ANALYSIS OF SMART BUILDING SOLUTIONS FOR OPTIMIZING THE ENERGY PERFORMANCE IN A NEW COMMERCIAL BUILDING

by

Norbert HARMATHY[*]

Department of Building Energetics and Building Service Engineering, Faculty of Architecture,
Budapest University of Technology and Economics, Budapest, Hungary

Original scientific paper
https://doi.org/10.2298/TSCI210410308H

Contemporary commercial building's demonstrate performance from a sustainability and environmental perspective. Usually, an appropriate energy performance is achieved using efficient mechanical systems, however, the operation method with smart control is significant in the overall energy consumption. The research follows a two-year design and construction process of a commercial building where the integration of smart technology was a mandatory requirement by the owner, alongside with the prerequisites of the LEED® green building certification. The goal was to design, build and optimize the performance of the new Innovation Campus commercial office building complex using smart building solutions. The research was performed with energy modelling and dynamic simulation until completion of the building, where the design and investment decisions were constantly evaluated. The new optimized building's performance demonstrated 42% of annual energy reduction and 34% of cost reduction according to the ASHRAE 90.1 Appendix G baseline Benchmark building.

Key words: *smart building, energy modelling, dynamic simulation*

Introduction

A lot of effort regarding energy savings has been spent due to large environmental problems and limited fossil energy sources. According to the European Energy and Climate Change Policy and its targets for 2050, different options and solutions are explored to reduce greenhouse gas emissions. The EU's first step is to reduce the energy demand of buildings through compliance with envelopes thermal property regulations and afterwards the utilization of efficient HVAC systems and renewable energy sources to cut down the buildings carbon footprint. [1, 2]

The motivation behind the long-term, two-year, research was to continuously inform the investor, designers, and engineers to incorporate a multi-criteria analysis procedure with dynamic simulation starting from the early phases of design to achieve high performance in the post construction phase. During the development process integrated design approach was prioritized and team members were continuously communicating together to formulate efficient solutions and evaluate their decisions.

The research scope was to integrate smart building solutions within a complex commercial office building, to evaluate its feasibility during the design and construction process. The HVAC automation was modeled and simulated in every phase of the project development

---

[*] Author's e-mail: norbert.harmathy@edu.bme.hu

to optimize the overall energy performance of the building, and to prepare the investment for adequate decision making. The smart building technology with the modeled building management system aided the investor and the design team to follow iteratively the whole design and construction process to make appropriate performance-oriented decisions, which will be verified during the post-construction phase when the building is operating.

Applied research method was dynamic simulation evaluate the energy reduction and economic benefits using smart building solutions in an office building for the climate conditions of Hungary. The dynamic simulations were performed according to the ANSI/ASHRAE 90.1 2010 standard [3] with IESVE software [4]. The European weather data for Budapest were used from the data packages of ASHRAE Climate Design Conditions and EP Weather Data by Region [5]. Local energy efficiency standard was also considered during the energy modelling process, and TNM (v.24.) 7/2006 version 2020 local regulation [6].

Integrated design process and dynamic energy simulation is widespread in the field of energy performance optimization during the planning and construction process. Dynamic simulation is used in determining hydrothermal properties of building assemblies, thermal comfort, HVAC system energy consumption, energy conservation techniques, *etc*. [7, 8]. Green buildings are also a new and innovative topic in mechanical engineering research, which is essential for achieving international Green building certification [9, 10]. Taken into consideration new technologies the energy performance testing methods with computational technologies is also emerging [11-14] In our previous research, we used multi-criteria optimization methodology to determine an optimal energy retrofit solution in case of adequate building envelope selection [15] and to accelerate the utilization of renewable energy sources for decarbonization in the commercial building sector [16]. Our previous research demonstrated an optimized building envelope model using multi-criterion optimization methodology to determine efficient window to wall ratio and window geometry in the function of indoor visual comfort, followed by the assessment of envelope's influence on the annual energy demand. Energy and environmental performance assessment should be parallelly analyzed [17, 18]. Smart building strategy is also a widespread topic for improving the energy performance, environmental awareness, and occupant comfort in buildings [19-23]. Energy performance strategies and various HVAC systems were analyzed in our previous research [24, 25]. The research evaluates the overall energy performance and operational costs of a 45171 m^2 gross floor area commercial office building of the modern Innovation Campus in Budapest, developed by Wing Ltd. [26] The whole design and the construction process of the building was aided and followed by dynamic simulation of the complex to optimize its performance and overall energy consumption. The simulation was used in the decision-making process, helping the investor and the design and construction team to make the building more energy efficient and optimized for the indoor climate conditions of occupants. The paper elaborates the complete design and construction stage of the represented office building and uses applied engineering solutions which were incorporated from the results of the building simulation.

