# SIMULATION SUPPORT FOR OPTIMIZING THE DESIGN AND OPERATION OF A LARGE OPEN-SPACE OFFICE BUILDING


**Milos Lain**
CTU in Prague
Mech. Eng. Faculty
Prague 6, Czech Republic

**Jan Hensen**
Eindhoven University of Technology
Building Physics & Systems
Eindhoven, Netherlands

**Jan Žemlička**
PBA International
Prague 7
Czech Republic



## ABSTRACT

This paper deals with design and post-design operational optimization studies for a new head office of a bank in Prague. The building can be characterized as a large open space office building.

During the design phase computational modeling and simulation was used to predict the performance of various design alternatives with respect to reducing the required cooling capacity, in order to verify the fan-coil capacity sizing and to optimize the ventilation system and strategy of the atriums.

Since the design included exposed concrete ceilings, the design intent was to use the building thermal mass for cooling load reduction and to employ a strategy for low-energy operation of the building. The maximum cooling demand for the initial design was estimated at 3 MW for the whole building. Computational simulations showed a potential reduction to 81 % of this value.

Additional simulations helped designers to optimize the thermal comfort in the open corridors in relation to the roof glazing and the shading devices of the atria.

During the commissioning process the simulation based performance predictions were checked.

During the first year of operation, various building control strategies were tested and optimized. Smoke tests, thermal comfort and draft measurements were carried out to verify the indoor environment.

During the commissioning process the field tests identified various important issues related to the designof large open space office buildings. These are also presented in the paper.


## BUILDING DESCRIPTION

The CSOB Group's central office in 333/150 Radlicka street, Prague, Czech Republic, is a modern office building. With a footprint of 220 x 75 m, it is one of the largest projects in the Czech Republic to date. The building includes office area with a capacity for more than 2500 employees. It has 8 floors; 5 above and 3 below street level. The main longitudinal axis is east-west.

The building structure is medium heavy and allows heat accumulation in its reinforced concrete load bearing elements such as ceilings, floors and columns. Most of the Envelope is glazed, with some lightweight elements. It has blinds as external shading.

The ground floor is divided in 6 sections (A – F), plus three large, glazed roof atriums and two small open atriums (Fig.1). The employees' workplaces are equally distributed in open space office areas. Smaller briefing rooms, conference rooms and single executive offices are adjacent to the atria. Toilets, kitchenettes and cleaners' rooms are concentrated near lifts and staircases. The roof has terraced gardens with deciduous trees. This paper focuses on the office areas.

## AIR-CONDITIONING SYSTEM

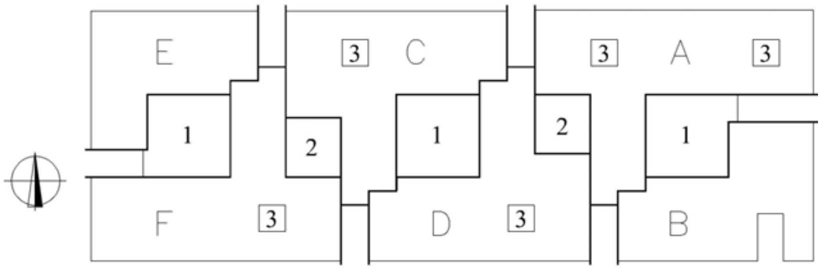

Figure 1. Typical floor: 1. large atrium, 2. small atrium, 3. air duct

There is a separate air-conditioning system for each section Depending on the particular section, the air supply is via VAV, VAC boxes or 4-pipe fan-coil units (FCU). The FCUs allow both cooling and heating. All pipes are located in the floor. The supply units have a 3 stage regulation. The FCUs have fan rotation speed control. The control system allows the shut-down of a particular FCU or VAV box, but the minimum supply of fresh air per person is guaranteed. A few ventilation units for air supply and exhaust are placed on the roof of each section. Both supply and exhaust fans of the units are equipped with frequency inverters. Some of the air is extracted by one unit from toilets, kitchenettes, storage and IT rooms, however the majority of the air is exhausted via the atriums.

