Dynamic B-SIM application for energy consumption estimation of DOAS with FCU HVAC system during design phase

Norbert Harmathy^{1,*}

¹Budapest University of Technology and Economics, 1111 Budapest, Műegyetem rkp. 3, Hungary

Abstract. The investigation presents a strategic approach during the design process using advanced energy performance simulation technology. Team coordination and building performance efficiency during the design process is aided by conducting a performance based assessment with comprehensive fully incorporated design, construction, energy, HVAC and annual building operation. Performance based decision making is demonstrated through an office building complex. The engineering decisions were based on performance enhancement and overall energy demand reduction, which was evaluated on an annual basis. The building envelope's dominant curtain wall system was analyzed in detail in order to demonstrate qualitative energy performance improvement. DOAS with FCU HVAC system's annual energy performance was estimated and evaluated from the aspect of end-use energy.

1 Introduction

The investigation covers the energetic and operational energy demand analysis of a 23 205 sqm office building complex [1]. Operational energy demands and HVAC system operation were analyzed in detail using complex input datasets: climatic database, building structure, thermal loads, occupancy and HVAC system documentation.

Various design alternatives were used to select the most preferable curtain-wall structure. The calculations were performed with detailed dynamic energy simulation in EnergyPlus [2] engine.

Our previous investigations were performed on existing buildings and their energy refurbishment processes [3-5].

Teams have demonstrated various approaches in energy analysis of office buildings using simulation techniques [6-8].

Our task was to justify which curtain-wall window structure would be the most preferable from the energy performance aspect, and to demonstrate which is the most appropriate window type contributing to higher energy efficiency of the building. During the investigation according to the buildings geometry the massing of the building contributed significantly to its energy performance.

* Corresponding author: harmathy@egt.bme.hu

We evaluated the influence of the curtain-wall structure on the heating and cooling energy requirements on an annual basis, from which we determined the annual energy savings. The report includes selecting the right facade glass structure that meets the energy and cost optimum requirements.

Furthermore, two types of HVAC systems were simulated in order to assess and evaluate their annual end use energy consumption in order to help decision-making in the early design phases of the energy strategy.

2 Research focus and methodology

During the energy performance analysis, we focused on the following:

- Building simulation and determination of energy demands
- Determining detailed heating and cooling energy requirements
- Analysis of thermal load alternatives
- Influence of internal heat loads on the annual energy balance
- Determining the energy influence of the glass structure annually
- Analyzing the effect of different curtain wall systems' thermal properties
- HVAC system simulation and end use energy determination of the project
- Total energy savings potential

The virtual environment was created in EnergyPlus software where the simulation was performed according to the calculation models from the EnergyPlus Engineering documentation [9].

The geometric thermal model was created in Sketchup [10] and the data were imported in OpenStudio [11] software.

3 Dynamic simulation input parameters

3.1 Weather data – climatological data sets

The climatic data was used from the Meteonorm [12] Swiss global database. The meteorological data package for Budapest contained more than 100,000 data.

In the simulation process 30 year hourly averages were applied. In the dynamic simulation we used the following climatic data; air temperature, relative humidity, direct and indirect solar radiation, pressure, wind direction and wind speed.

The weather data for Budapest were used from the data packages of ASHRAE Climate Design Conditions [13] which are shown in Table 1.

Depending on the size and complexity of the building, we divided the model into 22 thermal zones. The energy zone allocation by area and volume is shown in Table 2. The 3D model of the boundary surface model and the thermal zone model is shown in Figure 1.

3.2 Building envelope thermal properties

The building structure and layers were used in the thermal simulation according to the design and construction documentation.

The objective was to analyze and simulate the building envelope's dual pane glass construction on the annual building energy performance.

Table 1. Weather file for Budaors, Hungary (WMO: 128380) from Ashrae climate design conditions.

