Simulation to support passive and low energy cooling system design in the Czech Republic

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This paper deals with the passive and low energy cooling technologies in the Czech Republic. The role of computer simulation in low energy building design and optimization is discussed. The work includes buildings and systems analysis as well as climate analysis in order to estimate the potential of passive and low energy cooling technologies. The former is based on case studies, which include both building simulation and monitoring.

Computer simulation, low-energy cooling, air-conditioning, HVAC system, Building, Czech Republic,

1 INTRODUCTION

Buildings consume approximately 40 to 50% of primary energy in European countries. Energy consumption for cooling represents approximately 10% of the total consumption for commercial office buildings. The percentage of fully air-conditioned office floor area is increasing in Europe, especially in the Czech Republic, where full air conditioning is the current de facto standard in new or reconstructed office buildings. The increasing use of information technology has led to an increasing demand for cooling in commercial buildings. Cooling thus accounts for a significant proportion of the total energy consumption in buildings, and its impact on greenhouse gas emissions is enhanced by the fact that these cooling systems are usually electrically driven and electricity in the Czech Republic is mostly produced by coal power plants (Santamouris 1996, Heap 2001).

Low energy cooling technologies can be divided into two groups: those including the main source of cooling; whether it is ambient air or ground temperatures or warmer chilled water. Those technologies may be considered passive and hybrid cooling systems. (The term passive cooling should not be confused with passive cooling building design which is focused on reducing the cooling load).

Low energy cooling technologies can be divided into two groups: those including the main source of cooling and those that focus solely on delivery of cooling to the treated space (IEA 1995, Liddament 2000). The first group of systems rely on natural sources of cooling, but fans or pumps are required for most of them. Examples of such technologies are:

- Night ventilation
- Evaporative cooling
- Ground cooling

The second group of technologies focus on delivering the cooling to the treated space in an efficient manner, those technologies usually work well with lower grade sources of cooling.

2 CLIMATE IN THE CZECH REPUBLIC

The Czech Republic is an inland country located in the middle of Europe. The capital and also the biggest city is Prague. Most governmental and business offices are located there. The Czech climate can be described as warm (summer peak design temperature 32°C) and semi-humid (summer design moisture content 10 g/kg and wet bulb depression 9 K).

When comparing the Prague climate to other cities, where some low-energy cooling studies have been carried out, it was found that the summer climate is very similar to Berlin (Figure 2). Therefore the Berlin summer results and experiences can be used for preliminary studies for Prague.

For evaporative systems enthalpy hours are defined which take into account the humidity of the air (IEA 1995). The cooling degree hours (CDH) and enthalpy hours (EH) were calculated twice, using two different reference temperatures, namely 18°C (index 18) and 25°C (index 25). The reference relative humidity for calculating enthalpy hours was 40%. Enthalpy hours and cooling degree hours for Prague are compared to some other towns in Table 1.

3 RETROFIT OF HISTORICAL BUILDINGS

These are characterized by massive construction (brick, concrete), a window area up to 30% of the facade, and were build up to the 1950-ies. These buildings are usually not air-conditioned, nor mechanically ventilated. Retrofit of such buildings is always individual. Most heavy historical buildings can be operated without air-conditioning. High thermal mass helps to maintain thermal comfort as long as passive cooling rules (low internal gains, shading) are obeyed during retrofit. The thermal mass of the building can guarantee comfort requirements.

4 ART GALLERY IN SOVOVY MLNÝ

One of the main disadvantages of traditional engineering design methods for HVAC systems is the underestimation of the impact of thermal accumulation of the building structure. Neither periodic changes in outdoor air temperatures nor the influence of building structures can be fully considered in the traditional approach. This often leads to oversized heating and cooling system components, particularly in the case of historical buildings usually with very heavy constructions.