## OPTIMIZATION 1 – PROJECT

Every professional designer performs some kind of optimization in each stage of the design process in order to ensure a good indoor environment quality while limiting or minimizing energy consumption. But this task is very complicated in current practice because each stage of project documentation is processed by another subject and cooperation of specialists is limited. The role of the investor andtheir expert consultant is crucial for the coordination and transfer of ideas in this procedure. During the CSOB project, the expert consultant emphasized the energetic conception, and because in this case this consultant was the same person for all the stages of the project, all decisions were kept. Next, elements that help with optimization of the whole building concept as well as with particular details were individually assigned to pilot projects

Three pilot projects for the design of energetic conception of the CSOB building were processed in total. The first very extensive study "Environmental Strategy Assessment-CSOB Headquarters, Prague" was approved by the Buro Happold Company in 2004. This complex study set basic building parameters and system concepts regarding the energy balance, lighting, acoustics and air flow.

In the next stage, a second study considering the capacity of chiller was carried out at the Department of Environmental Engineering, CTU in Prague. The objective of this study was to find an optimal operation strategy to enable a decrease in the nominal output of chillers, and at the same time ensuring that the energy consumption will be as low as possible. The use of thermal storage of concrete ceilings without soffit was anticipated. Computer simulation of the building was carried out in ESP-r software, entered inputs were the detailed building description, internal heat gains and typical weather of a reference year (TRY) for Prague. The model consisted of 7 zones (each floor was one zone + atrium and 5$^{th}$ floor). Simulations were made for 8 operation alternatives in total. The differences were in the set value of desired inside temperature (24 or 26 $^{o}$C), energy saving mode after working hours, and chiller capacity and utilization of night ventilation (Tab. 1).

Computer simulation showed that with an appropriate control strategy the capacity of cold source for the building could be 20 % lower than in the original project, (which can be considered as a standard dimensioning in common design practice.) Adjustment of control system for air temperature of 24 $^{o}$C is assumed and in case of peak loads the air temperature will rise a maximum of 2 K. The temperature limit of 26 $^{\circ}$C will not be exceeded due to the accumulation ability of the building. The pilot project proved the positive influence of night cooling, which will significantly affect the cold consumption, but it has to be verified if this saving won't be offset by higher electricity consumption of fans.

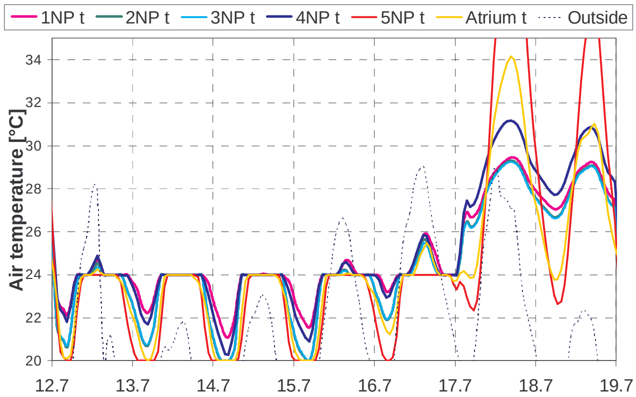


Figure 2. Air temperature profiles in each floor for chosen week and variant No 7.

Table 1: Selected results of computer simulations

| No. | Name | Temp. [°C] | Night vent. | Cooling capacity limit | Max. building cooling load kW | | Summer cold consumption MWh | |
|---|---|---|---|---|---|---|---|---|
| 1 | Always 24 | 24 | NO | NO | **2 851** | **100%** | **1 599** | **100%** |
| 2 | Always 26 | 26 | NO | NO | 2 543 | 89% | 1 181 | 74% |
| **6** | **Limited 24** | **24** | **NO** | **80%** | **2 319** | **81%** | **1 592** | **100%** |
| 7 | Night + Limited | 24 | YES | 80% | 2 317 | 81% | 1 222 | 76% |

## OPTIMIZATION 2 – COMMISSIONING

Theactivation procedure of HVAC systems should consist of two basic steps. The first is the take-over of the building and its systems by the investor, and the actuation of systems and verification of their function. This takes place partly during the construction of the building, partly before and during the final building approval, and eventually as a quality complaint during the guarantee period. Parts of the first step are also mandatory revisions and tests, as well as the checking and adjusting of basic parameters (air flow, etc.) The goal is to give the investor a fully functional building and system complying with the project documentation.

