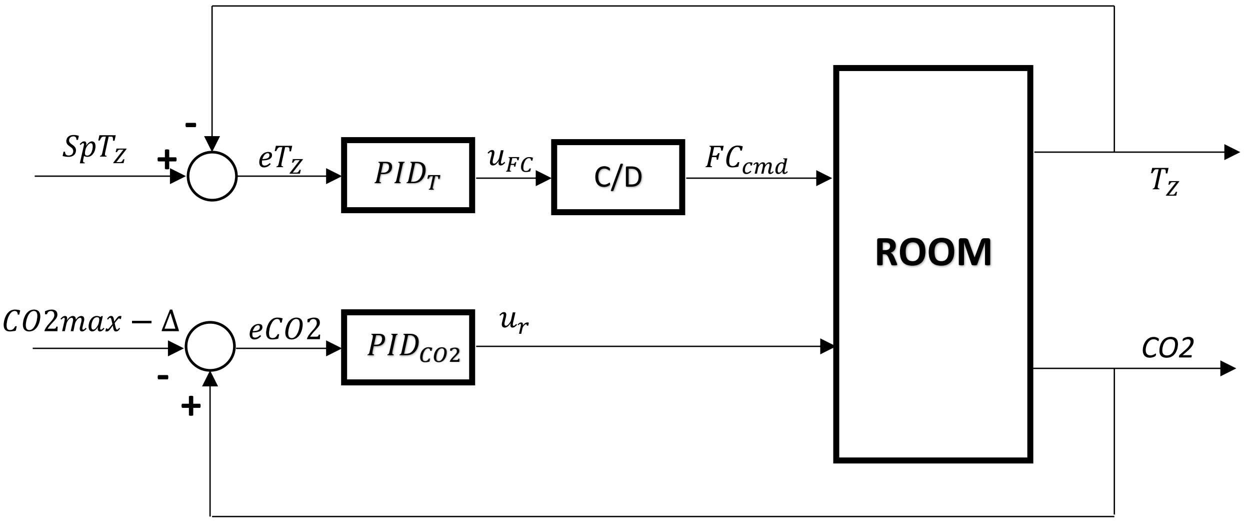

Figure 11: Current PID-based control architecture

Moreover, the PID output is subjected to a saturation phenomenon, meaning that the control action computed by the PID is not allowed to go beyond a maximum and a minimum level.

In Figure 11 the current PID-based control architecture is schematically presented. In particular, the following control scheme is installed:

- A PID controller is dedicated to the temperature control in each room. Such PID controller commands the fan coil devices of the relative room using as information the difference between the desired temperature set-point and the actual temperature measurement in the room.
  Being the fan coil devices command a discrete signal (0, 1, 2, 3) and the control action computed by the PID a continuous signal, an hysteresis-based conversion is applied as presented in Figure 12 and referred to as C/D in Figure 11. As shown in the figure, the digital signal sent to the fan coil devices will change only when the continuous signal has reached the $\pm 10\%$ interval of the associated discrete signal. The alternative to such hysteresis-based signal conversion would have seen a direct approximation of the continuous signal to the nearest integer value. However, this logic would have inevitably caused a chattering phenomenon among any two digital signal, which could have been avoided only by introducing a hysteresis bound – as currently applied – or a consistent delay in the transmission of the computed digital command to the fan coil devices – which is generally not recommended due to possible control performance deterioration.

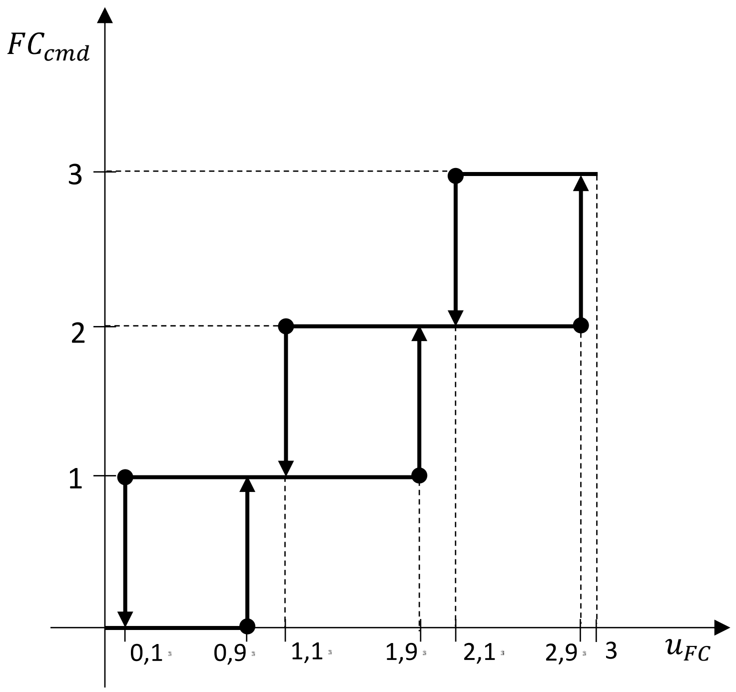

Figure 12: Hysteresis-based fan coil command conversion

- Another PID controller is dedicated to the CO2 level control in each room. As for the temperature-side PID, this controller controls the air recirculation fans speed of the relative room using as information the difference between the maximum CO2 level and the actual CO2 measured in the room.
  Differently from the temperature-side PID, the conversion from the continuous command computed by the PID and the actual command sent to the actuation system is not needed in this case, since the air recirculation fan speed accepts continuous values. However, a different control task is required in this case. In fact, the CO2-side PID controller is not used to maintain a specific CO2 set-point, while it is used to maintain the CO2 levels below a given maximum level. To solve the problem, the set-point given to the CO2-side PID controller is reduced by a fixed offset, so that the PID will actually enforce a control action before the maximum CO2 level is reached.

The advanced control algorithms presented in the next sub-sections are not substituting the two aforementioned PID controllers. In fact, these new control algorithms are developed so to be implemented over the current control architectures so to ease their implementation.

