Improving HVAC systems energy efficiency with cloud-based control algorithms - application to a shopping mall

TIZIANA BUSO
Enerbrain
*Corresponding author's email: t.buso@enerbrain.com

MARTIN VAHI
Enerbrain Nordics

STEPHANIE AUMANN
Enerbrain

JACOPO TONIOLO
Enerbrain,
Politecnico di Torino

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Abstract

The article presents the energy saving achieved thanks to the implementation of a retrofit measure applied to the Building Management System of an Estonian shopping mall. The retrofit project upgraded the HVAC-related BMS control features by exploiting IoT and ICT technologies and cloud-based machine learning algorithms. The application resulted in energy savings up to 45% with respect to heating and ventilation energy use of the whole building.

Introduction

In September 2020 the European Commission proposed to raise the 2030 greenhouse gas emission reduction target to at least 55% compared to 1990, as a stepping stone to the 2050 climate neutrality goal. To achieve this result, the EU should reduce buildings' greenhouse gas emissions by 60% (European Commission, 2020). Considering that at present roughly 97% of the EU's building stock is not energy efficient, and that only approx. 1% of the existing buildings is renovated each year (BPIE, 2020), the implementation of energy efficient retrofit measures for buildings has to accelerate significantly in the next decade.

With "energy efficiency first" and "affordability" among the guiding principles for this much longed Renovation Wave, advanced Building Automation and Control Systems (BACS) can play a major role in scoring the goal, as they can generate energy savings with rather low investment and installation burden (eu.bac, 2019).

The official definition of BACS is given by the European Standard EN 15232-1:2017 (CEN, 2017). The standard provides classification for these systems according to their energy efficiency from class D, not efficient, to class A, high performing, and quantifies the energy saving potential of high efficiency BACS (savings up to 96%). EN 15232-1 also defines the minimum functions that make high efficiency BACS capable of reaching the estimated savings: it requires the Technical Building Systems to be managed based on the monitored building status and predicted needs, optimizing occupants' comfort, maintenance and energy use. As concluded by the EPBD (European Parliament, 2018), these requirements will become mandatory for non-residential buildings with rated output for heating and ventilation of >290 kW, i.e. for the majority of the non-residential building stock, as of January 1st 2025.

The increasing implementation of Internet of Things (IoT) and Information and Communication Technologies (ICT) in buildings, which support an easier availability of a huge amount of building-related data, can hasten the adoption and further increase the impact of BACS for optimizing the energy performance of the building stock, leveraging the great opportunities provided by the current advances in applied Artificial Intelligence (AI) (Brandi et al., 2020).

This article aims at providing evidence of the energy saving potential of high performing, AI-powered BACS for the control of the Heating, Ventilation and Air Conditioning system of a tertiary building. Specifically, the following sections describe the solution implemented and the energy savings achieved in an Estonian shopping mall thanks to the implementation of the Enerbrain System - a cloud-based solution for the control of existing HVAC systems using IoT technologies and Machine Learning algorithms.

Case study

Building

The subject of this article is a three-floor, 30 000 m² shopping mall in Narva (Estonia), hosting over 50 commercial activities including a supermarket, a cinema and bowling facilities. The mall is open to the public from Monday to Sunday from 8:00 to 24:00, with opening hours varying from activity to activity.

Heat is supplied to the building by the municipality district heating, while chilled water is provided by three air cooled chillers. The main components of the HVAC system are five Full Air Handling Units, whose details are listed in **Table 1**.

The HVAC system is controlled by a Building Management System (BMS) and some independent local controllers, set up to maintain the desired indoor environmental conditions, listed below:

- Heating set-point: 22°C (heating season: October–May)
- Cooling set-point: 25°C (cooling season: June–September)
- Relative Humidity acceptability range: 30–50%
- CO_2 level acceptability threshold: 1 000 ppm

The mall's typical annual HVAC-related energy consumptions total to approximately 3 000 MWh of district heating and 1 700 MWh of electricity.

