A CALIBRATED WHOLE BUILDING SIMULATION APPROACH TO ASSESSING RETROFIT OPTIONS FOR BIRMINGHAM AIRPORT

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ABSTRACT

Whole building simulation is considered best practice when estimating impacts of large scale retrofit. The main aim of this paper is to illustrate the importance of a calibrated simulation model in this process. An evidence based methodology is used to calibrate a dynamic thermal simulation (DTS) model of the terminal building at Birmingham Airport with monthly utility data. A methodology has been demonstrated for the calibration of a very large building with highly variable occupancy and operating profiles. Methods for calculating model inputs from a combination of measured data and site survey results are also described. Potential economic and environmental outcomes were calculated for the model at each stage of calibration. Results confirm the importance of internal heat gains in the accurate simulation of this type of building and show large errors in estimated CO_2 and cost savings from models that are not calibrated.

INTRODUCTION

There is an established need to reduce global carbon dioxide (CO_2) emissions and a binding target of an 80% reduction against 1990 levels has been set for 2050 in the UK (HM Government, 2008). Airports are amongst the most energy intensive facilities on Earth (Edwards, 2005) and estimated to contribute 0.1-0.3% of global green house gas emissions some of which comes from their terminal buildings (Airports Council International, 2009). A predicted 87% of existing UK buildings will remain operational by 2050 (Kelly, 2009) and the majority of infrastructure that will serve UK airports for the next 40 years has already been built (Department for Transport, 2003). Large scale retrofit is therefore vital if airports are to contribute towards UK CO_2 reduction targets.

The primary aim of this paper is to measure how closely calibrated a very large dynamic building can be with real monitoring results using limited input data. It also aims to assess how useful the estimated effects of retrofit energy conservation measures (ECMs) are at each stage of calibration in the context of CO_2 reductions and investment appraisal. The focus of this case study is the terminal building at Birmingham International Airport (BHX).

Volatility in energy prices influenced widespread development of building ECMs in the late 20th century (Reddy, 2006). Building simulation has since become prevalent in the analysis of ECMs (Clarke, 2001). Whole building simulation is perceived as best practice when evaluating ECMs but there can be considerable differences between simulated and real performance (Raftery et al, 2011a). Simulation models can however be calibrated with their real counterparts so that retrofit ECMs are more accurately estimated.

Existing research in this area is summarized in the following literature review. The second section explains the calibration methodology used for a simulation model of the terminal at Birmingham airport in the UK. The 'case study calibration' section describes the building, the range of parameters that have been adjusted and results from the calibration exercise. The penultimate section presents results from retrofit ECMs added to the model at each stage of calibration. Results are analysed in the context of estimated CO_2 savings and forecast revenue costs.

Complexities and common characteristics of airport terminal buildings are described more thoroughly elsewhere (Parker et al, 2011). A number of qualities make terminal buildings exceptional. Architectural features such as large glazed facades (Gordon, 2008) and areas with high ceilings/open plan spaces (Balaras et al, 2003) combine with a wide range of functional space (Department for Communities and Local Government, 2011) to create a unique building type. Considerations related to 24 hour operations, acoustics, security, safety, occupancy, building age and redevelopment further complicate design and retrofit of airport terminals (Macintosh et al, 2010), (Parker et al, 2011).

LITERATURE REVIEW

A research project initiated in 2003 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) had the intention of developing a 'coherent and systematic calibration methodology.' An output from this project was an extensive literature review of existing techniques (Reddy, 2006). It is not necessary to reproduce this exercise but is useful to present a synopsis. It provides a simple definition of Calibrated Simulation as being a "...process of using an existing building simulation computer program and 'tuning' or calibrating the various inputs to the program so that observed energy use matches closely with that predicted by the simulation program."

The purpose of this calibration exercise is to inform 'investment grade' decisions regarding retrofit ECMs which is a widely acknowledged function of calibrated simulation (Reddy, 2006), (Raftery et al, 2011a), (Heo et al, 2011). It is also particularly important when retrofits are multiple and interactive.

Calibration approaches are split in to four categories by the review based upon: (a) manual, iterative and pragmatic intervention; (b) a suite of informative graphical comparative displays; (c) special tests/ analytical procedures; and (d) analytical and mathematical methods.

