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ESP-r: INTEGRATED SIMULATION TOOL FOR DESIGN OF BUILDINGS AND SYSTEMS

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Abstract

The paper attempts to outline the capabilities of the ESP-r simulation software used as a design tool for buildings and HVAC systems. This state-of-the-art application of building performance simulation is illustrated by means of three recent studies concerning a new office building development, conversion of historical building into a concert hall, and a special zoo pavilion. The paper elaborates the modelling and simulation work that was carried out to support the design teams of the three projects. This includes a discussion on how the simulation results were transformed in relevant design information.

Introduction

Computer modelling and simulation is one of the most powerful techniques currently available to engineers for predictions of future reality in combined building and plant configurations. This technique is maturing from the research and development stage into regular engineering practice.

In contrast to the traditional engineering methods computer based modelling better approaches the reality considering the building as an integration of sub-systems as schematically indicated in Fig. 1. Computer simulations are much more demanding in terms of input information and data processing than ordinary design work. On the other hand simulation techniques make it possible to analyse in detail a number of solutions for the building geometry and construction as well as for the design and operation of HVAC systems.

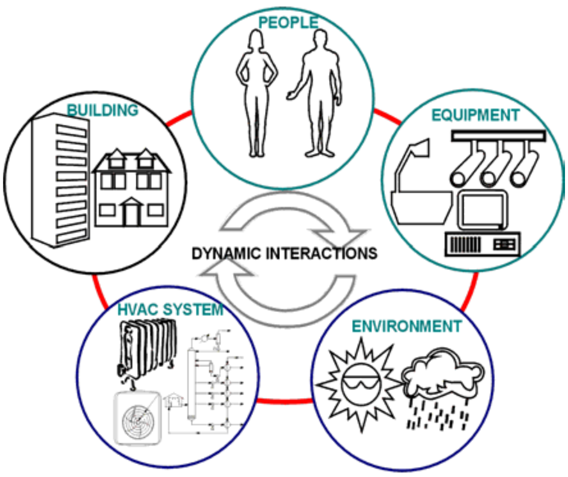

Figure 1: Dynamic interaction of sub-systems in a building context

To provide substantial improvements in energy consumption and comfort levels, there is a need to treat buildings as complete optimised entities, not as the sum of a number of separately optimised components. Simulation is ideal for this because it is not restricted to the building structure itself but can include the indoor environment, while simultaneously taking into account the outdoor environment, mechanical or structural systems, and traditional and renewable energy supply systems.

ESP-r (Energy System Performance – research) is an advanced integrated building and plant energy simulation environment, which has been continuously developed since the 1970's. The main aim is to permit an emulation of building performance in a manner that a) corresponds to reality, b) supports early-through-detailed design stage application and c) enables integrated performance assessments in which no single issue is unduly prominent. The system is graphically oriented, offers climate, construction, profiles database management, and incorporates shading, solar beam tracking, view factors, window power spectrum response, comfort assessment, condensation analysis, air flow modelling, etc. (see e.g. [1], [2] and [3] for details). The software is distributed under the *open source* license policy and it can be run on an ordinary PC with Linux operating system.

The simulations presented in this paper are based on the zonal modelling approach taking into account all building and plant energy flows and their interconnections. Relevant hourly weather data for the site in question are necessary. A test reference year (TRY) climate database or real weather data for a certain period can be used. In the current case the simulations were performed against the TRY database for Prague based on hourly values for five weather variables measured through a 14-year period [4], [5].

Example 1: A modern office building in Prague

Luxembourg Plaza is one of the most modern building developments in Prague. The future occupants should enjoy a high quality indoor environment and efficient internal space designed by the prestigious US architectural office Arquitectonica.

Our study [6] dealt with the part of Luxembourg Plaza, which is intended as a rental office space. The external dimensions of the building plan are 72 m × 69 m and its height is 28 m. The south and east façades are fully glazed up to the 5th floor. Other external walls consist of ribbon windows and concrete spandrel walls. The building will be situated in a typical urban area.