Table 1. *Features of the main HVAC components of the shopping mall.*

Building Area	HVAC component						
	Name	Year of installation	Heating Coil	Cooling coil	Supply Fan	Extract Fan	Other features
			Power [kW]	Power [kW]	Air flow [m³/h]	Air flow [m³/h]	
Shops area	AHU 1	2006	414.2 kW	340 kW	80 280	73 440	_VFD _Recirculation damper _Rotary heat exchanger
Cinema	AHU 2	2006	97 kW	61.4 kW	14 163	12 838	_VFD _Rotary heat exchanger
Shopping Center	AHU 3	2013	589.7 kW	374.5 kW	79 200	79 200	_VFD _Recirculation damper _Rotary heat exchanger
Supermarket	AHU 4	2013	62.56 kW (1) 160.68 kW (2)	118.7 kW	22 320	19 080	_VFD _Recirculation damper _Rotary heat exchanger
Shopping Center	AHU 5	2013	432.9 kW	319.1 kW	75 600	75 600	_VFD _Recirculation damper _Rotary heat exchanger

The goal of the building owner was to improve the energy efficiency of the HVAC system, thus reducing the related operational expenditures, without compromising occupants' comfort and with no major modifications to the existing set-up.

Implemented solution

The solution implemented to meet the stakeholders' expectations is made up of **IoT sensors, metering devices and controllers, and cloud-based adaptive and predictive algorithms**.

To avoid any changes to the installed components or to the existing BMS infrastructure, a "Man in the Middle" approach was proposed, i.e. the provision of a new control system to be positioned between the existing control system (the BMS) and the physical component steered by it.

Specifically, in "Man in the Middle" applications of the Enerbrain solution, IoT controllers are installed to act on selected actuators/controllers of the already in place HVAC system (e.g. to modulate fans speed by controlling VFD (Variable Frequency Drive) - see **Figure 1**. These actions on HVAC components are dictated by commands elaborated by the Enerbrain algorithm, that uses as inputs for its commands the desired settings for the building (e.g. temperature set-points and schedules), a number of external variables gathered in cloud (e.g. weather data) and the real-time conditions (e.g. indoor temperatures, CO_2, fluid temperatures) monitored by newly installed IoT wireless sensors.

Table 2 details the HVAC components and actuators object of the Enerbrain intervention in the shopping mall.

Figure 1. IoT controllers controlling the VFDs of supply and extract fans of AHU 1.

Table 2. *The Enerbrain "Man in the Middle" solution implemented.*

Building Area	HVAC component	Actuators/controllers under Enerbrain control	Indoor parameters monitored by Enerbrain
Shops area	AHU 1	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration
Cinema	AHU 2	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration
Shopping Center	AHU 3	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration
Supermarket	AHU 4	Pre-Heating coil valve Cooling coil valve Post-Heating coil valve	Air temperature Relative Humidity CO_2 concentration
Shopping Center	AHU 5	Heating coil valve Cooling coil valve Supply fan VFD Return fan VFD	Air temperature Relative Humidity CO_2 concentration

Note that for each HVAC component under consideration, the signal from/to the existing control system is maintained, and overwritten by Enerbrain control only when the Enerbrain System is active.

Additionally, monitoring devices were installed to provide sound evidence of the energy savings generated thanks to the optimized control of the above listed AHUs' (Air Handling Units) components:

- **electricity monitoring** devices able to measure the power of individual circuits were installed **for the five AHUs (fans electricity use) and for the three chillers;**
- daily readings of the **building District Heating meter** were gathered by installing a remotized digital camera.

Energy saving

Assessment method

To offer accurate projections of the energy savings achievable thanks to the optimized control of the five Air Handling Units, **Proof of Concept (POC) periods** were scheduled before the official activation of the new advanced control system. The winter POC period lasted from October 2019 to February 2020, the summer POC from May to June 2020.

