MODELLING A NATION OF BUILDINGS: ESTIMATING ENERGY EFFICIENCY POTENTIAL FOR LARGE BUILDING SAMPLES

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ABSTRACT

In this paper, we outline an innovative and robust approach to undertaking energy efficiency potential studies in large building samples. This Macro Modelling Process relies on building science and established energy simulation techniques. The process features the development of building archetypes, each representing a large class of buildings in the market. These archetypes are calibrated to the best available building energy use statistics. A demonstration of the process using data from a large study for the Canadian federal government shows that:

- The process is cost-effective in comparison with hour-by-hour simulation,
- The full modelling approach accounts for energy end use interactions, and
- The process can be used to develop a detailed picture of energy use in a large group of buildings, despite a lack of detailed energy consumption data.

INTRODUCTION

In 2000, Marbek was retained by nine Canadian federal departments to estimate the greenhouse gas (GHG) emission reductions that could be economically obtained from more efficient energy use in their buildings. This estimate would become part of the basis for setting an overall governmental target for GHG reduction by the year 2010, under the Federal House In Order (FHIO) program. FHIO is a component of the federal government's efforts to help achieve the goals of the Kyoto Accord.

Developing the estimate required the following steps:

- Define two emission reduction scenarios: a market-based approach in which energy management projects would be undertaken by Energy Service Companies (ESCOs) and a more aggressive approach including any energy management projects with a cost below $120/tonne of CO_2e reduction
- Identify a basket of energy management actions for each scenario, and determine an appropriate penetration rate for each action by the 2010 deadline
- Collect data on building stock and energy use
- Using building modelling (described in more detail below), estimate the energy, GHG, and economic impacts of applying the basket of measures to the building stock, for each of the two scenarios.

Available data were scanty and very aggregated. For most of the nine departments, detail below the level of whole building annual energy figures was unavailable. Indeed, the quality of departmental energy data placed an upper limit on the accuracy that could be achieved in the project. For the typical department, total energy consumption could be estimated to within approximately 10%, based on the buildings data available. Under these circumstances, even the best analytical method would be expected to yield results with at least 10% uncertainty.

Project budget and time constraints demanded a simple approach. Marbek staff modelled seven departments entirely in-house. We were required to model over 3,500 buildings, comprising over 6,000,000 m^2 of floor space, in approximately three months. Total staffing was four people, only two of whom were on the project fulltime for most of the period.

To meet the objectives within these constraints, we required a set of tools to interpret the available data. Models representing large groups of buildings were needed, with the results aggregated using the macro modelling process described below.

As the nucleus of the approach, Marbek used a simplified end-use model, the Commercial Energy and Emissions Analysis Model (CEEAM). CEEAM represents a compromise between the greater modelling rigour of the hour-by-hour simulation tools and the economy of a spreadsheet. Its calculation engine is an implementation of ASHRAE's modified bin method, as described in *Simplified Energy Analysis Using the Modified Bin Method* (Knebel, 1983).

Because the HVAC calculations within CEEAM are neither new nor innovative, this paper focuses primarily on the overall macro modelling process. The methodology section describes the process. This is followed by an example, using data drawn from the FHIO project (but disguised to preserve client confidentiality).

METHODOLOGY

In this section, we outline the method used to develop estimates of energy savings potential in a group of buildings. We identify the minimum amount and quality of building data needed, and describe the steps required. Figure 1 presents the approach as a flow chart.

