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Building Simulation (Innovation, Rapid Design, Design Support) & ICT

Rapid simulation of various types of HVAC systems in the early design stage

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Abstract

Considerations on indoor thermal comfort and energy efficiency need to be addressed early in the conceptual design stage of low-energy buildings. This paper describes an investigation on how to appropriately expand the hourly method of ISO 13790 to include performance assessment of different configurations of heating and cooling strategies. The implementation of the new thermal simulation procedure works as a plug-in to architectural sketching tool where it can execute an annual simulation within approx. 9 milliseconds. The plug-in may therefore qualify as a suitable tool for rapid and precise performance assessment of various heating and cooling strategies in the early design stage.

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1. Introduction

Computer-based building performance simulation (BPS) tools are ideal for supporting considerations on how potential design decisions affect building energy performance and thermal indoor climate [1-2]. However, the use of such BPS tools in actual early design processes is – for many reasons – currently limited [3]. The tool-related issues often pointed out as barriers to the uptake of BPS tools in the explorative early design stage is the additional time needed for setting up, running and modifying models in tools which are run in parallel to the architectural CAD tools [4]. The current trend to reduce geometrical modelling time is to make BPS available as plug-ins for the architect's sketching tool which enables the use of architectural model directly for simulation, e.g. Openstudio [5] or ICEbear [6]. Another issue that blocks the uptake is simulation speed and the vast amount of detailed input that many BPS needs to make a meaningful performance simulation. This issue can be addressed by substituting sophisticated methods with implementation of simplified calculation methods [2]. Regarding the latter issues, ISO 13790 [7] describes a simplified hourly method which in many cases has proven to be expedient for prediction of thermal indoor climate and energy performance compared to more sophisticated BPS tools [8-10]. However, the output of the ISO method is the heating and cooling *need*, i.e. it does not consider the thermo-dynamic consequences linked to *how* this need is provided; the use of solar shading, fan coils, increased ventilation rate, bypass of the heat recovery unit, cooled inlet air, etc. affects the thermal behavior of the building differently. Simulations of the energy need may therefore lead to a different architectural solution space than simulations of specific heating and cooling strategies.

This paper presents an investigation on how to appropriately expand the hourly method of ISO 13790 to include performance assessment of various heating and cooling strategies such as mechanical solar shading, variable air volume (VAV) ventilation, cooling/heating coils in the air handling unit, and regulation of heat recover unit. The differences in output from different cooling strategies simulated with the different implementations are then presented, compared and discussed.

2. Method

The option to include performance simulation of various specific ventilation cooling strategies such as solar shading, VAV, bypass of heat recovery and chilled inlet air, was implemented in C#.NET using the equations described in ISO 13790 annex C [7]. The implementation was conducted in two different ways: (1) using the linear interpolation procedure as described in EN ISO 13790 Annex C; and (2) by solving the 11 equations with 11 unknown variables analytically in Maple [11] to find the explicit formula for determining the exact cooling need.

Both implementations followed the procedure depicted in Fig. 1. The user defines a 3D building zone sketched in Rhinoseros [12], and HVAC settings. The performance prediction of the zone is initiated by calculating the hourly daylight illuminance and solar load of the zone using DIVA4Rhino and Viper [13], respectively, before stepping into the thermal simulation. Each hourly time step of the thermal simulation starts with a glare analysis: the shading device is activated if a glare set point is exceeded, which consequently also reduces the solar heat gain in the thermal calculation. Next, the indoor temperatures is simulated in ‘free float’ condition, i.e. the simulation results are only influenced by the weather data, the minimum user-defined system values (ventilation, lighting, internal loads etc.) and the energy properties of the building constructions. Thereafter, the need for bypass of the heat recovery unit (HR) – if defined by the user – is found by calculating the factor b_{VE} from the EN13790 formulas, which is an expression of the relation between inlet and indoor air temperature. In some hours of the year, full or throttled bypass of the HR may be enough to reach a desired operative temperature, but in other hours of the year, full HR may not be sufficient to prevent inlet air below desired minimum inlet temperature and may therefore cause a risk of draft. To prevent this, a heat coil can be activated (if user-defined) to heat up the inlet air (after HR) which consequently affects b_{VE}. Next, the indoor temperatures are calculated again. If then the returning operative temperature exceeded the user-defined comfort limits, direct room heating or user-defined cooling systems are activated according to a user-defined hierarchy. The hierarchy means that a cooling system is only activated if needed. For example, if the cooling hierarchy is ‘solar shading, VAV factor of up to two, venting’, the algorithm may find that solar shading and a VAV factor of 1.5 was sufficient to reach the desired operative temperature, then the algorithm does not activate venting. The final operative temperature may exceed the desired set point if the user-defined maximum capacity of heating or cooling is insufficient.