The two POCs took place in "ON/OFF" mode, alternating weeks OFF to weeks ON. Indeed, thanks to the Enerbrain "Man in the Middle" technical approach, the new system can be easily activated (Enerbrain ON) and deactivated (Enerbrain OFF) via a web application. In OFF periods the HVAC system was managed according to the existing control logics (e.g. by the BMS commands); in ON periods, the HVAC system was managed according to Enerbrain control logics (i.e. by the adaptive and predictive algorithms).

By applying the proper calculation method, the energy consumption in OFF periods can be compared to the energy consumption in ON periods, thus providing reliable results of the energy saving potential.

The savings calculation method used in this article is compliant with the guidelines given by the International Performance Measurement and Verification Protocol (IPMVP). The method involves the identification of a **calculation-based energy model** that describes the normal behaviour of a building's energy consumption, which can then be used as a **baseline** for comparison with the consumption measured after the implementation of an Energy Conservation Measure - in our case the installation of an advanced BACS. The **savings**, or rather, the "avoided consumption", is determined by the difference between the post-intervention measured consumption and the baseline energy model adjusted according to the variables.

Results and discussion

Energy

Figure 2, 3 and 4 display the recorded energy consumptions in Enerbrain OFF and ON periods for the whole building heating energy use, for the five AHUs and for the three chillers respectively.

In line with IPMVP prescriptions, the following approaches were applied to build the baseline energy models:

- **District Heating (DH) energy use**: linear regression equation using HDD_{20} as independent variable. The regression model is built by plotting the daily DH energy use monitored in days OFF with the corresponding HDD_{20}, derived from the nearest weather station (Weather station ID 26058, Narva. Data source: www.degreedays.net). **Figure 5** displays the plotted data and the resulting linear regression

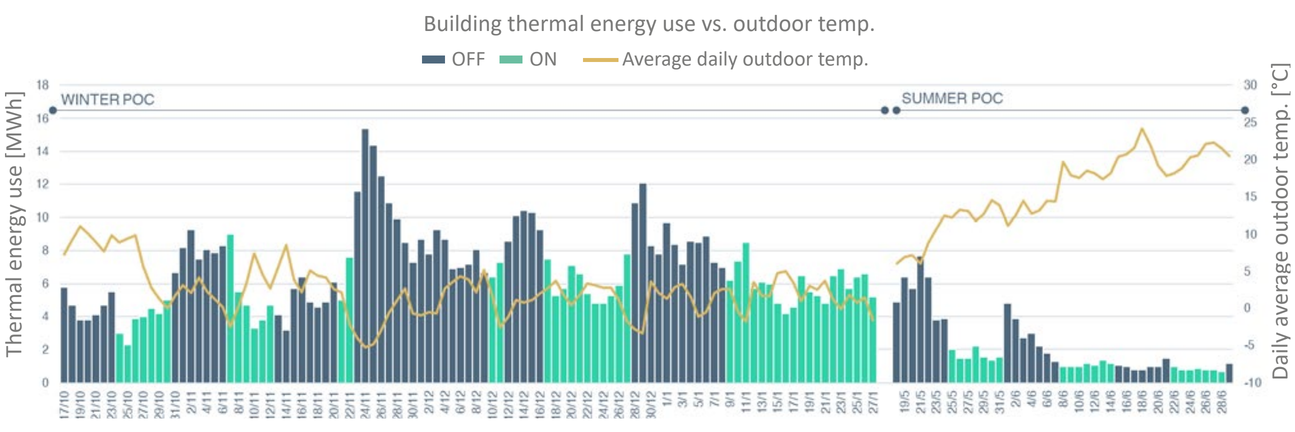

Figure 2. Recorded daily District Heating energy use of the whole building during Winter and Summer POCs.