The test operation of the building and system should be the second step. During the test phase, hidden problems and faults, caused both during the construction and design process, should be recognized. Further, optimization of both set parameters of the facility and its control modes should be carried out in order to ensure, with minimal operating costs, thermal comfort for users of the building. The test operation should be conducted for a period of at least one year (optimization and verification for various climatic conditions) and should be controlled by a group of experts capable of optimizatng the system operation. The test procedure is especially necessary for systems designed for low energy consumption.

## AIR TEMPERATURE OPTIMIZATION

As described above, this project deals with a very large building, in which the majority of offices, corridors and other rooms are connected to each other without the possibility of being separating. Individual temperature adjustment is therefore very limited and uniform temperature is anticipated for the whole building. This leads to strict requirements on its optimal value. Temperature in open space offices is measured by a control system with 187 points (1st - 4th Floor). In the experimental phase from May to October 2007, values were measured in 5 minute intervals. The analysis of these measurements shows that temperatures are quite uniform, with the minimum at 22 $^{o}$C and maximum at 26 $^{o}$C in most of the rooms for the experimental period. The whole building has a slight vertical temperature gradient, approximately 0,5 K between 1$^{st}$ and 4$^{th}$ Floor. Temperatures in the atypical 5$^{th}$ floor are considerably different.

Control and choice of the most suitable mode is based on values of two reference temperature sensors located on the 3$^{rd}$ Floor. Analyses of measured data proved that the sensors were chosen appropriately and that they showed good agreement with the average temperature of the whole building.

During the optimization of the control system, based on reactions of occupants an optimal profile of inside air temperature and corresponding adjustment of the regulation strategy was sought. This resulted in a temperature of 23 ± 1 °C in the morning (after the night cooling with fresh air from exterior), during the day the temperature rises gradually, and in the afternoon it is set to 26 ± 0.2 °C. Automatic temperature adjustment according to the outside air temperature based on an/the adaptive model of thermal comfort is being prepared.

VAV boxes and Fan-Coil units operation was also optimized, in the latter case by decreasing the maximum revolution speed and in parallel decreasing the revolutions according to the adjustment of heat exchanger regulation valve. It was found that the capacity of distribution elements is the critical point for air conditioning of the building. Both VAV outlets and FCUs cannot be operated at maximal capacity as the designed temperature of supply air is too low for outlets in the floor.

In terms of temperature, offices on the 5$^{th}$ Floor present particular conditions and requirements. They have a high ratio of glazing and small heat accumulating mass. Temperature profiles during the day are significantly different from the rest of the building and the need for cooling arises at the lower exterior air temperature of 14 $^{o}$C. Using the same air-conditioning system for these offices and the rest of the building, can be considered as a mistake of the project.

## MEASURING OF THERMAL COMFORT OF OCCUPANTS

In the experimental phase the evaluation of thermal comfort was based on the complaints of employees, which were discovered through individual interviews. . It was verified that a lot of complaints against thermal comfort and draught are strongly affected by psychological aspects, both objective (feeling draught in an open space office) and subjective (dissatisfaction with working in an open space office). These psychological aspects are also significantly influenced by the fact that most of the employees were moved into the new building from offices where they had been working for a long time. So, their dissatisfaction with the new environment may have caused the feeling of thermal discomfort.

To verify the complaints, a detailed control measurement of thermal comfort was carried out at 4 working places. Values of air temperature, relative humidity and mean radiant temperature were measured. In addition detailed data was gathered of temperature, air flow velocity and turbulence intensity for sitting persons (in compliance with CSN ISO 7730).

