# END-USE DEMAND IN COMMERCIAL OFFICE BUILDINGS: CASE-STUDY AND MODELLING RECOMMENDATIONS

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## ABSTRACT

While considerable progress has been made on developing high-resolution stochastic models of electricity demand for the domestic sector, non-domestic models remain relatively undeveloped. This paper provides general recommendations about how such models might be structured for commercial offices, based on detailed analysis of high-resolution end-use demand data for a single multi-tenanted office building. The results indicate that modelling of commercial office buildings could be viewed as analogous to modelling a group of dwellings with partial residency (to represent individual office units within the building), with communal heating and communal spaces, a limited number of work related appliances, and occupant activities restricted to those related to work.

## INTRODUCTION

The decarbonisation of the electricity supply industry could involve considerable impacts on low-voltage distribution networks. Of particular concern are high penetrations of low-carbon technologies, such as photovoltaic systems (Thomson and Infield, 2007), electric vehicles, or heat pumps (Pudjianto et al., 2013). If left unmanaged, such technologies could cause voltages to rise outside of statutory limits, or increase peak demand, such that networks might need to be reinforced, at considerable cost.

To help mitigate these potential impacts, there is an interest in quantifying the benefits of encouraging consumer demand to become more flexible, in terms of the timing of when electricity is consumed (Strbac et al., 2010), or in terms of service level expectations, such as thermal comfort (Hong et al., 2013). For example, to reduce voltage rise, consumers could be encouraged to increase demand during periods of peak solar generation using a feed-in tariff similar to that used in the UK, or in Germany post-2011 (McKenna and Thomson, 2013).

To better understand the extent to which flexible demand can help support networks, there is a value in characterising demand within buildings at the end-use level (Richardson et al., 2010). Considerable progress has been made in characterising end-use demand at the domestic level and in developing high resolution stochastic models of electricity demand in dwellings for low-voltage network modelling (Richardson et al., 2010; Widén and Wäckelgård, 2010). Low voltage networks, however, generally include a mix of domestic and services sector consumers. Electricity consumption in the services sector is similar in magnitude to domestic electricity consumption, 5.9 Mtoe versus 6.7 Mtoe in 2012 (DECC, 2012). If the full diversity of consumers connected to the low-voltage networks is to be accounted therefore a high resolution electricity demand model for the services sector would be necessary to complement existing domestic models.

A complicating factor to the development of a services sector demand model is the sector's diversity. It includes the following sub-sectors: commercial offices, communication and transport, education, government, health, hotel and catering, other, retail, sport and leisure, and warehouses (DECC, 2012). Some progress has been made on modelling end-use demand within the first of these sub-sectors: commercial office buildings. Page developed a high-resolution stochastic electricity demand models for offices (Page, 2007). The model is based on monitored data for occupancy and activity within a single university office building, and therefore might not be representative of a broader population, unlike the domestic models cited previously. Wang et al. developed a model of occupancy within office buildings (Wang et al., 2005; Wang et al., 2011), though again this is based on data from a single building and is for single-occupancy office rooms only. There is still therefore considerable scope for further development of representative high resolution demand models for the services sector.

A contributing factor to the lack of high resolution demand models for the services sector is the limited availability of data on which to base and inform the models. In the domestic sector, time use surveys serve as a useful source of data on which to base occupancy and activity models. No such similar surveys are readily available for the services sector. Monitoring studies of high-resolution end-use demand data in the domestic sector are rare (Energy Saving Trust et al., 2012), and rarer still in the non-domestic sector.

With the aspiration of developing such models in future, this paper investigates how they should be structured in comparison to domestic models and what features should be included. Of the sub-sectors described above, the paper will focus on doing this for commercial offices. To do this, the paper presents detailed analysis of high-resolution end-use demand data for a single multi-tenanted commercial office building. This provides the basis on which the general recommendations regarding model structure are founded.