Besides the two implementations of the procedure shown in Fig. 1, the standard procedure for calculating building zone heating and cooling need described in ISO 13790 was also implemented to make performance comparisons of the proposed simulation procedure and the standard procedure.

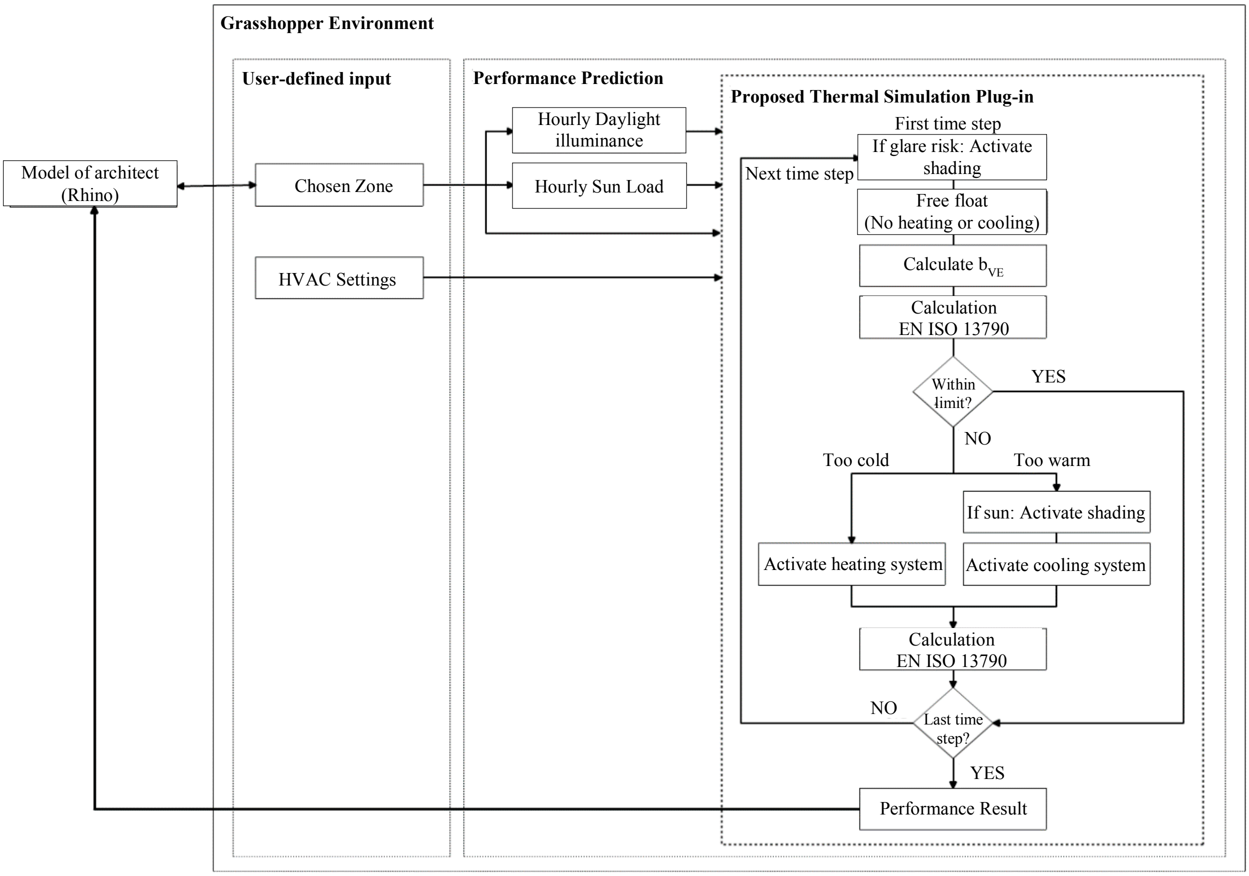

Fig. 1. Schematic of the simulation procedure of the proposed thermal simulation plug-in, and the connection to the sketched 3D-model.

2.1. Case building description

The performance of the two proposed implementations and the standard calculation procedure were evaluated by comparing simulations of a test room resembling a typical office in Denmark, occupied by four persons, each with a laptop of 60 W. Occupation time was five work days a week, 8:00-17:00, however only half occupation during lunch breaks 12:00-13:00. The room dimensions were 10 x 6 meters floor plan and a room high of 3 meters. Only one wall was facing the outdoors (10 x 3 m), while the rest of the room surfaces were calculated adiabatic. A one meter high three-layer glazed window (U=0.8 W/(m^2K); g=0.50; LT=0.65) was placed across the entire façade 0.8 meters above floor level. Venting was not possible. The external wall had an insulation factor of U=0.30 W/(m^2K) and the room thermal mass was 165000 J/K per m^2 floor area (middle heavy) with an effective mass area of 2.5 m^2 per m^2 floor area (according to ISO 13790). The room had an infiltration rate was 0.5 l/s/m^2 (at 50 Pa), VAV ventilation fulfilling Class II in EN 15251 [13] (maximum 1.75 l/s/m^2) with HR bypass (SFP=1.5 kJ/m^3, HR=0.80), heating coil and cooling coils to condition inlet air (minimum 18 °C). Electrical light was dimmable (0.1-6.0 W/m^2) floor area respecting a set point of 200 lux in a point located at the center of the room 0.8 meters