Hourly consumption data was not available for the terminal building which meant that approach (b) using different types of informative graphics was not appropriate (Haberl and Bou-Saada, 1998), (McCray et al, 1995). Potential use of approach (c) was also inappropriate due to 24 hour operation and general access/control of the building itself. Intrusive 'blink-tests' where groups of end-use loads are turned on and off to determine consumption could not be used as the terminal is always in use (Shonder et al, 1997), (Soebarto, 1997). Another approach in this category, short-term energy monitoring (or STEM tests) could not be used for the same reasons (Subbarao 1988), (Manke and Hittle, 1996).

Analytical/mathematical optimization approaches can produce inaccuracies due to the heterogeneous nature of buildings and limited number of parameters normally used in the process (Reddy et al 2006), (Reftery et al 2011a). Recent work defines a robust mathematical approach based upon Bayesian regression for normative models which is shown to be as accurate as a calibrated transient simulation (Heo et al, 2012). Despite its potential effectiveness, it was not best suited to this case study due to its high computational expense. An important step in this approach is screening parameters to identify those with the highest relative effect on results. For the basic model used to demonstrate the Bayesian technique this would take approximately 8 hours using an Energy Plus model that took only 3 minutes to estimate annual heating consumption (Heo et al, 2012). The Birmingham model took approximately 2 hours to calculate total annual energy consumption.

Limitations restrict accuracy of the first iterative approach (a) although work has been done to refine the process (Yoon et al, 2003). This approach is often based upon an analyst's own knowledge and understanding which can sometimes be applied in an ad-hoc manner (Reddy et al 2006). A recent improvement on the iterative approach uses the concepts of 'calibration signatures' and 'characteristic signatures' (Claridge, 2011). Calibration signatures are calculated from differences in the simulated and measured consumption and characteristic signatures are calculated from changes in consumption against a baseline simulation from a similar reference building type. This approach is ideally suited to calibrating heating and cooling system energy consumption. The signature values are plotted against a specified temperature range to allow errors to be visualised. This approach could have been suitable for this case study if either actual site temperature data or a similar reference building simulation characteristic signature were available.

Contemporary research has sought to define standard systematic methodologies for calibrated simulation which use a combination of the four types previously defined and a higher resolution and range of real data from the subject building, most accurately hourly end-use records (Reddy et al, 2007a) (Reddy et al, 2007b), (Raftery et al 2011a), (Raftery et al 2011b).

CALIBRATION METHODOLOGY

The calibration methodology used for the case study was derived from a combination of the described best practice. It is the size, complexity and dynamic nature of the terminal building that differentiates it from any case study buildings considered in the literature. Due to this, the security/access restrictions and the terminal's 24 hour operation it was not possible or practical to obtain the same resolution of input detail or monitoring data used in the most recent systematic approaches.

Outside the scope of this paper, the calibrated model will be used as part of a macro level assessment of interactive retrofit ECMs for UK terminal buildings. It is a transient simulation and as such has a relatively high level of detail. Therefore an evidence-based methodology based upon the approach described by Raftery et al has been used to calibrate this model. Hourly end-use data was not however available in this instance. The methodology used here demonstrates how actual data and benchmark estimates can be combined to determine more accurate model inputs. The age and complexity of the building meant that there were uncertainties over some of the parameters. Unfortunately, it would be computationally expensive and therefore prohibitive to use a similar technique to the Bayesian regression approach to quantify these uncertainties.

The model was produced using the DTS application of IES Virtual Environment software (Apache) which allows extensive adjustment of input variables (Integrated Environmental Solutions, 2011). Limitations in time, computational and human resources meant that the simulation could not include the extra detail of the 'ApacheHVAC' application which can be used to define specific systems at a room/micro level.

The four stages of calibration were: 1. Preparation; 2.

Data and information collection; 3. Iterative update of model inputs; and 4. Error checking.

1. In the referenced approach, it is assumed that there is an existing model and that an historical weather file is available for a baseline year. These were not available in this case therefore an initial model had to be created using as-built/design drawings and default constructions and thermal templates; these are described in the next section.

2. Monitored electricity and gas consumption measured at monthly intervals during 2010 was provided by the airport. Specific parameters were adjusted with reference to a wide range of documentation and sources. The approach upon which this case study is based (Reftery et al 2011a) suggests a source hierarchy. In order of priority, sources used included: data logged measurements; direct observations (site surveys); commissioning documents (as-built drawings and specifications); and standards, specifications and guidelines.

