TESTING RAPMOD: CAN A PORTABLE SCANNER COLLECT EXISITNG BUILDING DATA AND CREATE AN ENERGY MODEL FASTER AND MORE ACCURATELY THAN A HUMAN

Annie Marston[1], Eric Turner[2], Avideh Zakhor[2], Oliver Baumann[1], Philip Haves[3],
[1]Baumann Consulting, Washington DC, USA
[2]Indoor Reality, U.C. Berkeley, California, USA
[3]Simulation Research Group, LBNL, California, USA

ABSTRACT

The paper describes the testing of a portable scanning system (RAPMOD), which is worn like a backpack and allows the user to walk through a building to collect essential energy-related data. From this walk-through, the system collects data required for an energy model of the building using laser scanners, infrared scanners and cameras and converts these data into .idf format for use in EnergyPlus. The energy model includes the geometry of interior and exterior surfaces, window U-values, lighting levels, equipment levels and occupancy for each room. RAPMOD will be extended to include HVAC recognition in a subsequent phase of development. The main goal is to reduce the cost and skill level required to create energy simulation models for deep retrofit assessments, energy audits and retro commissioning for existing buildings through rapid and accurate energy model creation.

The tests described by this paper were carried out in a 3-story academic building. The building contains offices and lecture halls and is about 80 years old. The test procedures were designed to examine both how fast RAPMOD is in comparison to standard manual data collection as well as how accurately it can collect the information required for the energy model. Tests were completed for accuracy of the data input for geometry, u-value, lighting and equipment loads and occupancy in every room as well as overall predicted energy use output and time taken to create the model. RAPMOD created the model, including data collection, in 15% of the time it took to complete standard manual data collection and energy model creation for the building geometry and internal loads. The energy predictions of the RAPMOD model and the standard, manually created model agreed within 10%.

INTRODUCTION

On May 9th 2015 the global concentration of carbon dioxide in the atmosphere recorded at Mauna Loa, Hawaii surpassed 400ppm for the first time in recorded history (esrl.noaa.gov). The USA consumes nineteen percent of global energy, primary energy of that, the building sector consumes forty one percent. (buildingsdatabook.eren.doe.gov 2010). In the USA seventy-two percent of all buildings are over 20 years old (AIA 2013) and will likely have some kind of retrofit in the next 20 years. Rather than a standard retrofit, these buildings could have deep retrofits, 50% or greater energy savings. Energy modelling is an important tool to be able to do effectively. It helps designers understand the complex interactions of energy users within their buildings and more accurately, the energy savings gained through multiple energy efficient measures.

Energy Audits and Energy Modelling

In order to improve the energy efficiency of our existing buildings we must understand them better. The traditional way to do this is to hire an energy auditor or energy consultant to walk through the building and document the energy consuming equipment in the building, to assess utility data and building management system (BMS) data, and to suggest improvements based on life cycle cost analysis. Buildings are complex and energy usages within the building are often highly dependent upon each other. For instance, changing a light bulb will not only effect the electricity requirement of the light bulb, but also will affect the amount of heating, cooling, fan and pump use in the building. Creating an energy model of the building allows the designers and owners to understand all these effects thoroughly. The model is used to assess what the most effective efficiency measures are and how much energy the building could potentially save. In order to reduce the energy use of a building significantly (to over 50%) an energy model is vital to the design and analysis process.

Energy audits and data collection are a slow and expensive process. For older buildings information such as floor plans and mechanical schedules have long been lost and so all this information must be gathered onsite by qualified engineers. The data is processed and analysed once back in the office either using spreadsheet calculations or with an energy model. It can take a long time to develop an energy model (2-4 weeks) and often will require a highly skilled individual to understand how to use the software, even though a lot of the work is data entry work. This can often prove to be prohibitively costly for projects and so will often not be included.