3.6.2 Advanced control strategy 1: Fan coil command modularization

The first advanced algorithm strategy developed by PP7 pilot test concerns the manipulation of the control command computed by the temperature-side PID controller and sent to the fan coil devices. In particular, the present control strategy computes a correction signal that is added to the PID control command before reaching the fan coil devices. A representative scheme of the proposed advanced control strategy is presented in Figure 13, in which the differences with respect to the base control structure are highlighted in blue.

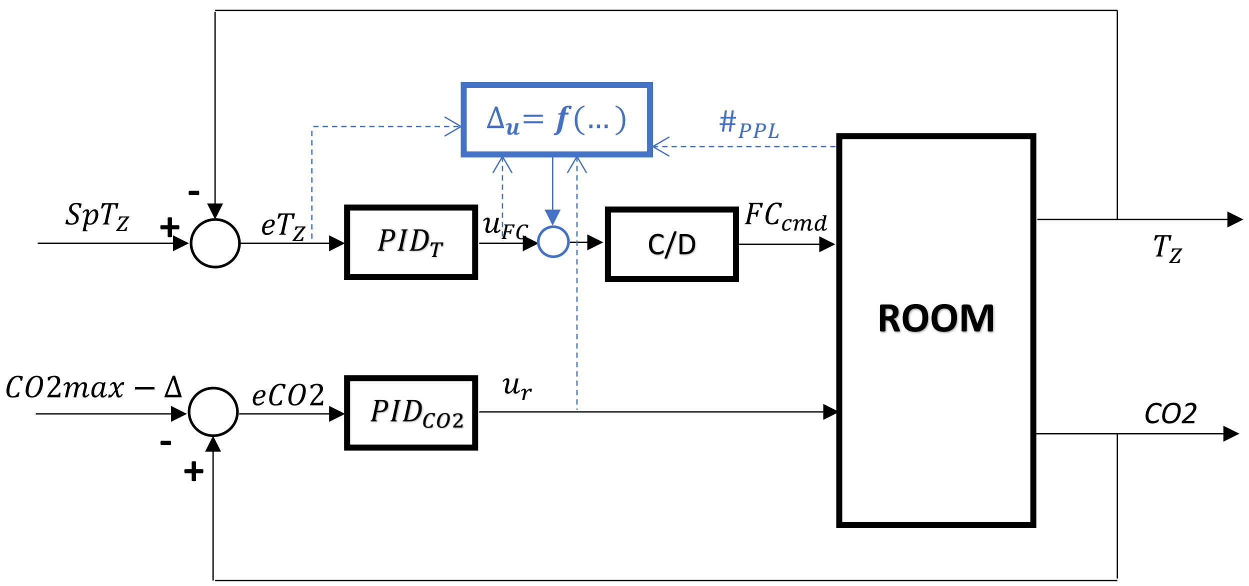

Figure 13: Advanced control strategy 1 scheme

Different ways to compute that corrective signal have been developed and tested and will soon be presented. Independently from the specific way of computing such signal, the underlying control logic is the same. In particular, this advanced control strategy intends to exploit the non-negligible heating action represented by the heat power produced by the people occupying the room. For this reason, this control strategy is meant to be applied only when a heating action is applied to the room. By directly or indirectly identifying the impact of the heat power produced by the people in the room, it is possible to reduce the heating effort commanded to the fan coil devices. In fact, the control command sent to the fan coil devices will be reduced according to the estimated heat power produced by the people occupying the room. The differences among the proposed ways to compute the corrective signal added to the control signal computed by the temperature-side PID controller rely on different estimation of the people heat power impact.

First formulation: using the air recirculation command

Assuming that there is no available measurement of the people occupation of the room, the people heat power impact can be estimated through the value of the air recirculation system. In fact, such value is logically correlated with the number of people occupying the room, since a higher amount of people will inevitably rise the CO2 levels in the room thus enforcing a higher air recirculation action. Moreover, assuming that the air recirculation system is well-seized, the effort required to the air recirculation system is likely to be highly descriptive of the actual people occupancy. In fact, a 100% control action is expected to be asked when the room is at it full capacity, while the same should gradually hold for all the other control action values.

This approach is surely considering a high level of simplification, which will impact on the overall performances over the temperature comfort levels. In fact, due to the nature of this control strategy, energy savings are surely guaranteed, while the simulation tests will draw conclusions on the eventual degradation of the temperature performance control.

In the end, the correction signal is computed considering the air recirculation command signal according to the following formula:

$$\Delta_u(t) = u_{FC}(t) * \frac{u_r(t)}{100} * f(e_T(t))$$

where u_{FC} is the command computed by the temperature-side PID, u_r is the command computed by the CO2-side PID – divided by 100 since it is expressed in percentage – and $f(e_T(t))$ is a function of the room temperature desired set-point and current measurement defined as:

$$f\big(e_T(t)\big) = min\left\{1\,, max\left\{0\,, \frac{2 - e_T(t)}{2}\right\}\right\}$$

In particular, the function $f(e_T(t))$ output ranges between 0 and 1 depending on the how close the temperature error is to the set-point. By analyzing the presented formulation, it is possible to conclude that this corrective term Δ_u can be assigned to any value between 0 and $u_r(t)$ depending on the value of $u_{FC}(t)$ and the value of the function $f(e_T(t))$. In fact, in case the air recirculation command $u_r(t)$ is assigned to its maximum value – i.e. 100%, which is allegedly associated with the maximum people occupancy – and the measured temperature is greater or equal to the desired set-point, the corrective term Δ_u is assigned equal to the command u_{FC}, resulting in the deactivation of the fan coil devices. On the opposite, if the air recirculation command is zero or the measured temperature is two or more degrees lower than the desired temperature set-point, the corrective term is assigned to zero, thus leaving the nominal temperature-side PID functioning unaffected.