3. The calibration process required ten updated versions and parameters adjusted are recorded in the next section. Model versions include: v0 Initial model; v1 Constructions; v2 Zone typing (defined using the NCM templates); v3 Heating, Ventilation and Air Conditioning (HVAC) systems; v4 Infiltration; v5 Set point adjustments; v6 Passenger occupancy; v7 Lighting energy; v8 Equipment energy; v9 Air flow; and v10 Boiler efficiency.

4. A breakdown of boiler/chiller energy consumption and a percentage split of utility data were available to carry out basic error checking. HVAC, material u-value input specifications and zone typing were also manually checked for error at this stage.

Accuracy of the calibrated model is measured using comparison of Mean Biased Error (MBE) and Cumulative Variation of the Root Mean Squared Error (CVRMSE) for monthly consumption data. Results are compared using total and utility level monthly energy consumption. ASHRAE Guideline 14 considers a model to be calibrated using monthly totals when the MBE is within 5% and the CVRSME is within 15% of measured data (ASHRAE, 2002). Formulae for these calculations have been published previously (ASHRAE, 2002), (Raftery et al, 2011b).

CASE STUDY CALIBRATION

Birmingham airport processed over 8.5 million passengers during 2010 (Civil Aviation Authority, 2011) making it the UK's seventh largest airport in terms of passenger numbers. Total floor area of the model (based upon digital plan drawings) is 96,887m^2. Including voids, there are 1780 individual spaces in the model connected by 982 holes and 3735 doors. Although external windows have been simplified, 480 separate units are included in the model. Measured consumption of electricity during 2010 was 26.95 GWh (64%) and gas consumption was 15.31 GWh (36%) providing a total consumption of 42.26 GWh. Using current UK fuel emission factors that is equal to 16,965 tons of CO_2; 13,935 tons from electricity use and 3,030 from gas.

Monthly energy consumption data was available for 2010 which made it appropriate for the base year. Importantly, a set of passenger occupancy data was also available for this period. It is pertinent to reiterate the highly dynamic nature of terminal facilities at this stage. Passenger numbers fluctuate every year in line with consumer spending and other external factors. Terminals are under constant change as buildings, especially the internal spaces. Between 2010 and 2011 BHX completed the 'one terminal' project, creating a single terminal system from the already interconnected Terminal 1 (T1), Terminal 2 (T2), Millennium Link (ML) block and International Pier (IP). Figure 1 shows a diagram of the whole terminal building in which T1 is shaded in blue (right), T2 in orange (bottom left), ML in turquoise (centre) and IP in green (top). HVAC systems were zoned according to these old designations and they are used as a reference in this case study. This state of change during the base year is not ideal for a calibration exercise and introduces some uncertainty from the outset. However, given the nature of the building, 2010 offered the best set of relevant baseline data.

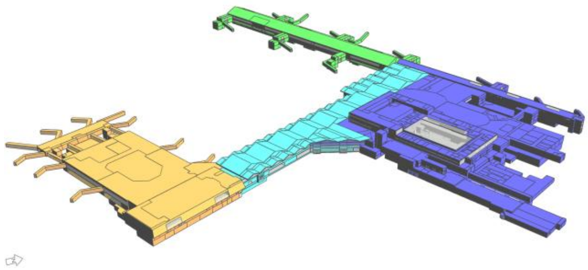

Figure 1: BHX terminal zones

Calibration Process

Allowing for group changes made to the functional space thermal templates, 118 individual parameters were updated from the initial model, too many to list within this paper. This number would increase if it included the number of specific values adjusted for each HVAC system or construction type for example. The following is a summary of the updates made at each stage of calibration.

v0 Initial model:

Geometry was created using plan, elevation and section drawings and all ceiling heights were surveyed on site. The Chartered Institute of Building Services Engineers (CIBSE) Test Reference Year (TRY) weather file for Birmingham airport was used and solar shading calculations for the site were performed using the IES software. Default constructions were specified that correspond with building regulations for the relevant year corresponding to the completed years of construction shown in figure 2.

A Constant Volume HVAC system with a variable fresh air rate was specified in the initial model. Remaining model parameters were controlled using National Calculation Method (NCM) thermal templates for airport terminals included in the software library (Department for Communities and Local Government, 2011). These templates control room conditions (heating/cooling schedules and set points), internal heat gain values and schedules (occupancy, lighting and equipment) and air exchanges (from infiltration and auxiliary ventilation).

