Bolzano's technology park: a building control and use optimization approach

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This paper presents an approach to optimize the control and use of the pilot building of the new Technology Park of Bolzano in northeast Italy designed by Chapman Taylor and Claudio Lucchin & Architetti Associati - Angelo Rinaldo Daniela Varnier and named “Black Monolith”. For this purpose, energy performance modelling plays an essential role in energy saving measures design. An integrated design process has been implemented from the early stage and has enabled the team to assess the challenges and focus the planning effort on the aspects with highest impact on building performance. Given the high importance of proper building management to obtain a good match between actual and nominal energy consumption, this paper presents the approach used in the final stage of the integrated design process to optimize the control strategies for heating, cooling, ventilation and lighting with regard to operation mode and parameter levels (e.g. temperature, flow rate, etc.). Furthermore, several parameters linked to the end-user behaviour have been varied such as internal loads, opening of windows and doors, air changes, set-points and shading configuration. A sensitivity analysis and parametric studies have been fundamental to sort these parameters according to their effects on energy consumption and comfort. The results enable to suggest effective control strategies, allowing the building energy manager to take informed decisions on optimizations of the building as an energy system that will help to meet the energy targets set for the project while keeping high comfort levels.

Keywords: commissioning; sensitivity analysis; optimization.

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ABSTRACT: We present an approach to optimize the control and use of the pilot building of the new Technology Park of Bolzano in northeast Italy designed by Claudio Lucchin & Architetti Associati - Angelo Rinaldo Daniela Varnier and Chapman Taylor and named "Black Monolith". For this purpose, energy performance modelling plays an essential role in energy saving measures design. Given the high importance of proper building management to obtain a good match between actual and nominal energy consumption, this paper presents the approach used in the final stage of the integrated design process to optimize the control strategies for heating, cooling and ventilation with regard to operation mode and parameter levels such as setpoints. A sensitivity analysis and parametric studies have been fundamental to rank these parameters according to their effects on energy consumption and comfort. The results enable to suggest effective control strategies, allowing the building energy manager to take informed decisions about optimizations of the building viewed as an energy system. These strategies will help to meet the energy targets set for the project while keeping high comfort levels.

Keywords: integrated design process; commissioning; sensitivity analysis; optimization; parametric simulation

INTRODUCTION

We present our optimization approach of the control strategy to be implemented in one of the buildings of the planned Technology Park of Bolzano located in the northeast of Italy. It will be erected on an ex-industrial area of the city where three main existing blocks listed as industrial historic buildings will be refurbished and other new buildings will be built. For the new buildings, both owner (Province of Bolzano) and designer (CLEAA – Claudio Lucchin E Architetti Associati) would like to achieve the target of Net Zero Energy Building and a total Primary Energy Index (PEI) lower than 60 kWh/m^{2}a. For this purpose, the control strategy and correct use of the building by the users play an essential role in energy performance and comfort.

The PEI has been introduced in the EU FP7 project DIRECTION [1] and is calculated as follows:

$$PEI = PE_t + PE_e + CE_t \cdot FC_t + CE_e \cdot FC_e$$

where PE_t (PE_e) is the auto-consumed thermal (electrical) energy from renewable sources, CE_t (CE_e) is the consumed thermal (electrical) energy from non-renewable sources and FC_t (FC_e) is the conversion factor from thermal (electrical) energy to primary energy.

BUILDING DESCRIPTION

As illustrated in Figure 1**Error! Reference source not found.**, the architectural concept of the building is a black monolithic block with an L-shaped plan view. The building has five floors and an underground floor. The ground floor will host an expo area. The upper floors will host offices, meeting rooms and service rooms. On the underground floor there will be several conference rooms. In the centre of the building and across the full height, a green patio is designed as a buffer zone to improve indoor comfort and daylighting.

Figure 1: A rendering of the building (source: CLEAA)

The envelope is a metal-glass curtain wall façade with a solar shading system on the south façade and a black aluminium foam cladding with various series of horizontal ribbon windows on the other façades.

The compact shape of the building contributes to minimize the heat losses through the envelope. The glass to wall ratio has been designed taking into consideration heat gains and losses through the transparent surfaces. The windows of the north, east and west façades are located on the internal surface of the external wall. This way, the deep reveal of the 55 cm thick walls acts as a sun shading system.