RAPMOD

RAPMOD has been under development for approximately eight years, over the last two years the team started to investigate using RAPMOD to help with identifying energy efficiency potential in buildings. RAPMOD allows an unskilled operator to walk through a building and collect all the data that is required to develop an energy model in EnergyPlus and to develop that model. The goal is to decrease the time and effort in studying a building for deep retrofit or extensive energy audit and increase the accuracy and quantity of data collected for an energy model. RAPMOD uses LIDAR, infrared and visual cameras, as well as temperature sensors to collect the data. The operator walks the building at a normal pace, going into each room. RAPMOD is unable to see through obstructions so in larger open plan offices the operator will walk through the office to ensure all data is collected. Once the walkthrough is completed, the operator downloads the data and algorithms, which have been specifically designed to capture and translate the data into .idf format to be run in an energy model, process the data (Turner et al, 2014). An energy modeller then takes this .idf file and updates it with any missing information to create a complete energy model, which accurately represents the building annual energy usage. Energy efficiency measures can then be studied and applied to the building.

RAPMOD is in development stage and to this point can collect and create the following information about a building from a simple building walkthrough: building geometry including orientation and dividing the rooms into separate thermal zones; window to wall ratio; window u-value, plug loads, lighting levels, and occupancy.

Figure 1 Generation 3 RAPMOD and operator

Other Software / Hardware

RAPMOD is not alone in trying to create accurate geometry for the construction industry; however, the other technologies under developed are focusing on Building Information Modelling (BIM) over Building Energy Modelling (BEM) applications. Bentley has Acute3D (acute3d.com) and Autodesk has ImageModeller (autodesk.com), both use photos to create a geometric shell of a building. Currently neither are focusing their efforts on turning these BIM models into BEM models other than through their standard software packages.

EXPERIMENT

Experimental Goals

It was important to know how close RAPMODs annual energy prediction is to the manual modelling annual energy prediction method. The following were the main goals for these experiments:

- Can RAPMOD collect data to the same or to a greater accuracy than an engineer conducting an energy audit?
- Can RAPMOD produce an energy model within a tenth of the time it takes to develop the equivalent manual model?
- Is RAPMODs annual energy prediction for the building within 10% of the manual models energy prediction for the building?

Experimental Building Details

The building that was selected for these tests was Mulford Hall, built in 1948 on the University of California, Berkeley's campus. Mulford Hall's exterior façade is concrete framed with metal stud and plaster partitions. The windows are from the original construction and are single paned with aluminum frames. The building has four stories, including a basement. The rooms are mostly offices and classrooms, with some laboratories, computer rooms, meeting rooms and storage rooms. Approximately five rooms are completely unoccupied. The building utilizes the campus's high-pressure steam in a forced air system; there is no mechanical cooling system and in most cases fresh air enters the rooms through operable windows.

Manual Collection Energy Audit

The manual testing procedure was based on the standard data collection done by a practising engineer for an ASHRAE energy audit level III.

The engineers first interviewed the building manager using a set of questions developed to find out as much about the control and operation of the building as possible. Both the RAPMOD energy model and the manual energy model used the answers from this interview as additional inputs.

The engineer then walked through the building one room at a time noting down assumed lighting levels, equipment levels, construction details, HVAC diffuser placement and condition, room temperatures and any envelope issues that might be relevant such as cracking between the window frame and walls. The engineer took thermal and visual photographs to use as reference when evaluating the building back in the office. The engineer also visited the mechanical rooms and noted, type of equipment, condition of equipment and any issues such as poor duct insulation, leaking pipes and so on.

After the walkthrough, the engineer took the data and created organised spreadsheets to pass it to the energy modeller to create the manual energy model.

RAPMOD Collection Setup

It was important that RAPMOD went around the building at the same time as the manual auditor so that similar information was available to both. RAPMOD is much faster at gathering the data required and so although both the engineer and the RAPMOD operator started their walk through at the same time, the RAPMOD operators walk through was much faster. The RAPMOD operator walked at a normal pace entering each room, turning and exiting each room in turn for three floors of the building.

Once the RAPMOD operator walked through the building, algorithms processed the data and created bound geometry with windows, number of occupants, equipment and lighting levels all placed in individual zones representing each room within the building. Using this data an .idf file was created to run an energy model of the building in the EnergyPlus engine.

Figure 2 shows a flow chart of the manual and RAPMOD data collection and analysis process.