Develop Building Specifications

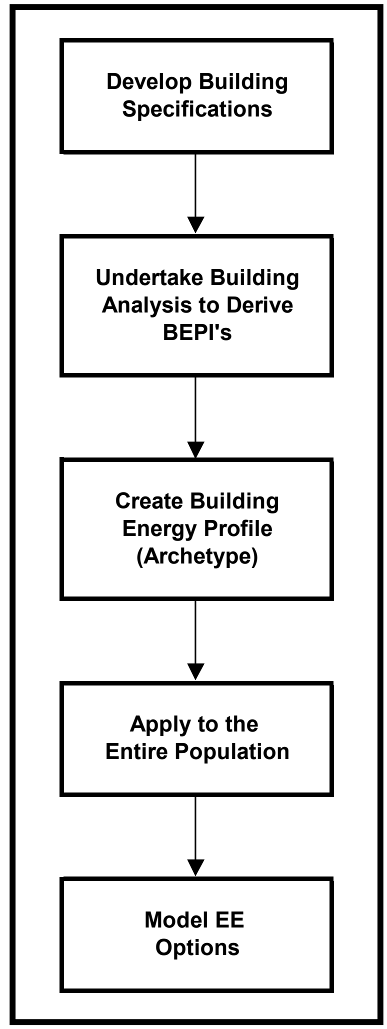
The first step in analyzing a large group of buildings is to subdivide the population into manageable categories. The objective is to identify groups of buildings that can each be represented by one archetypal model building mimicking the energy behaviour of the whole group. With the assistance of the client, we select from several different division criteria, including: building type (office, warehouse, laboratory, etc.), floor area, age, and geographic location.

With FHIO input data imposing uncertainty of at least 10%, an appropriate level of accuracy could be obtained by modelling buildings using 80% of the energy and extrapolating to the remainder. We began by identifying categories of large buildings, for the following reasons:

- The 80% energy consumption target could be met with a small number of buildings,
- Energy data for the largest buildings was easy to obtain and high quality, in comparison with the smaller buildings, and
- The clients had relatively easy access to other information on the largest buildings, such as their main purpose, or the type of energy-using equipment in them.

For several departments, additional categories including medium or smaller buildings were required to reach the 80% energy consumption target. We constructed databases including thousands of buildings, using data supplied by the clients. Information on small buildings tended to be very incomplete: for one department, there were no energy figures for over 1,000 of the small buildings.

Figure 1 Macro Modelling Process



For buildings in the categories to be modelled, we required the following data at minimum:

- Floor area,
- Primary purpose, and
- Annual energy consumption, divided between electric and non-electric energy.

For the remaining buildings, to be estimated by extrapolation, we required only the number and an aggregate floor area.

Derive Building Energy Performance Indicators

We then calculated average building energy performance indicators (BEPIs) for each category. For FHIO, the BEPIs used were:

- Average annual electrical energy consumption per unit of floor area, and

- Average annual non-electrical energy consumption per unit of floor area.

For other types of studies, other performance indicators could be used, such as maximum daily natural gas consumption and maximum peak electrical demand.

Archetype Development

We next constructed models of archetype buildings that will be used to simulate the behaviour of each category. The choice among available building simulation tools involved several factors, including in-house technical expertise, availability and quality of input data, required accuracy, and budget.

For many projects, only an hour-by-hour simulation tool, such as DOE2 or TRNSYS, can provide the accuracy required by the client. FHIO, with its tight budgetary and time constraints, and the uncertainty inherent in the input data, required only a first-order approximation of the building energy profiles.

The model we used, the Commercial Energy and Emissions Analysis Model (CEEAM), was originally developed for the CANMET Building Group, to characterize energy use patterns in commercial buildings, in support of the Building Technology Action Plan developed in the mid-1990s. The development drew on similar research by others, particularly researchers at Lawrence Berkeley Laboratory (Akbari et al, 1993).

The researchers at LBL set out to build a detailed understanding of commercial building energy use in the service territory of a large utility. They used building simulations to estimate energy end use intensities, and then calibrated them against whole building energy consumption data and load shapes. The work was very labour-intensive, requiring hundreds of DOE 2.1D simulations and the processing of over 1,300 sets of hourly monitored building data.

CEEAM was developed to accomplish similar objectives more economically. It was based on ASHRAE's modified bin method (Knebel, 1983), the best simulation methodology then available to us that could be implemented in a spreadsheet.

ASHRAE Fundamentals 2001 describes the modified bin method as follows: "The modified bin method (Knebel 1983) extends the basic bin method to account for weekday/weekend and partial-day occupancy effects, to calculate net building loads (conduction, infiltration, internal loads, and solar loads) at four temperatures, rather than interpolate from design values, and to better describe secondary and primary equipment performance."* Energy for space heating, space cooling, and HVAC electricity are calculated using this method.