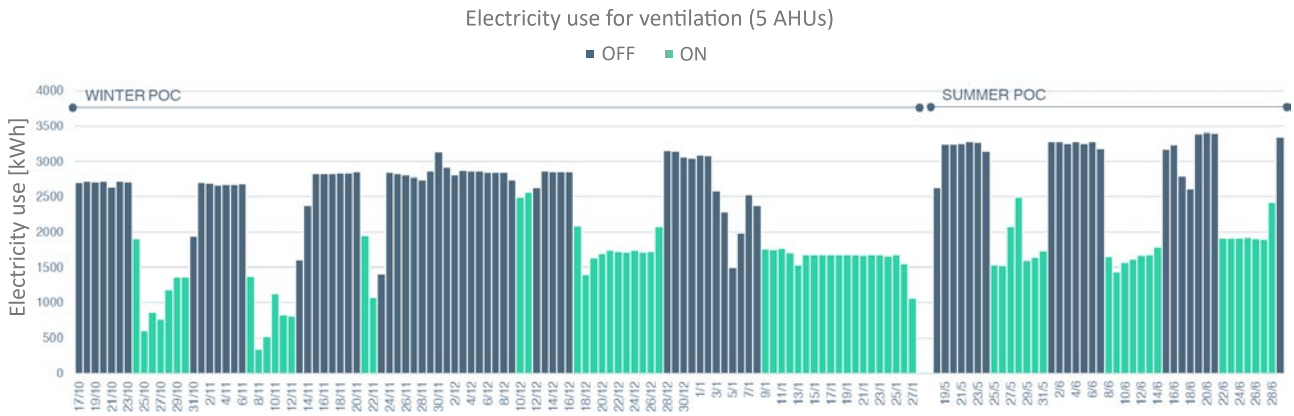

Figure 3. Recorded daily electricity use of the AHUs during Winter and Summer POCs.

equation describing the baseline District Heating energy use, i.e. the energy use without Enerbrain control in place.

- **AHUs energy use:** daily average consumption. No normalization factor applied because of the constant energy use profile detected.

Chiller's energy use: linear regression equation using outdoor temperature as independent variable. The regression line is built by plotting the daily electricity use of chillers monitored in days OFF with the corresponding daily average temperature, derived from the nearest weather station.

For each energy use, the energy savings were calculated by comparing baseline energy use calculated for the days of Enerbrain ON with the actual energy use monitored in those days. The resulting figures are summarized in **Table 3**.

Table 3. *Calculated energy savings during Winter and Summer POCs.*

Energy vector	Energy use	Energy savings	
		Winter POC	Summer POC
District Heating	Heating	29%	45%
Electricity	Ventilation (5 AHUs)	45%	43%
	Cooling	-	6%

These results are in line with the energy efficiency projections provided in EN 15232-1:2017, which estimates that in wholesale buildings a high performing BACS can improve the overall energy performance of up to 40% with respect to a standard BACS.

Comfort

The installation of IoT environmental sensors in all the areas served by the controlled AHUs allowed

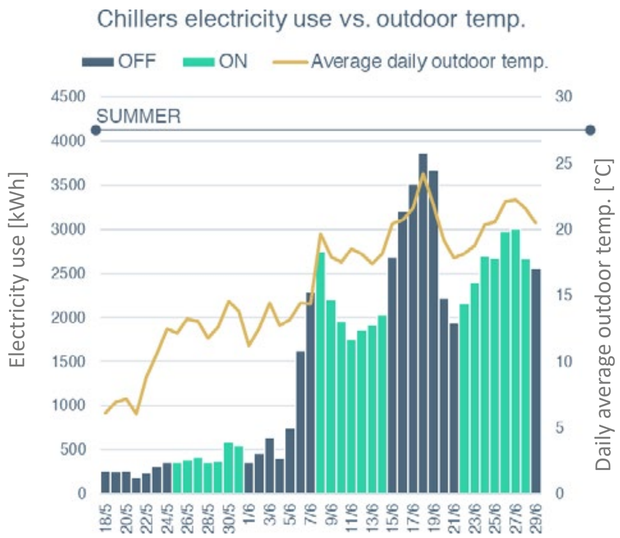

Figure 4. Recorded daily electricity use of the chillers during the Summer POC.