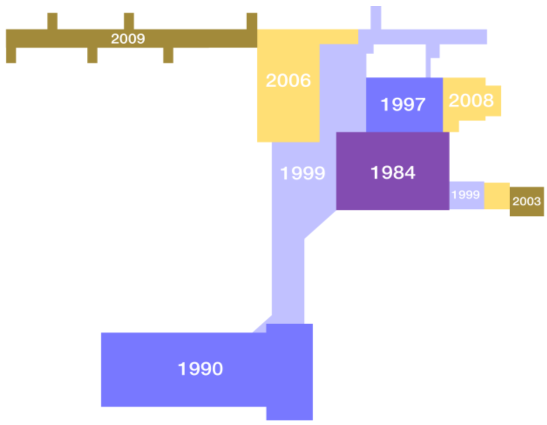

Figure 2: Development of BHX terminal building

v1 Constructions:

Specifications for the majority of external walls and glazing were available from either as built or design stage elevation and section drawings. Materials differed between areas mainly dependant on age (as shown in figure 2). There was clear information for the newer areas of the terminal but some of the older roof and wall constructions had to estimated and confirmed with the airport Fire Officer.

v2 Zone typing:

Current drawings used to create the geometry also described the room types. These were then grouped by function in accordance with NCM templates for airport terminal buildings. There are 23 different types of functional space in the NCM templates and an two additional categories were included for internal and roof voids.

The only inputs updated at this stage were those spaces that were vacant during the base year 2010. These were confirmed with the airport Energy Manager and all room conditioning, internal gains and ventilation were removed for this simulation.

v3 HVAC systems:

There are 7 main systems in the terminal and they were assumed to provide all space conditioning in their specific zones. There are also some localised small systems operating in areas that are also served by the main HVAC systems. This is common in sales and eating/drinking areas. Without further sub-dividing larger areas and specifying individual systems in these spaces it is not possible to simulate this in the software application used.

Details of system type, boiler and chiller efficiencies plus capacities for all 7 main systems were provided by the Energy Manager and input at this stage.

v4 Infiltration:

Building regulation compliance documentation for the International Pier section of the building confirmed a rate of 0.335 air changes per hour (ACH). For the remainder of the building a rate of 0.65 ACH used in accordance with a CIBSE estimated rating for an older leaky building on an exposed site.

v5 Set points:

Default NCM thermal templates specified a range of heating and cooling set points in different functional spaces. Actual heating and cooling set points were confirmed by the Energy Manager as 21°C and 23°C respectively across the whole building. These set points were used for all the conditioned spaces within the simulation model.

v6 Passenger occupancy:

Recording real occupancy data is especially complex in buildings as large and dynamic as airport terminals. Occupancy numbers are large and highly variable. Some basic occupancy data was provided by the airport for T1 and T2. This was used to create departures and arrivals occupancy profiles for their separate airside (passenger access only) and landside (general public) areas.

Data for the peak summer week in 2010, 26th July to the 1st August recorded passengers per hour arriving at the security check areas between landside and airside. It also included the number of passengers departing and arriving per hour. Average maximum density of passengers at the peak hour was first calculated for landside and airside areas. Using the T1 departures landside area as an example, the average maximum number of passengers in that area was 1245 between 5am and 6am. This maximum hour has a factor of 1.0 in the control profile. The average maximum between 1pm and 2pm was 964 passengers, resulting in factor of 0.77 for that hour (964/1245=0.77). This process was used to calculate hourly factors for an average day in this busiest week.

Monthly totals of arriving and departing passengers were used in a similar way to create a weighted factor for each month: using the T1 departure figures as an example, the busiest month was July with 351,503 passengers. There were a total of 218,037 in November giving it a factor of 0.56 (218,037/351,503). Monthly factors were applied to the hourly weighted factors to create average daily control profiles for each month of the year. Using the same example, the control factor for 1pm to 2pm for an average day in November would be 0.56*0.77=0.43. When applied to the maximum density for that area of 5.69m^2/passenger it results in a total of 535 people for that hour.