To support the design process of a new art gallery to be housed in the historical Sovovy mlinsky building in Prague, computer simulations were used to predict the required cooling capacity of the air-conditioning system. According to the standard design method, the cooling capacity was estimated at 100 kW. The cooling system components should have been sized to this value and the ventilation ducts would have to be designed to transport such a big cooling load. However, only minimum changes to the construction and to the historical interior appearance would be allowed; e.g. no extensive ductwork and the like.
The future art gallery will be situated on the 1st and 2nd floor in the building’s north wing. This part is built with heavy external masonry walls (80 cm thick) and the windows are equipped with internal wooden shutters. Thus the interior is actually well sheltered from solar heat gains and the building structure is also capable of significant thermal accumulation. A 3D model, with six thermal zones, was generated representing the relevant part of the building (see Figure 3).

The dynamic performance of the building was simulated with ESP-r taking into account the influence of the building structure, shading by surrounding buildings, interior operation (heat gains from occupants and lights) and extreme summer conditions in Prague represented by one-week real weather data measured in August 1997. The model was calibrated on the basis of air temperature measurements performed in the existing building.

The indoor thermal environment was analysed for the case when the building is ventilated by external air with optional cooling. The results showed a significant influence of internal heat gains from occupancy and lights. It was concluded that air-conditioning is necessary, but a total cooling capacity of only 25 kW could remove both the solar and internal heat gains while maintaining indoor air temperatures at 20°C or less. The total air volume flow rate would not be more than 6,000 m³/hour, which means small-sized ventilation ducts.

Figure 5 illustrates the optimised operating mode of the air-conditioning system. The gallery is continuously ventilated by external air; the cooling plant operates only when external air temperatures exceed the required supply air temperature (calculated on the basis of total heat gains in the gallery space).

The study helped not only to lower the investment costs to a significant extent but most of all to minimize the possible changes in construction and appearance of a valuable historical building.

**6.1 MODEL DESCRIPTION**

Simulations were carried out for a typical office of 4.92 by 5.5 m with a room height of 3.2 m. There are two south-east facing windows resulting in 55% glazing of one of the walls. The model of the office is shown in Figure 9. As indicated, the office model consist of two thermal zones (with uniform air temperature) representing the “office zone” and the “cooled ceiling zone”. Internal heat gains representing three occupants (3 x 62 W) each with PC (3 x 40 W) and monitor (3 x 58 W) are incorporated in the model.

**6.2 SIMULATION AND RESULTS**

Two passive cooling methods for improving thermal comfort in the not air-conditioned office in the summer were tested: decreasing the solar heat gains by shading or reflection and natural ventilation strategies.

The simulations were carried out for three ventilation strategies:

- **V1** only infiltration - air exchange rate 0.5 h⁻¹ for 24 hours a day
- **V2** night ventilation - air exchange rate 5 h⁻¹, from 18:00 to 7:00
- **V3** daytime ventilation - air exchange rate 10 h⁻¹, from 7:00 to 18:00

Three types of glazing were simulated:

- **S1** Standard double glazing with solar factor 0.71
- **S2** Antisun bronze glassing with solar factor 0.48
- **S3** Glazing with internal blinds, solar factor 0.2

All cases were performed without slab cooling (C0) and with slab cooling (C1), the cooling layer temperature was set to 17°C for 24 hours a day, 7 days a week. This makes 18 combinations.

The simulations were carried out for three summer months, using a weather test reference year (hourly data) for Prague.

Some of results for a selected period of two weeks are presented in Figure 11 and 12. The 3 months results are summarized in the Table 2.

**7 CONCLUSION**

According to the simulation results all three low energy cooling strategies help to improve the indoor thermal comfort in the office. It is recommended to use antisun glazing with blinds especially if there...
is not other cooling technology. The operative temperature was decreased by 10 K if just infiltration was used (Figure 11. left) and by 5 K for night ventilation (Figure 12. left). The natural ventilation has even a bigger effect on the inside temperatures; this is due to the fact that in our simulation very high air exchange rates have been selected. In reality it is difficult to reach such values and there are other practical problems with such intensive natural ventilation (safety, draft etc.).