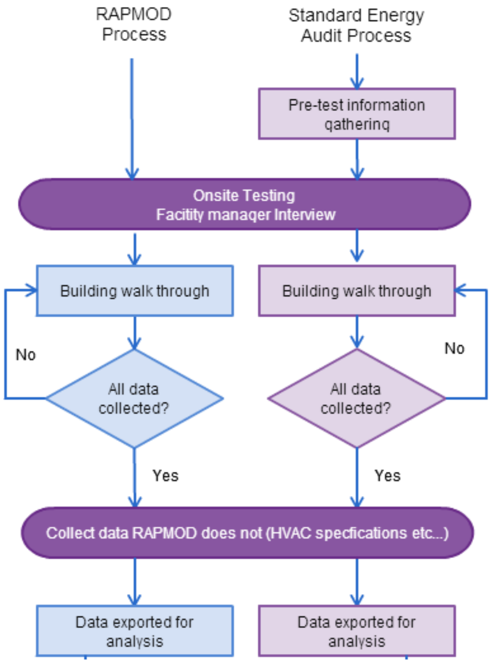

Figure 2 Flow chart detailing the data collection process

Energy Model Comparison Test

Some extra manual work was required to create a running energy model from the RAPMOD .idf file. The RAPMOD team did a small amount of manual adjustment to the geometry to reduce the number of surfaces as they were running the data through their algorithms. An alternative to this manual intervention from the RAPMOD developers is to use a plugin to the Simergy software that uses the EnergyPlus engine. This will allow the energy modellers, using the data from RAPMOD to do this geometry adjustment manually.

Furthermore, RAPMOD does not yet collect all data that is required to run a complete energy model in order to do the annual energy prediction comparison. The RAPMOD energy model had the following extra information added: schedules, thermostats, u-values for opaque constructions, all HVAC equipment and controls. The flow chart in figure 3 details this comparison test.

DISCUSSION AND RESULTS

Accuracy of RAPMOD In Comparison with a Manual Audit

For this analysis, the input accuracy of the RAPMOD energy model is compared against the input accuracy of data obtained from an engineer conducting an ASHRAE level III audit of a building. Specific ground truth tests are not included in this definition of accuracy; it is a comparison of data collection by the engineer versus data collected by RAPMOD.

Geometry

RAPMOD collected geometric data using a rapid scanning technique with LIDAR on the backpack and algorithms processed the data to produce the geometry shown in Figure 4. Zakhor, Turner and team developed these algorithms over the last ten years (Turner et al. 2014), (Turner Zakhor, 2014).

The manual model was created using the floor plans provided by the facilities manager on site. The floor plans were from the 1970s and so showed no changes to the interior spaces in the building. The floor plans were used to create the thermal zones for the building. The dimensions were taken from these pdfs and the thermal zones were drawn in the openstudio plugin for sketchup to create the geometry for the energy model. The manual model is visualised in Figure 3.

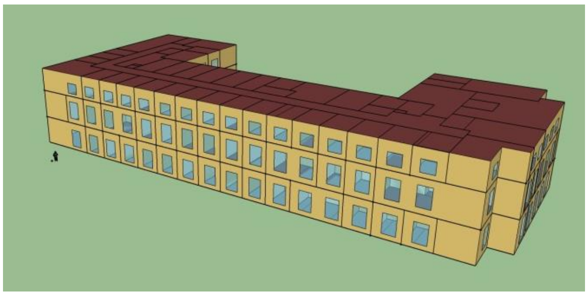

Figure 3 Visualisation of the manual energy model

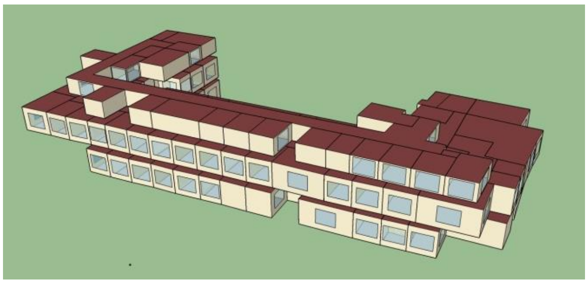

Figure 4 Visualisation of the RAPMOD energy model

It is clear that the RAPMOD energy model is not complete geometrically. The RAPMOD operator was unable to enter all the rooms in the building, the doors were locked or the room's occupant denied the operator entry. In these cases neither the manual auditor nor the backpack operator could access these spaces. Because of this around 30% of the geometry in the RAPMOD model is missing. In order to run the model and to compare the predicted annual energy use with both the manual model and the utility data from the building, the missing spaces were manually added to the RAPMOD energy model. Initially, in the RAPMOD model some of the interior walls had windows added to them, when adding the additional spaces these windows were removed manually.