## DESCRIPTION OF BUILDING AND DATA

To protect the privacy of the occupants and owners, the building analysed here is referred as ‘Building A’ and has characteristics as described in Table 1. It is detached, consisting primarily of commercial office units, but also holds an auditorium (used for conferences and events), and a cafe-restaurant with on-site all-electric kitchen. Of the 55 office units, 24 are two-person design occupancy office units, 26 are four-person office units, and 5 are eight-person units.

*Table 1 – characteristics of Building A.*

| | |
|---|---|
| **YEAR OF CONSTRUCTION** | 2011 |
| **NUMBER OF OFFICE UNITS** | 55 |
| **TOTAL AREA OF BUILDING** | 4023 $m^2$ |
| **TOTAL AREA OF OFFICE UNITS** | 1580 $m^2$ |
| **OCCUPANCY DENSITY (OF OFFICE AREA)** | 8 $m^2$/person |
| **SPACE HEATING SYSTEM** | Air-source heat pump and gas boiler |
| **SPACE COOLING SYSTEM** | Air-handling unit in auditorium, air-conditioning units for conference rooms |
| **DOMESTIC HOT WATER HEATING SYSTEM** | Gas boiler |
| **ENERGY PERFORMANCE ASSET RATING** | 26, equivalent to a ‘B’ |

The building has an extensive monitoring system which was fitted for the purposes of assessing the building’s energy and environmental performance, of which the data has been made available for this study. Data was available for the majority of sensors from November 2011 through to July 2013 with data resolution of approximately 10 minutes. This data has been sorted in the end-use categories as shown in Table 2. The end-use categorisation used by DECC was adopted (DECC, 2012). Note DECC includes a single lighting category, while here this has been divided into separate categories for internal lighting and external lighting. The heating category has also been separated into gas and electric sub-categories. Note that of the 55 office units, five had faulty monitors, in which case the power and lighting demand for these five units could not be accounted for in the computing or lighting categories, but instead was included in the ‘other’ category.

*Table 2 – data available from Building A.*

| END-USE CATEGORY | SENSORS INCLUDED |
|---|---|
| Catering | Kitchen power |
| Computing | Office small appliances (summed for all office units)<br>Comms room servers |
| Cooling and ventilation | Auditorium air-handling unit<br>Communications room air-conditioning<br>Meeting rooms air-conditioning |
| Lighting (internal) | Office lighting (summed for all office units)<br>Communal lighting<br>Basement lighting |
| Lighting (external) | External lighting |
| Heating (electric) | Air-source heat pump<br>Auditorium air-handling unit<br>Resistive heating of external pipework<br>Fans, pumps, and heating controls |
| Heating (gas) | Gas demand for space heating only |
| Hot water | Gas demand for hot water only |
| Other | Lift motor<br>Communal small appliances<br>Total demand for five unmonitored office units |

## RESULTS & DISCUSSION

### End-use demand and building tenancy

Building A had low tenancy at the start of the data monitoring period. Figure 1 shows the tenancy level rising from 15% in October 2011 to around 70% in July 2013. Tenancy refers to the proportion of the building that is rented out to tenants. Figure 1 also shows monthly energy end-use demand. There is a clear seasonal variation, with winter demand approximately twice that of summer. There is a general upward trend for monthly demand, presumably associated with the increasing tenancy. The seasonal variation can be seen to be caused predominantly by variations in heating demand. Note the heating demands during the two winters are quite similar even though tenancy in the first winter was less than one third of the tenancy during the second winter. Cooling remains low throughout the whole year, apart from an increase for two months during the summer. Hot water, internal lighting, other, and computing increase progressively over time, presumably due to increasing tenancy.