Materials and methodology

Thermal modelling strategy

The construction of new buildings on a brownfield requires a complex remediation process, however it reflects to the environmental awareness of the investors, due to the reduction of greenfield developments. From many aspects the architectural and engineering task is difficult, due to site, location, renewable energy supply and shading from surrounding buildings. The research methodology is demonstrated on the 45171 m^2 gross floor area commercial office building of the modern Innovation Campus in Budapest. The indoor office spaces with additional functions cover 27558 m^2 of gross area, 17613 m^2 is underground parking space. The representations of the multi-zone thermal model is shown in fig. 1, and a photograph of the finished building in fig. 2. According to the parcel regulations the building has six floors above ground with 3 m of usable height per story, and 4 levels of underground parking, including the technical and mechanical spaces. The thermal model consists of 274 thermal zones. The underground parking was excluded from the zoning calculation since neither heating, nor cooling is required. However, demand control ventilation (DCV) is mandatory in the parking garage for CO exhaust and jet fans in case of fire protection, which is included in the additional fans.

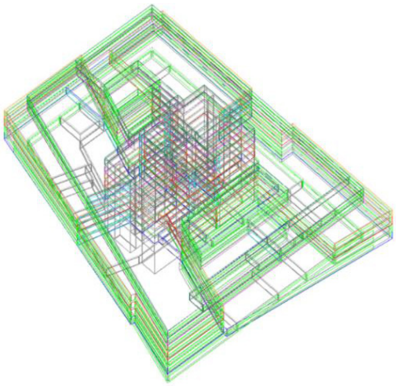

Figure 1. Thermal model

Figure 2. Innovation Campus office building [27]

The determination of building performance was assessed using the performance rating method where the designed (Proposed) building's performance is compared to an identical ASHRAE 90.1 *Appendix G* [3] benchmark building (Baseline). Two multi-zone models were created, taking into consideration the thermal properties, mechanical and electrical system, lighting, building operation, smart HVAC automation, energy consumption and operational costs for the following short descriptions:

- *Baseline building* according to ASHRAE 90.1 2010 *Appendix G* with HVAC System 7, variable air volume with reheat and economizer high limit shut-off, district energy system using utility district hot water for heating, water cooled chillers with cooling tower heat rejection, and
- *Proposed building* according to EU energy efficient building directive in Hungary, TNM (v.24.) 7/2006, version 2020 local regulation with dedicated outdoor air system, constant air volume, free-cooling economizer, water cooled chillers and dry-cooler heat rejection and district energy system (DES) using utility district hot water for heating, and air source heat pumps as renewable energy.

The energy performance analysis had the following focus:

- multi-zone thermal modelling and whole-building energy performance simulation,
- the HVAC system simulation and end-use energy determination for downstream equipment,
- smart building solutions in overall energy performance optimization, and
- total energy and cost saving potential.

Outline of the energy design concept

The energy design concept took into consideration the integrative design method, which addressed various design aspects:

- *Application of high performance glazing* and envelope with better thermal characteristics of construction assemblies compared to ASHRAE 90.1 climate zone 5A construction. [3] Thermal transmittance of building envelope and curtain-wall was determined according to Hungarian Energy Efficiency regulations [6].
- *Use of district heating* instead of gas furnaces, due to lower carbon footprint.
- *Installing efficient low flow fixtures* to minimize domestic hot water energy consumption.
- *Efficient interior lighting* design to decrease the lighting power density.
- *Air-Side HVAC* system applications:
  - Application of heat recovery system with high efficiency,
  - Plate heat exchangers with 84% efficiency,
  - Rotary heat-wheel exchangers with 74% efficiency, and
  - Efficient air source heat pump for pre-heating and pre-cooling of outdoor air for the air handling units (AHU): AHU-1, AHU-2, AHU-3, AHU-4, and AHU-5.
- *Water-Side HVAC* system applications:
  - Application high efficiency waterside heat recovery system,
  - Free-cooling plate heat exchangers approximately 1000 kW,
  - Efficient electric water-cooled chillers with dry coolers heat rejection, and
  - Air cooled chillers and standalone free cooling unit for cooling of server rooms and patch rooms.
- *Integrated Smart building solutions* for HVAC automation, since high performance can only be achieved by appropriate building operation with the following:
  - Heating and cooling system control according to outdoor air dry-bulb temperature,
  - The DCV, fresh air supply according to CO_2 sensors in conference rooms,
  - Demand-response program integration shift power loads, with the building management system,
  - Free-cooling economizer for the AHU preheating and precooling,
  - Smart elevators, for better efficiency, and
  - Reduced lighting density and dimming module.