When comparing the inputs to the model, only the spaces that were captured by RAPMOD are included in the analysis. Table 1 shows the floor area comparison between the spaces captured by RAPMOD and the manually created model.

Table 1 Floor area captured by RAPMOD vs floor area from manually created model

FLOOR	FLOOR AREA COMPARISON FOR THAT WHICH WAS CAPTURED BY RAPMOD		
	MANUAL	RAPMOD	% DIFFERENCE
1	1,111m²	981m²	12%
2	1,653m²	1,438m²	13%
3	647m²	592m²	9%
TOTAL	3,411m²	3,011m²	12%

In the manual model, the corridors and circulation spaces run into some of the areas that were not captured by RAPMOD. Figure 5 the floor plan from the manually created model and Figure 6 the floor plan from the RAPMOD created model show some of the areas that were different between the two models, these areas are highlighted by the red dotted lines.

There were multiple reasons why these zones were created differently in the manual model and in the RAPMOD model. Sometimes in order to produce a clean and quick running model, some areas are shortened or rooms are moved slightly to decrease the number of thermal zones. In other cases RAPMOD might have seen some barrier in the space and this it has assumed is a wall. Most of the differences happened in large spaces with more complex interior partitions and mezzanines.

In order to compared the models to utility data and analyse them effectively, the missing areas in the RAPMOD model were added manually (this also included a basement floor not shown on Figure 3 and Figure 4. The complete building floor areas for RAPMOD and the manual model were compared to understand as a whole how different the total area of the building model was.

- RAPMOD energy model total floor area = 6,073m²
- Manual energy model total floor area = 6,610m²

This gives an 8% difference in total floor area between the manually created model and the RAPMOD created model.

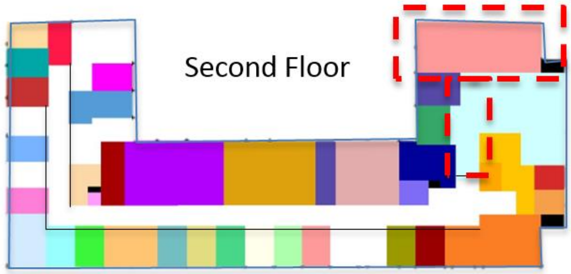

Figure 5 Second floor plan showing the thermal zones created for the manual model

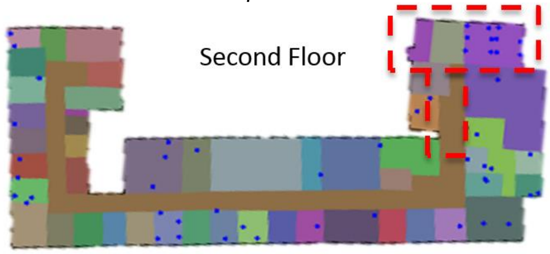

Figure 6 Second floor plan showing the thermal zones created for the RAPMOD model

Window to wall ratio

Each orientation had its window to wall ratio compared. For the manual energy model, the modellers used floor plans and reference photos and measurements of the typical windows from the onsite visit to estimate the window to wall ratio and draw the windows on to the energy model.

RAPMOD used a window identification algorithms developed for this project (Zhang and Zakhor, 2014). Using the point cloud that RAPMOD creates as well as the thermal and visual images, the developed algorithm finds windows on the exterior walls and estimate their size. Consideration of blinds and obstructions was taken into account and the developed algorithm was able to understand this as an obstruction for some of the time. The algorithm is still in development and this test looked at how accurate the window to wall ratio was despite the obstructions sometimes reducing the size of the window recorded.

The comparison of the window to wall ratios for each orientation and for the entire buidling can be seen in Figure 7 and Table 2 detail the number windows on each zone as well as areas of windows and walls for the entire building. This comparison was done only for the areas that the RAPMOD model created.