Natural ventilation has been used as a passive solution to reduce cooling needs and operation costs. The building has been divided into three zones depending on fire compartments as shown in Figure 2. For each zone, different natural ventilation configurations has been evaluated. Through the integrated design process, a stack driven cross ventilation has been chosen as the most effective configuration that balances performance needs with constrains given by fire compartments, acoustic comfort and privacy needs in the offices during the working hours. Connecting floor grilles increase the height between inlet and outlet openings. The floor grilles will be automatically controlled and closed during the working hours to avoid acoustic discomfort and maintain privacy between adjacent offices.

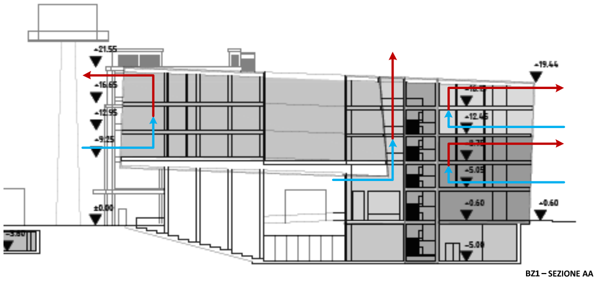

Figure 2: Cross section of the building showing the selected stack-driven cross ventilation configurations for the coloured zones

Openings are activated between 6 pm and 8 am if the following conditions are all met:

- External temperature higher than 14 °C
- Internal temperature higher than 24 °C
- External dew point less than 17 °C

The air humidity control has been introduced to ensure a comfortable absolute humidity (air temperature of 26 °C with 50% relative humidity).

SENSITIVITY ANALYSIS

We have performed a sensitivity analysis (SA) on the TRNSYS model to identify the key decision variables (called factors in this context) which affect the total loads for heating and cooling and the comfort in the offices (Table 1). We have used the elementary effects method which varies one factor at a time, computes the effects of that variation on loads or comfort and then computes sensitivity indicators that evaluate the importance of the factors on the outcome. The same internal gains multiplication factor has been used on the internal gains caused by persons, appliances and artificial lighting. Next, we have created a Design of Experiment (DoE), that is, a series of factor value combinations, with the following properties. In each combination, every factor takes one of four values obtained by dividing the respective range into three equidistant parts. Thus, a combination consists of 9 values, one for each factor. The first combination is selected at random. Each successive combination is then obtained from the previous one by varying exactly one value by a fixed increment or decrement, whereas the other values are kept fixed. This is done until the value of each factor has changed exactly once. This process leads therefore to precisely 10 combinations (the number of factors plus one), called a trajectory. By repeating this process, each time starting from a different (because chosen at random) combination, we have created 200 trajectories. From these 200 trajectories, we have selected 10 trajectories in the following way. We have chosen 500 times 10 trajectories from the 200 trajectories available. Then, we have selected the 10 trajectories with the maximum sum of the distances between a pair of trajectories [2]. In this way, we have ensured a good exploration of the design space with only 100 simulations.

Table 1: Factors used for the SA

Factor name and code	Range
Internal gains multiplication factor (IG)	0.75 – 1.25
Air changes per hour (ACH)	0.5 – 2.5/h
Heating setpoint (H SP)	20 – 22 °C
Cooling setpoint (C SP)	25 – 27 °C
Maximum relative humidity (RH)	50 – 70%
Shift of working hours (SH W), base: 8:00 to 18:00	-1 – 1 h
Shift of starting heating schedule (SH H), base: 6:00	-1 – 1 h
Shift of starting cooling schedule (SH C), base: 6:00	-1 – 1 h
Dew point (DP)	17 – 23 °C

Table 2: The first three combinations of the first trajectory of our DoE

Comb.	Factor values			
1	IG = 0.9	SH H = -0.3	ACH = 2.5	…
2	IG = 0.9	SH H = 1.0	ACH = 2.5	…
3	IG = 1.3	SH H = 1.0	ACH = 2.5	…

As an example, we have reported the first three combinations of the first trajectory of our DoE in Table 2. Combination 1 is generated at random and corresponds to a building with the offices internal gains reduced by 10% (multiplied by 0.9), 2.5 air changes per hour, a backward shift of the heating schedule by 18 minutes (-0.3 hours), etc. Combination 2 is equal to combination 1 except for the shift of the heating schedule which is changed from -0.3 to 1.0. Combination 3 is equal to combination 2 except for the internal gains multiplication factor which is changed from 0.9 to 1.3, and so on.