Lat:47.45N			Long:18.97E			Elev:132			StdP: 99.75			Time zone:1.00			Period:82-92		
Annual Heating and Humidification Design Conditions																	
Coldest Month	Heating DB		Humidification DP/MCDB and HR							Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB			
			99.6%			99%				0.4%		1%					
	99.6%	99%	DP	HR	MCD B	DP	HR	MC DB	WS	MC DB	WS	MC DB	MCWS	PCWD			
1	-11.2	-9.0	-14.4	1.1	-9.8	-12.3	1.3	-7.3	18.0	-0.9	16.6	0.7	1.9	270			
Annual Cooling, Dehumidification, and Enthalpy Design Conditions																	
Hottest Month	Hottest Month DB Range	Cooling DB/MCWB							Evaporation WB/MCDB							MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%			0.4%		1%		2%				
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD		
7	10.3	31.0	20.1	29.3	19.7	27.8	19.2	21.3	28.9	20.5	27.5	19.8	26.1	2.9	180		
Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 and 12.8/20.6		
0.4%			1%			2%			0.4%		1%		2%				
DP	HR	MCD B	DP	HR	MCD B	DP	HR	MC DB	Enth	MC DB	Enth	MC DB	Enth	MCD B			
18.6	13.7	24.3	17.9	13.1	23.6	17.3	12.5	23.0	62.1	28.9	59.4	27.9	56.9	26.1	923		
Extreme Annual Design Conditions																	
Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB									
				Mean		Stand.deviation		n=5 years		n=10 years		n=20 years		n=50 years			
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max		
13.9	11.6	9.3	24.3	16.3	33.5	5.1	1.4	-19.9	34.5	-22.9	35.3	-25.8	36.1	-29.4	37.1		
Monthly Climatic Design Conditions																	
			Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Temperatures, Degree-Days and Degree-Hours		Tavg	10.6	-0.3	1.0	5.6	11.2	16.2	18.2	21.1	20.5	16.9	10.7	4.0	1.5		
		Sd		4.86	4.66	4.47	3.47	3.27	3.04	2.99	3.20	3.06	3.98	3.79	4.18		
		HDD10.0	1236	319	253	147	27	2	0	0	0	1	38	182	266		
		HDD18.3	3072	577	486	396	216	81	38	9	16	64	236	431	523		
		CDD10.0	1452	0	1	9	62	193	247	344	326	206	62	2	1		
		CDD18.3	246	0	0	0	1	13	34	95	83	19	0	0	0		

	CDH2 3.3	2089	0	0	0	4	101	276	860	698	149	2	0	0
	CDH2 6.7	573	0	0	0	0	14	55	272	211	22	0	0	0
Precipitation	PrecA vg	560	38	34	32	43	59	67	49	51	41	38	61	46
	PrecM ax	823	78	136	59	83	128	141	106	114	114	154	173	120
	PrecM in	399	2	4	2	17	1	18	19	5	1	2	14	1
	PrecS D	112.1	19.6	29.5	17.2	18.0	35.0	32.9	25.4	32.1	28.1	40.1	48.0	28.3
Monthly Design Dry Bulb and Mean Coincident Wet Bulb Temperatures	0.4%	DB	10.5	16.3	21.3	24.3	28.8	30.3	33.2	32.4	29.3	23.1	15.5	14.4
		MCW B	7.0	10.2	13.0	15.3	17.7	20.2	20.3	20.5	19.2	16.1	11.6	10.8
	2%	DB	8.6	12.0	17.0	21.7	25.9	28.2	31.4	30.8	26.9	20.9	12.0	11.2
		MCW B	6.3	7.9	10.6	13.7	17.1	20.1	20.5	19.7	18.1	15.2	9.2	8.8
	5%	DB	7.4	8.8	14.6	19.6	24.1	26.4	29.7	29.1	25.1	18.8	10.3	9.1
		MCW B	5.4	5.7	9.5	13.0	16.7	18.9	20.0	19.5	17.8	13.6	8.1	6.9
	10%	DB	5.7	6.6	12.4	17.5	22.4	24.7	28.0	27.4	23.1	16.9	9.2	7.2
		MCW B	4.0	4.4	8.2	11.9	15.9	17.9	19.2	18.9	16.7	12.6	7.5	5.4
Monthly Design Wet Bulb and Mean Coincident Dry Bulb Temperatures	0.4%	WB	7.5	10.6	13.9	16.0	19.0	21.6	22.7	22.0	19.8	17.0	12.1	11.2
		MCD B	9.8	15.8	20.3	22.6	25.4	28.3	29.9	29.3	26.3	21.2	14.2	14.8
	2%	WB	6.6	8.1	11.2	14.3	18.0	20.7	21.4	21.1	19.1	15.5	9.6	8.8
		MCD B	8.4	11.5	15.9	20.2	24.3	27.0	29.4	28.9	25.8	19.9	11.1	10.9
	5%	WB	5.6	6.1	9.9	13.3	17.2	19.6	20.6	20.2	18.1	14.4	8.6	7.2
		MCD B	7.2	8.2	13.9	18.7	22.6	25.1	27.9	27.3	23.8	17.9	9.8	9.1
	10%	WB	4.2	4.7	8.6	12.3	16.4	18.6	19.9	19.5	17.2	13.2	7.6	5.5
		MCD B	5.6	6.5	12.0	16.8	21.4	23.5	26.3	25.8	22.1	16.1	9.0	7.1
Mean Daily Temperature Range		MDB R	5.0	6.3	8.1	8.8	9.1	9.0	10.3	10.1	10.2	9.2	6.4	4.8
	5% D B	MCD BR	6.7	10.8	12.4	12.4	12.3	12.4	13.4	13.4	13.0	12.3	8.2	6.8
		MCW BR	4.8	7.1	7.4	6.2	5.2	5.3	4.7	5.0	5.5	6.9	5.8	4.8
	5% W B	MCD BR	6.0	9.3	11.3	11.0	10.5	11.3	11.9	11.7	12.2	10.8	6.9	7.0
		MCW BR	4.5	6.4	7.0	5.9	4.8	5.3	4.6	4.6	5.5	6.9	5.8	4.8