The presented control strategy has been tested on the multi-room model to validate its performances according to the following conditions:

- A random occupancy profile has been generated for each room: such set of occupancy profiles have been applied equally to both the control strategies tested, i.e. the baseline current control strategy and the proposed new control strategy;
- The external temperature profile measured over 12 weeks by the SCADA system has been applied;
- The thermal power delivered to the room has been used as basis to compute the simulated consumption of each room, which is then compared among the control strategies to validate their performance;
- One random week of one random room is presented in the test figures so to clearly represent the test results;
- A table presenting relevant performance indexes for each room is presented. The performance indexes used are the same of pilot phase 3, with a difference in the $E_{Thermal}$ index, which is now including the thermal energy consumed by the air recirculation units.

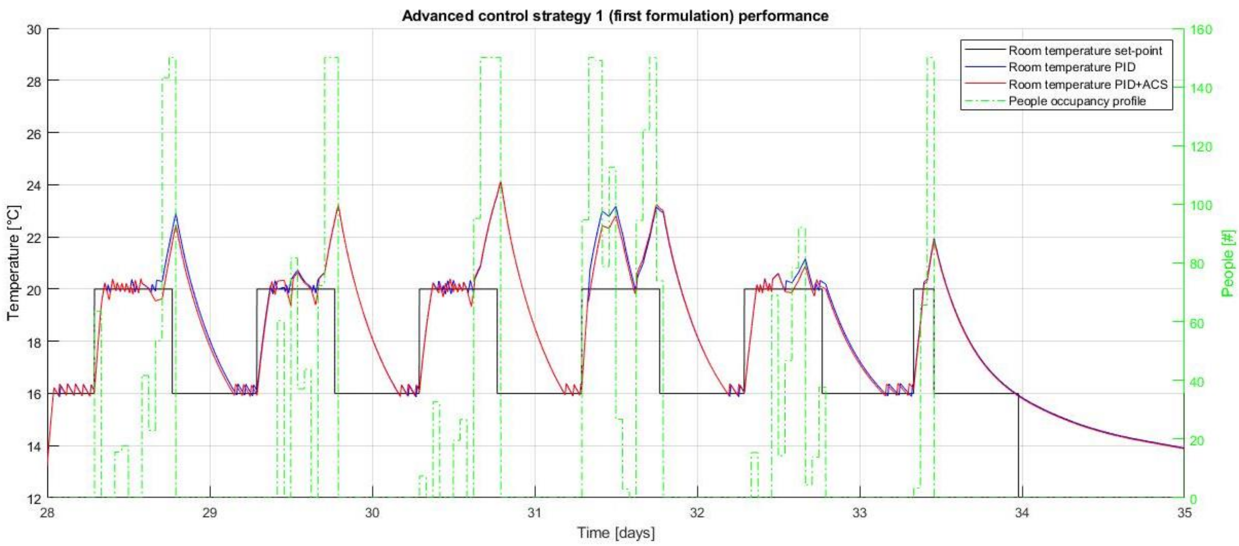

Figure 14: Advanced control strategy 1 (first formulation) performance

In Figure 14 an explanatory time window of the advanced control strategy 1 performance with respect to the baseline control strategy is presented. In Table 2 the performance indexes results computed over all the 12 weeks are presented.

Table 2: Advanced control strategy 1 (first formulation) performance indexes

Performance Index		D01	D04	D11	D12	D21	D24	D31	D32	Av.	Δ
$T_{av.}$ [°C]	**Base**	20.9	21,1	21	21	21.2	21.1	21.4	20.8	21.1	-0.2°C
	ACS1	20.8	20.9	20.9	20.8	21	21	21.1	20.6	20.9	
$Freq_{Overheat}$ [%]	**Base**	77%	78%	78%	77%	75%	80%	78%	78%	78%	-8%
	ACS1	71%	72%	72%	69%	70%	73%	73%	71%	71%	
$T_{Overheat,av.}$ [°C]	**Base**	1.56	1.79	1.59	1.6	1.62	1.54	1.74	1.6	1.63	-0.06°
	ACS1	1.49	1.69	1.56	1.53	1.57	1.49	1.65	1.56	1.57	
$Max(T)$ [°C]	**Base**	27.3	27.4	27.3	28.3	27.4	27	26.5	27.2	27.4	0°C
	ACS1	27.3	27.3	27.3	28.2	27.2	27	26.4	27.1	27.4	
$E_{Thermal}$ [KWh]	**Base**	2834	2783	2810	2830	2813	2811	2791	2820	2812	-31kWh
	ACS1	2806	2748	2778	2805	2784	2775	2767	2790	2781	

As it can be seen, good results have been obtained especially on the consumption reduction. However, through the second formulation, better performance increases will be appreciated.

Second formulation: using the people occupancy measurement

Assuming that the people occupancy measurement is available, the previously presented computation of the corrective term can be reformulated according to the following formula:

$$\Delta_u(t) = u_{FC}(t) * g(\#PPL) * f(e_T(t))$$

with $f(e_T(t))$ defined as in the previous formulation and:

$$g(\#PPL) = min\left\{1\,, max\left\{0\,, \frac{\#PPL}{PPL_{max}}\right\}\right\}$$

As it can be seen, this formulation resembles the formulation presented in the previous computation of $\Delta_u(t)$. However, in this case, the people occupancy measurement is used in the function $g(\#PPL)$ instead of the information on the air recirculation command. This formula is characterized by a tuning parameter PPL_{max}, which refers to the maximum people occupancy measurement over which the corrective term $\Delta_u(t)$ is assigned to $u_{FC}(t)$, resulting in a command FC_{cmd} equal to 0 and the consequent deactivation of the fan coil system.

This formulation, although conceptually similar to the previous one, is able to capture more effectively the impact of the people heat power. In fact, the people occupancy measurement is directly proportional to such heat power, while the air recirculation command exploited in the previous formulation is not completely correlated with such heat power both in time and in amplitude. For this reason, the testing of this second formulation provided better results with the first one.