The ceiling cooling was approved as system which only one can fully guarantee thermal comfort in the office. The effect of ceiling cooling was much stronger that other considered technologies. The simulation results even show occasional overcooling of the office. The question of the optimal ceiling (cooling water) temperature and the control of the slab cooling system remain for future research.

8 NIGHT VENTILATION
There is a high potential for night ventilation in the Czech Republic. As can be seen in Figure 13, the difference between maximum day temperature and minimum night temperature is usually more than 10 K. (The mean daily temperature range is 11.6 K). Also, the minimum night air temperatures are well below 18°C.

Not only night ventilation but also daytime ventilation can be used for cooling purposes in the Czech Republic. During 93% of the cooling season the outside air temperature is below 24°C. For working hours this is 94 percent.

9 OFFICE BUILDING WITH TOP COOLING
This case study deals with the use of computer simulations both for design support of a new building including its heating, ventilation and air-conditioning (HVAC) systems and for optimization of the HVAC control strategy during operation of the completed building.

In the early design phases of the building computer simulations were carried out to prove the concept of night cooling ventilation and to study some other effects.

9.1 BUILDING CONCEPT
The new headquarters for the ČEZ power company (one of the top ten largest European energy utilities and the strongest business entity on the Czech electricity market) in Prague is the first headquarters building in the Czech Republic to employ night-cooling and top cooling for most of its office spaces. Occupied by ČEZ since April 2002, it won the “Czech building of the year 2002” award by the Czech AFB foundation (Dvorna 2002).

The building is divided into tree parts. It has two wings (six floors above ground, 600m² each) with open-plan offices and an all-air system with top cooling and night ventilation. The central part houses the reception on the ground floor and individually air-conditioned offices on the higher floors. For night cooling, the thermal mass of the building is very important. The building features exposed concrete ceilings with ribs and concrete floors without any carpets. More than 50% of the façade is transparent. All south facing windows are fully shaded throughout the summer by external facade elements (Figure 14).

The all-air centralized system for the two wings is controlled according to the return air temperature. It is a top cooling system meaning that the capacity is less than it would be according to the current cooling load standard. The cooling capacity is based on simulations in the early design phase. There

Thus effectively the heating was on all the time. The fans had been operated just at half speed because of noise complaints in some offices. The night ventilation was not used at all. When the major problems were fixed and a night cooling regime was introduced, subsequent monitoring proved that the system functioned satisfactory.

9.4 THE SIMULATIONS MODEL CALIBRATION
The second stage of the work used a more complex simulation model (Figure 15) for system optimization. For calibrating this model, there were three types of measured data available. Firstly data from the building energy management system. Secondly data acquired from long-term monitoring of inside temperature and humidity and from short-term detailed measurements of indoor temperatures and velocity distribution near the diffusers. Finally weather data from the CTU meteorological laboratory.

The fifth floor of wing C (37.9x15.7x2.7m) was modeled in ESP-r as one zone including all constructional details, shading properties and internal gains. The exposed ceiling and the uncovered floor are of concrete. The façade is insulated according to the Czech standard (u = 0.36 W/m²K) and the double glass windows (u = 1.3 W/m²K; g = 0.5 ).

The result of the building model calibration based on the measured data is the working day internal gains profile as presented in Figure 16. The real equipment gain is 34% of the nominal value.

Next, the building model was extended with an explicit plant system model. This model comprises ducts, heat recovery, fans and cooling coil. The plant model was calibrated as well. The calibration results (Figure 17) show similar inside temperature and cooling flux to the zone. When comparing simulation results with measurements in a real building we should not expect a perfect fit. There are too many uncertain parameters (e.g. material properties) and unknown variables because they are not monitored (e.g. operable windows). Also the real system sensors are not very accurate. Finally, an office is not really a well mixed zone; at any point in time there may be air temperature differences within the office up to 1.5 K.
The calibrated building and plant models were simulated using Prague reference year weather data to find out the operation schedule with lowest overall energy consumption. It is important to include the electricity consumption for fans and chiller (cooling water source). The overall COP of the chiller system was assumed to be 2.5. Fan electricity consumption grows exponentially with flow rate, therefore just comparing cooling energy consumption does not represent the systems properly. The energy consumption of the fan was calculated as a function of flow rate.