Weather data

The climate data was used from the Meteonorm [28] Swiss global database approved by ASHRAE. The weather data for Budapest were used from the data packages of ASHRAE Climate Design Conditions which are shown in tab. 1. The location and weather data were imported from EP Weather data center [5]. The imported weather data were design conditions for HVAC system sizing from *Climate Design Data 2009 ASHRAE Handbook*. ASHRAE design conditions are generated in an EPW format for a period of 30 years suitable for the use of heating and cooling load calculations and energy consumption modelling. [5]

Table 1. Weather file for Budapest from ASHRAE Climate Design Conditions

<table>
<tr><th colspan="5">Extreme annual design conditions</th></tr>
<tr><td rowspan="3">Extreme max wet-bulb temperature [C]</td><td colspan="4">Extreme annual dry-bulb temperature [C]</td></tr>
<tr><td colspan="2">Mean</td><td colspan="2">Standard deviation</td></tr>
<tr><td>Min</td><td>Max</td><td>Min</td><td>Max</td></tr>
<tr><td>26.8</td><td>–16.0</td><td>34.9</td><td>3.2</td><td>1.9</td></tr>
<tr><td colspan="5">Sizing runs according to ASHRAE 90.1 2010, <i>Appendix G</i> section G3.1.2.2.1.
(system sizing runs shall be based on historical hourly weather data containing peak conditions)</td></tr>
<tr><td>Coldest month</td><td>January</td><td colspan="3">Heating system sizing, 99% for heating design temperature</td></tr>
<tr><td>Hotest month</td><td>July</td><td colspan="3">Cooling system sizing, 1% for cooling design temperature</td></tr>
</table>

Building design and properties

All new buildings in Hungary must comply with the European Regulations and Hungarian requirements of the TNM 7/2006 (V 24.) version 2020 on the Determination of the Energy Efficiency Characteristics of Buildings. For this project the team used more stringent regulations compared to ASHRAE 90.1 2010. The building envelope was designed according to the thermal transmittance values of TNM 7/2006 (V 24.) regulation *Appendix 6* Nearly Zero Energy building.

Thermal characteristics: The heat gains and losses due to high performance envelope were minimized, thus resulting in less energy consumption for heating and cooling.

District heating: We have analyzed different heat sources and systems and concluded to use DES district hot water, which is more efficient, and a more environmentally friendly way of heating compared to gas furnaces. The DES was modeled with purchased heating in the baseline and proposed case. Local annual flat-rates for purchased heating were used to determine the costs. The energy models accounted for the downstream equipment and purchased heating according to DES Path 1: ASHRAE 90.1-2010. The district heating energy system in Hungary over the past five year started utilizing renewable energy sources by 10-20% depending from the provider, thus making each year the system more efficient.

Optimizing domestic hot water: During the project design the team decided to apply district hot water for domestic hot water production in spaces where large amount is needed, as for the main kitchen/restaurant, showers, and sanitary block in the basement. Electric boilers are provided for each sanitary block on each floor of the office building where hot water is only necessary for hand washing. Thus, the energy consumption due to the strategic energy planning is more efficient. Efficient low flow fixtures were installed to minimize domestic hot water energy consumption. According to the results, annual baseline water consumption is 9297825 liters per year; annual design water consumption 5473750 liters per year; where the total annual percent of water use reduction is 41.13%.

Interior lighting design – Decrease the LPD below standard value: The team's decisions was to decrease the energy consumption of interior lighting by using efficient interior lighting design to decrease the lighting power density (LPD) below the LEED standard value. According to the ASHRAE 90.1 the maximum allowable interior lighting power density (including parking) is 7.46 W/m^2. Our analysis shows that it is cost effective to reduce interior lighting value with high efficiency LED lamps to 5.62 W/m^2 LPD (including parking), as seen it tab. 2. With this intervention we can reduce the lighting energy demand and passive heat gains which contribute to less cooling demand.

People, infiltration, and ventilation for the office spaces is shown in tab. 3.

Simulation methodology and input data

Multi-zone thermal model representation

The modelling process was performed according to the ASHRAE 90.1 *Appendix G* standard. The baseline building was modeled with the same number of floors and identical conditioned floor area as the proposed design, the space types, space use classification, building operation and schedules, thermal blocks – HVAC zoning was identical as in the proposed building.

The differences were the building envelope's window to wall ratio (WWR), as seen in tab. 4, the HVAC system, and the proposed smart technology using HVAC automation. The 3-D thermal zone models with its surrounding buildings are shown in figs. 3 and 4, where the proposed 50.9% WWR and baseline 40% WWR is applied.

Table 2. Interior lighting design

Space type	Total space type area [m^2]	Baseline maximum allowance [Wm^{-2}]	Proposed design LPD [Wm^{-2}]
Office – enclosed	918	11.90	9.00
Offce – open plan	17 899	10.50	9.00
Conference/meeting/multipurpose	828	13.20	9.00
Classroom/lecture/training	160	13.30	9.00
Laboratory – medical/industrial/research	1 666	19.50	9.00
Electrical/mechanical	1 788	10.20	6.00
Dining area – bar lounge/leisure dining	714	14.10	5.00
Corridor/transition	1 710	7.10	5.00
Storage	676	6.80	3.00
Lobby	384	9.68	5.00
Restrooms	815	10.50	5.00
Parking garage – garage area	17 613	2.00	1.70