Radiant temperature measured with the black sphere thermometer differed minimally from the air temperature in all places. Control measurement of surface temperatures on walls and ceilings also showed only minimal differences between these temperatures and air temperatures. Therefore, the mean radiant temperature is almost the same as the air temperature, and the operative temperature will be also equal to the air temperature.

Measured values of air temperatures in higher levels, i.e. at working places 1 and 2 exceeded the upper limit of 25,3 °C, while at working place 3 they fell under the lower limit of 23,7 °C. At working places 1 and 2 the air temperature exceeded the temperatures required by the control system. Nevertheless it was evaluated as absolutely satisfactory by the employees. During the operation of air conditioning, the FCUs are set so that they are automatically turned off if the window nearby is opened. Automatic turn-off even of a small number of FCUs as a result of opened windows may cause a local rise in air temperature at a particular working place compared to the value required by the control system.

Average air flow velocities from particular measurements varied between 0,1 and 0,2 m/s, at working place 2 they were below the limit of 0,1 m/s, so that conditions at working places comply with Czech statutory order No. 178/2001 Sb., according to No. 523/2002 Sb. and 441/2004 Sb.

The percentage of occupants dissatisfied as a result of draught is an overall indicator of thermal comfort at a working place. When the draft risk (DR) value is below 20 %, the working place is suitable. Average values of the DR measured at particular working places did not exceed 10 %, so the working places are classifiable in A category as fully complying with CSN EN 7730.

## ELECTRICITY CONSUMPTION

In the CSOB building, electric meters for all chillers were installed and connected to the control system. Values from sources of cold for central ventilating units, sources for FCUs and partly sources of cold for air conditioning of computer rooms (IT) are used for analyses. Also, profiles of maximal consumption values and monthly total consumption of electricity for the whole building are available. These values are used to determine the energy consumption of the chillers and the ratio of the consumption of the whole building. Total energy consumption of the building, including all consumption like lighting, ventilation, cooling, heating, etc., is measured by the main electric meters.

From the total energy consumption for the monitored summer period, the highest ratio (20 %) of electricity consumed by the cooling units in relation to the total consumption occurred in August (Fig.3).

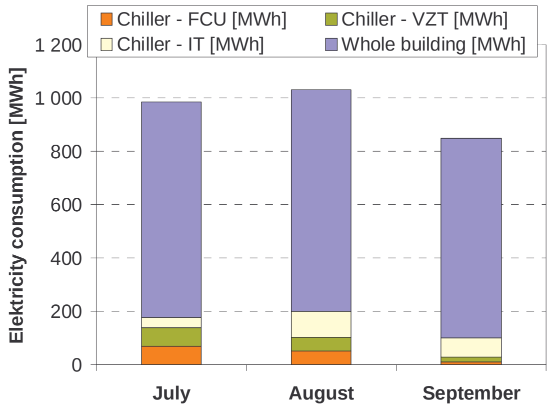


Figure 3. Electricity consumption CSOB.

Figure 4. plots a typical profile of electricity consumptions, regarding the time mode of operation It is proved that work of cooling of IT rooms is independent on operation of other systems. Chillers for ventilation units and FCUs do not consume any electricity from 24:00 to 02:00, when only fresh air is supplied to the building,. At weekends, the FCUs and VAV boxes are operated in limited mode, i.e. they are turned on only if the temperature range of 21 to 28 °C is exceeded. This leads to shorter periods of operation for the cooling units.

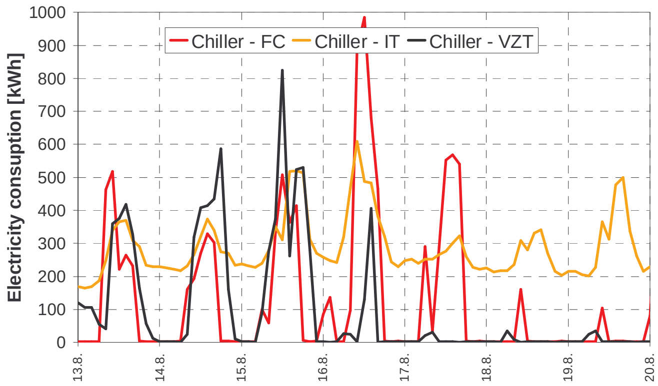


Figure 4. Electricity consumption profile.