In total, ten operation scenarios were simulated. In the first six simulations various combinations of flow rates and time periods were tested. For the next five cases the cooling coil capacity was reduced. Case 10 actually represents operation of the building without any cooling. For comparison, case FC represents the performance of the same building without thermally active ceiling (added insulation on inside surface) and floor (carpet) when just a minimum of fresh air is supplied during working hours and cooling is provided by a fan-coil system.

9.6 Results analysis
Changing the flow rates during the day and night does not influence the overall energy consumption strongly as can be seen from the Cases 0 to 5 results in Figure 18. Although the coil cooling energy consumption decreases considerably with higher flow rates, the higher energy consumption of the fan results in small differences in total energy consumption. In the cases with limited cooling coil capacity (Cases 6 to 10), the overall energy consumption decreases. In the cases when the cooling coil capacity was limited to 5 kW or to zero (Cases 8 and 10) the inside air temperatures are above the thermal comfort limits for a significant part of the summer, which is not acceptable (Figure 19).

Finally Case 9, in which a reduced flow rate of 1.06 kg/s is applied over 24 hours during week days and the cooling coil capacity is limited to 7 kW, can be recommended. For the given weather data, the total energy consumption is estimated at 11.6 MWh representing a 12% reduction compared to Case 1. The inside air temperatures would not exceed 28°C at any time.

10 evaporative cooling
Applicability of direct evaporative cooling in office or residential buildings is limited due to thermal comfort considerations. If the maximum internal air temperature is 26 °C and humidity is 60%, the enthalpy of the external air should not exceed 52 kJ/kg. Analyzing the climate data it was found that there are 180 working hours when the outside enthalpy exceeds 52 and 82 hours when 26°C is exceeded as well. This is a considerable part of the cooling season. That is why direct evaporative cooling is usually combined with another cooling technology, in order to provide comfort throughout the whole year. The maximum capacity of the chiller would not decrease significantly, if such a hybrid system consists of a direct evaporative cooling device and standard chiller. However, the number of operation hours and energy consumption decreases markedly (Lain 2003).

For spaces with higher required humidity (some industrial and agricultural applications) evaporative cooling is more suitable.

For indirect evaporative cooling the situation is similar, for the few hours in the year, the outside air enthalpy is so high that the system would not work.

Although the Czech climate is semi-humid, dehumidification is not needed for non-industrial buildings. Most air-conditioning systems incorporate some dehumidification by means of cooling coil condensation. If there is no condensation (or dehumidification) anywhere in the system the inside humidity exceeds the recommended maximum as can be seen in Figure 20 (Lain 2003).

11 the Prague zoo “Indonesian jungle” pavilion
The “Indonesian Jungle” pavilion is a new feature of the Prague Zoo. The indoor environment, plants and animals represent the climate and a small section of the flora and fauna typical for the tropical Indonesian jungle.

Building performance simulations were carried out during the concept design stage of the building; i.e. before the detailed design of the building and the associated heating, ventilation and air-conditioning (HVAC) systems. The aim of the simulation study was to support the HVAC system designers. The main objectives were to assist in deciding the system concept by estimating energy demands and predicting maximum loads for sizing the HVAC system and main components.