above floor level, and work lamps (0.2 W/m^2 floor area) were on/off-activated if <500 lux. External shading device (F_{heat}=0.2; F_{light}=0.2) was on/off-activated at 2000 lux in a horizontal sensor point to prevent glare. The room had a direct room heating system of maximum 90

W/m^2. The cooling hierarchy was 1) bypass of heat recovery (desired operative temperature 23.5 °C, minimum inlet of 18 °C), 2) solar shading, but only if sun load exceeded 50 W/m^2 window area, 3) increased mechanical ventilation rate (VAV), and 4) mechanical cooling of inlet air. Outside occupant hours the ventilation system was either turned off or activated for night cooling (set point of 22 °C), if necessary.

3. Results and discussion

There was only a few hours difference in thermal performance and few kWh difference in energy need between the two proposed calculations procedures for expanding the method of EN 13790 (Table 1). Difference in simulation time for the two implementations was not significant: 10 000 simulations took approx. 1.5 minute in both implementations (on a 64-bit PC with an Intel I5-3210M CPU, 2.50 GHz and 16 GB RAM) equivalent to approx. 9 ms per thermal simulation. However, there was a significant difference in simulation outputs compared to the original calculation procedure of EN 13790 annex C, in which the mechanical room cooling capacity was approximated to the cooling capacity of the VAV ventilation system. The reason was that the energy need for ventilation decreased because VAV-based cooling was approximated into mechanical room cooling, and because the need for heating was underestimated due to the lack of pre-heating of inlet air. The increased energy need for lighting was because the shading system was activated more often in the standard implementation due to the lack of HR bypass.