An elementary effect associated with a factor i is given by:

$$EE_i^j = \left(y(c_{k+1}) - y(c_k)\right)$$

y denotes the outcome, that is, total loads or comfort. c_k and c_{k+1} denote two consecutive combinations which differ only by the i-th factor value. For each trajectory j, a single elementary effect associated with factor i is obtained. The mean elementary effect associated with a factor i is then given by the average of the single elementary effects associated with that factor:

$$\mu_i = EE_i = \frac{1}{r}\sum_{j=1}^{r} EE_i^j$$

where r denotes the number of trajectories (equal to 10 in our case). In addition to the sensitivity indicator μ it makes sense to compute also the following two sensitivity indicators:

$$\mu_i^\star = \frac{1}{r}\sum_{j=1}^{r} |EE_i^j|$$

$$\sigma_i^2 = \frac{1}{r-1}\sum_{j=1}^{r}\left(EE_i^j - \mu_i\right)^2$$

$\mu_i^\star$ is the absolute mean of the single elementary effects associated with factor i. σ_i^2 is the variance of the elementary effects associated with factor i. As the unit of measurement of the variance of a factor is the square of the unit of measurement of that factor, we will not report σ_i^2 in the results but the standard deviation σ_i.

We have computed the importance of the factors listed in Table 1 on a) total loads needed to heat and cool the offices and b) comfort. We have computed the total loads by integrating over the sensible and latent heating and cooling loads of all offices. We have assessed comfort through the Predicted Mean Vote (PMV) calculated by TRNSYS by setting up the comfort type indicated in Table 3. In Bolzano, heating is allowed from 15th of October to 15th of April. Therefore, we have set the heating period to this time period and the cooling period to the rest of the year.

Table 3: Comfort type used to compute the PMV

Period	Clothing factor [clo]	Metabolic rate [met]
Heating	1.0	1.2
Cooling	0.5	1.2

We have computed the absolute yearly mean of the hourly PMV values during working hours and assessed the factors' importance on that value. This means that, as we haven't taken into account the signs of the hourly PMV values, we have assessed the overall discomfort without distinguishing between "too cold" and "too hot".

SENSITIVITY ANALYSIS (SA) RESULTS

Figure 3 reports the factors ranked by decreasing effect (influence) on the total loads as measured by the absolute mean effects $\mu_i^\star$. We can observe that, by varying the air changes per hour within the range listed in Table 1, that is, from 0.5 to 2.5, the total loads vary by a mean of 6.7 kWh/m^2. Changing the cooling setpoint by 1 K changes the total loads by a mean of 4.6 kWh/m^2. Varying the relative humidity setpoint between 50% and 70% has an influence on the total loads by a mean of 3.0 kWh/m^2, and so on.

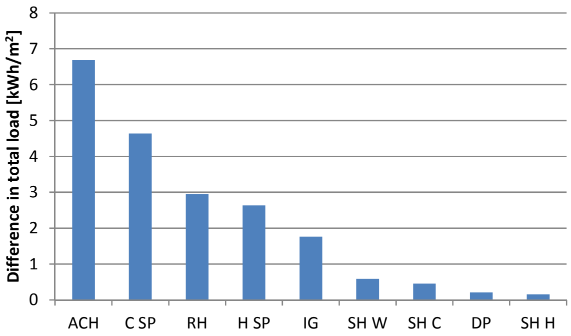

Figure 3: Factors ranked by decreasing effect on the total loads

To understand in more detail how the total loads vary, we have to look at the mean effects μ_i and the standard deviations σ_i of the effects. This information is given in Figure 4. The air changes per hour have a positive mean effect (feedback) on the total loads. This means that an increase in the air changes per hour produces an increase in the total loads. By contrast, the cooling setpoint has a negative mean effect (feedback) on the total loads: an increase of the cooling setpoint produces a decrease of the total loads. The standard deviation tells us how far from the average the outcome is spread. It gives us also information on the interaction of a factor with the other factors. The higher the standard deviation, the more the single effect of the air changes per hour on the outcome depends on the values of the other factors (the building's specific setting). For example, we have already reported an increase of the total loads by a mean of 6.7 kWh/m^2 if we increase the air changes per hour, but the actual increase depends on all factor values and ranges from 4.8 to 8.8 kWh/m^2 in our case. If the standard deviation is very low, for example in case of the dew point, then the factor's effect on the outcome is almost independent from the other factor values. In other words, the (small) effect of the dew point on the total loads will be almost the same even if we change the internal gains or the heating/cooling setpoints, shift the working schedule, etc.

