EEE: A PROTOTYPE TOOL FOR THE EVALUATION OF EMBODIED ENERGY AND GREENHOUSE GASES EMISSIONS OF EXTERIOR ENVELOPE OF CANADIAN HOUSES

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ABSTRACT

The exterior envelope has a major contribution to the life-cycle energy use, life-cycle greenhouse gas emissions and life-cycle cost of a house. Therefore, there is a need to design the exterior envelope in such a way as to minimize these environmental and economical impacts.

The Energy & Emissions Estimator (EEE), a prototype tool, is developed in order to help engineers and architects estimate the life-cycle cost, the life-cycle energy use and the equivalent CO_2 emissions generated throughout the life-cycle of a house; and therefore to provide them with a decision support tool for their design. The EEE tool calculations use energy analysis results from the HOT2000 program and a built-in database.

This article presents the main flowchart of the EEE tool, the data import from the HOT2000 program, the available databases, the calculation methods, and the results obtained. Future improvements of the tool are also discussed.

INTRODUCTION

Significant amount of energy is used throughout the life-cycle of houses in order to ensure the desired level of interior comfort. The energy is used for the house's operation (e.g., heating, lighting or appliances) over its physical life, and is also embodied in materials and sub-systems which were used for its construction.

The exterior envelope has a major contribution to the life-cycle energy use of a house since it influences the energy use for heating and cooling and contributes to the total energy embodied in the house. Therefore, it is essential to design the exterior envelope in such a way to minimize the life-cycle cost, life-cycle energy consumption, and the associated environmental impacts.

The prototype tool presented in this paper, called Energy & Emissions Estimator (EEE), is developed to help engineers and architects to estimate the life-cycle cost, the life-cycle energy use and the equivalent CO_2 emissions generated throughout the life-cycle of a house. The calculations use the results of energy analysis performed by the HOT2000 software, and a built-in database containing values of embodied energy, greenhouse gases emissions corresponding to the embodied energy (called in this paper "embodied emissions"), and purchasing and installation cost of a number of common building materials.

This article presents the main flowchart of the EEE tool, the import of house description and energy consumption and cost from HOT2000, the available databases, the calculation methods, and the results obtained. It also discusses future improvements of the tool.

DATA IMPORTED FROM HOT2000

HOT2000 is an energy analysis software, developed by Natural Resources Canada, that estimates monthly and annual operating energy consumption and cost of a house located in Canada. Calculations are based on a description of the house (e.g., plan shape, number of floors, dimensions and orientation of exterior walls, composition of exterior envelope, and definition of mechanical systems). The user can select the relevant weather data file among those available for several Canadian locations.

The EEE tool imports two types of data from the HOT2000 program: (1) the annual energy consumption and cost per fuel type, i.e. electricity, natural gas, oil, propane, and (2) the detailed description of the exterior envelope.

The exterior envelope is defined by the user of the HOT2000 program as an assembly of ceilings, above grade and basement walls, exposed floors and foundations. Each of these components may include elements such as lintels and openings (doors and windows) and is composed of a number of layers of building materials, categorized as wood frame (framing material and cavity material), steel frame (framing material and cavity material), continued medium, continued insulation and strapping.

The description of each component of the exterior envelope (e.g., wall) and the dimensions and thermal properties of its constituting elements is required. Some of this information is exported to the EEE in order to estimate the life-cycle cost, embodied energy, and direct and indirect generation of greenhouse gas emissions. For instance the following information is imported for an above-ground wall:

- dimensions: height, length, gross area and net area;
- description of the different layers constituting the wall: frame layer (framing material, dimension and spacing), cavity insulation (material and thickness), additional layer of continued insulation (material and thickness), interior finish layer (material and thickness), sheathing layer (material and thickness), exterior cladding layer (material and thickness), and the number of studs used at corners and intersections;
- dimensions and material used for lintels and openings in the wall.

Although other sub-systems such as intermediate floors have a significant impact on the initial cost, embodied energy and corresponding greenhouse gas emissions, they are not taken into account in the calculations performed by the EEE; they are regarded as independent components which do not affect the annual heating cost.

CALCULATION METHODS

Figure 1 illustrates the main flowchart of the EEE and shows: (1) the import of data from HOT2000, (2) the use of databases, and (3) the results of calculations performed by the EEE program.