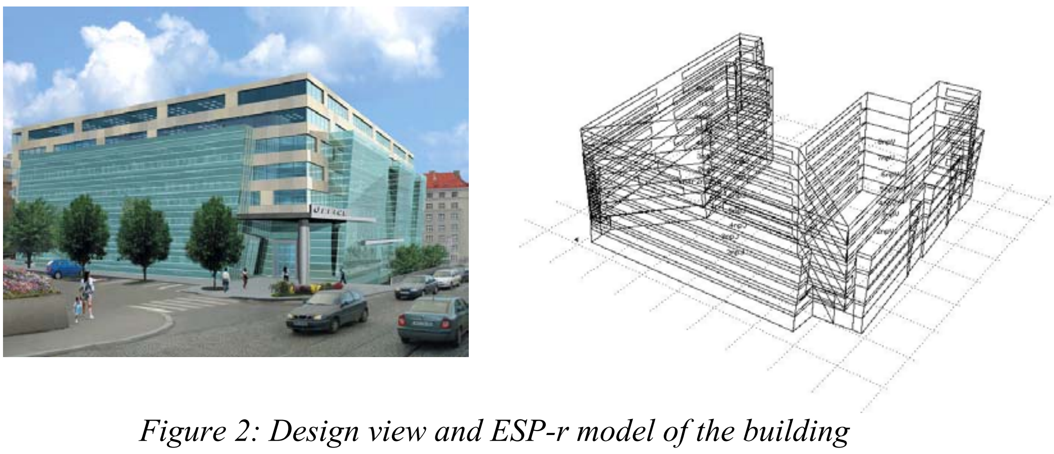

Figure 2: Design view and ESP-r model of the building

Large portions of the external walls are designed as transparent (glazed). Therefore the optical and thermal properties of glazing will strongly influence the overall building energy and comfort performance. An advanced double-glazing system was assumed for all windows and glazed walls featuring high visible transmittance (63%) but low solar energy transmittance (29%) and low overall heat gain factor (32%).

The building performance study was carried out in two steps. At first the peak loads and annual energy consumptions were predicted for several alternative design solutions regarding the façade construction, required indoor air temperature and internal heat gains. Each case was also evaluated with respect to indoor thermal comfort based on the predicted percentage of dissatisfied index (PPD).

An example of the first-step results can be seen in Fig. 3. The most important conclusions from the first-step study were drawn as follows:

1. The building is exposed to high internal heat gains and it will need cooling all over the year.
2. The changes in the façade construction introducing parapet walls instead of fully glazed walls cause only minor energy savings (not more than 8% of the annual energy consumption) and the use of internal Venetian blinds has almost the same effect.
3. The indoor environment is not acceptable when the maximum allowed indoor air temperature is 26°C. On the other hand, a significant rise (by 46%) in the cooling energy consumption occurs if the maximum indoor air temperature is only 22 °C.
4. The maximum indoor air temperature set to 24 °C in combination with internal blinds installed on the windows and fully glazed façades should provide a good level of thermal comfort while keeping the energy consumption at a reasonable level.

