Identification of thermal model of DOE library

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1. System identification

This section describes an identification of a thermal dynamics model that is used in this paper. First we describe the system — a second floor of DOE (Department of Engineering) library. The identified model uses a measured sun thermal load, that is explained in subsection 1.2. A thermal model of the whole floor is detatiled in subsection 1.3. Utilizing the identified model, we can estimate a thermal load in each zone. This estimation process and an estimated thermal load are shown in subsection 1.4. In a real building zones may be coupled, in subsection 1.5 we discuss this effect of interference between the zones.

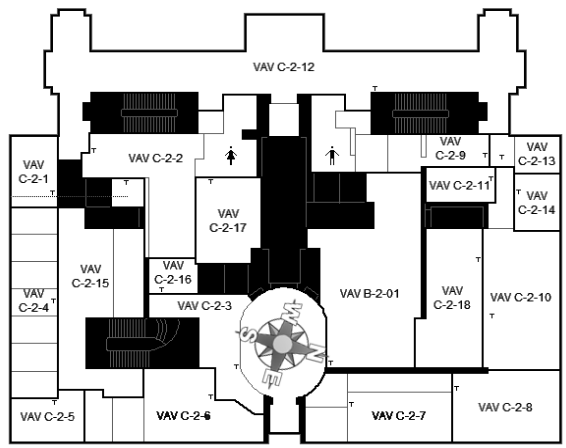

Figure 1: Second floor of DOE library.

1.1. Building description

The second floor of DOE library (Figure 1) consists of 16 thermal zones. Each zone is controlled by a single VAV box, that includes both heating and cooling coils. For each zone, available measurements are supply air temperature, supply air flow rate and zone temperature. In addition, temperature of the outside air is known. The north direction is indicated by a compass rose symbol in Figure 1. This direction is important when sun thermal load is considered.

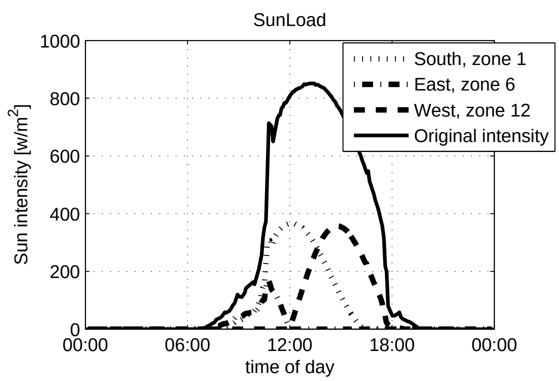

Figure 2: Total sun intensity, and intensities for east, south and west walls.

1.2. Sun thermal load

Sun radiation can add a significant power to the system, therefore, if sun load is not considered explicitly, model uncertainties increase. First, sun radiation intensity, measured by a nearest (3 km) weather station [1], is measured. Next, for each time zone, we compute a sun radiation, that is falling on an outside wall, using a scalar vector product of the sun direction vector and a normal to the outside wall.

$$I_i(t) = I_{sun} \sum_{w \in W_i} \max(0, < u_{sun}(t), u_{wall_{i,w}} >) \quad (1)$$

where $I_i(t)$ is the intensity of sun radiation that falls on zone i at time t, I_{sun} is the total intensity of sun radiation at time t, W_i is the set of all outside walls of zone i, $u_{sun}(t)$ is a unit vector at sun direction at time t and $u_{wall_{i,w}}$ is a unit vector normal to an outside wall w of zone i. The orientation of wall shifts in time the sun intensity profile. Figure 2 examplifies a total sun intensity and intensities for three different zones. As expected, the eastern wall experiences first the load, next the southern wall, and the western wall is the last.

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1.3. Model description

The identified model is a third order, auto regressive, bilinear model (2). Each zone is identified separately from other zones.

$$\begin{aligned} T_i^{k+1} &= P_{1i}T_{oa}^k + P_{2i}T_{oa}^{k-1} + P_{3i}T_{oa}^{k-2} + P_{4i}(T_{si}^k - T_i^k)\dot{m}^k \\ &+ P_{5i}T_i^k\dot{m}_i^k + P_{6i}I_i^k + P_{7i}I_i^{k-1} + P_{8i}I_i^{k-2} + P_{9i} \\ &+ P_{10i}T_i^k + P_{11i}T_i^{k-1} + P_{12i}T_i^{k-2} \end{aligned} \tag{2}$$

where $i \in \{5, 15\}$ is the zone index, P_{ji} are the model coefficients for zone i, T_{oa}^k is the temperature of outside air at time k, T_{si}^k is the supply air temperature to zone i, $\dot{m}_i^k$ is the supply mass flow rate to zone i, I_i^k is the sun load intensity for zone i and T_i^k is the zone i temperature at time k.