The ratio of electricity consumption of chillers dedicated to FCUs and ventilation units to the total building consumption is not as high as anticipated. It should be mentioned that the considered consumption includes only the electricity consumed by the cooling units. With regard to points of installation of electric meters, it is not possible to determine the consumption of pumps and other components of the whole cooling system. The ratio of cooling on the total consumption is generally more significant in the summer period. The maximal measured ratio of the total building consumption occurs in peaks: 37 %. Because the consumption of chillers is recorded in intervals of 2 hours, the extreme peak value can be even higher.

**VERIFICATION OF CHILLERS CAPACITY**

In the experimental phase the internal temperature was set between 23 and 26 °C. In the evening the building was cooled with outside air. Night cooling with outside air was only utilized when necessary to keep the requirement for $\Delta t = 4$ K. During the installation of chillers for FCUs and ventilation, the results of simulations were taken into account, leading to the final cooling capacities being smaller than the original values (see tab 2.)

According to the results of computer simulation, the cooling capacity needed is 2 780 kW ( this does not include some specific areas). This led to a decrease in capacity of the originally designed chillers' system from 5 419 kW to 5 017 kW. From the measured value of consumption of cold sources, their maximal utilization during the summer of 2007 was determined at 65 %, which corresponds to a cooling capacity of 3 276 kW.

**CONCLUSION**

During the test operation in 2007, verification of ventilation and air conditioning systems as well as optimization of their parameters were carried out.

Following the experiments and optimization, operation modes of the building were achieved as economically as possiblewhich now comply with limits required for the comfort of employees.. In comparison with the original project, not only were the time schedule of units changed, but the maximal values of air flow were also decreased.

The analysis of electricity consumption of cooling units during the monitored period showed that they consume 20 % of electricity for the whole building per month.

Thermal analysis proved the right choice of reference sensors. Based on the smallest difference from the average temperature in the building, the choice of the 3rd Floor as the reference floor was further proved correct. Limiting of the supply air amount of ventilation units to 95 % of revolutions speed of frequency transducer enabled even for the highest peaks keeping the maximal air temperature set by the control system at 26 °C.

Maximal utilization of cooling units in the summer, 2007 period was 65 %. The decision of the investor to decrease the installed capacity against the original project values was correct.

During the whole process, from the first concepts to finishing the building and optimizating during the test operation, the role of investor expert consultant proved to be extremely important. For buildings with ventilation and air conditioning systems, an expert consultant of investor should always exist to ensure the continuity of concepts and transfer of ideas in all stages of the project and the optimization of the building operation.

*This research was supported by a grant of Czech Ministry of Education no. MSM6840770011.*

**REFERENCES**

ČSN EN ISO 7730, ČSN EN ISO 7726, *Ergonomics of the thermal environment.*, European standrads, Český normalizační institut, 2006

Lain, M.: *Low-energy Cooling of Buildings* [Ph.D. thesis] CTU in Prague, 2008. 176 p. (in Czech). 2008

Lain, M. - Ivanova, M. - Zmrhal, V. - Zemlička, J.: *Airconditioning of Extensive Office Building Optimalization* In: 18. Konference Klimatizace a větrání 2008. Praha, 2008, p. 299-306. ISBN 978-80-02-01978-7. (in Czech).

Lain, M.; Drkal. F.; Hensen, J.; Zmrhal, V., (2005), *Energy simulations of the building in Prague 5 – I. + II + III.*, Research report, Department of Environmental Engineering, Mech Eng, Faculty, CTU in Prague.

Table 2: The chillers capacity

| Technology | Maximal cooling capacity [kW] | | | |
|---|---|---|---|---|
| | Design | Simulation | Installed | Measured |
| VENTILATION | 3 127 | 2 780 | 3 325 | 2 081 |
| FCU | 2 292 | | 1 692 | 1 474 |
| TOTAL | 5 419 | 2 780 | 5 017 | 3 044 |