11.1 Building description and model
The pavilion is basically a transparent (acrylic) dome with a surface area of 1900 m² covering a volume of 14700 m³. Both human visitors and jungle animals (monkeys, birds and others) are present in the building. The majority of the animals are in the main space; i.e. they have no special housing in which a specific indoor environment could be kept. The animals are separated from and protected against people (and vice versa) by water basins. The indoor environment represents the Indonesian jungle outdoor climate. Zoological experts specified the design brief. The daytime indoor temperature should - all year round - be maintained between 22 and 25 °C. Short excursions outside this range are allowed down to 18 and up to 35 °C. The relative humidity (RH) should be kept over 70%. At nighttime lower temperatures (by 4 to 6 °C), with a minimum of 18°C, are allowed. The temperature of the water in the basins is not controlled. The base of the building is constructed of concrete and has thermal insulation. The base is partly inserted into the ground massive, which helps to keep a stable indoor climate. A transparent elliptical dome forms the countertops and roof. The dome has an acrylic ( Plexiglas) double-skin construction.

The size and shape of the ESP+ computer model is based on similarity with the real building in terms of volume and external surface areas.

The elliptical plan was changed into a polygonal shape. The arched roof (a part of ellipsoid) was approached as a shape with 13 flat surfaces as shown in Figure 21. The space was divided into 3 thermal zones according to the volumes and associated future usage of the building. The two large zones A and B represent in reality one open space with – perhaps - different temperatures. Therefore these two zones are divided by a horizontal fictitious surface. The smaller zone C represents a special cave-like corridor exposition area for nocturnal animals.
Infiltration and ventilation was modelled by assuming specific air change rates as detailed below.

11.2 Model "CALIBRATION"

Model calibration is a very important quality insurance step in the modelling and simulation process. However, it is very difficult since there are no experimental results available. Also, for the current building it is not even possible to compare the results with typical values for similar buildings because such values do not exist to the best of our knowledge.

One of the few practical ‘options’ is to very carefully analyse the simulation results so as to gain increased confidence in the model based on professional knowledge and intuition.

Another practical option is to investigate the sensitivity of the results to uncertain input parameters. In the current case, the casual sensible and latent heat gains due to people and animals are very uncertain input parameters. To investigate the sensitivity of the results to number of people and animals, the model was run for 0, 100 and 200 persons. One person’s production was set to 77 W sensible heat and 83 W latent heat.

As can be seen in Figure 22 the simulation runs prove that the system loads and/or indoor environment are almost independent of the number of visitors and also that the influence of the animals is negligible.

After calibration, the model was used for simulations in order to find the ‘optimum’ fresh air ventilation rate. The simulations were run for a winter period assuming three levels of fresh air ventilation: 0, 0.5 and 1 ACH. After evaluating the resulting heating losses, it was concluded that the fresh air supply should be as low as possible. For the reasons of indoor air quality (although this cannot be specified for monkeys) it was recommended that the fresh air supply should not be less than 0.5 ACH. For the summer, simulations were run assuming fresh air ventilation rates of 0, 0.5, 1, 2, 3, 4 ACH. The results show that increasing the fresh air ventilation rate decreases the cooling energy demand, but increases the peak cooling load. An average fresh air ventilation rate of 3 ACH was recommended as the best compromise.

Direct evaporative cooling by spraying water in the pavilion interior was considered in order to adiabatically cool the air and thus to reduce the summertime cooling energy consumption and to lower the maximum cooling loads. This was considered an interesting option since the Czech Republic has a relatively dry summer climate while the jungle pavilion requires high levels of relative humidity, i.e. in the range of 70% to 90%.

As can be seen in Figure 23, the simulation results indicate about 50 kW or 25% reduction in maximum cooling load due to evaporative cooling. The time when the cooling system would be in use will be reduced from 2000 hrs to about 1000 hrs per year. The number of operating hours with high cooling loads, e.g. loads over 120 kW, will occur during 80 hours per year only.

In terms of cooling energy demand the differences are even bigger. Without direct evaporative cooling the cooling energy demand over a typical summer amounts to 89 MWh. With direct evaporative cooling and a maximum indoor relative humidity of 70% this reduces to 41 MWh (54% reduction). With a maximum relative humidity of 90% the cooling energy demand reduces to 13 MWh (85% reduction).