The whole building window to wall ratio recorded by RAPMOD is 11% of the manually recorded window to wall ratio.

The RAPMOD model does not account for the wall area between the ceiling of one floor and the floor of the one above. This is approximately 60cm for both storeys. Adding this extra wall area (which is included in the manual model) the window to wall ratio reduces from 29% to 24% which means the whole building window to wall ratio recorded by RAPMOD is now -6% off the manual calculation.

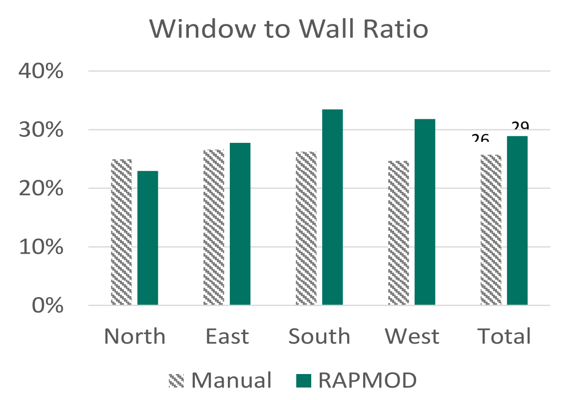

Figure 7 Window to wall ratio comparison between RAPMOD and manual models

Table 2 Comparison of the window details for the RAPMOD and Manual Models

*	Manual	RAPMOD
Number of windows	*115*	*80*
Number of zones missing windows (99 zones total)	*0*	*22*
Area of windows	*449 m²*	*458 m²*
Area of walls	*1941 m²*	*1585 m²*
Window to wall ratio	*26%*	*29%*

Window u-values

The u-value of the window assembly (glazing andframe) from the RAPMOD estimation is 5.8W/m².K with a SHGC of 0.4. The RAPMOD operator collects this u-value using the glass check pro GC 3000, a hand held device which, when touched to the window will calculate the u-value from its record of the layers and films it can identify. The operator only recorded u-values on typical windows and did not record every window in the building.

The manual model, estimated the window u-value based on age and type of window used and the manual auditors best knowledge of window types of the era the building was built. A value of 5.5W/m².K with a SHGC of 0.8 was used.

Lighting Levels

RAPMOD identifies lighting loads in each space using visual recognition algorithms and infrared imagery (Oreifej et al., 2014). These lighting levels were applied to their respective thermal zones in the RAPMOD energy model.

For the data collection for the manual energy model, The onsite engineer counted the light bulbs in the space and their wattages and lighting type to identify the lighting levels. Figure 8 compare the differences between lighting levels collected by RAPMOD and the onsite engineer.

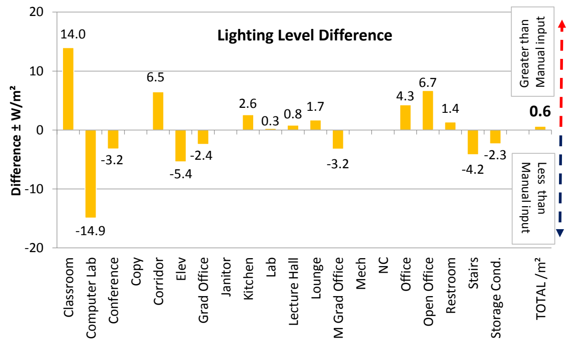

Figure 8 Lighting level difference between manual model and RAPMOD inputs

Room such as the classroom and computer lab have slightly different areas between the RAPMOD model and manual model, as shown in Figure 5 and Figure 6. This accounts for their larger differences. Overall though the lighting levels only differed by 0.6W/m² for the whole building.

Plug Loads

Two techniques developed to identify and calculation the power consumption of computers. The first a technique based on convolutional neural networks to detect and count computers was developed. The second a SVM based power estimation algorithm is developed for computers using a handheld IR camera which captures both IR and visible light simultaneously. RAPMOD identified the computers using optical and IR detection and it used the SVM based power estimation algorithm to estimate the wattage.

For the manual testing the engineer onsite measured the plug loads in each room and for each computer using a wattmeter and recording the wattage at 15 second intervals for one minute.