Table 3. People, infiltration, and ventilation

Definition	Value	Unit
90.1-2010 – Open office people definition	8	[m^2 per people]
90.1-2010 – Open office infiltration per exterior surface area	0.007	[m^{3}h^{-1}m^{-2}]
90.1-2010 – Open office ventilation (outdoor fresh air method)	40	[m^{3}h^{-1} per person]

Table 4. Above grade wall and vertical glazing area by orientation

	Baseline			Proposed		
Orientation	Above grade wall area [m^2]	Vertical glazing area		Above grade wall area [m^2]	Vertical glazing area	
		[m^2]	[%]		[m^2]	[%]
North	2627	1080	41.1%	Identical to baseline	1355	51.6%
East	2236	902	40.3%	Identical to baseline	1146	51.3%
South	2672	1083	40.5%	Identical to baseline	1378	51.6%
West	1810	682	37.7%	Identical to baseline	874	48.3%
Total	9345	3747	40.1%	9345	4753	50.9%

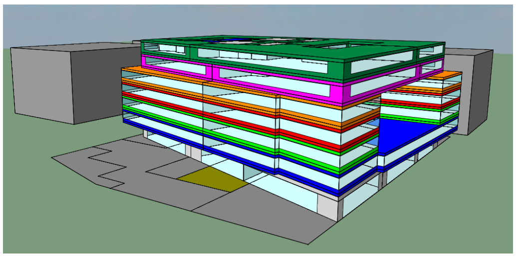

Figure 3. Proposed window to wall ratio

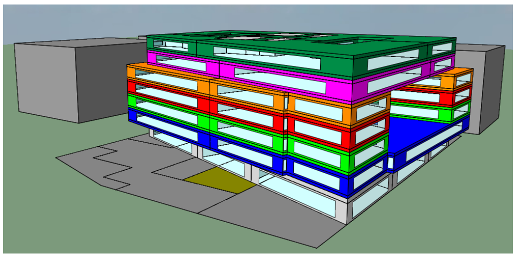

Figure 4. Baseline window to wall ratio

Input data of thermal models

The building constructions thermal properties and fenestration properties were determined according to the Hungarian Energy Efficiency Regulations (TNM energy efficiency regulation 7/2006 *Appendix 5* for construction thermal properties and *Appendix 6* for nearly zero energy performance buildings) [6]. The bearing structure is reinforced concrete. The building envelope is curtain wall system with 50% of glazed area and 50% shadow-box area. The thermal transmittance of the glazing assembly with frame is 1.4 [$Wm^{-2}K^{-1}$]. The fenestration is steel framed double-glazing system with Argon gas and low-E layer. The building has three types of vegetated roof with different soil thicknesses. The resulting thermal transmittance properties of the building construction for both baseline and proposed building are shown in tab. 5. The Baseline building construction is modeled according to ASHRAE 90.1 *Appendix G*, Climate zone 5A. All detailed information can be found in the standard. Further explanation for tab. 5. is: acc. to ASHARE 90.1 *F-factor* is the perimeter heat loss factor for slab-on-grade floors. Acc. to ASHARE 90.1 2010 *C-factor* (thermal conductance) is the time rate of steady-state heat flow through unit area of a material or construction, induced by a unit temperature difference between the body surfaces. Assembly is without air film resistances.

Table 5. Baseline and Proposed building construction thermal properties

Above grade envelope summary			
Construction	Baseline *U*-factor [$Wm^{-2}K^{-1}$]	Proposed *U*-factor [$Wm^{-2}K–1$]	
Exterior wall	0.365	(shadow-box curtain wall) 0.22	
Roof non-walkable	0.273	0.16	
Green roof type 1	0.273	0.17	
Green roof type 2	0.273	0.14	
Green roof type 3	0.273	0.13	
Below grade envelope summary			
F-factor and C-factor	Baseline [$Wm^{-}2K^{-1}$]	Proposed [$Wm^{-}2K^{-1}$]	
Construction F-factor ground floor	0.214	0.88	
Construction C-factor underground wall	0.678	0.47	
Exterior fenestration			
Construction	Fenestration assembly *U*-factor [$Wm^{-2}K^{-1}$]	Glass SHGC, *g*-value	Glass visible transmittance
Baseline exterior window with frame	2.56	0.4	0.6
Proposed exterior window with frame	1.26	0.3	0.6

Building operation schedule and HVAC design parameters

The thermostat schedules were set according to the following date, time intervals and indoor air temperature levels as shown in tab. 6. The air temperature (AT) setpoints were assigned according to the EN ISO 7730 [29]. The default schedules and indoor AT setpoints as seen in tab. 6 were identical in both thermal models, including throttling ranges of 2 °C during occupied hours.