Clear Sky Solar Irradiance	taub	0.330	0.355	0.376	0.377	0.378	0.388	0.391	0.396	0.376	0.357	0.354	0.332
	taud	2.453	2.302	2.299	2.283	2.266	2.239	2.275	2.286	2.366	2.461	2.464	2.482
	Ebn,noon	747	794	838	874	884	875	867	845	829	789	709	699
	Edn,noon	67	94	110	123	130	134	128	121	102	80	67	59

Table 2. Thermal zoning with area and volume.

Thermal zone		Area [m²]	Volume [m³]
1	Open Office North 0	1425.15	6595.03
2	Open Office North 2	1278.78	3580.57
3	Open Office North 3	1278.78	3580.57
4	Open Office North 4	1155.29	3234.81
5	Open Office North 5	1161.40	3251.92
6	Open Office North 6	1161.40	3251.92
7	Open Office South 0	1576.57	6936.89
8	Open Office South 1	3402.77	10208.32
9	Open Office South 2	1432.48	4010.94
10	Open Office South 3	1432.48	4010.94
11	Open Office South 4	1432.48	4010.94
12	Open Office South 5	1519.52	4254.66
13	Open Office South 6	1519.52	4653.65
14	Open Office South 7	690.57	2386.66
15	Sanitary & Communication 0	390.75	1904.55
16	Sanitary & Communication 1	317.60	952.80
17	Sanitary & Communication 2	379.35	1062.18
18	Sanitary & Communication 3	379.35	1062.18
19	Sanitary & Communication 4	379.35	1062.18
20	Sanitary & Communication 5	379.35	1062.18
21	Sanitary & Communication 6	379.35	1062.18
22	Sanitary & Communication 7	132.30	370.44
Total		23204.57	72506.51

Fig. 1. 3D thermal zone model.

The building envelope's glass structure consisted of three glass structure types of which all are Argon filled, where under glazing A1 two different glass structures are applied according to project documentation:

1. Glazing A1; U-Factor = 1.40 W/m²K, SHGC1= 0.4, SHGC2= 0.3, Glass Visible Transmittance1 = 0.70 with inner pane shading and Argon gas (Southern facade), Glass Visible Transmittance2 = 0.70 without inner pane shading.
2. Glazing A2; U-Factor = 1.40 W/m²K, SHGC= 0.5, Glass Visible Transmittance = 0.73 (East and West orientation)
3. Glazing A3; U-Factor = 1.40 W/m²K, SHGC= 0.6, Glass Visible Transmittance = 0.80 (North orientation)

The focus was on the structural and energetic performance of the facade glazing. The use of adequate glazing is of utmost importance for efficient energy reduction and user comfort. Choosing the right glass structure depends from; building's type and function, the building floor area, window to wall ratio, facade orientation, internal heat loads, building location and climate zone. The listed parameters all affect the efficiency of the glass structure, building on the energy of the building. We investigated the influence of the heat transfer factor (U), the solar factor (g) and the light transmission factor (τ) on the yearly energy requirements and user comfort of the building. The title is set in bold 16-point Arial, justified. The first letter of the title should be capitalised with the rest in lower case. You should leave 22 mm of space above the title and 6 mm after the title.