As no dwell time data was available it was assumed that passengers were in the landside departures area for 1 hour, the airside departures area for 1 hour, the airside arrivals area for 30 minutes and the landside arrivals area for 15 minutes. The arrivals passenger densities were adjusted from the totals to allow for the reduced dwell time in each hour. There is no published data for passenger dwell times in UK airports. Dwell times used here were confirmed as reasonable estimates with BHX staff. Example occupancy rates for T2 are shown in figures 3 and 4.

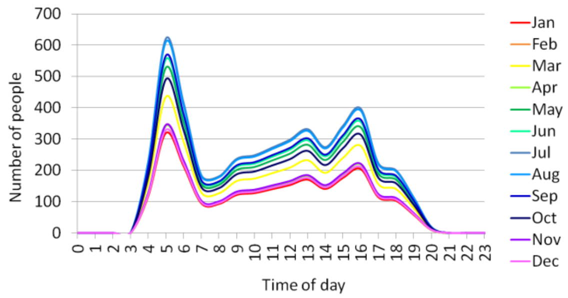

Figure 3: Passenger occupancy profile for T2 departures landside

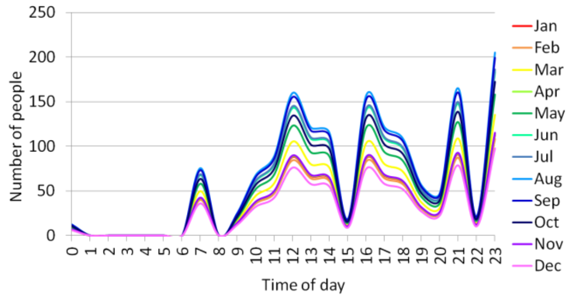

Figure 4: Passenger occupancy profile for T2 arrivals airside

In reality passengers are not the only occupants. At busiest times, the airport estimate there to be 750 staff working in the terminal. There are also non-flying members of the public either accompanying departing passengers or meeting arriving passengers plus assorted contractors working on site. To allow for this, passenger occupancy profiles were applied to the check in, circulation and waiting areas only. Occupancy in other areas was controlled using the NCM estimates.

v7 Lighting:

No end-use consumption data was available for lighting energy. Some lighting load data was collected from a visual survey carried out with an electrical contractor employed by the airport. The number and type of fittings in selected areas were recorded. Total load for that area was then calculated with a 10% allowance for control gear (ballast and starters) consumption as agreed with the Energy Manager. Results were used to create revised inputs in a W/m^2 format. Updated values were created for circulation, waiting, sales and eating/drinking areas. Inputs were also adjusted for the toilet areas in reference to information provided for the International Pier.

v8 Equipment:

Plug loads account for a large proportion of total consumption but were subject to the greatest degree of uncertainty. The extensive range of equipment within the building and lack of end-use data are the main reasons for this. Some large loads relating to baggage handling systems, escalators and lifts are not measured in isolation. Some updated values were calculated by using the surveyed lighting loads and sub-metered consumption for tenant electricity use. Lighting loads were subtracted from total consumption to produce updated equipment loads.

v9 Air movement:

Operatives at Birmingham assert that a large amount of space conditioning energy use is attributable to extensive air exchange through external openings. Evidence for this is anecdotal only but has been supported by other airport operators involved in work outside the scope of this paper. At Birmingham, this is particularly prevalent in the passenger access areas (both departures and arrivals), baggage reclaim areas and baggage handling halls (all heated spaces). A nodal airflow model within the IES software allows multi-zone air movement to be simulated however, due to the size and complexity of the model the simulation would not run on the available hardware. Annual simulation runs for previous versions of the model took 2 hours; this was increased to over 12 hours (estimated) once the multi-zone air movement parameters were added to the DTS model.

In order to account for the air exchanges from openings, an additional ventilation rate of 2.0 ACH, scaled in proportion to passenger numbers, was added to spaces with regularly used external openings. This additional ventilation was added to increase space heating demand because results from v8 estimated boiler energy to be considerably lower than the actual gas consumption. The anecdotal evidence described above also supported this update.

v10 Boiler efficiency:

Updated boiler efficiencies were applied to the model for this version to account for the older boiler systems serving the T1, T2 and ML zones. After considering the parameters that had been adjusted up to this point in the calibration process, discussions with the Energy Manager suggested that lower boiler efficiencies were most likely to account for the additional actual gas consumption. As estimated electrical consumption was within the ASHRAE tolerances chiller efficiencies were not altered.