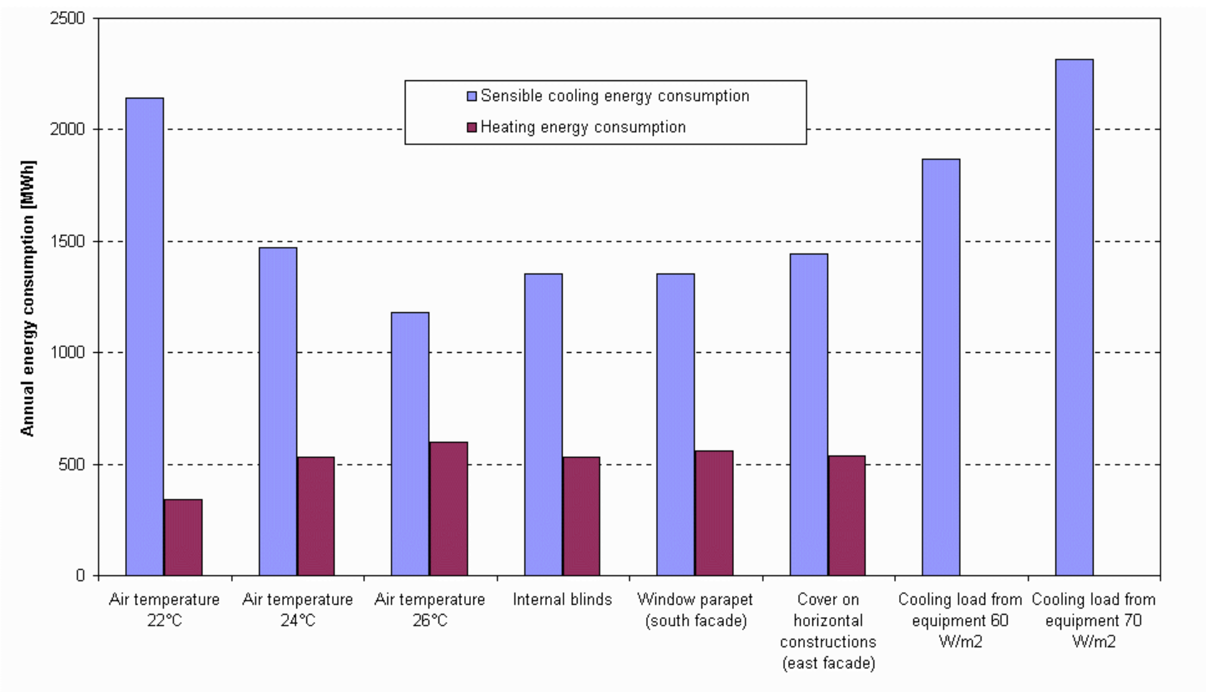

Figure 3: Comparison of different design concepts with respect to energy consumption

Based on the discussions about the first-step results, the design team defined the final version of the building, HVAC system operation and control. Further computer simulations were then performed for the whole administrative section of the Luxembourg Plaza building yielding the following results.

Internal Venetian blinds should be used on transparent façades and windows. The blinds do not cause very large energy saving but they substantially improve the indoor thermal comfort. During the summer the PPD < 18% for most of the working hours providing the indoor air temperatures do not exceed 24 °C.

The building is very well thermally insulated. In the winter, if the building is without heating, occupancy or other internal gains for a couple of days (e.g. weekends), internal air temperatures should not fall below 15 °C. One exception is the glazed part of the atrium due to the low thermal resistance of its walls. It will require heating over nights and weekends in the winter. In the summer, if the building is not cooled or at least ventilated by fresh air, the internal air temperatures could reach 40 °C.

The predicted maximum sensible cooling load for the building is 1633 kW. Based on the thermodynamic balance, the predicted latent load does not exceed 10% of the maximum sensible load. In the real cooling device (fan coil units without automatic control of humidity) the rate of latent heat removal will be higher, reaching approx. 20% of the sensible cooling load and thus it should not be difficult to keep a reasonable level of indoor relative humidity in the summer. Assuming the mentioned ratio between the latent and sensible loads, the maximum total cooling capacity could be estimated to 1960 kW. The predicted annual consumption of sensible cooling energy is 1764 MWh. The consumption of the total cooling energy could not be determined on the basis of the indoor space thermodynamic balance.

The predicted maximum sensible heating load for the building is 754 kW including the ventilation heating loss. Humidification will be required during the winter period. The predicted maximum humidification load (i.e. latent heat) is 331 kW. The predicted annual consumption of sensible heating energy is 182 MWh and the consumption of latent energy (used for the humidification) is 341 MWh. The building requires heating only during short periods particularly in the morning before the working hours. During the working hours from 8 am to 6 pm the internal heat gains are so high that cooling rather than heating will be required in the winter.

Example 2: A concert hall in the former church

Restoration of historical buildings and their adaptation to a different way of use introduces questions about the changes in internal operations and their influence on the building structures. This type of problem occurred also during the conversion of the former St. Anna church in the Old Town of Prague into a concert hall. The design team was concerned about indoor airflows, air temperature and humidity distribution, and possible moisture condensation on the internal wall surfaces. At the same time only natural ventilation through window openings at street level and roof windows was possible in order to preserve the original look of the building.

In this case a zonal method was applied for coupled energy and airflow simulations [7]. A 3D model for ESP-r was generated, with 8 thermal zones, taking into account shading objects and adjacent buildings (see Fig. 4).

