Development of a prototype tool for the evaluation of the sustainability of Canadian houses

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Abstract

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Human activities such as building construction have a major impact on the environment. These impacts are associated with the consumption of natural resources such as materials, energy, and water, as well as the release of pollutants to the air, water, and soil. Among them, fossil fuel depletion and global warming have been identified as priority issues nationally and internationally. The reduction of these impacts is necessary for a sustainable development of the planet, and can be achieved through a responsible building design.

Traditionally, the annual energy used for the operation of buildings is estimated and optimized during the design process using one of the many available energy analysis tools. Today, building designers must consider as well minimizing the fossil fuel energy use and emissions of greenhouse gases throughout the buildings life cycle. Data, methods, and tools necessary for this task are available in the literature but are not easily accessible to designers.

Hence, a prototype tool, Energy and Emission Estimator (EEE), was developed within the framework of this research project in order to meet the needs of designers and provide them with a tool that estimates the life cycle energy use, greenhouse gas emissions and cost of Canadian houses. EEE is coupled with an existing energy analysis tool HOT2000,

through the collaboration of Natural Resources Canada. The tool uses for its calculations, data and methods selected from the literature for their relevance and applicability to the Canadian context. EEE has a user-friendly interface and is easy-to-use. It is also time and effort effective since it requires little inputs from its users. The tool imports the description of the house envelope and its annual energy consumption and cost directly from the HOT2000 program. Detailed results are generated from the tool and are presented in an Excel file in order to allow flexibility of interpretation to its users.

The EEE tool was applied to study some sustainability indices of a one-storey single-detached house located in Montreal. The life cycle energy use, emissions, and cost of the house were evaluated and the impacts of different design parameters were compared including different levels of insulation of the exterior envelope, different locations, and use of different energy sources for space heating and domestic hot water supply.

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Table of Contents

List of Figures

List of Tables

Chapter 1

INTRODUCTION

According to the Worldwatch Institute [1], building construction consumes 40% of raw stones, gravel, and sand, and 25% of the virgin wood used in the world each year. Buildings also account for 40% of the energy consumed annually worldwide and for 16% of water usage. Energy-consuming and resource-depleting human activities such as those related to buildings contribute significantly in altering the Environment at the local and global levels. For instance, resource depletion and biodiversity losses may be caused by raw materials extraction. Building product's manufacturing and transport, and building's operation draw important amounts of fossil-fuel energy, generating emissions linked to global warming, acid rain and smog. Solid waste generation can lead to landfill problems.

Increasing concerns about the state of the Environment are gaining economical and political scenes nationally and internationally. Particularly, fossil fuel energy depletion and the planet's global warming have been identified as priority issues, and many countries ratified –or are in the process of ratifying- international protocols such as the Kyoto Protocol, for the reduction of greenhouse gases emissions. This kind of initiatives comes within the framework of the Sustainable Development recommended by the international community at the first Earth Summit held in Rio de Janeiro in 1992. The objective from a Sustainable Development is to meet the needs of people today without compromising those of future generations, mainly through a responsible use of the planet's resources and the minimization of environmental burdens.

In the building sector, engineers and architects must also join in this endeavour. More attention should be brought to the minimization of fossil fuel energy use and emissions of greenhouse gases associated with new and rehabilitated buildings, and traditional design practices must be changed accordingly. It is common that the annual energy used for the operation of buildings is estimated during the design process using one of the many available energy analysis tools. However, new concepts such as embodied energy in building products, and greenhouse gas emissions are rarely taken into consideration.

Applicable methods and data necessary for the evaluation of the energy use and emissions of greenhouse gases associated with a building's life cycle are becoming available in the literature. Some of them are integrated in computer-aided tools to assess buildings' environmental performance. Theses tools range from embodied energy tools that only quantify the energy embodied in a building, to more detailed design tools that assess several environmental impacts. The calculations performed by such tools are based on detailed inventory databases that reflect the use of natural resources and the emission of pollutants associated with different building materials, products, and processes. A small number of tools include as well, life cycle cost evaluation of design alternatives. Most recently developed tools automatically integrate inputs and results provided by existing tools such as CAD tools or energy analysis software tools. This approach makes calculations more precise and the tool easy-to-use.

In Canada, there is a need for easy-to-use tools that can provide accurate life cycle environmental assessment of buildings and that also includes life cycle costing. Ease-to-use and accuracy of the calculations can be obtained through the coupling of the tool with existing Canadian energy analysis software.

Thus, the proposed research aims to provide designers with a methodology and a prototype tool that estimates the energy use and greenhouse gases emissions throughout the life cycle of Canadian houses, and evaluates its associated life cycle cost. More specifically, the prototype tool is intended to help engineers and architects design building envelopes in such a way that the life cycle energy and emissions are minimized. The tool will be coupled with HOT2000 an energy analysis tool developed by Natural Resources Canada, and will use a database, which was developed within the framework of this project through an extensive literature survey including information from the Athena Sustainable Material Institute and the Means residential cost database.