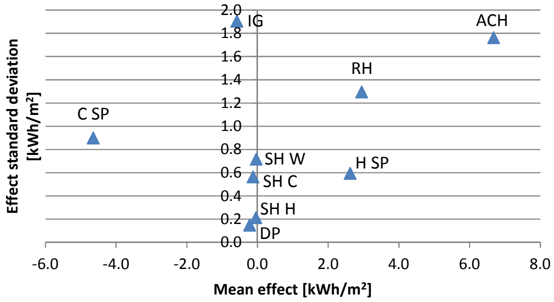

Figure 4: Mean and standard deviation of effects on total loads

The lowest total loads of 17 kWh/m^2 have been achieved for minimum air changes (0.5/h), a low heating setpoint (20 °C), a high cooling setpoint (27 °C) and a high relative humidity setpoint (70%). The internal gains have a less clear effect on the total loads and depend strongly on the building's setting. Indeed, the absolute mean effect is much higher than the mean effect, and the standard deviation is high. The shift of the working hours has a mean effect close to zero, although the absolute mean effect is 0.6 kWh/m^2. Thus, similar as for the internal gains, its effect depends strongly on the building's setting. The total heating load, equal to the sensible heating load (as no humidification has been performed), is 3.7 kWh/m^2 (22% of the total loads). The total cooling load is 12 kWh/m^2 (68% of the total loads). 5.3% of the total cooling load is latent cooling. The solution with the lowest total load is also the solution with the highest absolute mean PMV of 0.66. Interestingly, the solution with the second lowest total loads (18 kWh/m^2) has a considerably lower absolute mean of the PMV of 0.33. In the latter solution, the heating and cooling loads are more balanced with 5.8 kWh/m^2 total heating load and 12 kWh/m^2 total cooling load.

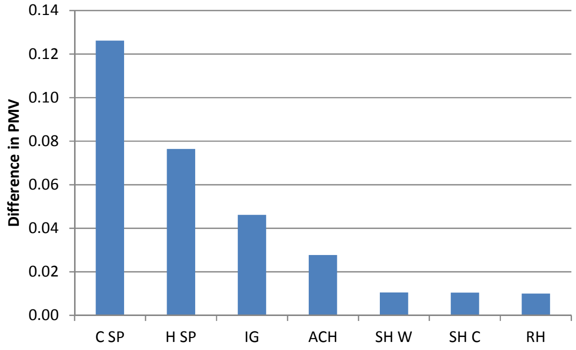

Figure 5: Factors ranked by decreasing effect on PMV

The highest total loads obtained have been 38 kWh/m^2. The energy spent pushes the absolute mean of the PMV down to the lowest value of all solutions, 0.12. This solution is quite opposite to the solution with the lowest total loads: maximum air changes (2.5/h), a high heating setpoint (22 °C), a low cooling setpoint (25 °C) and a setpoint of 50% RH. The total heating load equal to the sensible heating load is 14 kWh/m^2 (36% of the total loads). The total cooling load is 24 kWh/m^2 (64% of the total loads). 27% of the total cooling load is latent cooling.

Figure 5 shows the factors' ranking by decreasing effect on PMV. The cooling setpoint has the biggest effect on comfort, therefore it should be kept as high as acceptable. Similarly, the heating setpoint should be kept as low as acceptable. While the internal gains' effect on the loads depends strongly on the building's setting, this is not so much the case for the PMV which generally increases with an increase of the internal gains. In most simulated cases, if comfort is of concern, air changes per hour should be as high as possible within the range considered. However, high air changes per hour increase the loads.