3.3 Thermal comfort demand and building operation data

The energy simulation allows detailed analysis of building operation according to schedules. Its significance lies in the fact that we can investigate the energy and heat loads of a building according to various time dependant scenarios. With energy simulation, we calculated the building's energy demand annually using the following data:

- Heating period (indoor air temperature):
Minimum indoor air temperature was 20°C during permanently occupied periods.
Outside working hours the maximum allowed temperature fall was 4°C.
The heating system operates with an automatic indoor air temperature sensor setting.
- Cooling period (indoor air temperature):
Maximum indoor air temperature was 26°C during permanently occupied periods.
Outside working hours the cooling system is not operating. The cooling system operates with an automatic indoor air temperature sensor setting.

In both periods, the perimeter values of air temperatures were maintained daily in 10 hour intervals (8-18h). In case changes in occupancy schedules of the building, number of people and work hours, the energy demands will change. The results of the energy simulation apply only to the specified 10 hours working time and to the perimeter values of the specified air temperature. Air change rate and specified air volume in thermal zones was calculated according to equation 1 where n is the number of people and A is the area in m².

$$q_{tot} = n \times 25,2 + A \times 2,52 \quad (1)$$

$$q_{tot} = 2520 \times 25,2 + 21400 \times 2,52$$

$$q_{tot} = 117432 \text{ m}^3/\text{h}$$

For the office spaces 0.46 ach was assumed. In the simulation we counted 0.8 1/h air change was the maximum intensity during working hours. During unoccupied periods the air change rate was 0.1 1/h. The intensity of air exchange depends on working time. From 7 to 18 hours constant air volume was estimated.

3.4 Internal loads - heat sources

Internal heat loads are the thermal load delivered by users and office equipment (electrical equipment). Based on the functional “open office” disposition of spaces, the number of people occupants per floor was estimated.

Table 3 shows the number of occupants per floor area. The internal gains were taken into consideration as constant loads for all 3 scenarios in the simulation to estimate adequate heating and cooling requirements of the building.

In case of occupant heat gain, 120W of constant heat load was calculated in the function of work hours. A total of 2520 PC's were assumed in the building, where 150W of heat load was assumed per PC in the function of work hours, where the highest intensity is between 8-12h and 13-17h. Lunch break between 12-13h was included respectively.

Table 3. Occupancy per floor.

Level	No. of occupants	Area [m ²]	m ² / person
ground floor	230	2000	8,7
1	450	3766	8,4
2	350	2995	8,5
3	350	2995	8,5
4	350	2995	8,5
5	350	2937	8,4
6	350	2937	8,4
7	90	777	8,6

4 Energy performance results

4.1 Annual energy demands for heating and cooling

With the energy simulation run-time of 8760 hours annual heating and cooling energy demands were determined for two operational scenarios:

1. Permanent maximum heat loads – entire building is occupied during working hours
2. Without internal heat loads – estimation of internal loads influence on the energy performance

Particular emphasis was placed on the curtain wall's glass structure and its energy performance. The heating and cooling energy requirements with different grazing types from the simulations are shown in Table 4 and Figure 2.

The energy demands were classified according to the parameters of the facade glass structure. Table 5 shows the percentage deviation of the aggregate annual energy demand. Table 6 summarizes active and passive heat gains and losses.

The highlighted vales are considering the heat addition and heat removal via the glazing structure.

Table 4. Annual energy demands for heating and cooling.

Curtain wall glazing properties	Heating [MWh/a]	Cooling [MWh/a]	Heating per m2 [MWh/m ² /a]	Cooling per m2 [MWh/m ² /a]
With constant maximum internal heat loads				
A1 g ₁ =0,4; g ₂ =0,3	1228	658	53	28
A2 g=0,5	1184	800	51	34
A3 g=0,6	1151	941	49	40
Without internal heat loads				
A1 g ₁ =0,4; g ₂ =0,3	1557	60	67	3
A2 g=0,5	1475	138	63	6
A3 g=0,6	1415	228	61	10

Table 5. Annual energy demands percentual deviation.

	Total energy [MWh/a]	Percentual reduction [%]	Reduced energy [MWh/a]
A1	1886	9,8% according to A3 5% according to A2	206 98
A2	1984	5% according to A3	108
A3	2092	0%	0

Table 6. Annual energy demands percentual deviation.