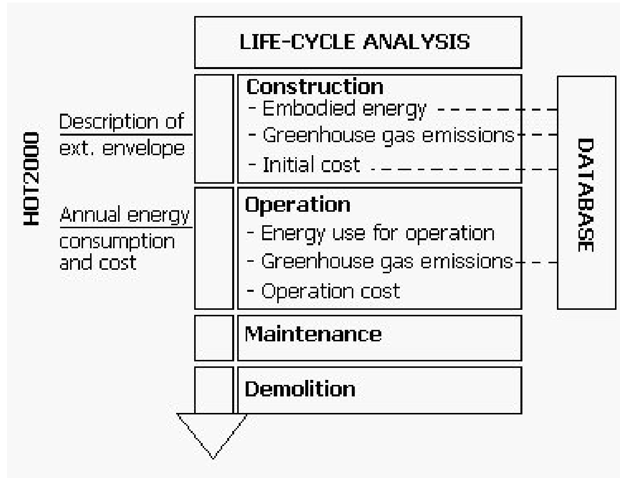

Figure 1. Flowchart of the EEE tool

After the HOT2000 program finishes the calculations, a specially designed output file is created, and imported into the EEE program. The original file, that has the format of a tab-separated text document, is then converted into a spreadsheet file to facilitate the location and retrieval of information.

Besides the imported data, the calculations performed by the EEE tool require information from the EEE database and user-defined inputs. The EEE interface guides the user to select from the EEE database the necessary data for performing the calculations of embodied energy, greenhouse gas emissions, and cost. The EEE database and its content are presented in the following section.

In the EEE program, the life-cycle is decomposed into four phases: construction, operation, maintenance, and demolition. Construction includes the acquisition of the house components and sub-systems, and the construction process itself. Rehabilitation is not included as a life-cycle step since it is considered as the first step in the construction of a new house.

The calculation approach used for estimating the energy use, greenhouse gas emissions, and initial cost is presented below for each phase of the life-cycle:

• **Construction**

Energy use Energy used for the manufacturing of building components and sub-systems, and their installation on site is accounted for in the "construction" phase. It is called embodied or initial energy. The specific values of the embodied energy, in MJ/kg, as published in more than 25 references, were analysed, and then implemented into a database [Baouendi et al., 2001]. The user has three options: (1) to use a default value selected for each material, (2) to access the entire database and select a specific value upon the analysis of references, or (3) to input a user-defined value.

The amount of embodied or initial energy is calculated by multiplying the appropriate specific embodied energy value for each material, component or sub-system by its volume and density. The volume of each material is calculated using data imported from HOT2000 program and considering the construction practice appropriate to each house. For instance, the volume of wood studs used for the exterior envelope is calculated by considering parameters such as height and width of each wall, dimensions of studs, spacing between studs, or number of studs installed at the intersection with partitions or other exterior walls. The material density is either selected by the user from the EEE database or is input by the user.

It is worth mentioning that most specific values of embodied energy found in the literature do not consider the energy used for the transportation of products to the site and the construction process itself.

Greenhouse gas emissions The specific values of greenhouse gas emissions, in kg of gas per kg of material, which were generated during the manufacturing of building products and their installation on site, were also selected from different references, and finally implemented in the EEE database. The total amount of greenhouse gas emissions are calculated by multiplying the specific value of emissions for each material by its mass.

The results are first expressed as tons of emissions of different greenhouse gases, and then are converted to equivalent CO_2 emissions by using the Global Warming Potential (GWP) indexes [IPCC, 2002]. These indexes can either be input by the user or selected from the EEE database, and are given for different time horizons, i.e. the time where the global warming effect will be felt. For instance, the associated GWP_{100} for CH_4 is 21, which indicates that 1 kg of CH_4 released today will have the same impact, over the next 100 years, as 21 kg of CO_2. Therefore, given an example where x tons of CO_2 and y tons of CH_4 are released due to the embodied energy of an exterior envelope, the equivalent CO_2 emissions is equal to (x+21y).

Initial cost The initial cost of the exterior envelope is calculated using unit prices of different building materials and corresponding labour costs from the Building Construction Cost data [RS Means, 2002].

• **Operation**

Energy use The annual operating energy consumption, in MJ per fuel type, is imported from the HOT2000 simulation results. The life-cycle operating energy consumption is calculated by multiplying the annual energy consumption by the economic life of the house, in years, as defined by the user.

Greenhouse gas emissions The on-site use of natural gas, oil, propane, and wood generates greenhouse gases. The emissions of CO_2, SO_2, NO_x, CO, CH_4, and Particulate Matter are estimated using conversion coefficients, expressed in kg of gas per MWh of energy used, given in terms of fuel type [Buhl, 1997]. For instance, 178 kg of CO_2 are emitted when burning natural gas on site to produce 1 kWh of energy for heating.