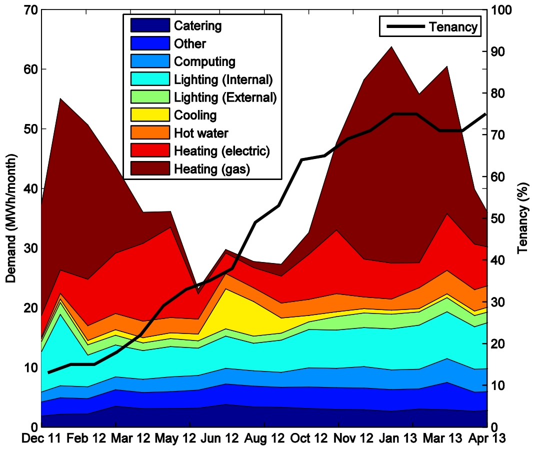


*Figure 1 – building tenancy and monthly end-use demand.*

The association between end-use demand and tenancy is explored further in Figure 2 which plots monthly end-use demand versus building tenancy. Computing has the strongest and most significant correlation with tenancy, followed by internal lighting. Catering, other, and hot water have less significant association, and only moderate correlation. Cooling and heating do not appear to be correlated with tenancy.

Table 3 compares the relative end-use demand for Building A with average annual values for commercial buildings (DECC, 2012). Note the values include gas and electricity end-use demand. Building A has similar demand for hot water, heating, computing and lighting. Notable differences include cooling, which is considerably lower than the average (the building is predominantly naturally ventilated). Catering and other demand in Building A is over twice the average. For catering this is owing to the on-site kitchen which serves the cafeteria-restaurant. As for other demand, this could be associated with including five unmonitored office units in this category. Together, heating and lighting account for between 69% of total demand.

*Table 3 – end-use demand as percentage of total for Building A compared to typical values from DECC.*

| END-USE | DECC | BUILDING A |
|---|---|---|
| Catering | 3% | 7% |
| Computing | 8% | 7% |
| Cooling | 11% | 4% |
| Hot water | 6% | 6% |
| Heating | 53% | 49% |
| Lighting | 17% | 20% |
| Other | 3% | 8% |

## Variation of end-use demand by time-of-day and day-of-week

The previous section considered monthly end-use demand and its relation with building tenancy. This section considers how end-use demand varies by time-of-day and day-of-week. Figure 3 shows end-use demand profiles for an illustrative week in November 2012. There is a clear distinction between weekday and weekend end-use demand profiles. Catering, computing, internal lights, and hot water demonstrate increases during working hours on weekdays. For the week shown, it is clear that the building is heated over the weekend, though the office units do not appear to be occupied due to the low levels of internal lighting and computing. Heating therefore appears to follow a schedule which is based on assumed occupancy rather than actual occupancy, which could explain the lack of correlation between heating and tenancy shown previously. Cooling loads for this week were neglible. When the building is unoccupied, during the night for example, there is considerable base-load demand, composed primarily of catering, other, lighting and computing end-uses. Working hours clearly have a considerable influence on demand with three distinct periods within which end-use demand appears to be broadly consistent:

- weekdays during working hours (8am-6pm);
- weekends during working hours;
- and all hours outside of these (6pm to 8am).

## Lighting and computing demand

Figure 4 shows the demand profiles for lighting (internal and external) and computing, averaged over the entire monitoring period. For external lighting, demand is highest from 6 pm to 2 am (~4 kW), and negligible from 9 am to 2 pm. For internal lighting, a base-load of 5 kW to 6 kW continues from 9 pm to 6 am on weekdays, and throughout the weekend. From 6 am to 9 am, internal lighting ramps up to 16 kW, a three-fold increase, which then remains roughly constant until 4 pm, at which point it ramps down more slowly until it reaches the base-load again at around 9 pm.

The office, corridor and toilet lighting in Building A is switched using passive infrared sensors. Lighting in these areas therefore switches on when occupants first enter the area in the morning, and then switches off after 20 minutes of no discernible occupant movement. Other communal area lighting is manually switched. The occupants appear to arrive between 8 am and 9 am.