Table 1: Performance results of the implementations

Type of implementation	Hours above			Hours at	Heating	Cooling	Ventilation	Lighting
	27 °C	26 °C	25 °C	23.5 °C	(kWh)	(kWh)	(kWh)	(kWh)
Proposed (interpolation)	0	1	563	162	165.1	117.9	522.5	1019.6
Proposed (analytical)	0	1	564	165	165.5	119.4	520.3	1019.9
Standard (interpolation)	0	0	723	66	149.6	1553.0	233.5	1029.7

According to the calculation procedure in EN 13790, b_{VE} should be regulated according the inlet air set by the user, e.g. 18°C. However, b_{VE} is not near-linear correlated to the inlet temperature (Fig. 3a), which means that determining b_{VE} based on a linear regression between b_{VE} and the inlet temperature causes erroneous simulation results. If, instead, the indoor air temperature was found in a linear regression between inlet temperature and indoor air temperature, which have a near-linear correlation (Fig. 3b), and used for calculating b_{VE} then a significant interpolation error can be avoided: The difference in operative temperature between simulations of the case building using the interpolation in Fig. 2a and 2b (worst case, time step 5109), respectively, is 16.8 °C. Furthermore, using interpolation based on indoor air temperature also poses a pitfall in the case that the rate of mechanical ventilation is increased to avoid overheating while keeping the inlet temperature at 18 °C. As b_{VE} is a function of the inlet temperature, indoor and external air temperature, b_{VE} must be found through three-dimensional interpolation which increased the complexity of the algorithm (thus risk of implementation errors).

With an execution time of approx. 9 ms per annual thermal simulation, the two proposed implementations were equally fast. The two implementations only resulted in slightly different temperatures caused by the small non-linearity of the curves for interpolation. However, the implementations initially had differences of up to approx. 1 °C, see Fig. 3, but were in general below 10^{-2} °C. The larger deviations were caused by the on/off-regulation of the external shading device which was activated if the operative temperature was above 26 °C. Due to the inherent differences between the two implementations, one implementation could calculate an indoor operative temperature that exceeded this temperature limit slightly, e.g. by 10^{-3} °C (and therefore activated the shading), while the other implementation calculated an operative temperature slightly below 26 °C (and therefor did not activate the shading). This numerical inexpediency was eliminated by rounding the temperature to its first decimal during all calculation steps in the implementations, and not just on the final simulation results. Doing this, the two implementations returned equal output.