Calibration Results

As described previously, ASHRAE guidelines for model calibration require the MBE of results to be within +/-5% of the actual and the CVRSME to be within +/-15%. Results in figures 5 and 6 illustrate the percentage error at each stage of calibration.

In terms of total energy consumption the final v10 model is within the ASHRAE tolerances for the MBE and CVRSME with errors of 1.37% and 5.82% respectively. This is similar for electricity consumption with an MBE of -1.15% and a CVRSME of 3.98%. The simulation estimate for gas consumption was conversely slightly outside the ASHRAE tolerance range with an MBE of 5.82% and a CVRSME of 20.15%.

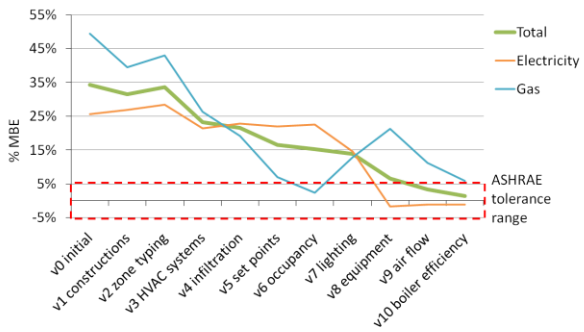

Figure 5: MBE at each stage of calibration

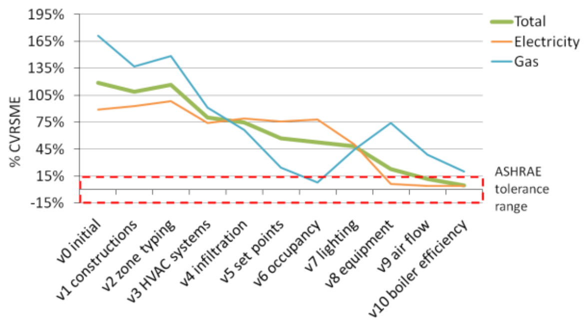

Figure 6: CVRSME at each stage of calibration

It is possible that this error rate was due to using the TRY weather file rather than a 2010 specific weather file. Comparing average monthly dry bulb temperatures from the Birmingham Airport TRY file with data recorded at the University of Birmingham in 2010 show lower actual temperatures during the winter months. The recorded average temperature for the winter months (December, January and February) was 3.16˚C lower than the TRY data (British Atmospheric Data Centre, 2012). Unfortunately, the detailed data required to create a simulation weather file is not available for this theory to be tested using the existing model. Errors for factors beyond the weather files require further investigation on site.

RETROFIT SIMULATION RESULTS

A hypothetical scenario was used to assess differences in the forecast impacts of retrofit ECMs. Interactive ECMs added to each version included a biomass boiler (90% efficiency), thermal wheel heat recovery (65% efficiency), an additional 200mm of EPS insulation to all roofs and LED lighting throughout specified at 3.9W/m^2/100 lux. The first set of results shown in figure 7 compare the estimated percentage CO_2 savings against the model at each stage of calibration (dark bars) and the actual emissions for 2010 (light bars). For example for 'v1 constructions' the dark bar compares the percentage CO_2 saving achieved by the retrofit version of v1. The light bar shows the percentage CO_2 saving from the retrofit version of v1 when compared to the total CO_2 emissions from the building in 2010.

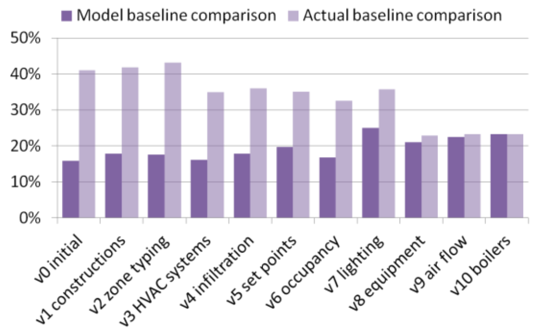

Figure 7: Estimated percentage CO_2 saving from retrofit ECMs at each stage of calibration

There is a relatively limited range of predicted savings when measured against each calibrated simulation stage. The final calibrated model (v10) estimates an additional 7.32% saving from v0 which in the context of the +/-5% MBE range for calibration is not that significant. However, when compared to actual figures, it is not until all internal gains have been updated in v8 that estimated CO_2 savings become reasonably accurate and are within a few percent of the final estimate.