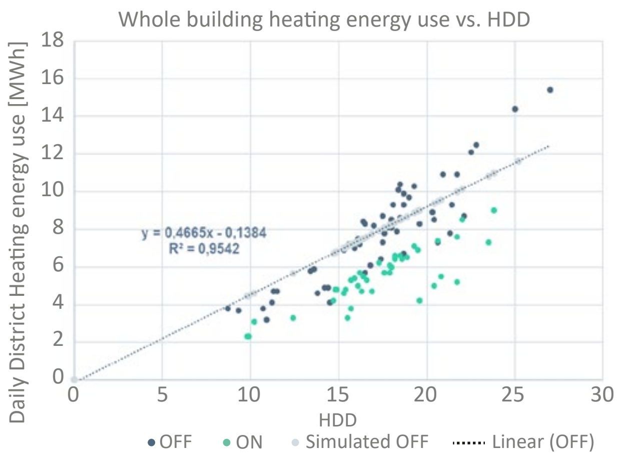

Figure 5. Daily DH energy use versus HDD, and linear regression equation resulting from the plotted data in OFF days.

building managers to verify if the achieved energy savings jeopardised the indoor comfort conditions. **Figure 6**, by displaying the hourly average temperatures recorded for each area for the whole POC duration, gives evidence that **similar comfort conditions were maintained in OFF and ON periods**.

Conclusion

This article describes the implementation of a solution to upgrade the BMS control features in a shopping mall, making it possible to have the features of an advanced BACS. Indeed, by exploiting IoT and ICT technologies and AI, the proposed solution offers the opportunity to continuously analyse the real-time conditions of the HVAC system and to modify control settings accordingly.

This retrofit measure, implemented to steer only selected components of the HVAC system via a non-invasive installation, resulted in energy savings up to 45% with respect to heating and ventilation energy use of the whole building, with no consequences on the indoor environmental quality levels.

Such results provide further evidence of the crucial role of building controls systems in supporting the transition toward an energy efficient building stock, able to meet both the long term EU carbon neutrality expectations as well as the short term building owners' financial KPIs. ■

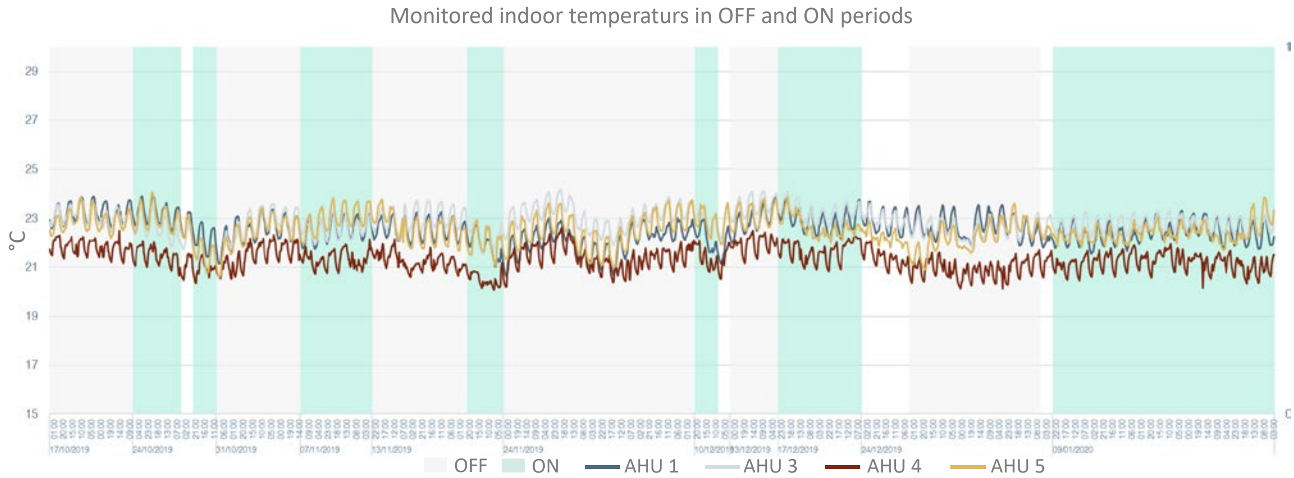

Figure 6. Hourly average indoor temperatures monitored in the areas served by the controlled AHUs.

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