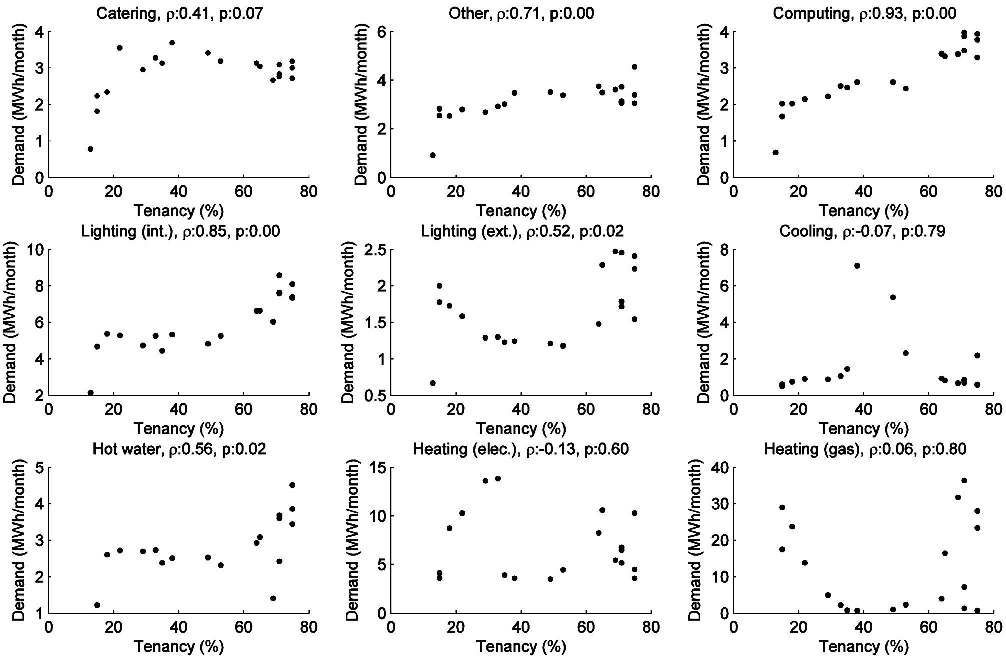


*Figure 2 – monthly end-use demand versus building tenancy. ρ values indicate Pearson's linear correlation coefficients between end-use demands and tenancy, while p indicates p-values for the correlations.*