The presented control strategy has been tested on the multi-room model to validate its performances according to the same testing conditions presented for the first formulation. In the test figure the performances of the first formulation of this advanced control strategy are presented along with the second formulation performances to highlight the benefits coming from the people occupancy measurement. To ease such comparison, the same week and the same room used for the first formulation test are used.

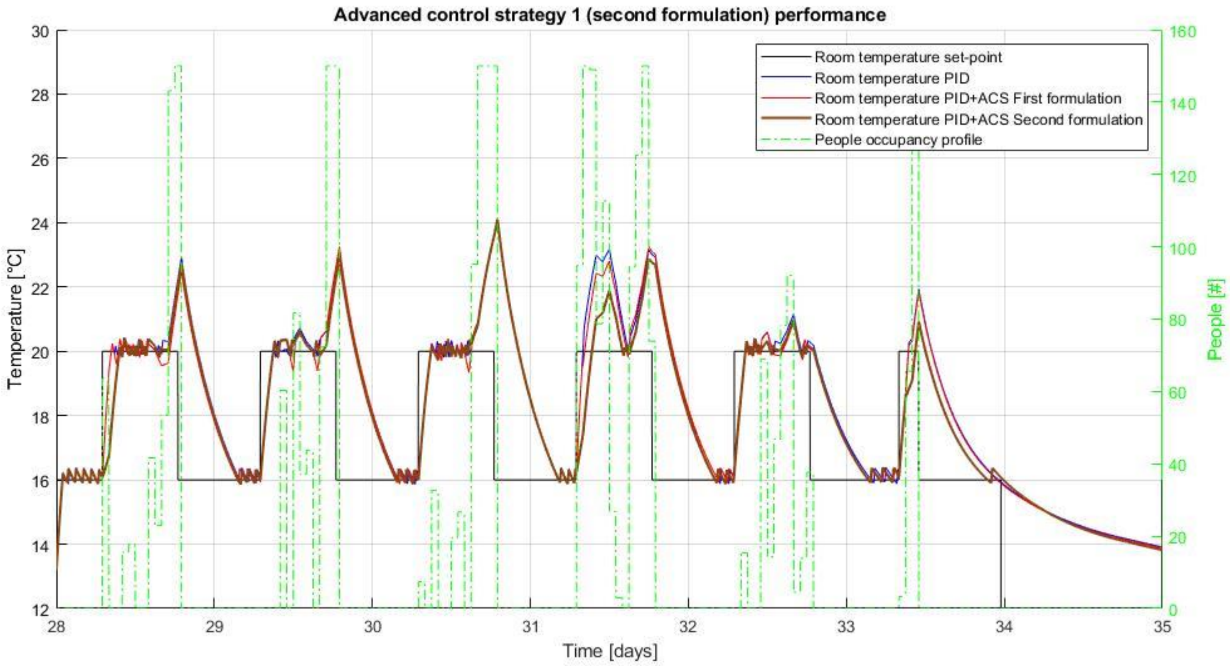

Figure 15: Advanced control strategy 1 (second formulation) performance

In Figure 15 an explanatory time window of the advanced control strategy 1 performance – in both its formulations – with respect to the baseline control strategy is presented. In Table 3 the performance indexes results computed over all the 12 weeks are presented.

Table 3: Advanced control strategy 1 (second formulation) performance indexes

Performance Index		D01	D04	D11	D12	D21	D24	D31	D32	Av.	Δ
$T_{av.}$ [°C]	***Base***	20.9	21,1	21	21	21.2	21.1	21.4	20.8	21.1	-0.5°C
	ACS1	20.5	20.7	20.6	20.6	20.5	20.4	20.7	20.6	20.6	
$Freq_{Overheat}$ [%]	***Base***	77%	78%	78%	77%	75%	80%	78%	78%	78%	-12%
	ACS1	65%	67%	66%	68%	64%	66%	65%	67%	66%	
$T_{Overheat,av.}$ [°C]	***Base***	1.56	1.79	1.59	1.6	1.62	1.54	1.74	1.6	1.63	-0.13°
	ACS1	1.43	1.65	1.54	1.51	1.51	1.4	1.6	1.51	1.5	
$Max(T)$ [°C]	***Base***	27.3	27.4	27.3	28.3	27.4	27	26.5	27.2	27.4	-0.3°C
	ACS1	26.8	27.2	27	28.3	26.9	26.7	26.5	27	27.1	
$E_{Thermal}$ [KWh]	***Base***	2834	2783	2810	2830	2813	2811	2791	2820	2812	-147kWh
	ACS1	2686	2639	2673	2718	2644	2642	2650	2666	2665	

As it can be seen, appreciable results have been obtained especially on the consumption reduction. Moreover, this second formulation allowed for better increase in the performance index with respect to the first formulation. For this reason, it is possible to conclude that the measurement of the people occupancy profile returns a considerable benefit on both the thermal user comfort and the overall thermal energy consumption.

3.6.3 Advanced control strategy 2: Temperature set-point manipulation

The second advanced control strategy presented in pilot PP7 envisages the manipulation of the temperature set-point. Such manipulation is defined in function of the people occupancy measurement. The concept underlying this control strategy lays on the possibility of slightly reducing the thermal comfort in the room while a given people occupancy threshold is not met. This comfort reduction is imposed through the manipulation the room temperature set-point according to the following formula:

$$SpT_{NEW}(\#PPL) = SpT + 2 * \left(\frac{min\{PPLmin, \#PPL\}}{PPLmin} - 1\right)$$

where $\#PPL$ is the people occupancy measurement, SpT_{NEW} is the manipulated temperature set-point sent to the room, SpT is the original desired room temperature set-point and $PPLmin$ is a tuning parameter. This tuning parameter specifies the minimum number of people occupying the room over which the temperature set-point variation is nullified.

This simple manipulation of the temperature set-point is meant to minimize any energy waste relative to uselessly heating a room which is not used by any student. Although the maximum allowed set-point reduction is just 2°C, this simple control strategy can lead to consistent energy savings.

The presented control strategy has been tested on the multi-room model to validate its performances according to the same testing conditions presented for the first advanced control strategy.