Along with capital costs, annual revenue costs form part of any Simple Payback or Net Present Value (NPV) calculations commonly used for financial appraisal of ECMs. Revenue estimates are based upon Department for Energy and Climate Change (DECC) average industrial fuel prices and include costs for the CRC Energy Efficiency Scheme and returns for biomass available through the Renewable Heat Incentive (RHI). CRC costs are set at £12/ton of CO_2 (The Environment Agency, 2010), Electricity costs at 6.9p/kWh, Gas costs at 1.8p/kWh (DECC, 2011a), Biomass at 2.1 p/kWh (E4tech, 2010) and the RHI tariff for this size of biomass system is 2.9p/kWh (DECC, 2011b). Estimated annual revenue savings are shown in figure 8.

As with the predicted CO_2 savings, it is not until the internal heat gains have been updated in v8 that predicted revenue savings are similar for both the calibration and actual comparisons. The implications of not using a calibrated model are more significant in this context. Using the savings predicted against each stage of calibration before v8 would result in the retrofits having a much longer payback period and less favourable NPV than suggested by the final calibrated model. Inversely, the opposite effect would be experienced if potential savings were measured against the actual costs for the baseline year. At its height (v2), there is a difference of over £700,000 between these figures for annual savings.

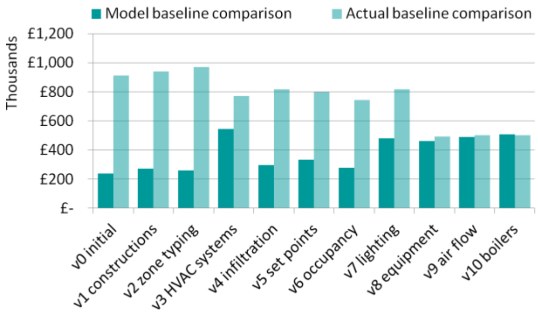

Figure 8: Estimated annual revenue cost saving from retrofit ECMs at each stage of calibration

CONCLUSION

In this calibration exercise it was the revised occupancy, lighting and equipment inputs that had the greatest impact on the estimated energy consumption. Only when these parameters were updated was the estimated total monthly energy use close to the ASHRAE tolerances. Results show that accurate inputs for construction details, HVAC systems, infiltration, heating and cooling set points, occupancy profiles, and both heating and lighting gains are all essential when calibrating this type of model. However, for the model to be calibrated at a utilities level further updates were required.

Direct energy consumption from both lighting and equipment was shown to be very important when calibrating buildings of this type. Some of the NCM thermal template W/m^2 estimates for lighting and equipment appear to be much lower than those found in the real building. Further survey work and benchmarking is required to establish if this is common at other UK airports. This could have a profound effect on estimates or designs for this type of building if the NCM templates are used (including Energy Performance Certificates).

The assertion that historical weather files are crucial if simulation models are to be finely calibrated was upheld by these results. Although TRY and real data can be compared to support assumptions regarding additional heating energy this type of evidence is only circumstantial. Results also supported the notion that a wide range of detail is required to calibrate large complex buildings. Collecting simulation input data for the calibration of a model of this scale requires extensive documentation and operator knowledge. It is difficult to quantify how much more detail could be amassed due the size and complexity of this type of facility. It was however possible to calibrate the model to ASHRAE tolerances for monthly consumption using the data described.

In terms of estimating CO_2 savings from ECMs, results show that with updates to the parameters described above, a reasonable macro-level estimate can be made of potential CO_2 savings, especially when allowing for the calibration MBE tolerance of +/-5%. In fact, this was true even before equipment gains were updated. This is not the case when comparing estimated revenue costs for financial appraisal. Despite estimated savings from v8 of the model being very close to those in the final v10 the difference in estimated revenue cost equates to £46,142/year. If used in NPV calculations and forecast over a 20 year life span this could mean that potentially effective ECMs appear to be economically unviable. A clear conclusion from the entire exercise is that results for ECMs tested on non-calibrated models should never be compared against actual monitoring data from a base year as there is likely to be a large margin of error.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance provided by staff of Birmingham Airport and particularly Kevin Turnbull who made this work possible. The authors also wish to thank Stefan Smith for his assistance sourcing actual weather data.

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