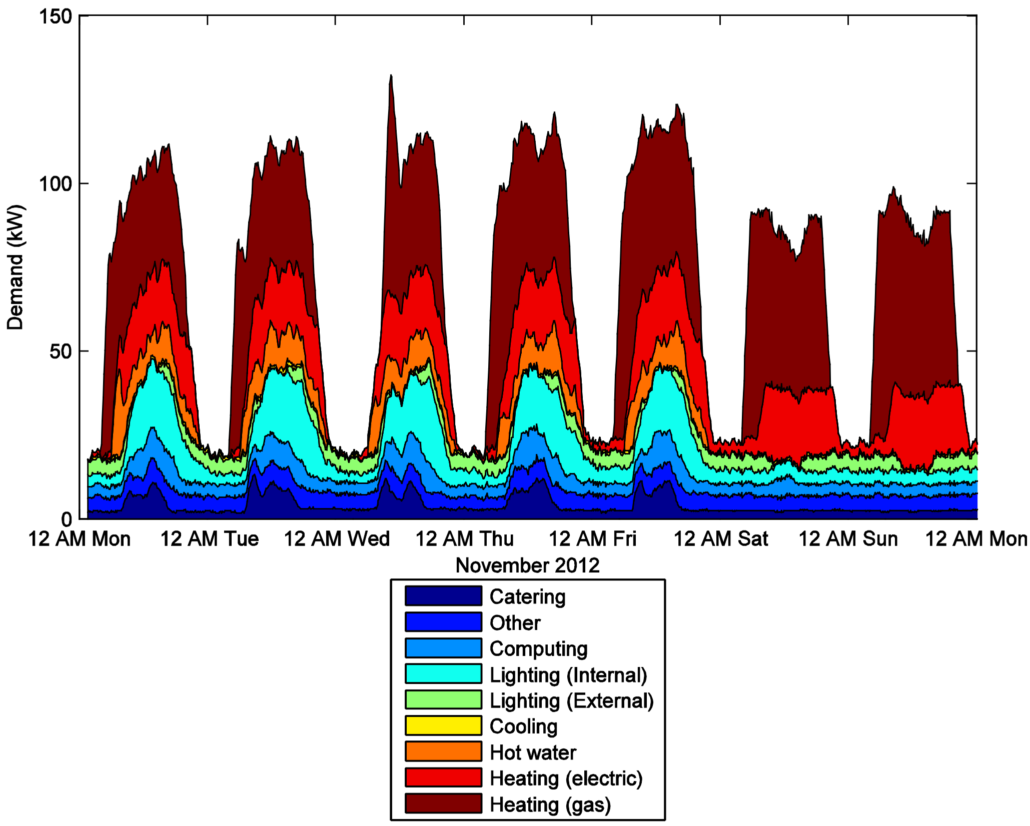


*Figure 3 – an illustrative week in November showing demand profiles for the end-use categories*

The demand profile for computing is similar to that for internal lighting, which might be expected as occupancy should be an important cause for both. There are, however, some important differences. Computing has a higher base-load compared to its peak than lighting. This suggests that proportionally more computing is left on overnight than lighting. In the morning, between 7 am and 10 am, computing has a slightly delayed and less steep morning ramp up compared to lighting. On the other hand, the evening ramp down is steeper for computing, occurring between 4 pm and 7 pm. This can be explained by the fact that computing is less of a shared commodity than lighting. For example, in an office unit occupied by four people each with their own computer, if three leave then it might be reasonable to assume that computing demand would fall by three quarters, while lighting might reasonably be assumed to remain unchanged as the last person in the office would still require lighting. The same logic can be used to explain the slower morning ramp up.

**Implications for the structure of a high-resolution demand model for commercial offices**

This section discusses the potential structure for a high-resolution demand model for commercial offices based on the detailed analysis above. Figure 5 illustrates the general structure of such a model, and Figure 6 provides additional detail about the structure governing demand in individual office units. The following describes the specific features of the model and, where appropriate, compares these to the structure of a domestic model, as described fully in (Richardson et al., 2010; Richardson et al., 2008; Richardson et al., 2009).

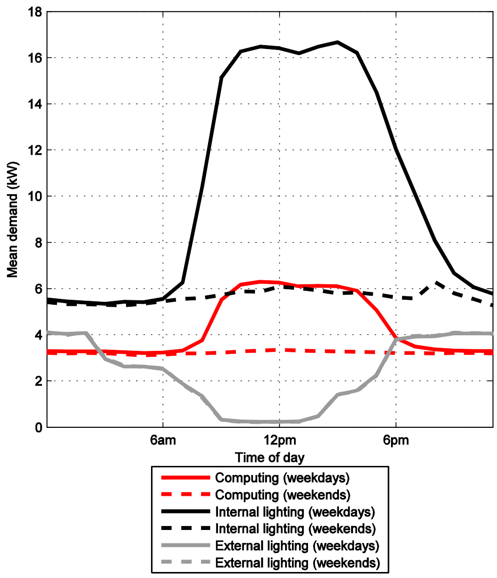


*Figure 4 – computing and lighting demand profiles.*

**Thermal model**

Firstly, the inclusion of a thermal model should be noted. This paper's results indicate the importance of including a thermal model within a demand model for commercial office buildings. An energy model that simulated heating demand alone would account for 49% to 53% of total energy demand (see Table 3). Including cooling and hot water demands would bring this up to between 59% and 70%. This is in contrast to the domestic electricity model, which does not include a thermal model, and yet can provide a reasonable representation of domestic electricity demand due to the prevalence of gas heating, at least in the UK.

A thermal model should represent building occupancy to account for passive heat gain from people and their use of lighting and office equipment within the building. It should also account for where occupants are within the building as different parts of the building have different environmental requirements. For example, a person occupying a meeting room might be heating a space which air-conditioning is trying to cool, whereas the same person in a heated room will have the opposite effect. Occupant activity can also be important for thermal modelling, for example whether people open and shut windows, change temperature set-points, and how much and when hot water is used.