In addition, CEEAM models the following building end uses:

- Service hot water,
- General lighting,
- Architectural lighting,
- Other (high bay) lighting,
- Office equipment and plug loads,
- Food service equipment,
- Refrigeration equipment, and
- Miscellaneous.

The model accounts for interactions between energy end uses, such as the effect of lighting energy on heating and cooling.

Besides benefiting from the inherent speed of commercial spreadsheet software, the approach further reduces simulation time by using technology profiles. Essentially, CEEAM represents the mix of buildings as a single building with end use characteristics based on weighted averages. Table 1 includes part of the profile table for general lighting systems, showing that the user can specify percentage of floor area lit at different lighting levels, as well as the percentage lit by incandescent, compact fluorescent, T12 fluorescent and T8 fluorescent lighting.

Table 1 Lighting Profile

Light Level (LUX)	**300**	**500**	**700**	**100**	**TOTAL**
% Distr.	10%	25%	65%	0%	**100%**
Weighted Average					**610**
System	**INC**	**CFL**	**T12**	**T8**	**TOTAL**
Present (%)	0%	0%	75%	25%	**100%**
Efficacy (L/W)	15	50	63	90	

The model uses the lighting profile to calculate average lighting energy use for the buildings represented by the archetype. Because we are able to represent a mix of buildings with different lighting systems, we can model

* The method is presented in detail in the 1989 ASHRAE Fundamentals Handbook, pp. 28.10-28.17.

a large group of diverse buildings without the need to run repetitive simulations.

The profile approach can be largely replicated for other simulation tools by calculating average lighting power densities or boiler efficiencies outside the software and entering the result. The real strength of creating a composite building based on the mixture of buildings being modelled is in modelling multiple ventilation system types (e.g., 50% constant and 50% variable volume) along with different heating and cooling plants.

Ideally, we fill in the technology profiles based on hard data on the equipment present in the buildings. For the FHIO project, we also used sources such as client data on the age and purpose of the buildings, records of previous energy upgrades, and Marbek's library of information on typical characteristics of commercial building stock.

Finally, we calibrated the model to the BEPIs developed earlier. We adjusted the model until it satisfied the following conditions:

- The total modelled consumption for space heating and service hot water was within 5% of average non-electric consumption from the building data,
- The total modelled consumption for the other end uses was within 5% of average electrical consumption from the data, and
- Individual end uses had realistic values in comparison with available data on similar building types.

Application to the Population

The breakdown of energy consumption by end use, derived from the models for each building archetype, was supplied to a macro model. The model calculated energy consumption by end use for the whole population of buildings, along with associated GHG emissions. The model incorporated data on:

- Proportion of different types of fuels used in the buildings,
- Energy cost information,
- Floor space, including building or divestment plans, and
- Average GHG emissions per unit of energy for the different fuel types.

Application of Energy Efficiency Options

To estimate the savings potential in the building population, we modelled the application of a set of energy efficiency options in the buildings. Using the lighting example in Table 1, for example, the upgrade scenario included replacement of all but 5% of the T12 lighting with T8 technology. The upgrade also included reduced lighting levels, increasing the floor area lit at 300 lux to 37% and decreasing the area lit at 700 lux to 38%. Altogether, 19 different measures were included in the most aggressive of the upgrade scenarios, ranging from low-cost measures such as temperature setback to capital intensive building envelope improvements.

To estimate the financial impacts of the energy efficiency options, average implementation cost was added to the macro model. The model output included average payback, life cycle cost, cost per kilowatt of reduced electric demand, and cost per tonne of greenhouse gas reduction.

SIMULATION

To demonstrate the method, we created a fictional federal department using disguised data from three different FHIO departments. Shoes, Ships and Sealing Wax Canada (SSSWC) has 250 buildings, consisting of the following three categories:

- 20 large offices built between 1970 and 1980,
- 200 small offices, mostly built in the 1980s, and
- 30 laboratory/office combination buildings, of varying ages.