Table 6. Thermostat schedules

Schedule	Date	Time	Indoor air temperature
Heating set-up schedule	01.10. – 31.03.	Monday to Friday 6 a. m. – 22 p. m.	21-23 °C
		Monday to Friday 22 p. m – 6 a. m.	Minimum 16 °C
		Weekend 0 a. m – 24 p. m.	Minimum 16 °C
Cooling set-up schedule	01.04. – 30.09.	Monday to Friday 6 a. m. – 22 p. m.	24-26 °C
		Monday to Friday 22 p. m. – 6 a. m.	Maximum 28 °C
		Weekend 0 a. m. – 24 p. m.	Maximum 28°C

Results with discussion

According to LEED v4 Green building certification in the Energy and Atmosphere category credits for optimizing building energy performance reflect the economic improvement of the energy performance. The building operation is reflected through achievement of increasing levels of energy performance beyond the prerequisite standard to reduce environmental and economic harms associated with excessive energy use [30].

The HVAC system sizing for Baseline and Proposed was performed according to the microclimatic condition criteria for occupant thermal comfort. The validation of the HVAC systems sizing was determined according to the operative temperature oscillation ranges in the building, to have identical indoor climate conditions in all three scenarios. The calculation method for system sizing in IESVE is validated and accredited by ASHRAE 140, ISO 52000, CIBSE TM33 [31]. The software has the capability to simulate multiple-zone interactions on both thermal and mechanical equipment level in the thermal model. It also models hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat setpoint, and HVAC system operation separately for the thermal zones. The applied calculation methods were the following [31]:

- *Building physics*: Heat Balance model, Heat Air and Moisture Transfer (HAMT) model.
- *Mechanical system*: the loop and HVAC equipment sizing were performed according to the Design Weather data, external and internal gains, and thermal comfort criteria according to validated calculation methodology.

Figures 5 and 6 shows the *IES-ApacheHVAC* interface of the system modelling protocol with the air side HVAC loop where the heating, cooling units, fans, heat recovery, thermal zone group and controls are visible.

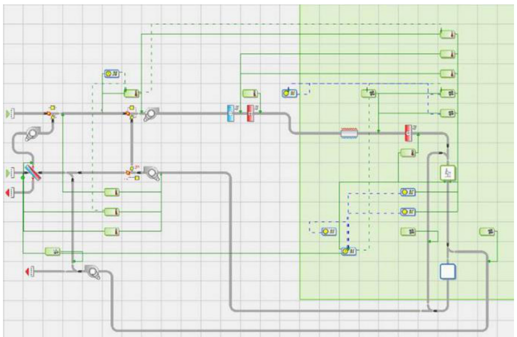

Figure 5. Baseline VAV system interface

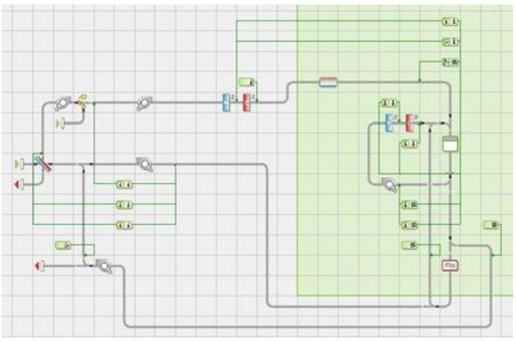

Figure 6. Proposed DOAS system interface

Baseline HVAC VAV with reheat, fig. 5, was sized according to ASHRAE 90.1 2010 *Appendix G* with HVAC System 7 VAV consisting of hot, chilled and condenser water loops including the sized components.

Proposed HVAC DOAS with FC and packaged rooftop heat pump, fig. 6, according to energy efficient building minimum requirements. The summary of system and components is presented in tab. 7.

Table 7. Proposed and baseline HVAC system summary

Model input parameter HVAC	Baseline		Proposed	
	Description	Properties	Description	Properties
Primary HVAC	System 7 VAV with reheat	7753 kW	DOAS with FC, heat recovery air-side and water-side, air source heat pump	2394 kW
Secondary HVAC	System 3 packages single zone air conditioning for servers	78 kW	Compact water-cooled chillers with two pipe FC units for servers	344 kW
Fan control and power	VSD, system fan power	447 kW	VSD, system fan power	243 kW
Fan supply air-flow	Supply air-flow	205751 Lps	Supply air-flow	99670 Lps
Economizer control	Air side economizer acc. to ASHRAE 90.1	high limit shut off	Waterside economizer	1006 kW
DCV	Parking and meeting rooms	*n/a*	Parking and meeting rooms	*n/a*
Chiller	Three water cooled chillers	3*2603 kW, SEER 6.17	Three water cooled chillers, waterside heat recovery	3*798 kW, SEER 6.89
Chiller water loop and pump	Primary/Secondary	58 kW/77 kW	Primary/Secondary	44kW/56kW
Hot water loop	District hot water	4200 kW	District hot water	1200 kW
Pre-heating	*n/a*		Air source heat pump	556 kW
Cooling tower	Cooling tower	9133 kW	Dry coolers	3132 kW
Condenser water loop and pump	Riding the pump curve	301kW/1000 Lps	Variable speed pump	275kW/1000 Lps

The validation of the thermal models was performed according to the thermal comfort compliance criteria of ISO 7730 standard. Both models fulfilled the requirements. The tab. 8 shows the indoor air temperature control band for the heating and cooling. From the 274 thermal zones 13 regularly occupied spaces were selected for the South-East (S/E) and North-West (N/W). The indoor air temperatures were in adequate ranges during occupied hours.