Thermal zone	People Sensible Heat Addition [kWh]	Lights Sensible Heat Addition [kWh]	Equipment Sensible Heat Addition [kWh]	A1 Window Heat Addition [kWh]	A2 Window Heat Addition [kWh]	A3 Window Heat Addition [kWh]	Infiltration Heat Addition [kWh]	Window Heat Removal [kWh]	Infiltration Heat Removal [kWh]	Opaque Surface Conduction and Other Heat Removal [kWh]
1	29.75	38.72	56.26	53.07	68.77	88.25	2.11	-38.23	-76.20	-81.17
2	25.40	34.74	50.49	19.51	29.25	38.54	1.34	-26.87	-62.14	-24.81
3	25.37	34.74	50.49	20.53	30.96	40.82	1.32	-27.19	-62.35	-23.26
4	22.91	31.39	45.61	20.35	30.43	40.26	1.18	-24.61	-56.47	-21.47
5	23.10	31.55	45.85	23.59	39.99	52.40	1.18	-29.61	-56.60	-21.42
6	23.11	31.55	45.85	31.69	53.44	69.57	1.16	-30.95	-56.63	-27.82
7	32.46	42.83	62.24	102.7	131.3	167.86	2.27	-35.27	-84.46	-130.5
8	68.03	92.45	134.3	82.55	112.2	144.60	3.82	-46.54	-166.7	-137.5
9	28.10	38.92	56.55	52.65	74.60	96.58	1.49	-34.48	-71.05	-43.42
10	27.99	38.92	56.55	51.32	72.73	94.44	1.46	-35.65	-71.69	-33.47
11	28.01	38.92	56.55	51.35	72.62	94.35	1.45	-36.07	-71.73	-32.59
12	29.85	41.28	59.99	56.57	92.45	119.45	1.53	-41.60	-75.59	-39.12
13	29.87	41.28	59.99	73.24	119.5	153.95	1.54	-49.56	-77.99	-40.62

14	13.57	18.76	27.26	42.61	68.46	88.34	0.72	-26.84	-37.07	-21.40
15	6.51	10.25	2.21	0	0	0	4.82	0.00	-160.7	0
16	4.29	7.06	0.54	0	0	0	2.61	0.00	-138.8	0
17	5.10	8.43	0.64	0	0	0	2.61	0.00	-166.5	0
18	5.09	8.43	0.64	0	0	0	2.42	0.00	-168.1	0
19	5.09	8.43	0.64	0	0	0	2.36	0.00	-168.7	0
20	5.09	8.43	0.64	0	0	0	2.33	0.00	-169.0	0
21	5.08	8.43	0.64	0	0	0	2.30	0.00	-169.6	0
22	1.78	2.94	0.22	0	0	0	0.89	0.00	-58.80	0
Total Facility	445.28	618.33	814.16	681.66	996.66	1289.16	42.78	-483.3	-2226	-678.6

Fig. 2. Annual energy demands for heating and cooling.

4.2 HVAC system energy performance simulation

Following the heating and cooling demand assessment according to adequate glazing assignment two of the Dedicated outdoor air system (DOAS) with fan-coil units (FCU) HVAC system was simulated in order to assess their annual operating performance.

The following table 7 shows the end energy uses for the DOAS FC system’s energy end use. The electricity end energy use for the DOAS system resulted with 1465 GJ/a or 407 MWh/a. Table 8 shows the annual electricity consumption of interior lighting and equipment.

Table 7. Annual energy demands percentual deviation.

	Electricity [GJ]	Natural Gas [GJ]
Heating	161.64	930.45
Cooling	803.35	-
Fans	500.43	-
Total End Uses	1465.42	930.45

Table 8. Annual energy demands percentual deviation.

	Electricity [GJ]
Interior Lighting	2226.45
Interior Equipment	2931.12

Proportional presentation of the total annual energy consumption for each energy consumer per category is shown in Figure 3 for DOAS with FCU system.

Fig. 3. Annual end energy consumption for DOAS system including lighting and equipment.

5 Conclusion

The investigation presented that the energy demand could be influenced by the selection of adequate glazing type which can be determined by analysing the curtain wall’s influence on the total energy demand as function dependant. Findings indicated that for an office building with high internal heat gains can lower its heating demands by selecting glazing in wider SHGC interval from 0.3 to 0.6. The changes between the total energy demand (heating and cooling) scenarios for the three simulated glazing types was max. 9,8% on annual basis. However, investment in glazing with more efficient low-E layers is higher. Nevertheless, cooling should be taken in account seriously since the deviation was 30%. It was concluded that high energy reduction can be achieved according to the HVAC system operation, the electricity end energy use for the DOAS system resulted with 1465 GJ/a or 407 MWh/a.

6 Acknowledgement

The research reported in this paper was supported by the Higher Education Excellence Program of the Ministry of Human Capacities in the frame of Artificial Intelligence research area of Budapest University of Technology and Economics (BME FIKP-MI/SC).

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