Table 2 SSSWC Building Stock

Bldg. Type	**No.**	**Area (000s of m^2)**	**Elect. EUI (MJ/ m^2)**	**Fuel EUI (MJ/ m^2)**	**Total EUI (MJ/ m^2)**
Large office	20	1,087.4	1,010	422	1,432
Small office	200	204.1	664	697	1,361
Lab/ office	30	314.8	832	695	1,527

Table 2 shows the floor area and BEPIs for the three building types, calculated from energy figures provided by the departments. The BEPIs used for this work are energy utilization indices (EUI): annual consumption per unit of floor area. The table shows electrical EUI, non-electric or fuel EUI, and total EUI. The majority of energy for space heating and service hot water was from natural gas, except for 20% of the small offices, which used oil. Other end uses were electric.

To demonstrate the macro model, we applied the following three energy efficiency measures to the SSSWC buildings:

- Retrofit of up to 45% of the floor area with T8 fluorescent systems, capped at 95% of the floor area (i.e., if 90% was already T8, only 5% would be retrofit), at an estimated cost of $\$8/m^2$ of floor area.
- Lighting redesign to reduce lighting levels to 300 lux in up to 27% of the floor area, capped at 90% of the floor area, at an estimated cost of $\$20/m^2$ of floor area, and
- Retrofit of up to 45% of the floor area with high-efficiency boilers, capped at 60% of the floor area, at an incremental cost (above the cost of an already-planned replacement) of $\$5.50/m^2$ of floor area.

Many of the large offices and the laboratory/office combination buildings had received energy efficiency upgrades in the past. Very few of the small offices had. The assumptions used to build technology profiles for the three building archetypes were therefore quite different. For example, we assumed very high penetration of T8 fluorescent systems in the large offices, both because of the previous energy work and because the building owner had data on the presence of these systems. We assumed much lower penetration of T8 systems in the small offices.

RESULTS

We modelled the three building types using three separate CEEAM archetypes. Below we present the main findings, including the baseline profiles for lighting levels, lighting technology, and boiler efficiencies, as well as the energy end use breakdown for the three archetypes. We then show the application of this end use breakdown to the whole population. We present the results of modelling the application the energy efficiency measures, first separately and then together, to demonstrate the degree to which interaction between end uses affects the results. Finally, we briefly present the GHG and economic implications.

Building Profile

Table 3 shows the profiles for general lighting levels, general lighting technology, and boiler technology in each of the three building archetypes. These profiles form the baseline penetrations for proposed energy efficiency measures.

Table 3 Lighting and Heating Profiles

Profile	Large Office	Small Office	Lab/ Office
Lighting Levels			
% 300 lux	10	10	20
% 500 lux	10	25	20
% 700 lux	80	65	60
Weighted avg. (lux)	640	610	580
Lighting Technology			
% T-12	10	75	50
% T-8	90	25	50
Boiler Efficiency			
% std. (73% eff.)	70	85	60
% high-efficiency (88% eff.)	30	15	40

Table 4 shows the energy end use profiles for each of the three building types, as modelled by CEEAM archetypes calibrated to the BEPI figures.

Table 4 Energy End Use Profiles

Energy End Use	Large Office	Small Office	Lab/ Office
	(MJ/m^2-yr)		
Space Heating	384	673	657
HVAC Electricity	270	186	288
General Lighting	255	262	236
Space Cooling	261	80	39
Office Equipment & Plug Loads	183	111	143
Service Hot Water	38	24	38
Architectural Lighting	39	23	23
Other (High Bay) Lighting	2	2	44
Miscellaneous Eqpt.	0	0	43
Refrigeration	0	0	12
Food Service	0	0	4

Application to the Building Population

We applied the above end use profile to the population of buildings, to obtain the breakdown of overall energy consumption by end use shown in Table 5.