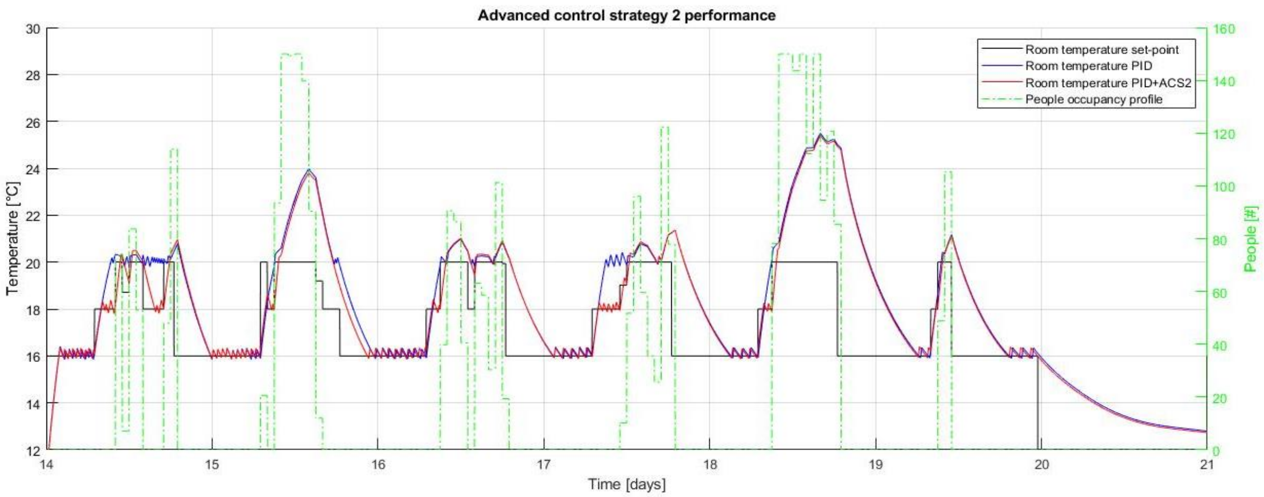

Figure 16: Advanced control strategy 2 performance

In Figure 16 an explanatory time window of the advanced control strategy 2 performance with respect to the baseline control strategy is presented. In Table 4 the performance indexes results computed over all the 12 weeks are presented. Only the thermal energy consumption index is presented, since the other performance indexes do not represent a valid info on the system behavior due to the temperature set-point manipulation.

Table 4: Advanced control strategy 2 performance indexes

Performance Index		D01	D04	D11	D12	D21	D24	D31	D32	Av.	Δ
$E_{Thermal}$ [KWh]	***Base***	2834	2783	2810	2830	2813	2811	2791	2820	2812	-109kWh
	ACS2	2723	2661	2692	2719	2708	2703	2692	2716	2703	

An appreciable consumption reduction can be seen from the performance indexes.

Finally, the combination of the two presented advanced control strategy – using the second formulation of the advanced control strategy 1 – is presented. The performance resulting from this combination is compared with the performance obtained with the baseline control strategy currently adopted in Building 25.

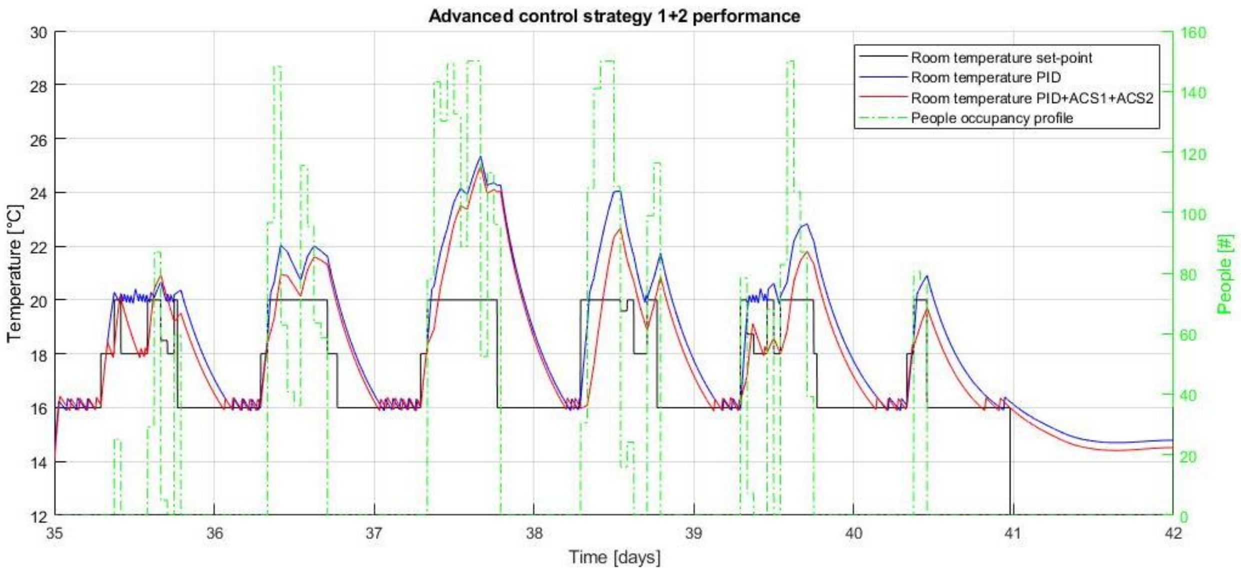

Figure 17: Advanced control strategy 1+2 performance

In Figure 17 an explanatory time window of the combination of the two advanced control strategies performance with respect to the baseline control strategy is presented. In Table 5 the performance indexes results computed over all the 12 weeks are presented.

It can be noticed that the two advanced control strategies do not negatively interfere with each other. Moreover, the advantages with respect to the baseline control strategy are higher than the advantages obtained by the application of a single advanced control strategy.