Table 8. Indoor air temperature correspondence during occupied hours

Zone	Air temperature [°C] – hours in range		
	< (Heating set point maximum 23 °C –3 °C)	Controlled band During occupied hours	> (Cooling set point minimum 23 °C +3 °C)
1 Open Office S/E	0	2520	0
2 Open Office S/E	0	2519	1
3 Open Office S/E	0	2520	0
4 Open Office S/E	0	2520	0
5 Open Office S/E	0	2447	73
6 Open Office S/E	0	2472	48
3 Open Office N/W	0	2520	0
0 Open Office N	1	2519	0
1 Open Office C N/W	0	2520	0
4 Open Office N/W	0	2520	0
6 Open Office N/W	0	2520	0
2 Open Office N/W	0	2520	0
5 Open Office N/W	0	2520	0

Performance rating output

The smart control system implemented into the Proposed thermal model tended to minimize the HVAC system's power demand. The smart building control included sensor system, used for measuring the indoor air temperature, air velocity, relative humidity, fresh air demand and distribution, water demand in the building. The results are presented as load duration curves for justification of the building automation's contribution shortening the higher power demands on annual basis. As seen in fig. 7 the power demand for the HVAC is categorized as high demand above 350 kW for 400 hours, medium between 200-350 kW and low during total 6260 hours between 50-200 kW. Considering the district hot water demand for heating, in fig. 8 the max power demand is shrinked to 100 hours above 180 kW, middle is between 40-180 kW for 1200 hours and the low demand is below 40 kW for the remaining hours in a year. The building does not use DHW for heating after approximately 3600 hours and the value is 0.

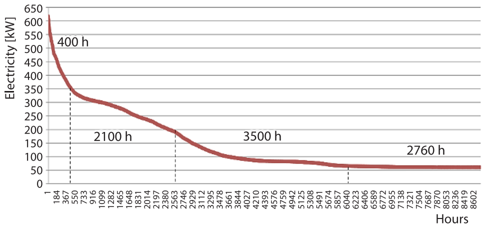

Figure 7. Load duration curve for HVAC power demand

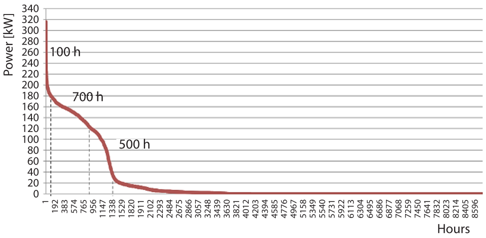

Figure 8. Load duration curve for DHW power demand

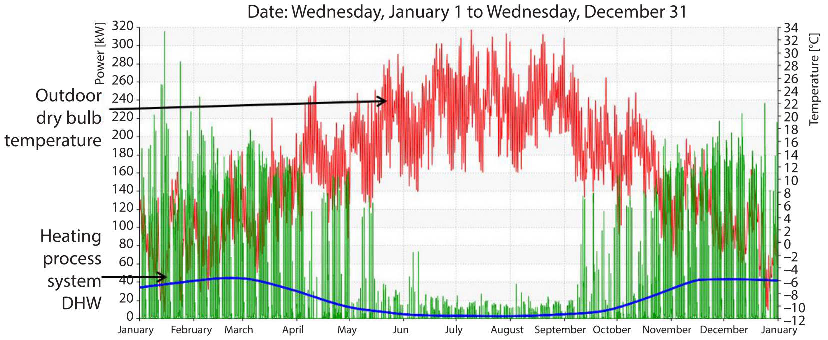

Figure 9. The DHW annual power demand according to outside air temperature

The HVAC system performance and the smart building automation was analyzed in detail. The indoor heating and cooling are controlled by the operating schedule, indoor environmental parameters, which is influenced by the outdoor weather data. One of the basic heating controllers is the outdoor dry-bulb air temperature. As shown in fig. 9 the district heating system receives the information from the BMS and the heating is adjusted according to the outdoor dry-bulb air temperature alongside with the indoor demands.

The same analysis was performed for the cooling system. The HVAC cooling power demand is also influenced by the outdoor weather data. One of the basic cooling controllers is the outdoor dry-bulb air temperature. As shown in fig. 10 the electricity consumption demonstrates both cooling and ventilation, so when no cooling is required during winter period the AHU still consume electricity, as the power demand graph shows from November till April. The AHU power demand for fresh air is identical on workdays as shown. The cooling system receives the information from the BMS and the heating is adjusted according to the outdoor dry-bulb air temperature alongside with the indoor demands.