Table 5 Overall Energy End Use Consumption

Energy End Use	Large Office	Small Office	Lab/ Office	Total
	(TJ/yr)			
Space Heating	418	137	207	762
HVAC Electricity	294	38	91	423
General Lighting	277	54	74	405
Space Cooling	284	16	12	312
Office Eqpt & Plug Loads	199	23	45	266
Service Hot Water	41	5	12	58
Architectural Lighting	43	5	7	55
Other (High Bay) Lighting	3	0	14	17
Misc. Eqpt.	0	0	14	14
Refrigeration	0	0	4	4
Food Service	0	0	1	1
TOTAL	1,558	278	481	2,317

Lighting Energy Savings

Table 6 shows the new general lighting profiles for the three building types. A comparison with Table 3 reveals that the lighting levels were reduced in all three building types, but major retrofits of T-8 fluorescent technology were possible only in the small offices and lab/office combination buildings.

Table 6 Lighting Profiles

Profile	Large Office	Small Office	Lab/ Office
Lighting Levels			
% 300 lux	37	37	47
% 500 lux	10	25	20
% 700 lux	53	38	33
Weighted average (lux)	532	502	472
Lighting Technology			
% T-12	5	30	5
% T-8	95	70	95

Table 7 show the savings predicted for the lighting end use, neglecting the effects of lighting energy on the heating and cooling systems.

Table 7 Lighting Savings

	Large Office	Small Office	Lab/ Office
Baseline General Lighting EUI (MJ/m^2-yr)	255	262	236
New General Lighting EUI (MJ/m^2-yr)	206	167	143
Lighting Savings (MJ/m^2-yr)	49	95	93
% Savings	19	36	39

Heating Energy Savings

Table 8 shows the new heating profiles for the three building types. A comparison with Table 3 reveals that substantial boiler retrofits were modelled in all three building types, limited by the predetermined maximum penetration for the technology: 60% of the floor area.

Table 8 Heating Profiles

Profile	Large Office	Small Office	Lab/ Office
Boiler Efficiency			
% standard (73% eff.)	40	40	40
% high-efficiency (88% eff.)	60	60	60

Table 9 show the savings CEEAM predicts for the heating end use.

Table 9 Heating Savings

	Large Office	Small Office	Lab/ Office
Baseline Heating EUI (MJ/m^2-yr)	384	673	657
New Heating EUI (MJ/m^2-yr)	363	620	633
Heating Savings (MJ/m^2-yr)	21	53	24
% Savings	5	8	4

End Use Interactions

Two types of end use interactions affect the accuracy of simulations: interactions between measures applied to the same end use, and interactions between end uses. As an example of the former, if the two lighting measures are applied to the small office buildings separately, the following savings occur:

- Reduced lighting levels, considered separately, save 46 MJ/m^2-yr.
- Conversion to T-8 technology, considered separately, saves 59 MJ/m^2-yr.
- Simple summation of the two measures would give savings of 105 MJ/m^2-yr, but CEEAM predicts only 95 MJ/m^2-yr savings with the two measures applied together. Simple summation would therefore overestimate savings by over 10%.

If savings from lighting and heating measures were simply added together, with no consideration for interaction between end uses, we would present the following results:

- For large offices, total savings will be 70 MJ/m^2-yr, or 4.9%.
- For small offices, total savings will be 148 MJ/m^2-yr, or 10.9%.
- For lab/office combinations, total savings will be 117 MJ/m^2-yr, or 7.7%.

When lighting energy use in a building is reduced, however, the heating load typically increases while the cooling load decreases. Table 10 shows the results of accounting for these interactions. The table includes the new EUIs and savings figures for lighting, heating, and cooling, along with total savings.

Table 10 Savings with Interactions

	Large Office	Small Office	Lab/ Office
New General Lighting EUI (MJ/m^2-yr)	206	167	143
New Heating EUI (MJ/m^2-yr)	370	650	651
New Cooling EUI (MJ/m^2-yr)	255	71	35
Lighting Savings (MJ/m^2-yr)	49	95	93
Heating Savings (MJ/m^2-yr)	14	23	6
Cooling Savings (MJ/m^2-yr)	6	9	4
Total Savings (MJ/m^2-yr)	69	127	103
% Savings	4.8	9.3	6.7

Table 11 shows the energy consumption and savings that result from application of these energy efficiency actions to the full population of buildings. The table also shows the degree to which these savings would be overestimated if interactions between end uses were ignored.

