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SIMULATION TO SUPPORT SUSTAINABLE HVAC DESIGN FOR TWO HISTORICAL BUILDINGS IN PRAGUE

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ABSTRACT: This paper attempts to outline the current state-of-the-art in the Czech Republic regarding the use of integrated building performance simulation as a design tool.
Integrated modeling and simulation of buildings is illustrated by means of two recent studies for conversion of historical buildings (a water mill and a former church; both dated back to the 14th century) into a museum and a concert hall respectively. The paper elaborates the modeling and simulation work that was carried out to support the design teams of the two projects. This includes a discussion on how the simulation results were transformed in relevant design information.
The paper finishes by indicating directions for future work that is needed to be better equipped in order to address design problems in the field of construction or restoration of buildings and their heating, ventilation and air-conditioning systems.
Conference Topic: 3.4 Monitoring

1. INTRODUCTION

The technique employed in this work is computer modeling and simulation. This is one of the most powerful techniques currently available to engineers for predictions of future reality in combined building and plant configurations.

Computer modeling and simulation for the design of buildings and heating, ventilation and air-conditioning (HVAC) systems as well as for the evaluation of building energy and environmental performance is maturing from the research and development stage into regular engineering practice. In contrast to the traditional engineering methods (not considering the system dynamics), computer based modeling better approaches the reality. Currently the main modeling and simulation techniques in the above field are:

1. energy and mass balance based modeling systems to predict and evaluate the energy performance of integral buildings and HVAC systems,
2. computational fluid dynamics (CFD) methods for prediction of air flow and temperature fields in rooms and around buildings.

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 analyze in detail a number of solutions for the building geometry and construction as well as for the design and operation of HVAC systems.

Many buildings are still constructed or remodeled without consideration of energy conserving strategies or other sustainability aspects. To provide substantial improvements in energy consumption and comfort levels, there is a need to treat buildings as complete optimized entities not as the sum of a number of separately optimized 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, electrical or structural systems, and traditional and renewable energy supply systems. By assessing equipment and system integration ideas, it can aid building analysis and design in order to achieve a good indoor environment in a sustainable manner, and in that sense to care for people now and in the future.

1.1 Integrated Building Performance Modeling and Simulation

In the current case the energy simulation environment ESP-r was used, which is an advanced building and plant energy simulation environment, which originates from the University of Strathclyde in Glasgow. In this context the term ESP-r refers to the European Reference Model for building energy simulation.

ESP-r is a building energy simulation environment, which is based on a numerical approach in which all building and plant energy flows and their interconnections are fully taken into account. Its objective is to simulate the real world as rigorously as possible to a level, which is dictated by international research efforts/ results on the topic in question. 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 modeling, etc. (see e.g. [1], [2] and [3] for details).

Simulations are performed against relevant hourly weather data for the site in question. A test reference year (TRY) climate database or real weather data for a certain period can be used. Available TRY database for Prague is based on hourly values for 5 weather variables measured through a 14-year period [4], [5].

1.2 Computational Fluid Dynamics (CFD)

Often detailed information is needed about the pattern of airflow and the distribution of air temperature and pollutants in a space when mixing is not uniform. In the past, design has sometimes been based on the measurement of airflow patterns made in test chambers. More recently, CFD techniques have been applied. Specific applications include the simulation and prediction of:

- room air flow in rooms and large enclosures;
- air change efficiency;
- pollutant removal effectiveness;
- temperature distribution;
- air velocity distribution (for comfort, draught etc.);
- turbulence distribution;
- pressure distribution;
- airflow around buildings (for wind pressure distribution);
- fire and smoke movement.

These methods approximate the enclosed space by a series of control volumes or elements. The system of discretization can be non-uniform, so that clusters of elements can be located at areas of greatest interest. Airflow, turbulence, energy propagation and contaminant spread are represented in each of the control volumes by a series of discretized transport equations. In structure, these equations are identical but each one represents a different physical parameter. Considerable computational effort is normally necessary to solve this series of equations with processing times sometimes taking many hours.

The Fluent CFD software was used for a detailed airflow analysis within the work presented in this paper.