The estimation of greenhouse gases emissions due to the off-site generation of electricity must take into account several factors:

(1) The energy sources used in the power plants. The users can select the average contribution of energy sources for each province of Canada (default values) or can input their own selection. For instance, the electricity is generated in Alberta using coal (84% of total energy used), oil (8%) and nuclear (8%), whereas in Quebec it is produced using hydro-electricity (96.7%), natural gas (1.1%), oil (1.1%) and nuclear (1.1%).

(2) The combined efficiency of 0.33 is used as default to account for the efficiency of combustion process and the transmissions losses [Falcon 2000, Winkelmann et al. 1993]. The users can select the default value or input their own selection. The off-site annual energy consumption for generating electricity is then calculated by dividing the annual on-site electricity consumption by the combined efficiency of generation and transport. Annual emissions of each greenhouse gas are calculated by multiplying the conversion coefficient for each gas (in kg/MWh) by the annual

energy consumption (in MWh). The final result is expressed in equivalent CO_2 emissions.

Similarly to the construction phase, the amounts of greenhouse gas emissions resulting from the operation phase are expressed as tons of emissions of different greenhouse gases, and are also converted to equivalent CO_2 using the GWP indexes by using the Global Warming Potential coefficients for a selected time horizon.

Operating cost The annual operating energy cost in CAN$ per fuel type is imported from the HOT2000 simulation results.

The life-cycle energy cost is calculated using the Present Worth Value method, which converts the annual energy cost (EC), in CAN$/year, calculated over the economic duration (n in years) of the house, in one single payment today (NPV) [Revelle et al. 1999]. If uniform series of annual payments are considered (e.g., there is no variation on energy cost), the following formula is used:

NPV = EC [$(1+i)^n$ - 1]/[I$(1+i)^n$], where i is the nominal interest rate.

If geometric gradient series are considered (e.g., energy cost increases by the annual rate of e), the following formula is used:

NPV = EC [1-$(1+e)^n$ $(1+i)^{-n}$]/[i-e]

- **Maintenance & Demolition**

In some references the embodied energy values include the energy use for the maintenance and demolition phases, however most references do not consider it. Due to the lack of reliable data, the EEE tool does not estimate, as default, the embodied energy corresponding to these two phases of the life-cycle. The users can, however, input their own defined values.

EEE DATABASE

The EEE database is composed of:

- **Specific values of embodied energy**

Embodied energy values of 145 common building materials are available in the database. These values are presented in six categories depending on the phases of the life-cycle, which were taken into consideration for the assessment of embodied energy. The seven categories consider respectively the following phases of the life-cycle of materials/components/sub-systems:

Category 1: Manufacturing only;
Category 2: Extraction of raw materials and manufacturing;
Category 3: Extraction of raw materials, manufacturing and transport;
Category 4: Extraction of raw materials, manufacturing, transportation and construction;
Category 5: Extraction of raw materials, manufacturing, transport, construction and maintenance;
Category 6: Entire life-cycle;
Category 7: This category contains all reference values for which the methods used for the assessment of embodied energy are not clearly defined in the literature.

The embodied energy values come from different sources and different geographic origins. The EEE interface enables two search types: (1) a quick search providing default values, selected from a number of North American references, and (2) an advanced search giving access to all the available values and presenting detailed information concerning the sources. This last type of search enables the user to compare different values of embodied energy associated with a given material and select the most appropriate value. Some default values obtained through a quick search are presented in table 1.

Material	Embodied energy (MJ/kg)	Reference
Aluminium	211	Samuels, 1994
Cement	5.85	Venta, 1999
Clay brick	2.14	Sheltair Scientific Ltd., 1991
Concrete	1	Samuels, 1994
Glass	15	AIA, 1994
Cellulose insulation	1.75	EBN, 2000
Mineral wool insulation	15.6	EBN, 2000
Fibreglass insulation	30.3	AIA, 1994
Wood	7.38	Sheltair Scientific Ltd., 1991

Table 1. Default values of embodied energy

• **Embodied greenhouse gas emissions from building materials**

Embodied greenhouse gas emissions values are available for a number of common building materials. They are expressed in kg of emission of each greenhouse gas per ton of material (e.g., according to Venta, 1999, the production and transport of 1 ton of cement emits up to 876.36 tons of CO_2, 18 kg of CH_4, 402 kg of CO, 7.14 tons of NO_x, 234.48 kg of SO_x and 1.78 tons of particulates).