**Occupancy, working hours and tenancy**

While the domestic model differentiates between weekdays and weekends when creating demand profiles, a commercial model would need to include detail on working hours to inform occupancy of the building. Demand on Saturdays, for example, might be considerably different to demand on Sundays depending on working hours.

Tenancy is also important and should be included given its correlation with most end-use demands. Again this is in contrast to domestic models, which does not include any concept of partial residency of dwellings.

End-uses such as lighting and computing increase as more people move into the building – lights are used more and more appliances are plugged in. Large portions of these are, however, left on overnight, producing high base-loads for these end-use demands. It is as a result important for the model to account for high base-loads, for example by including a probability that appliances or lights are left on even though office units are unoccupied. While a domestic model can reasonably ignore the effect of occupants leaving lights on overnight, as this is a relatively small proportion of overall demand, the same cannot be said for a commercial demand model.

### Sharing of appliances and lighting

In a domestic model, it is important to account for the sharing of appliances and lighting among occupants. Two occupants can be watching same television, or using the same light. Similarly, a commercial model also needs to account for sharing of lighting and appliances.

This is particularly important for lighting, as it is the second largest end-use demand, accounting for 20% of overall energy demand in Building A. Internal lighting is occupancy driven, but the extent of this varies depending on the lighting control system in place. In Building A, office lighting is fully automated, with lights switching on and off according to the activity within the immediate vicinity of a light's passive infrared sensor. Other buildings, however, might not have such control systems, and might rely on manual switching instead. Accounting for the diversity of control systems is important because it has implications on energy use, for example manually controlled lights might be left on more when the building is unoccupied.

Another important concept regarding lighting simulation is to accurately account for the sharing of lighting among occupants: a single lighting unit can be used by multiple people. It is as a result important to account for the division of office buildings into 'units', as a single 8-person office unit will have different lighting demand to four 2-person office units.

How appliance use is associated with occupant activity could conceivably be simpler in a commercial model than in domestic models, for example by having computing equipment being either on or off depending on whether an occupant was within their office unit or not. So while a domestic model requires many activity profiles to represent occupant behaviour (e.g. watching TV, washing, laundry, cooking, etc.), a commercial model might reasonably include a much reduced number of activities, or indeed ultimately just a single 'working' activity profile that is directly correlated with the occupancy of the office unit.

The remaining ~20% of demand is then made up of catering, computing and other end-uses. A large portion of this is base-load, particularly for the other category, and effectively consists of small appliances that are continuously in operation. The demand that remains is then occupancy related e.g. computers being switched on and off when people arrive and leave the office, or equipment being used to prepare food in kitchen. Again these might reasonably be associated with the simplified 'working' activity profile mentioned above.

### Division of building into office units and communal space

As mentioned above, it is important to consider how office buildings are divided into units of offices, as many smaller office units will exhibit different characteristics than fewer larger ones. This is similar to the case of modelling of domestic demand, as two single-occupancy dwellings will have different demand characteristics to a single double-occupancy dwelling e.g. in terms of the probability of multiple occupants departing or arriving home at the same time. Modelling commercial office buildings could therefore be viewed as equivalent to modelling a group of dwellings with communal heating, a limited number of work related appliances, and occupant activities restricted to those related to work.

Unlike domestic models, however, a concept of communal spaces would need to be included in a commercial office model, in which case the occupancy model would also need to be extended to be able to differentiate between an occupant being in an office unit, being in a communal space, and being outside of the building.

## SUMMARY

There is a value in developing high resolution stochastic models of end-use electricity demand within buildings to quantify the impacts of low-carbon technologies and flexible demand on low-voltage distribution networks. While considerable progress has been made on developing such models for the domestic sector, the non-domestic sector has remained relatively undeveloped. High resolution end-use demand data is rare for the non-domestic sector and this paper analyses such a dataset to inform how a commercial office demand model might be structured.