1.3 Model calibration

Model calibration is a very important quality insurance step in the modeling and simulation process. However, it is very difficult since there are often 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 analyze the simulation results so as to gain increased confidence in the model based on professional knowledge and intuition. Another practical option would be to investigate the sensitivity of the results to uncertain input parameters.

2. ART GALLERY IN SOVOVY MLYNY

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 mlyny 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 1).

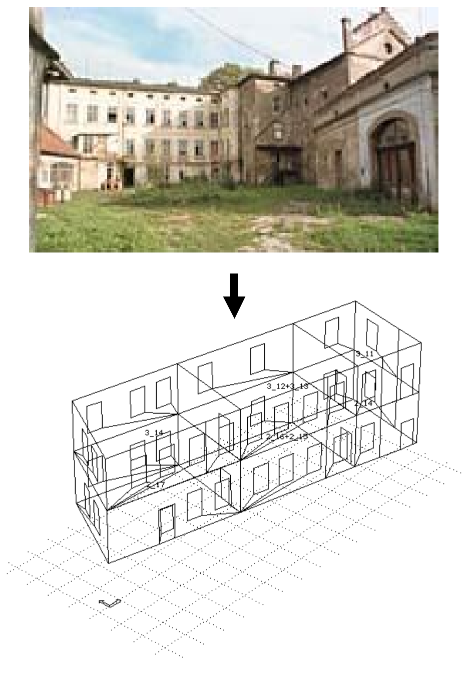

Figure 1: Outside view of the building and the ESP-r model of the considered part

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 of 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 26°C or less. The total air volume flow rate would not be more than 6,000 m^3/hour, which means small-sized ventilation ducts.

Figure 2 gives an example of indoor air temperatures in the building ventilated by external air without cooling. The internal sensible heat gains were assumed 15 W/m^2 from lights, plus 6.4/m^2 W/m^2 (i.e. one person per 10 m^2 of the floor area) from occupants.

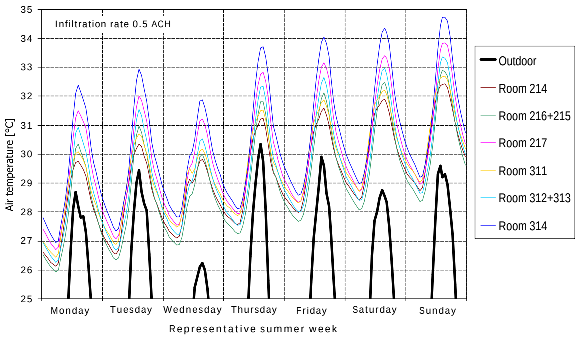

Figure 2: Temperatures of indoor and outdoor air (ventilation without air-conditioning)

Figure 3 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).

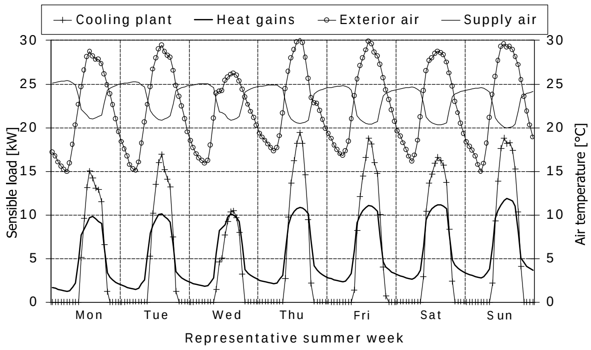

Figure 3: Optimized operation of air-conditioning system (indoor air temperature set point is 26 °C)

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. After completion of the building, we hope to be able to monitor the HVAC system and the indoor conditions, in order to compare the predictions with reality.