Table 5: Advanced control strategy 1+2 performance indexes

Performance Index		D01	D04	D11	D12	D21	D24	D31	D32	Av.	Δ
$T_{av.}$ [°C]	**Base**	20.9	21,1	21	21	21.2	21.1	21.4	20.8	21.1	-1.2°C
	ACS	19.9	19.9	19.8	19.9	19.8	19.7	19.9	19.8	19.9	
$Freq_{Overheat}$ [%]	**Base**	77%	78%	78%	77%	75%	80%	78%	78%	78%	-17%
	ACS	61%	63%	62%	63%	61%	59%	62%	60%	61%	
$T_{Overheat,av.}$ [°C]	**Base**	1.56	1.79	1.59	1.6	1.62	1.54	1.74	1.6	1.63	-0.01°
	ACS	1.6	1.72	1.58	1.62	1.57	1.5	1.73	1.6	1.62	
$Max(T)$ [°C]	**Base**	27.3	27.4	27.3	28.3	27.4	27	26.5	27.2	27.4	-0.3°C
	ACS	26.7	27.2	26.8	28.3	26.7	26.4	26.8	27.4	27.1	
$E_{Thermal}$ [KWh]	**Base**	2834	2783	2810	2830	2813	2811	2791	2820	2812	-413kWh
	ACS	2448	2365	2402	2457	2389	2359	2387	2390	2399	

3.6.4 Advanced control strategy 3: Air recirculation feed-forward

The last advanced control strategy presented through PP7 pilot envisages the manipulation of the air recirculation control. In particular, the people occupancy measurement is used to anticipate any CO2 level increase. Consequently, an additive command is sent to the room air recirculation system to preventively compensate such increase before its actual manifestation. In the end, this control strategy is meant to provide a better comfort in terms of CO2 level control.

The control signal sent to the room air recirculation system – previously referred to as $u_r(t)$ – is now composed by the sum of the original CO2-side PID output and the aforementioned additive signal as shown in the formulation below:

$$u_{r_{NEW}}(t) = u_{r_{PID}}(t) + 100 * min\left\{1\,, \frac{\#PPL}{PPL_{MAX}}\right\}$$

As shown, the additive term is a value in the range [0 , 100] as the original CO2-side PID output $u_{r_{PID}}(t)$. The additive term is assigned to 0 when no people occupancy is measured, while it is assigned to 100 when the measured people occupancy is equal or higher than a given parametrical number PPL_{MAX}.

The presented control strategy has been tested on the multi-room model to validate its performances according to the same testing conditions presented for the first and second advanced control strategies. The performances are evaluated both on the temperature side and on the CO2 side.