When testing RAPMOD two tests were carried out:

1. On a computer room with ten machines
2. On the entire building recording all plug loads

In both cases the auditor and RAPMOD operator tried to pass through the rooms at roughly the same time however in the whole building test the RAPMOD operator was much faster at collecting the data and so in some cases the computers would have been in different states of usage.

In the first test RAPMOD power estimation for the computer room was 14.2 W/m² and the manually measured power consumption was 12.8 W/m² giving a difference of 1.4 W/m².

Figure 9 shows the power estimate for each room type for the whole building test and Table 3 shows the number of computers identified by RAPMOD and by the manual audit.

The most noticeable difference between the RAPMOD energy model inputs and the manual model inputs were the plug load levels in the offices and graduate offices. Due to the nature of this building, there were mini refrigerators and coffee machines in many offices. RAPMOD does not yet recognise these as plug loads and so the overall differences between the plug load inputs are greater than anticipated.

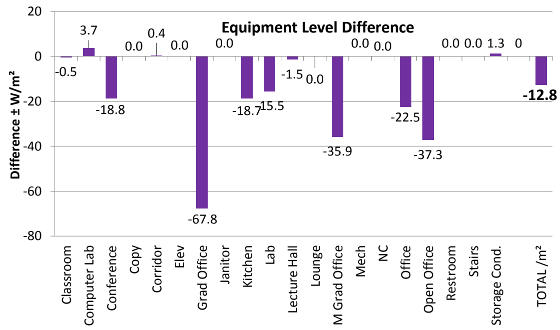

Figure 9 Plug load level difference between manual model and RAPMOD inputs

When comparing the number of computers counted by the onsite engineer with the number of computers picked up by RAPMOD, shown in *Table **3***, the numbers were more closely aligned.

Table 3 number of computers recognised by RAPMOD vs. picked up by onsite engineer

LEVEL	MANUAL	RAPMOD	DIFFERENCE
1	30	32	2
2	57	53	-4
3	24	26	2
TOTAL	111	111	0

Time Comparison

The time taken to do each part of the work was noted down in order to compile a time comparison between RAPMOD and a manual audit with model creation. The goal was to get RAPMOD to collect data and create the model in a tenth of the time it takes an engineer. As RAPMOD does not collect all the data required for a fully running energy model, Table 4 shows the time comparison according to different stages of the process

Table 4 Energy use prediction comparison with utility data

	MANUAL	RAPMOD	% TIME SAVED
Data collection	71 hours	6 hours	91%
Load calculation	72 hours	30 hours*[1]	58%
HVAC into energy model	46 hours	46 hours*[2]	0%

*[1] RAPMOD does not collect the schedule data and this is added post site visit. In the future generic schedules and constructions will be input and applied to the model; the modeller can either use this or change it to suit the type of building.

*[2] RAPMOD does not collect enough information at this point to be able to automatically put in an HVAC system. This is still done manually by an engineer.

Overall, for the data RAPMOD actually collects and processes into an energy model the time saved is significant. Figure 10 shows the total times for RAPMOD data collection and processing against the same process done manually.

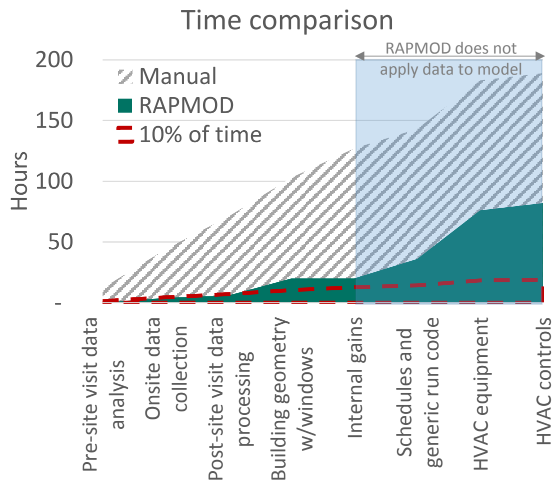

Figure 10 Time difference in data collection and model creation between RAPMOD and the manual process

RAPMOD is close it is goal of 90% time savings for what it is able to collect currently. Some of the items that took more time such as inputting schedules and adding missing geometry are being improved.