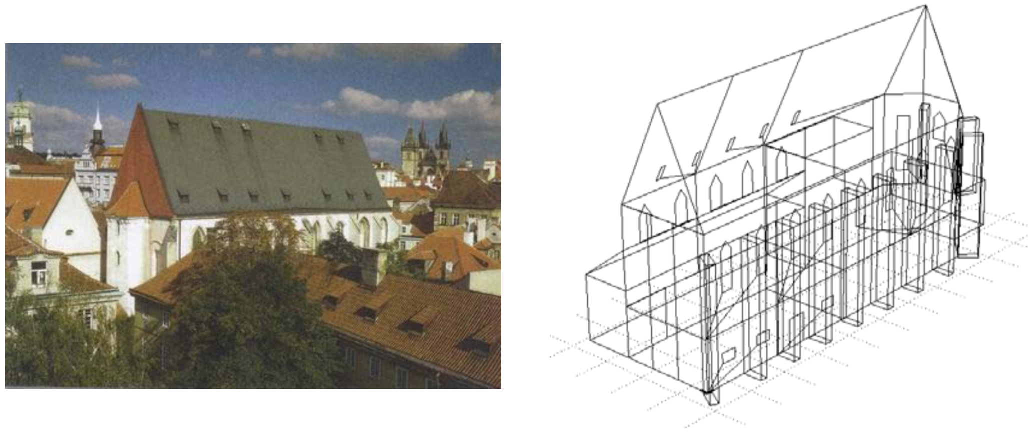

Figure 4: Photograph and ESP-r model of the building

The former church itself is basically one large enclosure, which was subdivided into 5 fictitious thermal zones with a nodal airflow network (see Fig. 5 where the fictitious surfaces are indicated by dashed lines). The simulation predicted air and surface temperatures as well as air flow rates due to natural ventilation.

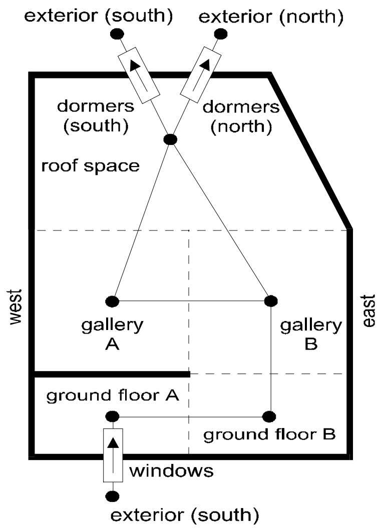

Figure 5: Diagram of thermal zones and airflow network

Fig. 6 shows time variations of surface temperature and dew point temperature in the winter period. It is obvious that the occurrence of moisture condensation on internal walls is very rare (i.e. only when the surface temperature is lower than the dew point temperature).

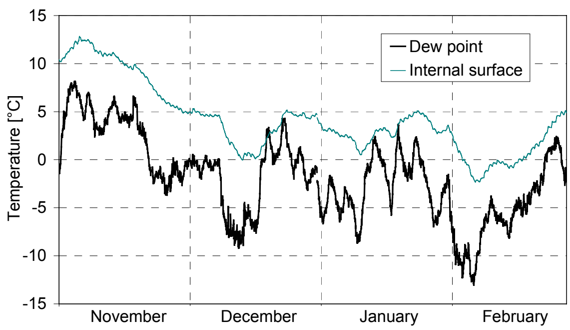

Figure 6: Internal surface temperature on the north wall and dew point temperature

Fig. 7 gives time variations of air temperatures in the building and outdoor environment. While the ground floor part of the concert hall would be strongly influenced by visitors and heating of seats (used in winter), the remaining space shows a good thermal stability. This is particularly important for the ancient wooden roof trusses.

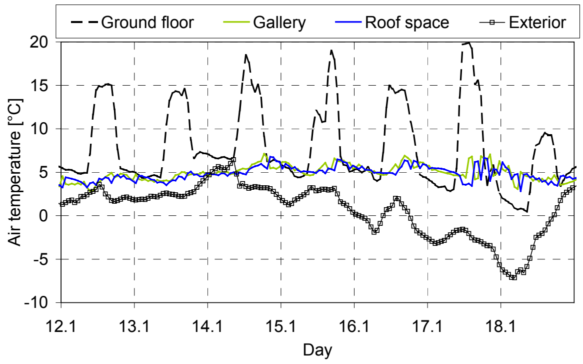

Figure 7: Air temperatures during a typical winter week

Example 3: Indonesian Jungle pavilion in the Prague Zoo

The "Indonesian Jungle" pavilion will be a new feature of the Prague Zoo. The indoor environment, plants and animals will 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 main objectives were to assist in deciding the HVAC system concept by estimating energy demands and to predict maximum loads for sizing the HVAC system and main components [8].