• **GWPs**

Global Warming Potential (GWP) coefficients are provided by the Intergovernmental Panel on Climate Change [IPCC,2002]. Database contains the GWP values for the greenhouse gases considered in the calculations (CO_2, SO_2, NO_x, CO, CH_4, and Particulate Matter) for time horizons of 20, 100, and 500 years. Examples of GWP coefficients are presented in table 2 for CO_2 and NO_x. It is worth mentioning that the uncertainty associated with the calculation of these coefficients is about ±35% [IPCC, 2002].

Greenhouse gas	GWP (Time Horizon in years)		
	20 yrs	100 yrs	500 yrs
CO2	1	1	1
NOx	275	296	156

Table 2. GWPs coefficients [IPCC,2002]

• **Material and labour cost**

This unit costs for materials and labour are selected from the Building Construction Cost Data [RS Means, 2002].

• **Contribution of energy sources to the off-site electricity generation**

The EEE database contains data for four Canadian provinces as well as average data for Canada, collected from provincial web sites. For each location, the contribution to the off-site electricity generation of the following energy sources is available: hydro-electricity, nuclear, natural gas, oil, coal, and "other sources"(see Table 3).

Province/ Country	Coal	Oil	Natural gas	Nuclear	Hydro-electricity	Other sources
British Columbia	2	2	2	-	94	-
Alberta	84	8	8	-	-	-
Ontario	4.33	4.33	4.33	54	26	-
Quebec	0	1.1	1.1	1.1	96.7	-
Canada	19	3.5	3.5	12	62	-

Table 3. Contribution of energy sources to the off-site electricity generation

• **Conversion coefficients for greenhouse gas emissions**

The database contains the conversion coefficients for CO_2, SO_2, NO_x, CO, CH_4, and Particulate Matter generated through the use of 1 MWh of energy, in terms of fuel type [Buhl, 1997]. These coefficients are expressed in kg/MWh and are presented in table 4.

Energy source	Emissions in kg/MWh of:					
	CO_2	SO_2	NO_x	CO	HC	PM
Gas	115	0.00059	0.137	0.034	0.00058	0.003
Oil	170	1.04667	0.36667	0.03333	0.008533	0.08667
Coal	200	2.9444	0.584	0.20856	0.00417	0.03
Electricity from gas	115	-	0.2	0.039078	0.001661	0.00293
Electricity from oil	170	-	0.3	0.033175	0.0069	0.1
Electricity from coal	200	-	0.7	0.02886	0.00481	0.1

Table 4. Conversion coefficients for greenhouse gas emissions [Buhl, 1997]

RESULTS

The EEE tool estimates, for a given description of house, the life-cycle energy use in MJ or MJ/m^2 of heated floor area, the life-cycle greenhouse gas emissions in tons of equivalent CO_2 or tons CO_2/m^2 of heated floor area, and the life-cycle cost in CAN$ or CAN$/$m^2$ of heated floor area.

Figures 2 and 3 show two examples of interface: one for the construction phase, and another for the operation phase.

FUTURE WORK

Several developments are planned for the future:

- Extend databases by connecting the EEE tool over the internet with other databases such as BEES, ATHENA, or MEANS.

- Develop indices of sustainability based on the life-cycle analysis.

- Couple HOT2000 program and EEE tool within an optimization program and a Decision Support System.

- Add to the list of greenhouse gases the list of indoor pollutants (e.g., VOC) from building materials

- Compare the results of EEE tool with those provided by software such as Timberline Cost Estimating or ATHENA.

CONCLUSION

Recently, major concerns about the health of our planet urged building designers to integrate sustainable design approaches to the classical design process. Life-cycle energy use and life-cycle generation of greenhouse emissions have been identified as new parameters of decision to be added to the list of criteria that a good design should fulfil.

The EEE tool enables engineers and architects to estimate the life-cycle cost, the life-cycle energy use and the equivalent CO_2 emissions generated throughout the life-cycle of a house, and consequently provides them a support for design decisions.