11.3 HVAC SYSTEM FAILURE RESPONSE

The study included predictions on what will happen in case the air-conditioning system would fail and recommendations on how to deal with such emergencies in winter and summer.

For both situations, short periods with extreme temperatures were selected. Figure 24 shows the summer situation. Critical will be the rapid rise in temperature and rapid drop in relative humidity. In the case of emergency this may be partly compensated by spraying water and by introducing outdoor air by opening “windows” and also shows the winter situation. Critical will be the rapid drop in indoor temperature. In case of emergency it is recommended to tightly close the building and move the animals to some heated boxes.

11.4 HVAC SYSTEM CONCEPT

Based on extensive modelling and simulation work, the following HVAC system concept was recommended. Natural ventilation cannot be used; the building is relatively flat (low height) and it is not possible to create substantial ventilation openings in the lower part. Apart from the entrance most of the building is underground. Due to the shape and materialization, it is difficult to create openable parts in the roof. The incoming air has to be conditioned (especially in winter).

Two air-conditioning units (24000 m$^3$/h each) will supply air to the pavilion; two units were recommended because of transport to the site, installation, space requirements, regulations and for safety in the case of system failure. The pavilion will be heated mostly by hot air. To use heat recovery preheating above 0 °C will sometimes be necessary in order to avoid freezing of the heat exchanger. The heat recovery efficiency can be expected to be relatively high because of the high enthalpy (very humid) of the outgoing air. The amount of fresh air supply should be minimal in order to save energy. During the summer more outside air will be used. The supply air should be humidified in the air-handling unit and by spraying water inside the pavilion. Mechanical cooling is needed only during a fraction of the time.

Cold storage has not yet been considered in this stage of the design process.

12 GROUND COOLING

The Czech Republic has quite a rugged topography on a relatively small area. There are regions with very high underground water levels and artificial lakes (south Bohemia) as well as dry plains, mountains and river valleys. The soil differs very much from place to place and it is necessary to do geological prospecting to find local ground properties for underground systems.

Small air ground cooling systems are currently popular for low energy family houses with central air system in order to decrease summer peak temperatures. There is only one larger building in the Czech Republic which used ground cooling by means of buried pipes. This is the Skanov Ecological Education Center (SEV) designed for the city of Olomouc (Figure 25).

13 CONCLUSIONS

For passive and low energy cooling technologies, the dynamic behavior and interactions of building, systems, occupants and environment is very important. To design such systems and verify its performance the standard design methods based on peak gains are not suitable. In contrast to the traditional simplified calculating methods (not considering the system dynamics), computer based modeling approaches reality much closer. The use of computer modeling and simulation for the design and evaluation of buildings and HVAC is quickly moving from the research and development stage into everyday engineering practice.

The benefits of using low energy and passive technologies are potentially very high in the Czech Republic. Although there exist no major technical barriers, these technologies are not rapidly introduced due to economic reasons.

Only for a few recent offices a passive cooling concept was considered during the design. There exists no large new office building which was designed to use only passive cooling. Designing office buildings with more effective thermal mass and good quality shading in order to lower cooling loads is nowadays considered as good practice.

The design and commissioning of low energy systems is usually more complex than using standard air-conditioning. It requires better cooperation of all participants in the building design, construction and maintenance. Bad experiences with some systems are mostly due to lack of information exchange.

Finally, we would like to make the point that for design support such as in the current case it is really necessary to have sufficient domain knowledge. As Banks and Gibson (1997) rightfully point out:

>“Simulation is a discipline, not a software package; it requires detailed formulation of the problem, careful translation or coding of the system logic into the simulation procedural language regardless
of the interface type), and thorough testing of the resulting model and results. There are at least two different skills required to be successful at simulation. The first skill required is the ability to understand a complex system and its interrelationships. The second skill required is the ability to translate this understanding into an appropriate logical representation recognized by the simulation software." So it is not a case of making software so easy to use that (almost) anyone can use it, but rather to focus on how to make building performance simulation software more efficient and easier to use for domain experts. We feel that this is a rather different approach than the one which is often advocated and pursued in ‘simulation for design’ papers and research.