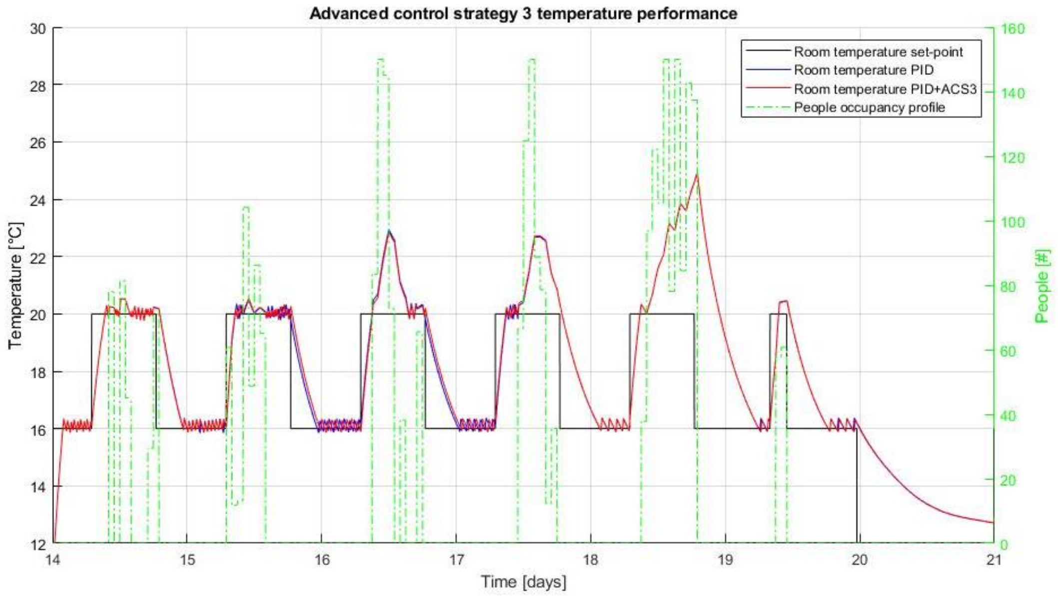

Figure 18: Advanced control strategy 3 temperature-side performance

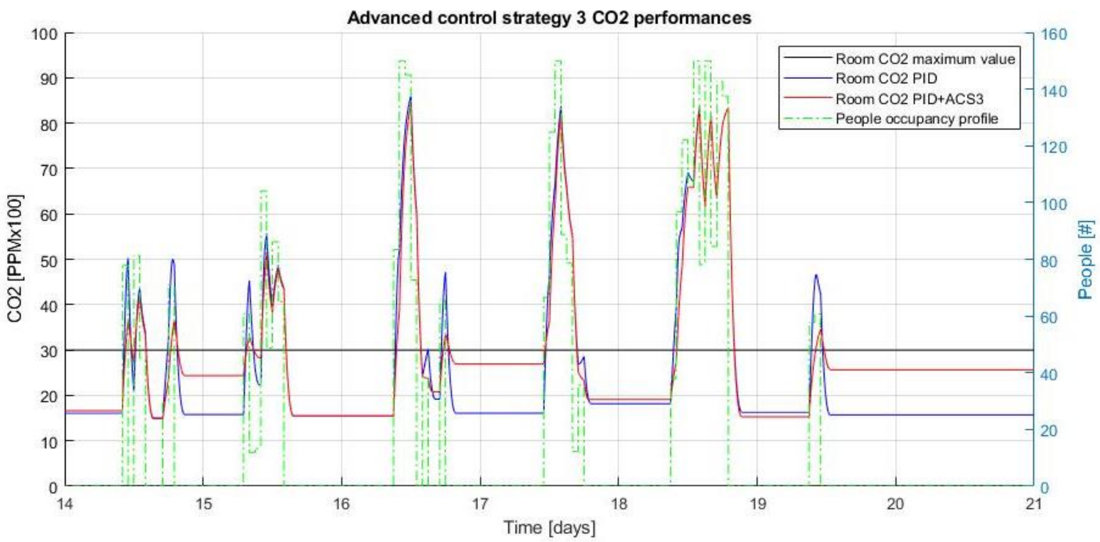

Figure 19: Advanced control strategy 3 CO2-side performance

In Figure 18 and Figure 19 explanatory time window of the advanced control strategy 3 performance with respect to the baseline control strategy is presented. In Table 6 the performance indexes results computed over all the 12 weeks are presented. The temperature-side performance indexes are not presented, since from Figure 18 it is possible to see that this advanced control strategy do not provide any relevant impact on the room temperature.

Table 6: Advanced control strategy 3 performance indexes

Performance Index		D01	D04	D11	D12	D21	D24	D31	D32	Av.	Δ
$CO2_{av.}$ *[PPMx100]*	***Base***	42.4	43.8	43.4	42.6	43.1	42.6	43.9	43.1	43.1	-2.1 PPMx100
	ACS3	40.2	41.7	41.3	40.5	41.3	40.8	41.9	40.8	41.0	
$Freq_{HighCO2,av.}$ *[%]*	***Base***	60%	62%	60%	60%	62%	62%	63%	63%	62%	-8%
	ACS3	53%	55%	53%	52%	55%	56%	56%	55%	54%	
$CO2_{HighCO2,av.}$*[PPMx100]*	***Base***	26.9	28.3	28.2	27.4	26.9	26.2	27.7	26.6	27.3	-0.7 PPMx100
	ACS3	26.1	27.7	27.9	27.2	26	25	27.2	25.9	26.6	
$Max(CO2)$ *[PPMx100]*	***Base***	93.4	93.5	93.6	93.5	93.5	93.5	93.6	93.6	93.6	-0.1 PPMx100
	ACS3	93.3	93.5	93.5	93.4	93.4	93.5	93.5	93.5	93.5	
$E_{Thermal}$ *[KWh]*	***Base***	2834	2783	2810	2830	2813	2811	2791	2820	2812	+86kWh
	ACS1	2926	2875	2895	2917	2896	2894	2873	2910	2898	

As shown in the table, the air quality performances are increased, especially in the frequency at which high levels of CO2 are registered. However, such benefits are paid through an increase of overall energy consumption, due to the higher exploitation of the air handling units. In the end, the studies regarding this advanced control strategy can be further deepened so to ensure better air quality performance without compromising the overall energy consumption.

3.6.5 Conclusions on advanced control strategies

All the previous simulation tests performed over the proposed advanced control strategies have shown the possibility to increase both the user comfort and the energy consumption. These advanced control strategies have been intentionally developed in a simplified way so to relevantly ease their implementation effort, aiming at maximizing their permeation in the widest building energy management practice.

The best results in terms of energy savings and thermal user comfort have been shown by the application of the advanced control strategy 1 and 2 together. By implementing these two control strategies – which rely on the measurement of the people occupation – it is possible to appreciate an energy consumption reduction up to 15% and a user thermal discomfort frequency decrease of 17%.

Another advanced control strategy finalized to the air quality management has been presented. Such control strategy does not provide any reduction in the thermal energy consumption, while the air quality performance indexes show improvements.

Future work will see the implementation of self-tuning procedures finalized at the optimization of such advanced control strategies, together with their possible integration with the thermal generators (heat pumps and air handling units).

4 Conclusions

This chapter is dedicated to the detailed presentation of the conclusions drawn from the PP7 pilot case. A section is dedicated to each main conclusion to have a clear representation of the goals achieved through the pilot deployment.

4.1 Performance assessment methodology

Through pilot PP7 it was possible to develop a performance assessment methodology to describe the building control performances. Such performance assessment methodology is able to effectively represent the capability of the thermal network and the control structure to impose some specific user requirements on the rooms temperature and air quality.

In particular, the performance indexes developed to assess the building control performances rely on the temperature and the CO2 measurements of each room. For both the room temperature and the room CO2 levels, four indexes have been developed. Such indexes are able to represent both the average behavior and the magnitude of the control deficiency phenomena (overheating and excessively high CO2 levels) for both the room temperature and the CO2 levels.

These indexes represent a quantitative analysis for the Building 25 current performances. Moreover, such indexes were found to be coherently applicable to the performance analysis of any other related building, thus constituting a reliable performance assessment methodology for other related analyses.

4.2 Sensor network installation

An IoT multi-sensor network has been successfully installed in Building 25. The specific configuration of such network has proven its applicability to any similar context. Moreover, the lack of any cabled connection stresses the minimum implementative effort required to equip any smart building with such multi-sensor network.

Multiple advantages coming from the installation of such network have been highlighted in detail in the current pilot deployment presentation. It is possible to summarize these advantages in two main categories:

- The network installation can both provide a better insight on the current building control performance by exploiting the reliability of its measurements. The data collected by such sensor network can easily be represented by a data monitoring system so to provide a real-time performance assessment to the building management unit. In this way, the real-time insight of the building status allows the decision and imposition of any necessary corrective action finalized at the optimization of the building behavior itself.

- The multitude of measurements provided by these multi-sensors can be exploited to develop mathematical models of the building itself. As shown in the previous chapter, such models can be used as an investment tool to investigate multiple innovation possibilities on the building thermal network. Moreover, the new measurements provided by this IoT sensor network enable the application of advanced control strategies, which are able to better enforce the user comfort requirements and reduce the overall building energy consumption.