Annual Energy Usage

Four years of electricity data and two years of steam utility data were available from Mulford Hall, however due to missing data only two years had both steam and electricity data. Figure 11 and Figure 12 show the pattern of electricity usage and steam usage for the building.

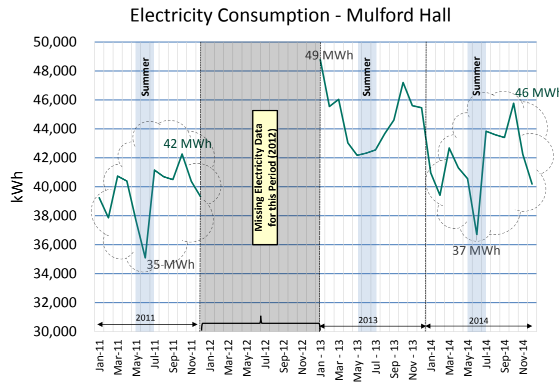

Figure 11 Three years of electricity utility data for Mulford Hall

Electricity data was missing for the year 2012. It appears that the electricity use has increased year on year, 2011 and 2014 have similar patterns of electrical use and 2013 looks to have been an anomaly year with a slightly different pattern of usage.

It is clear from figure 10 that the steam consumption was high in the winter spanning 2012/2013. When looking at the heating degree day (HDD) data for Berkeley it was found that the number of HDD for Berkeley in 2012-2013 was 2,088, and for 2013-2013 there were 1,010 [www.weatherdatadepot.com/]. The average HDD for Berkeley is 1,436 [weather file stats].

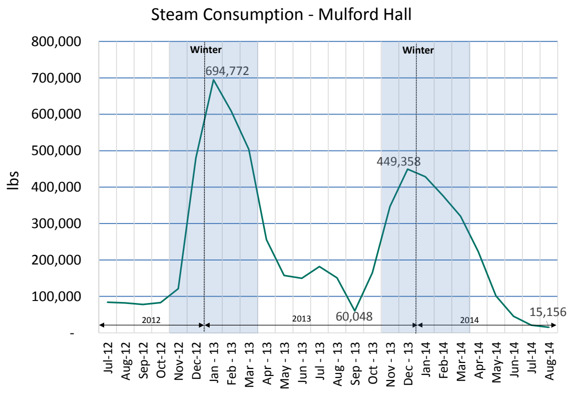

Figure 12 Three years of steam data for Mulford Hall

The utility analysis allowed the team to develop schedules, which represented the term and holiday times for the building. There are clear dips in the electricity use in June in both the 2001 data and the 2014 data and from May to July in the 2013 data, representing the summer holidays. It was known that the approximately 50% of staff remained in the building over these times. Using the ASHRAE 90.1-2007 user manual office schedules as a basis we halved these values for the summer holidays usage. These schedules were then applied to the people, lighting and equipment usage in the building. The two energy models were run using weather data obtained from the LBNL weather station and annual energy prediction was split between gas and electricity monthly and plotted against each other and the utility data. Figure 13 and Figure 14 show these results.

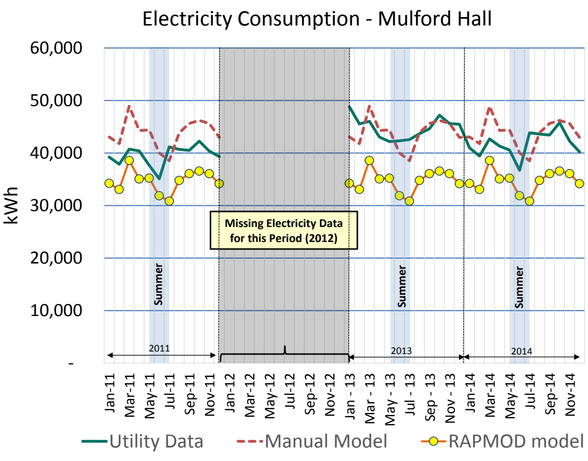

Figure 13 RAPMOD and manual electricity prediction plotted against utility data

Figure 13 shows that both the manual model and the RAPMOD model follow a similar pattern to the actual electrical use in the building. The electricity prediction by the RAPMOD model is lower than the manual model as it is has not picked up all the plug loads in the building. RAPMOD only recognises computers as plug loads and did not account for all the refrigerators, portable heaters, and coffee machines that are accounted for in the manual energy model. Due to the nature of this building, with graduate students taking half the offices, the times when plug loads will be in use is very hard to predict.