1.4. Load estimation

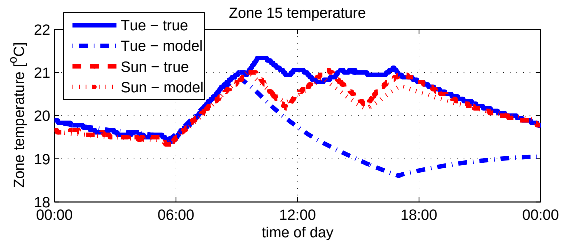
The model was identified using data from weekends duirng four sequencial monthes. By comparing weekdays data to the weekend based estimation, we can identify thermal load profile generated by people and equipement. We define a load profile as a difference in temperature between a local model prediction and the true value. By local model prediction we mean prediction in very short horizon — one time step. Formally speaking, the load is calculated as following.

$$L = \frac{T_{k+1} - \hat{T}_{k+1|k}}{\Delta t} \tag{3}$$

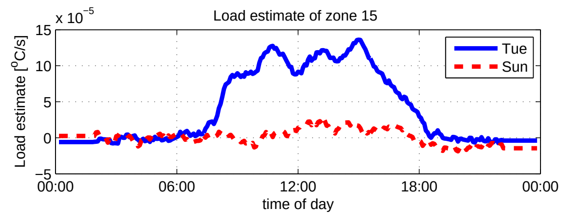
where L is the load profile, expressed in $^o\mathrm{C}/s$, T_{k+1} is the measured zone temperature, $\hat{T}_{k+1|k}$ is the zone temperature prediction with the identified model (2) using data from the previous time step and Δt is the sampling period. Measurement noise and quantization errors usually have larger amplitude than that of the load, especially, when the load is measured at single time step. Any simple filering technique, such as a moving average that we employed, filters out the noise.

Load estimate can vary significally with zone. For some zones, such as zone 15, the load estimate is clear and very consistent. Figure 3 demonstrates temperature prediction and load estimation in zone 15 at typical Tuesday and Sunday. As can be seen at Figure 3(b), the load profile is clearly distinguishable when weekday and weekend are compared. This load difference leads to an error of 2^oC in temperature prediction for weekday, as can be seen at Figure 3(a). For some zones, the load difference between working and weekend days is less clear.

An additional learning phase may be applied, to classify zones according to their load profiles. This classification may partition zones to groups of nominal zones, with a valid thermal load, and zones that exhibits severe model mismatch, that cannot be explained by thermal load.



(a) True and estimated temperature of zone 15.



(b) Load estimate in zone 15.

Figure 3: Zone temperature and load estimate for representative working and weekend days.

1.5. Inerference between zones

The identified model (2) is based on an assumption that all zones are separated from each other. This assumption can be challenged by inspecting the correlation between the power supplied by VAVs and the change in zone temperatures.

$$\rho_{i,j} = \frac{\sum_k \left[T_i^{(k+1)} - T_i^k\right]\left[\dot{m}_j^k(T_{sj}^k - T_j^k)\right]}{\sqrt{\left\{\sum_k \left[T_i^{(k+1)} - T_i^k\right]^2\right\}\left\{\sum_k \left[\dot{m}_j^k(T_{sj}^k - T_j^k)\right]^2\right\}}} \tag{4}$$

This correlation is shown in Figure 4. Perhaps surprisingly, for many zones, VAVs other than the VAV associated the zone have very large influence on zone temperature. For example, zones 4 and 15 are equally affected by the same VAV (#4). If this cross-correlation pattern is taken into account in the identification process, better model, with less uncertainties, can be found.

References

[1] "Station kcaberke22, www.wunderground.com."

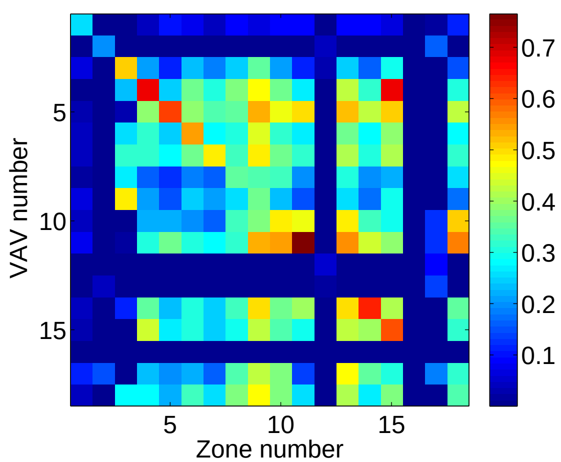


Figure 4: Correlation between the heating/cooling energy of VAV and change of zone temperature