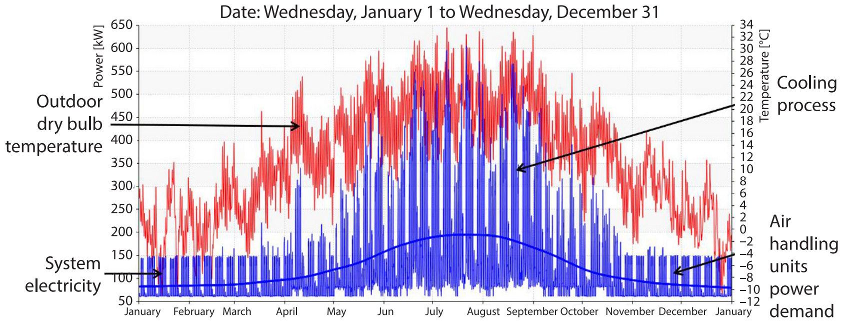

Figure 10. The HVAC system annual power demand according to outside air temperature

End-use and source-use energy consumption

End-use source energy for the HVAC systems was calculated according to the Hungarian source energy conversion factors which is 2.5 for electricity [6]. The economic analysis was performed according to the end-use consumption, as summarized in tab. 9, using Hungarian utility tariffs. The total end-use energy consumption and costs are shown in tab. 10 [32]. The findings demonstrated that Proposed system demonstrated an overall operational cost reduction of 34.7%**.**

Table 9. Building energy consumption and savings due to synergies

End user	Energy type	Baseline annual energy consumption, ASHRAE 90.1 Appendix G [kWh per year]	Proposed annual energy consumption TNM 7/2006 v.24 v.2020 [kWh per year]	Energy savings per end-use category
Interior lighting	Electricity	661 682	413 481	37.5%
Exterior lighting	Electricity	3 896	2 273	41.7%
Space heating	District Hot Water	2 759 058	109 811	96.0%
Service water	District Hot Water	124 227	107 903	13.1%
Air source heat pump	Electricity	0	283 380	–100%
Space cooling	Electricity	679 065	361 568	46.8%
Pumps	Electricity	143 341	171 865	–19.9%
Heat rejection	Electricity	460 589	258 028	44.0%
Fans - interior ventilation	Electricity	982 655	506 630	48.4%
Fans – parking garage	Electricity	13 468	13 468	0%
IT equipment	Electricity	420 080	420 080	0%
Kitchen equip.	Electricity	146 304	146 304	0%
Additional fans	Electricity	2 860	2 860	0%

Table 10. Performance rating energy consumption and savings summary

Energy type	Baseline			Proposed			Percent savings	
	Site energy use [kWh]	Source energy use [kWh]	Cost [$]	Site energy use [kWh]	Source energy use [kWh]	Cost [$]	Site energy use	Cost [$]
Electricity	5 839	18 335	537 225	4 823	15 144	443 722	17.4%	17.4%
DHW	2 883	3 459	161 464	217	261	12 192	92.4%	92.4%
Total	8 722	21 795	698 689	5 040	15 405	455 914	42.2%	34.7%

Conclusion

The utilization of the building simulation during the design process aided the decision making for appropriate investment and performance. Throughout the design and construction phase synergies were drawn to optimize the building operation and HVAC system control. The smart building automation demonstrated lower power demand and energy consumption of the HVAC system which resulted in an overall 42% energy and 34.7% cost reduction.

Further research will include the energy, carbon footprint and economic analysis of various HVAC systems for buildings. The carbon footprint is highly important due to the environmental impact and decarbonization strategy when improving building performance.

Acknowledgment

The research reported in this paper and carried out at BME has been supported by the NRDI Fund (TKP2020 IES, Grant No. BME-IE-MISC) based on the charter of bolster issued by the NRDI Office under the auspices of the Ministry for Innovation and Technology.

Nomenclature

Acronyms

AHU – air handling unit
VAV – variable air volume
SEER – seasonal energy efficiency ratio
DOAS – dedicated outdoor air system
BMS – building management system

References

[1] ***World Energy Council, https://www.worldenergy.org/data/resources/country/hungary/geothermal/

[2] ***National Office for Research and Technology, Hungarian National Environment Protection and Energy Center, https://nkfih.gov.hu/strategy/archive/in-hungary/research-and-development#, 2019

[3] ***, ASHRAE 90.1 2010 Standard, https://www.ashrae.org/resources, 2017

[4] ***, IESVE, https://www.iesve.com/, 2018

[5] ***, ASHRAE Climate Design Conditions, http://ashrae-meteo.info/index.php, 2018

[6] ***, Hungarian 7/2006 TNM Energy Efficiency Regulation for Buildings, https://net.jogtar.hu/jogszabaly?docid=A0600007.TNM, 2019