The results indicate the importance of accounting for thermal demands and lighting. Heating, cooling and hot water account for between 59% and 70% of overall demand. Including lighting brings the figures up to between 79% and 87%.

Similar to domestic demand models, the active occupancy concept can usefully be included in a commercial demand model due to is importance in modelling of both thermal demands and lighting. It does however need to be associated with the additional concepts of tenancy (to account for partially tenanted buildings), working hours, and occupancy of communal spaces as distinct from occupancy of office units (i.e. a multi-zone occupancy model).

Furthermore, the concept of sharing of appliances and lighting should be included, though this is more applicable to the latter. The sharing of appliances and lighting implies that it is important to account for how commercial offices are divided into 'units', as a single 8-person office unit can be expected to have a different lighting demand to four 2-person office units.

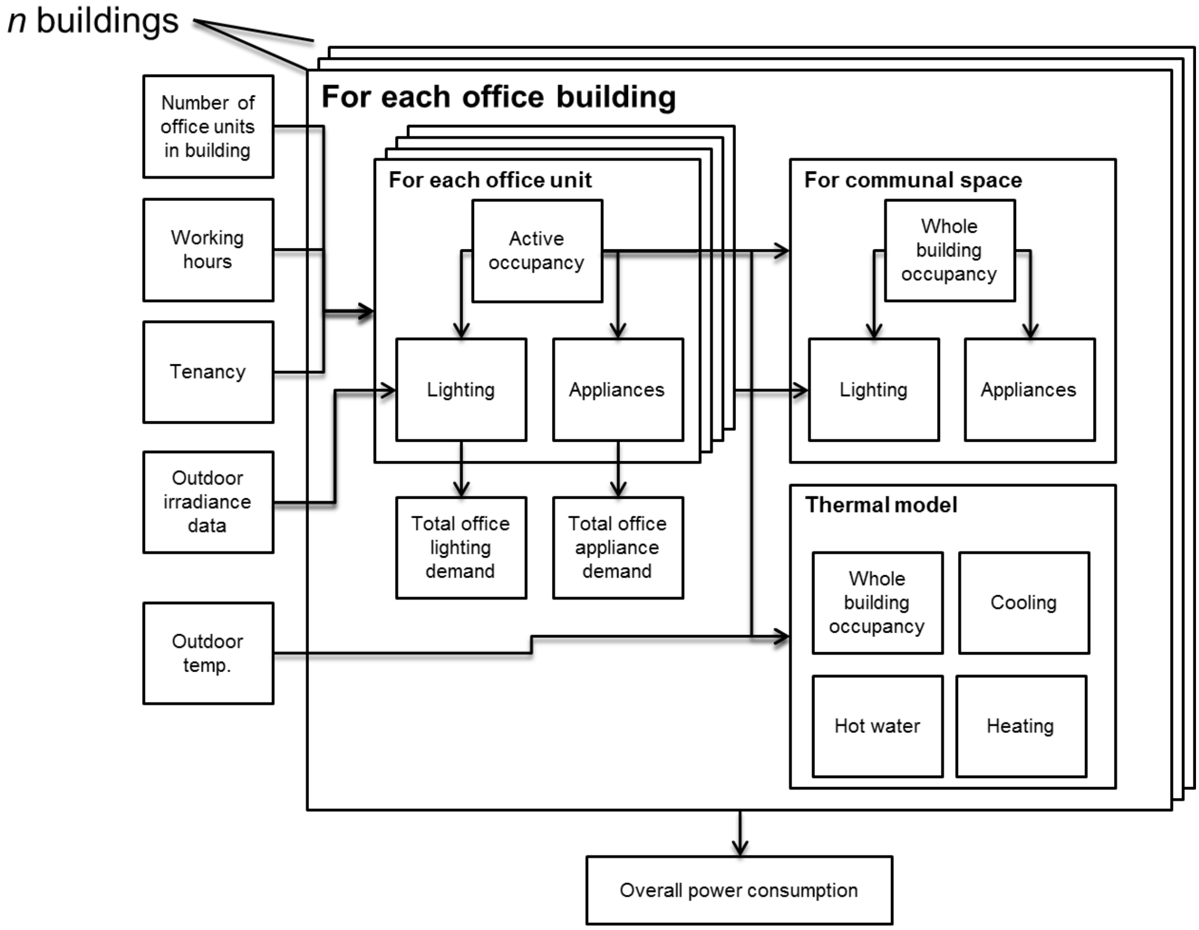