3. CONCERT HALL IN THE FORMER CHURCH OF SAINT ANNA

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. A 3D model for ESP-r was generated, with 8 thermal zones, taking into account shading objects and adjacent buildings (Figure 4)

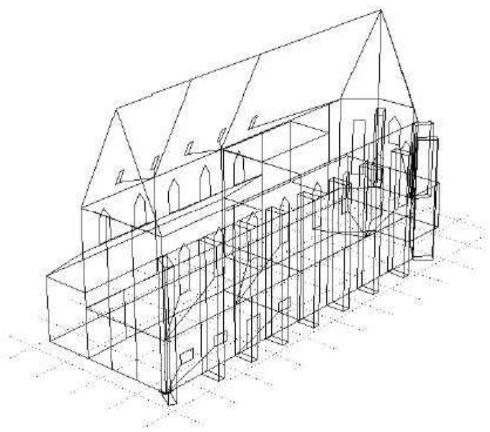

Figure 4: ESP-r model of the building

The former church itself is basically one large enclosure, which was subdivided into 5 fictitious thermal zones with a nodal airflow network (see Figure 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 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).

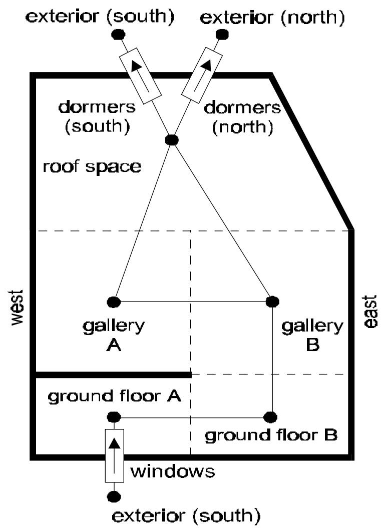

Figure 5: Diagram of thermal zones and airflow network

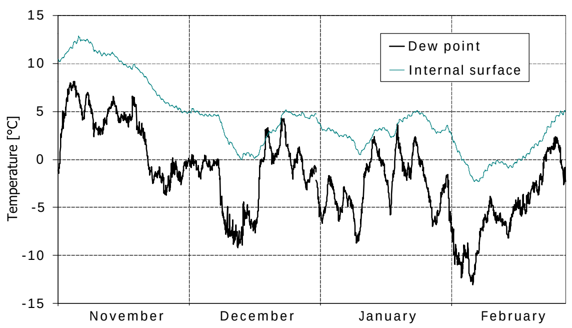

Figure 6: Internal surface temperature on the north wall and dew point temperature during the winter period

Figure 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.

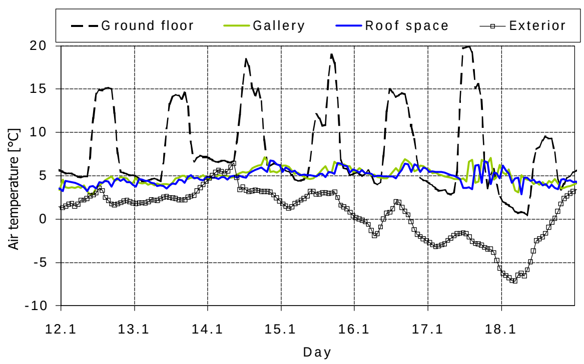

Figure 7: Air temperatures during a typical winter week

A detailed investigation of indoor air velocities and temperatures distribution was performed using the Fluent CFD software [6]. The building interior (approx. 9,630 m^3) was divided by an unstructured grid into more than 1,895,000 control volumes. Boundary conditions in terms of internal surface temperatures were transferred from the results of the zone-based ESP-r simulations.

Two cases were considered: with open or closed roof windows, yielding two modes of indoor airflow. While the former causes a stable vertical gradient of air temperature (Figure 8a) and natural ventilation with an acceptable rate of approx. 1 ACH, the latter makes the air temperature distribution uniform (Figure 8b) because of significantly circulating air flow (Figure 9).

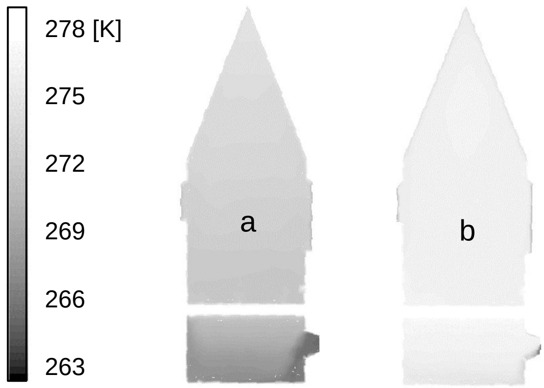

Figure 8: Air temperature distribution in the transversal section for cases with (a) open and (b) closed roof windows