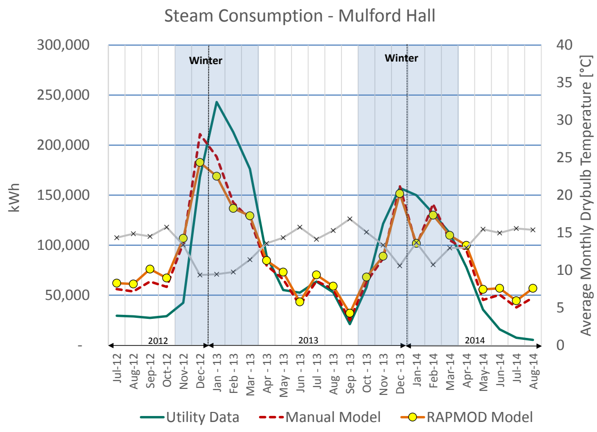

Figure 14 RAPMOD and manual steam prediction plotted against utility data

The steam prediction shown in Figure 14 is almost identical between the RAPMOD model and the manual model because RAPMOD does not currently pick up much information about the HVAC in the building and so the HVAC for this building has been modelled the same in both models. The steam predictions from both models show that the differences in geometry, window to wall ratio and window u-value are not very relevant to this building model in this climate.

Figure 15 Energy use prediction comparison with utility data

	MANUAL	RAPMOD	UTILITY
ELECTRCITY			
Average annual energy use [MWh]	525	416	504
EUI [kWh/m²]	79	76	69
Percentage difference to utility	-4%	17%	0%
GAS			
Average annual energy use [MWh]	1,076	1,096	1,052
EUI [kWh/m²]	163	181	159
Percentage difference to utility	-2%	-4%	0%
TOTAL			

Average annual energy use [MWh]	1,602	1,513	1,557
EUI [kWh/m²]	242	249	236
Percentage difference to utility	3%	-3%	0%

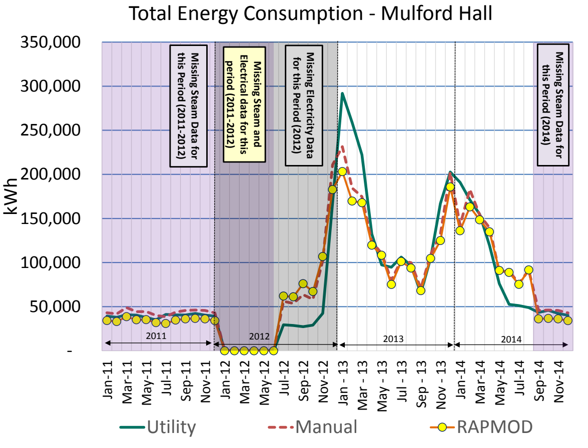

Figure 16 Total predicted energy use from the RAPMOD and manual models compared with utility data

The utility data average energy use takes all the data provided and divides by the number of years, three years for electricity and two years for steam. The overall difference in the total annual energy prediction for the models compared with the utility data are both under 10%, which was the aim of this project. The difference in annual energy use between the RAPMOD model and the manual model is 6%, again under 10% and so regarded as a successful result.

CONCLUSIONS

Although RAPMOD is still in development, the first tests have shown promise. So far, only one building has been tested in one climate, California. However, more will be completed in different climate zones to fully understand how the envelope recorded by RAPMOD affects the energy prediction of its model. This one test has shown that RAPMOD collects large quantities of data, processes it and creates an energy model. Once completed by a modeller the annual energy prediction is within six percent of the manually created model, and three percent of the three year averaged utility data. The time taken to collect the data and create the model using RAPMOD is 84% faster than a manual model when comparing the times for what RAPMOD can collect and 55% faster overall.

Immediate further work will increase the recognition of plug loads by RAPMOD and increase the speed with which to create the model.

ACKNOWLEDGMENTS

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