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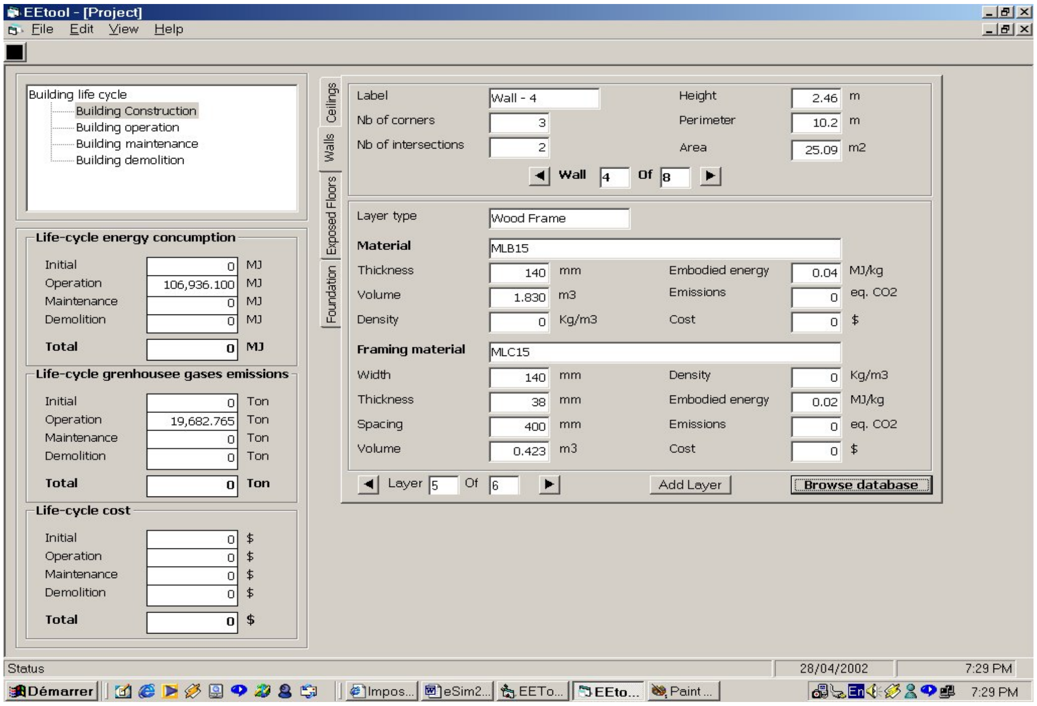

Figure 2. EEE tool: Construction phase

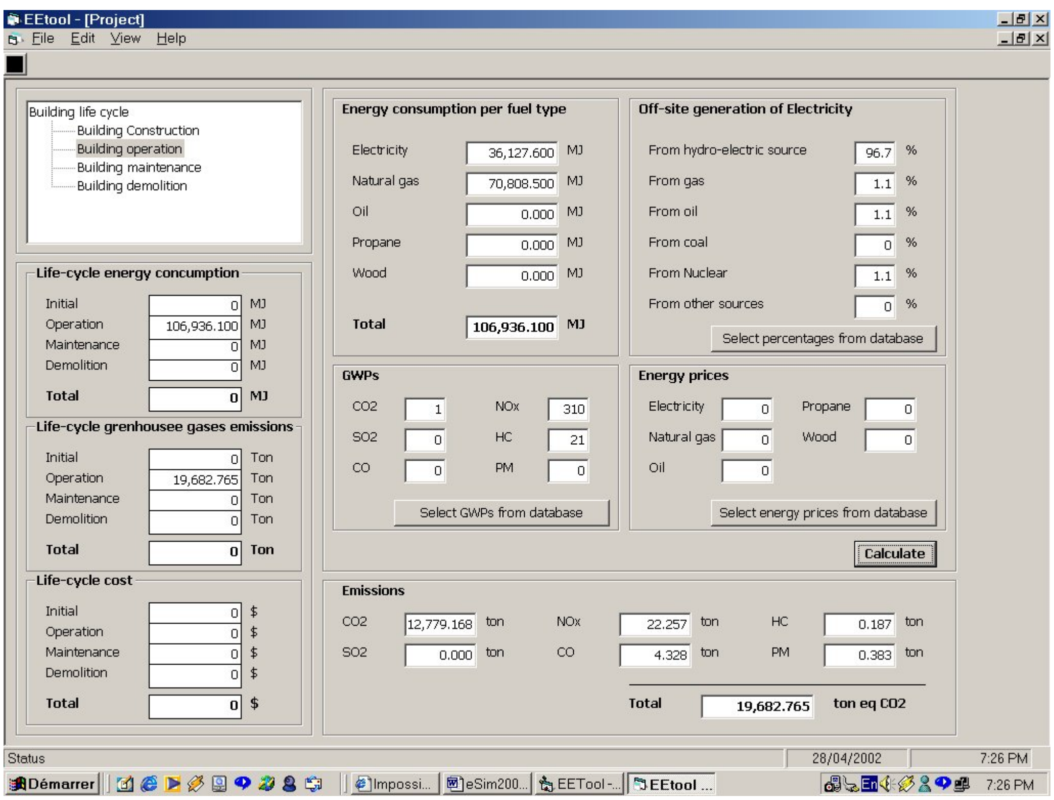

Figure 3. EEE tool: Operation phase