[7] Kmekovaa, J., Energy Efficient Retrofit and Life Cycle Assessment of an Apartment Building, *Energy Procedia*, *78* (2015), Nov., pp. 3186-3191

[8] Sacht, H., *et al*., Glazing Daylighting Performance and Trombe Wall Thermal Performanceof a Modular Facade System in Four Different Portuguese Cities*, Indoor and Built Environment*, *24* (2015), 4, pp. 544-563

[9] Liu, Z., *et al*., Performance and Feasibility Study of Hybrid Ground Source Heat Pump System Assisted with Cooling Tower for one Office Building, *Energy*, *173* (2019), Apr., pp. 28-37

[10] Vanaga, R., *et al*., Solar Facade Module for Nearly Zero Energy Building, *Energy*, *157* (2018), Aug., pp. 1025-1034

[11] Togashia, E., *et al*., Development of Building Thermal Environment Emulator to Evaluate the Performance of the HVAC System Operation, *Journal of Building Performance Simulation*, *12* (2019), 5, pp. 663-684

[12] Amin, U., *et al*., Performance Analysis of an Experimental Smart Building: Expectations and Outcomes, *Energy*, *135* (2017), June, pp. 740-753

[13] Wolisz, H., *et al*., Cost Optimal Sizing of Smart Buildings' Energy System Components Considering Changing end-Consumer Electricity Markets, *Energy*, *137* (2017), Oct., pp. 715-728

[14] Pavlak, G., *et al*., Evaluating Synergistic Effect of Optimally Controlling Commercial Building Thermal Mass Portfolios, *Energy*, *84* (2015), May, pp. 161-176

[15] Harmathy, N., *et al*., Multi-Criterion Optimization of Building Envelope in the Function of Indoor Illumination Quality Towards Overall Energy Performance Improvement, *Energy*, *114* (2016), Nov., pp. 302-317

[16] Harmathy, N., *et al*., Investigation of Decarbonization Potential in Green Building Design to Accelerate the Utilization of Renewable Energy Sources, *Thermal Science*, *25* (2021), 6A, pp. 4269-4282

[17] Gang, W., *et al*., Robust Optimal Design of Building Cooling Systems Considering Cooling Load Uncertainty and Equipment Reliability, *Applied Energy*, *159* (2015), Dec., pp. 265-275

[18] Krstic-Furundzic, A., *et al*., Assessment of Energy and Environmental Performance of Office Building Models: A Case Study, *Energy and Buildings*, *115* (2016), June, pp. 11-22

[19] Eui-Jong, K., *et al*., Urban Energy Simulation: Simplification and Reduction of Building Envelope Models, *Energy and Buildings*, *84* (2014), Dec., pp. 193-202

[20] Pantović, V. S., *et al*., Rising Public Awareness of Energy Efficiency of Buildings Enhanced by "Smart" Controls of the in-Door Environment, *Thermal Science*, *20* (2016), 4, pp. 1307-1319

[21] Turanjanin, V. M., *et al*., Different Heating Systems for Single Family House Energy and Economic Analysis, *Thermal Science*, *20* (2016), Suppl. 1, pp. S309-S320

[22] Ignjatović, M. G., *et al*., Sensitivity Analysis for Daily Building Operation from the Energy and Thermal Comfort Standpoint, *Thermal Science*, *20* (2016), 5, pp. 1485-1500

[23] Roel, C. G. M., *et al*., Review of Current Status, Requirements and Opportunities for Building Performance Simulation of Adaptive Facades, *Journal of Building Performance Simulation*, *10* (2017), 2, pp. 205-223

[24] Urbancl, D., *et al*., Geothermal Heat Potential – The Source for Heating Greenhouses in Southestern Europe, *Thermal Science*, *20* (2016), 4, pp. 1-11

[25] Harmathy, N., *et al*., Energy Performance Modelling and Heat Recovery Unit Efficiency Assessment of an Office Building, *Thermal Science*, *19* (2015), 3, pp. 865-880
[26] ***, Wing Ltd., https://wing.hu/en/, 2020
[27] ***, Innovation Campus Office Building Image, https://wing.hu/portfolio/evosoft-szekhaz-en/, 2020
[28] ***, Meteonorm, http://www.meteonorm.com/, 2018
[29] ***, EN ISO 7730:2005, Ergonomics of Thermal Environment, https://www.iso.org/standard/39155.html, 2020
[30] ***, USGBC, LEED, https://www.usgbc.org, 2019
[31] ***, IESVE Validation, https://www.iesve.com/software/software-validation, 2020
[32] ***, Electricity tariff, https://elmuemasz.hu/egyetemes-szolgaltatas/szolgaltatasok/villamos-energia/villamos-energia-tarifak, 2020

Paper submitted: April 10, 2021
Paper revised: July 5, 2021
Paper accepted: July 15, 2021

Published by the Vinča Institute of Nuclear Sciences, Belgrade, Serbia.