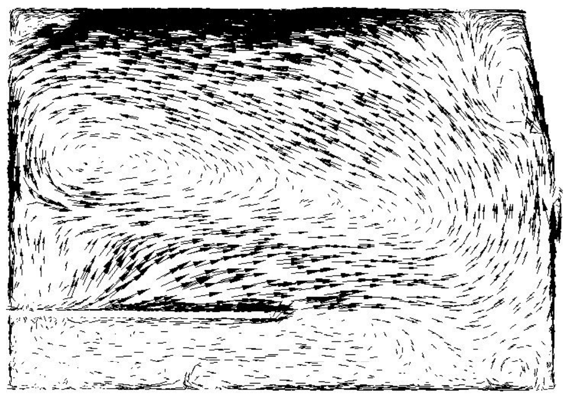

Figure 9: Air velocity filed in the central longitudinal section for the case with closed roof windows (max. velocity 0.6 m/s).

The energy and air-flow simulations showed that the building can serve as a concert hall for up to 300 visitors while the internal environment can be maintained by natural ventilation and (in winter) by heating of the seats. In the winter period (which is seen to be a critical part of the year) the internal air temperatures in the roof space would be quite stable and not far from outdoor conditions while the risk of moisture condensation on the walls is reasonably low. Indoor air velocities should not exceed 0.6 m/s, which is favourable both for the visitors and the construction parts of the former church.

4. CONCLUSIONS AND FUTURE WORK

We would like to emphasize that for simulation based design support such as in the current case it is really necessary to have sufficient domain knowledge. As Banks and Gibson [7] 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.

In general terms, but still related to the kind of design support as described in the current paper, we would welcome – amongst others – future work as follows.

It would be very useful to have databases with parameters for operational characteristics (e.g. sensible and latent casual heat gains, infiltration and ventilation estimates, etc.). This type of data exists but very fragmentary.

Very often there is a mismatch between the data provided by the manufacturers and the parameters needed for building performance modelling (i.e. thermophysical and optical properties of building materials). Somehow the manufacturers should be convinced that it would be useful to provide the missing data. Ideally building material and component manufacturers would make technical documentation (including the parameters needed for building performance modelling) on-line available. This is starting to happen but there are still "one or two mountains to climb" [8].

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, few (Czech) practitioners have expertise in using these technologies. This will quickly change due to the introduction of: performance based standards; societies such as the International Building Performance Simulation Association (IBPSA); and appropriate training and continuing education [9].

There still remains a lot of work to be done to promote building simulation so that it will be generally recognized and accepted by practitioners in the Czech Republic as a powerful tool in the field of environmental engineering. This is a very challenging task for the future.

REFERENCES

[1] Clarke, J.A. 1985. Energy Simulation for Building Design. Adam Hilger Ltd., Bristol.
[2] Hensen, J.L.M. 1991. On the Thermal Interaction of Building Structure and Heating and Ventilation System. PhD thesis. Technische Universiteit Eindhoven.
[3] ESP-r (Environmental Systems Performance – research) software; www.esru.strath.ac.uk
[4] Dunovska, T. 1999. Mathematical Modelling and Computer Simulation of Thermal Balance in Environmental Engineering [in Czech]. PhD thesis. Czech Technical University in Prague.
[5] Bartak, M., J.L.M. Hensen, M. Lain, L. Paulovic. 2000. "New Solar Data in Climate Database TRY Prague" [in Czech]. In proceedings of Simulace budov 2000. IBPSA-CZ, Prague.
[6] Fluent Inc. 2001. Fluent 5.5 Software Documentation; www.fluent.com
[7] Banks, J. and R.R. Gibson. 1997. "Simulation Modelling – Some Programming Required". IIE Solutions. Feb. 1997.
[8] Bunn, R. 2001. "Specifying on the Net". Building Services Journal. No.2, 49-50. CIBSE, London.
[9] Drkal, F. 2000. "Simulation Techniques in Environmental Engineering and the Mission of IBPSA-CZ" [in Czech]. In proceedings of Simulace budov 2000. IBPSA-CZ, Prague.