Table 11 Overall Energy End Use Consumption

Energy End Use	Large Office	Small Office	Lab/ Office	Total
Total Energy Consumption (TJ/yr)	1,482	252	448	2,182
Total Savings (TJ/yr)	75	26	32	133
% Savings	4.8	9.3	6.7	5.8
Comparison with Estimate Neglecting End Use Interaction				
Total Savings without Interaction (TJ/yr)	76	30	37	143
Overestimate (%)	1.4	16.5	13.6	7.3

GHG Reductions and Economics

Based on the mix of fuels used in these buildings, the macro model estimated that implementation of these measures would result in 7% GHG savings—slightly more than the 5.8% energy savings.

Payback was estimated at approximately 5 years, based on the measure costs and the energy savings. Using the discount rate of 10% specified by the client, the value of savings exceeded the capital costs, resulting in a net cost of -$16 per tonne of GHG reduction.

DISCUSSION

The FHIO project was a new application of commercial sector end use modelling, an approach that can be applied to the commercial or institutional building stock of a government department, a large corporation, a utility service territory, or a whole nation. In this case it was used to set targets for GHG emission reduction. Utility planners can use it to characterize the structure of electrical demand, information that is needed to prioritize specific interventions in the marketplace.

The modified bin method proved a cost-effective approach in a project where accuracy was limited largely by the quality of the energy data available. CEEAM, as a component of the macro modelling process, facilitated the analysis of thousands of buildings in only three months. At the same time, as the results of this exercise show, CEEAM provides greater accuracy than simpler models that fail to account for measure interactions. By simply adding the effects of the three measures considered above, savings would have been overestimated in the small office category by nearly 25%. This difference is sufficiently large to cause errors in setting priorities in an energy efficiency program.

If a client requires results with less than 5% uncertainty, both better data and more rigorous simulation techniques would be required. Utility clients can typically provide energy sales data with uncertainty below 5%. If project budget permits, hour-by-hour modelling can provide excellent results. For example, in project work for BC Hydro, Hepting et al were able to model energy sales within 1% of the utility sales data, and to model peak demand within 10% of actual figures using DOE2 simulations (Hepting, 1993).

For non-utility clients, energy consumption data will continue to be a constraint. In our experience, large databases of energy data collected by the client often have many gaps and other errors. Data obtained directly from the energy utilities is more accurate, but also more costly to gather. An effective alternative is to seek utility data on a random sample of buildings. In one recent project, Marbek used utility data from a sample of 131 buildings (out of 2,700) to estimate energy consumption within 10% of the actual value (with 95% confidence). In contrast, data obtained from the client's accounting system, including over 1,500 of the buildings, overestimated energy consumption by 25%.

As building energy data is improved, the accuracy of the simulation methods becomes the limiting factor in the quality of the results. Researchers in the U.S. are pioneering promising ways to use hour-by-hour simulation while keeping costs down. Sonderegger et al use detailed DOE2 simulations running unattended, within a system that automatically calibrates the simulation to a set of weather-normalized monthly utility bills (Sonderegger, 2002). The resulting tuned simulation can produce load shapes within 10% of those measured in actual buildings.

A key advantage of the approach Sonderegger described is that it demands less intensive engineering knowledge of buildings on the part of the user. A comparison of the results from automatically tuned hour-by-hour simulations versus simplified models tuned by building experts would be an interesting topic for future research.

CONCLUSIONS

End use analysis of large groups of buildings demands a balance of efficiency and accuracy. The macro model described here, with CEEAM at its core, provided an effective balance for the FHIO project. Hour-by-hour simulations, while indispensable in many projects, would not have been appropriate where the quality of input data limited the accuracy of the final results. On the other hand, more simplified models can introduce inaccuracies as great as 25%, potentially causing errors in program planning.

The macro modelling process provided the tools to interpret scanty energy data and give the FHIO clients the information needed to set targets and priorities for their GHG reduction programs.

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