*Figure 5 – potential structure for commercial office demand model.*

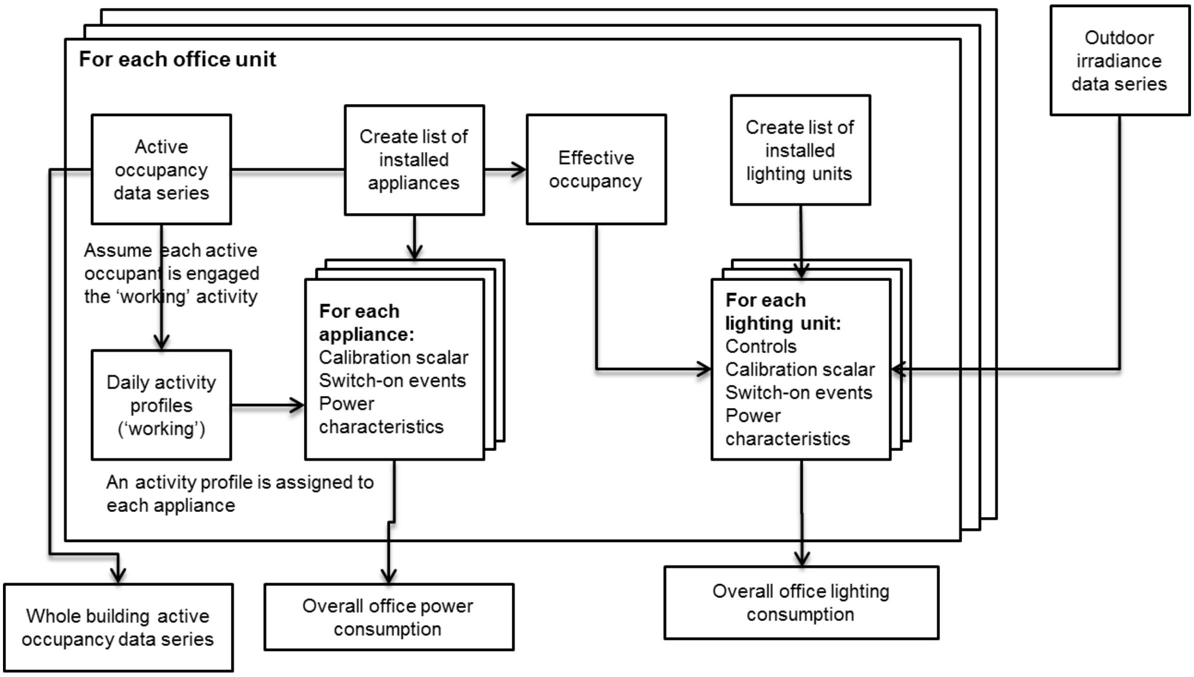


*Figure 6 – detail of 'office unit' box for commercial demand model.*

Regarding occupant activity and hence appliance use within commercial offices, this might reasonably be modelled by associating appliance use with a simple 'working' activity profile that is directly associated with occupancy. This would offer a simplified alternative to the domestic case, where many activity profiles were required.

Modelling commercial office buildings could therefore be viewed as analogous to modelling a group of dwellings with communal heating and communal spaces, a limited number of work related appliances, and occupant activities restricted to those related to work.

Finally, in contrast to domestic dwellings, commercial offices appear to exhibit high base-load demand for lighting and small appliance use. It is therefore important to account for such loads being left on overnight, even though buildings may be unoccupied.

## ACKNOWLEDGEMENT

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