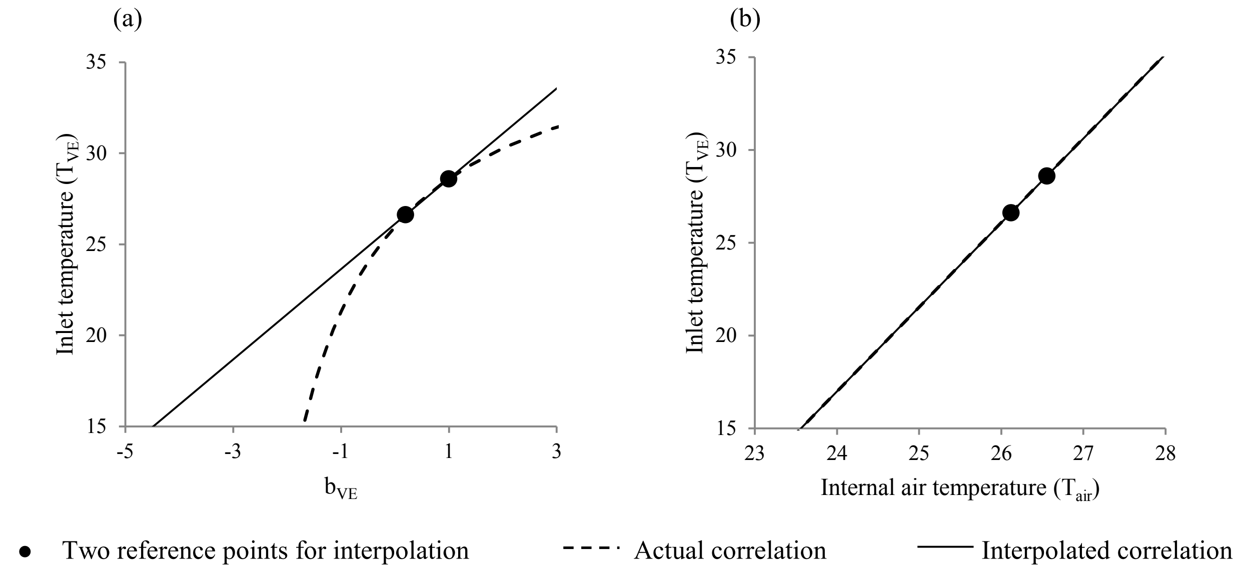

Fig. 2. The correlation between inlet temperature and (a) b_{VE}-factor and (b) indoor air temperature, at time step hour 5109 in the case building.

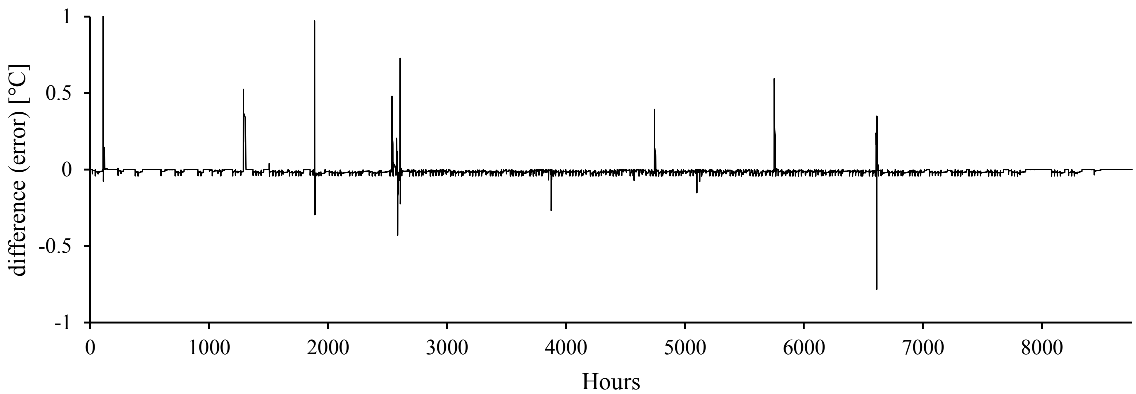

Fig. 3. Hourly differences between the two implementations ($T_{op,interpolation} - T_{op,analytical}$) regarding operative temperature

The profound risk of making errors when implementing the interpolation approach can be eliminated by using the analytical approach. This is why we recommend developers that are interested in implementing the hourly method in ISO 13790 suggest use the analytical approach, which also was easier to script and demanded fewer lines of code. However, if developers insists on using the interpolation approach for an implementation similar to the one described in this paper, we have the following recommendations to avoid erroneous results: 1) Make sure you only apply linear interpolation for variables which physically are near-linear correlated, 2) always round temperatures to their first decimal whenever they are calculated throughout the code, and 3) be aware of the need for three-dimensional interpolation to find b_{ve}.

4. Conclusion

This paper proposes a procedure to expand the hourly method in EN13790 to enable performance simulation of various cooling strategies instead of just calculating the energy need for heating and cooling. There is a significant difference in simulation results between the new procedure and the standard calculation if a room has VAV-based cooling. This illustrates the need for using the proposed procedure when investigating the performance of various types of HVAC systems in the early design stage.

Based on our experience in implementing this procedure, we recommend other developers with the same interest to base their implementation on analytical solutions to the equations in EN ISO 13790 rather than the linear interpolation procedure described in EN ISO 13790 Annex C due to potential pitfalls when implementing the interpolation method.

If potential pitfalls are avoided by following the recommendations listed in this paper, both types of implementation for the proposed calculation procedure results in rather fast performance predictions (approx. 9 ms per annual thermal simulation) and there are no differences in simulation results. The proposed procedure imbedded in an architectural CAD program therefore accommodates one of the main barriers for uptake of building performance simulation in the early design stage, namely the need for rapid and reliable performance simulations of the effect of various cooling strategies on the architectural solution space.

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