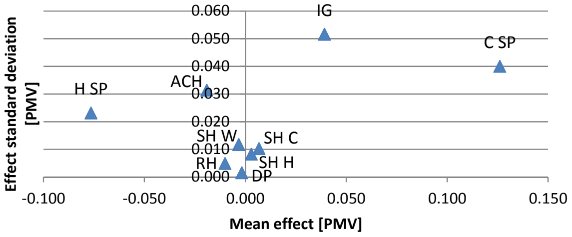

Figure 6: Mean and standard deviation of effects on comfort

CASE STUDY OPTIMIZATION

The results of the SA have given us insight on possible control strategies that optimize consumptions while maintaining high levels of indoor comfort.

The SA has given the parameters related to the control that affect energy consumption. Not all of these parameters, however, can be realistically changed. The ventilation rate cannot be changed without compromising adequate healthy air exchanges; the setpoints for heating and cooling cannot be changed without compromising the indoor comfort during working hours.

The SA has shown that the building's energy demand is lower if the dew point is not taken into account in the control of natural ventilation. Moreover, it has shown that the comfort in summer is ensured even with an indoor relative humidity of 70% instead of 50%.

As for the setpoints for heating and cooling, we have thought of a way to ensure the setpoints only during working hours. The setpoints for heating and cooling have been changed as reported in Figures 7 and 8.

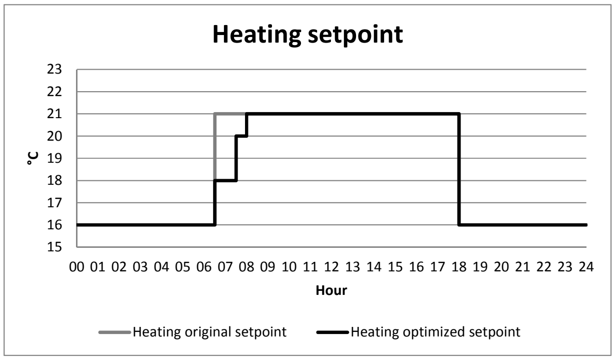

Figure 7: Heating setpoint optimization

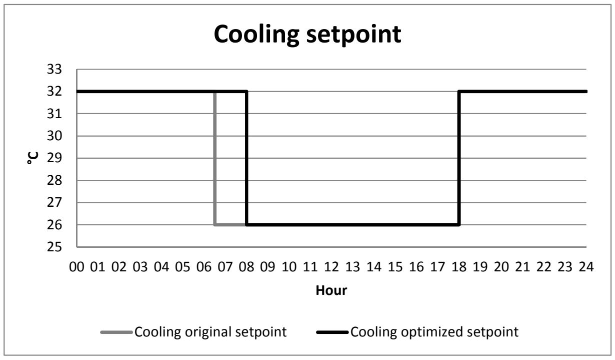

Figure 8: Cooling setpoint optimization

The energy simulations carried out have given the results summarized in Table 4.

Although each single intervention yields only modest energy savings, adding them together allows achieving a reduction of the Primary Energy Index (PEI) of 6.6%, bringing it very close to the target fixed by the designers.

Table 4: Energy simulation results

	Heating load [kWh/y]	Cooling load [kWh/y]	Primary energy index [kWh/m^{2}y]
Initial configuration	158,345	189,676	64.71
Dew point nat. vent.	158,346	187,284	64.53
Optimized setpoints	156,104	188,238	64.37
Summer RH set point	158,345	140,374	60.96
Optimized config.	**156,106**	**136,483**	**60.43**

CONCLUSION

We have performed a sensitivity analysis to determine the control parameters that may be worth optimizing. Based on the results of this analysis, we have run a parametric analysis on possible building configurations.

As already stated, PMV varies between 0.12 and 0.66, so people are mostly comfortable. As the building is both heated and cooled, the comfort is affected mainly by the kind of activity, clothing and radiant temperature. The differences in PMV in absolute values are all rather small. Thus, it may be more convenient to keep the loads down than to push on comfort.

Our analysis pursues two purposes. First, it tells the building energy manager which parameters affect energy consumption and user comfort and should therefore be constantly monitored and kept under control. Second, it demonstrates how energy savings and benefits on comfort can be achieved by optimizing control without additional costs for new infrastructure or components.

This type of analysis and approach can be easily applied to all buildings, both new and existing.

Our monitoring experience has shown that ineffective or incompatible control strategies in buildings may lead to a large waste of energy (up to 20% total primary energy consumption [3]). Applying the optimization measures presented here to these buildings will most certainly reduce their energy requirements at virtually no cost.

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