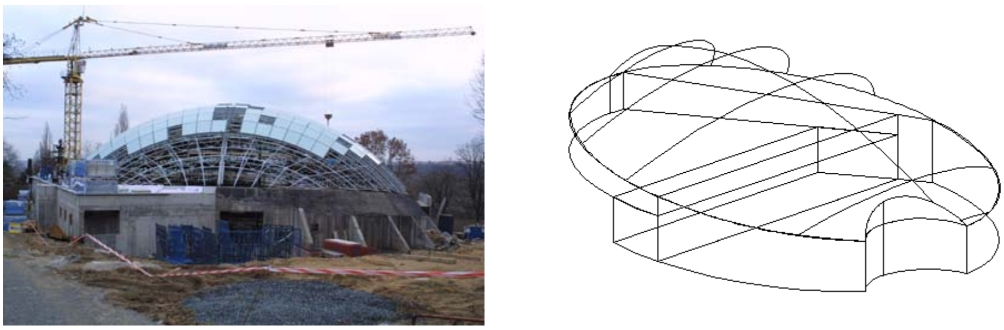

Figure 8: Construction work and wire frame CAD drawing of the pavilion

The pavilion is basically a transparent dome with a surface area of 1900 m^2 covering a volume of 14700 m^3. 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 night 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.

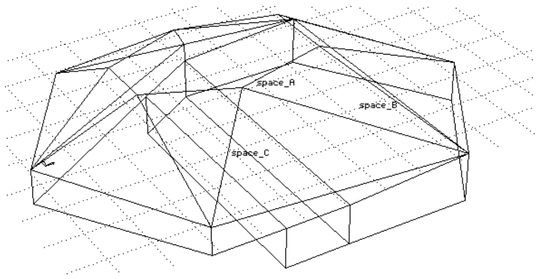

Figure 9: ESP-r model of the pavilion

The size and shape of the ESP-r 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 as shown in Fig. 9. The arced roof (a part of ellipsoid) was approached as a shape with 13 flat surfaces. 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.

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 is 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%.

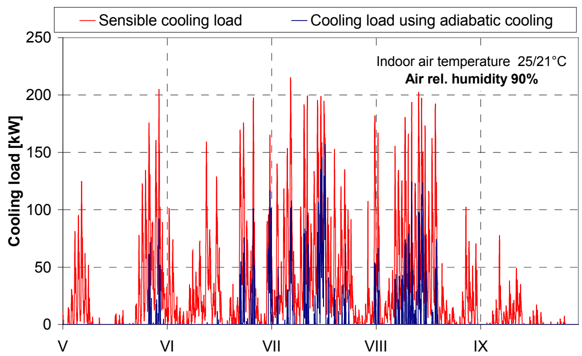

Figure 10: Reduction of the cooling load due to direct evaporative (adiabatic) cooling

As can be seen in Fig. 10, 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).

With the high indoor relative humidity, which is required, it is more than likely that during the winter considerable condensation will occur on the inner surface of the roof. Simulations were carried out to predict the inner surface temperatures. These could then be compared with the predicted dew point temperature of the indoor air. Based on similarity between heat and mass transfer condensation rates up to 30 kg/hr would have to be expected; this is assuming inside air temperature of 22°C, surface temperature of 5°C, convective heat loss through the roof of 30 kW, and absolute moisture content difference between air and surface of 5 g/kg. In the first approximation, the condensation rate of 30 kg/hr has to be compensated by the additional (latent) space heat load of 20 kW. In reality this will be less because the surface temperature will rise due to the condensation heat, and subsequently the condensation rate will decrease.

Based on extensive modelling and simulation work, the 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. Maximum sensible cooling load was predicted at 100 kW, maximum sensible heating load (including pre-heating and ventilation losses) should be 530 kW.

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.

Conclusions

As indicated in the current paper, our experience in building and systems simulation for the construction industry and HVAC designers covers a range of cases from offices, historical buildings to a zoo. Building performance simulation has come a long way since the early seventies. Instead of focus on the modelling aspects, there is now an increasing demand for better integration of the technology in the design, construction and operation processes of buildings and the systems which service them. One of our main conclusions in this respect is that simulation is much more than just software; it is an engineering discipline that can only be applied effectively if the user has sufficient domain knowledge.

Many heating, ventilation and air-conditioning (HVAC) design practitioners are already aware of building simulation technologies and its benefits in terms of environmental performance assessment of building designs. However, as yet, not many practitioners have expertise in using these technologies. We believe that this will quickly change due to the introduction of performance based standards, appropriate training and continuing education, promotion and other activities. Current software is able to deliver an impressive array of building performance assessments, but there are still many issues which must be resolved for routine application in practice, such as (1) accuracy and confidence in the results, (2) earlier technical promises have been achieved only partly, and (3) simulation can be costly.

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