REFERENCES


This research was supported by research plan MSM6840770011.

Figure 1: The building as an integration of energy systems.

Figure 2: Cumulative distributions of the dry-bulb temperature (left) and humidity ratio (right) comparing Prague to five other climates (Bene 1997).

Figure 3: Outside view of the building and the ESP-r model of the considered part.

Figure 4: Temperatures of indoor and outdoor air (ventilation without air-conditioning).

Figure 5: Optimized operation of air-conditioning system (indoor air temperature set point is 26 °C).

Figure 6: ESP-r model of the building.

Figure 7: Diagram of thermal zones and airflow network.

Figure 8: Internal surface temperature on the north wall and dew point temperature during the winter period.

Figure 9: Air temperatures during a typical winter week.

Figure 10: Air temperature distribution in the transversal section for cases with open and closed roof windows left and air velocity distribution in the central longitudinal right.

Figure 11: Operative temperature during two summer weeks assuming infiltration only, different glazing types, without (left) and with ceiling cooling.

Figure 12: Operative temperature during two summer weeks assuming night ventilation (right), different glazing types, without ceiling cooling.

Figure 13: Air temperature difference variation in Prague during the cooling season.

Figure 14: Principle of the shading and of the nighttime forced ventilation.

Figure 15: The ESP-r model of the building 5th floor.

Figure 16: The internal gains profile for 1 day.

Figure 17: The building with plant system calibration results.

Figure 18: Comparing el. Energy consumption over whole summer for all simulated test cases.

Figure 19: The inside air temperature distribution.

Figure 20: Cumulative distribution of indoor relative humidity for all air system (right) and indirect evaporative cooling (left).

Figure 21: Wire frame CAD drawing of the pavilion (left) and ESP-r model of the pavilion (right).

Figure 22: Sensitivity to sensible heat gains from people (or animals) of the cooling load during a warm summer day (left) and during a cold winter week (right).

Figure 23: Reduction of the cooling load due to direct evaporative (adiabatic) cooling.

Figure 24: Indoor conditions immediately before and after HVAC system failure on a warm summer day (left) and during a cold winter afternoon (right).

Figure 25: Ground plan of the Slunakov building.
Figure 17

Figure 18

Figure 19

Figure 20
Figure 21

Figure 22

Figure 23

Figure 24
Table 1: Cooling degree hours and enthalpy hours

<table>
<thead>
<tr>
<th>Town</th>
<th>CDH</th>
<th>EH</th>
<th>CDH18</th>
<th>EH 18</th>
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<tr>
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<td>361</td>
<td>3,047</td>
<td>4,581</td>
<td>25,198</td>
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<tr>
<td>Dresden</td>
<td>527</td>
<td>3,040</td>
<td>5,154</td>
<td>28,068</td>
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<td>Stockholm</td>
<td>150</td>
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<td>1,000</td>
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<td>15,942</td>
<td>68,783</td>
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<td>7,643</td>
<td>40,831</td>
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</table>

Table 2: Number of working hours during three summer months with the operative temp. in a specific interval

<table>
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<tr>
<th>Operative temperature</th>
<th>18</th>
<th>24</th>
<th>28</th>
<th>32</th>
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<tr>
<td>Ventilation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Glazing</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Antisun</td>
<td>0</td>
<td>0</td>
<td>74</td>
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<td>Blinds</td>
<td>0</td>
<td>48</td>
<td>370,271</td>
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<td>270</td>
<td>119</td>
<td></td>
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<td>Night vent. Blinds</td>
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<td>487,218,16</td>
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<td>Day vent. Std.</td>
<td>133,415,172</td>
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<td>Day vent. Antisun</td>
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<td></td>
<td></td>
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<tr>
<td>Day vent. Blinds</td>
<td>227,464,35</td>
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<td></td>
</tr>
</tbody>
</table>

Figure 25

Figure 26

Figure 27