4.3 Scalable thermo-dynamic models

As presented in pilot phase 5, dynamic models of the building behavior have been developed. The models have then been tuned on a set of collected data from Building 25 and validated on a further data set.

Such models allow a vast range of investment investigation, from the building structural elements to the thermal network devices and the application of advanced control strategies. The investigative capability of the developed models is related to the model nature itself. In fact, the models have been developed in a gray-box fashion, thus maintaining the physical representativeness of any of its parameters. In this way, it is possible to actually manipulate the model and simulate its behavior so to investigate the impact of any real building parameter on the overall performances, both in terms of user comfort and energy consumption.

The developed models present only a starting point of the possible investigation enabled by the realization of PP7 pilot. In fact, thanks to the IoT multi-sensor network installed, new models will be developed and studied.

4.4 Efficiency-oriented control strategies

The last phase of PP7 pilot envisaged the development of advanced control strategies. Once the current control strategy operating on Building 25 has been identified, multiple advanced control strategies have been developed and tested against such baseline control strategy to evaluate their impact. Such control strategies have been developed by exploiting a new measurement allowed by the installed IoT multi-sensor network: the people occupancy profile.

The developed advanced control strategies have proven an appreciable performance increase in both the user comfort requirements and the overall energy consumption. The best results in terms of energy savings and thermal user comfort have been shown by the application of the advanced control strategy 1 and 2 together, which are able to return an energy consumption reduction up to 15% and a user thermal discomfort frequency decrease of 17%.

The mentioned advanced control strategies have been intentionally developed in a simplified way so to relevantly ease their implementation effort, aiming at maximizing their permeation in the widest building energy management practice. Moreover, these control strategies are meant to be implemented over the existing building control strategies, thus further decreasing their implementation effort.

The introduction in the building management environment of advanced control techniques supported by a robust IoT sensor network represent an investment which is able to return considerable savings in the building energy consumption while maintaining a small overall implementative cost. The control field is then proven capable of efficiently tackling the building energy efficiency goal.

5 Future work

A final chapter is dedicated to the presentation of the future work ideas arising from the conclusions of PP7 pilot. Relying on the newly installed IoT multi-sensor network and the dynamic models developed, a plurality of studies and implementation tests can be performed. Each section is then dedicated to the detailed presentation of such future development ideas.

5.1 Equipment investment analysis

In PP7 pilot it was possible to develop dynamic models of the room-side behavior of the building, both its temperature and its CO2 levels. A future work idea envisages the study of the impact of equipment investment.

Thanks to the developed model it is now possible to simulate the behavior of different thermal devices and compare them with the current situation. By integrating such new components in the dynamic model, it is possible to conduct a performance comparison between the existing equipment and any other upgrade or substitution.

For example, it is possible to evaluate an investment regarding the introduction of a three way valve on each room which is able to manipulate the water temperature entering the fan coil devices, thus effectively manipulating the room heating function. Moreover, through such system it is possible to have a direct information on the required water temperature for each room, thus eventually minimizing the operative point of the industrial heat pump serving the whole building and consequently saving energy on the generation side of the thermal network.

Moreover, it is possible to exploit the developed model to study the impact of the introduction of renewable energy sources. By defining a set of relevant economical indexes, it is possible to assess the economical convenience of such investment. This information can then be used to promote the penetration of renewable energy sources in the widest range of the building management field.

5.2 Multivariable models study

Exploiting the IoT multi-sensor network installed in Building 25, it is possible to collect a sufficiently complete data set to study the mathematical relationship among the different measured variables. Different modeling techniques can be applied to gain a better insight over the impact of the measured variable over both the user comfort requirements and the building overall energy consumption.

A relevant study in the multivariable model development envisages the identification of the impact of people occupancy on the quality of air, on the user thermo-hygrometric comfort and on the energetic consumption of the thermal generation devices. By gaining a deeper understanding over these dynamics, it is then possible to investigate their compensation through both building equipment investment and advanced control strategies application.

5.3 Data monitoring system

The data acquired through the IoT multi-sensor network can be efficiently integrated into a data monitoring system. Thanks to the wide availability of open source software dedicated to this purpose, it is possible to study the development of a data monitoring system optimized for building management. In particular, such tool is meant to represent the building control performances by combining the multi-sensor measurements under specific innovative indexes developed through the aforementioned multivariable model study.

The efficiency of a data monitoring system on the building overall performances lays on the quality of the information returned to the operator. In particular, a well-posed data monitoring system is able to provide the operator the correct insight over any eventual building malfunctioning, thus enabling a customized corrective action which often is achievable only due to the operator unique expertise and knowledge of the building.

In the end, the data monitoring system represents a powerful tool for the building administration and management unit. In fact, by exploiting the information provided by the data monitoring system, the administration unit is enabled to optimize the building rooms occupation and the consequent usage of the heating and cooling thermal network.

5.4 Advanced control strategies

The advanced control strategies developed in PP7 pilot have been described in the pilot phase 6 presentation. Although these advanced control strategies have been proven to return a relevant performance increase on both the user thermal comfort and the building energy consumption, two main development branches are still open:

- By exploiting the developed model and any future multivariate model, it is possible to develop further advanced control strategies. Such additional strategies can eventually foresee an equipment upgrade or the integration with the thermal generator (heat pumps and air handling units). Although the already developed dynamic models have been validated over the building measurements, it is possible to consider the development of new models for the thermal generation side so to support new control strategies embracing the overall thermal network management.

- Considering the tuning parameters of some of the advanced control techniques presented, it is possible to study an adaptive strategy to automatically tune them. Such adaptive strategy would foresee the definition of a control performance index used to correct the control parameters in an online fashion.

- By studying the possibility to interact with the current building control architecture, it is possible to test the developed advanced control strategies over Building 25. The IoT multi-sensor network can then be used to assess the performances of such real testing phase. The collected data will then be used to validate the actual performances of the proposed advanced control strategies and to eventually apply some modifications deduced by the tests results.

6 List of figures and tables