Chapter 2

LITERATURE REVIEW

The literature survey conducted for the purpose of this study aimed to identify the existing methods and tools that are used at the design stage to assess the environmental impacts of buildings. A summary of the findings in the literature are presented in this chapter and includes a description of the Life Cycle Analysis (LCA), a commonly used method for the evaluation of buildings' environmental performance, and a review of a number of computer-aided tools applying the LCA to the building and construction industry. Four examples of LCA-based tools are presented in further details.

This chapter focuses as well, on two environmental impacts commonly addressed in a LCA and considered of major importance at the economical and political levels: the energy use and greenhouse gases emissions. An analysis of available data used for the estimation of embodied energy and greenhouse gases emissions throughout buildings and building products life cycles is also presented.

Finally, the objective of the present research project is stated.

2.1. THE LIFE CYCLE ANALYSIS METHOD

The literature review showed that the approaches used to evaluate the environmental performance of building design alternatives range from single-criterion methods of assessment such as embodied energy evaluations, to more exhaustive methods of assessment considering several environmental impacts. The Life Cycle Analysis (LCA) method recommended by the International Standards Organization, ISO [2], is the most recommended approach for the environmental assessment of buildings.

The ISO defines LCA as a "systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life-cycle, from acquisition of raw materials through final disposal" [2]. In the case of building design, the *product* is the building –a group of materials and products- and the *process* involves all activities taking place throughout its life cycle i.e., its construction, operation, maintenance and end of life.

The LCA methodology is broken down into four steps:

Step 1: Definition of the ***goal and scope*** of the assessment.

Step 2: *Inventory analysis*. The environmental inputs and outputs associated with a product are identified and quantified over its entire life cycle. Environmental inputs include water, energy, land, and other resources. Environmental outputs correspond to production, resource and energy use, emissions to air and water, and waste generation.

Step 3: *Impact assessment*. This step seeks to relate the parameters quantified at the inventory stage to measures of environmental concern. The environmental impact categories that are generally included in an impact assessment vary from one source to another and depend on a number of parameters including environmental pressures, political and economical priorities, and advance in the field of research. A synthesis based on the impact categories provided in references [3, 4, 5, 6, 7] is presented below.

Input related categories

- Natural resource depletion (Fossil fuel extraction, Water extraction, Mineral extraction)
- Biotic resource depletion (Flora: Wood forest harvesting…)
- Land use (Landscape degradation, habitat alterations, impacts on biodiversity)

Output related categories

- Global warming
- Acidification
- Eutrophication
- Smog formation
- Toxicity (Ecological and human toxicity)
- Noise
- Odour
- Ozone layer depletion
- Solid waste disposal
- Indoor air quality

Step 4: ***Interpretation*** of results. The information provided by the inventory and the impact assessment is interpreted in relation with the goal of the study in order to reach conclusions and recommendations.

2.2. LCA-BASED SOFTWARE TOOLS

A survey of software tools using the LCA method was conducted [8]. The documents found, mainly on the World Wide Web and in a number of research publications, include survey reports on LCA tools and descriptive documents of individual tools. Survey reports on LCA tools compare either general tools used for the assessment of any kind of products [9, 10, 11] or tools applicable only to the building and construction industry [12, 13]. Documents describing individual LCA-based tools include a user manual [6] and official web sites of different tools.

LCA tools are described, according to the International Energy Agency Annex 31 [12], as mainly "computer aided conversions of calculation and assessment methods" using the Life-Cycle Assessment (LCA) method. An LCA-based tool provides an interface for the input of project data, suitable access to the calculations and environmental information databases, calculation of assessment, and suitable representation of outputs. The literature survey of LCA-based tools conducted encompasses also instruments such as checklists that do not allow the direct input of project specific data.

In the building and construction industry various LCA tools are available and are used for different purposes by building professionals including public authorities, building owners/investors, architects, engineers, constructors, services enterprises (during the period of use), researchers and consultants. The purposes of the tools range from environmental labelling or certification, to product/building environmental improvement, audit, and sustainable design.

LCA-based tools are most useful at the design stage where life cycle impacts of the building on the environment are mostly determined. Six categories of LCA-based tools can be used by architects and engineers [13]:

Type 1 – Checklists and guides: These instruments are available online or in printed form, and are qualitative guides to building products and issues which need to be considered. Therefore, they are used early in the design process.

Type 2 - Embodied energy tools and/or emissions evaluation: These tools are generally based on Input/Output (I/O) analysis of industry sectors and sub-sectors and/or information obtained directly from manufacturing industries, and provide information on the embodied energy of the entire building relatively quickly. They are used in the detailed design phase for material selection.

Type 3 - Detailed LCA modeling tools: These tools focus on materials, components and processes. They are mainly used by building designers for material selection.

Type 4 - LCA design tools: These tools use LCA as a basis for whole-building environmental impacts evaluations. The results obtained are usually presented in an aggregated form using scores. They are easy to use by designers at the conceptual design phase in order to quickly evaluate the generated designs.

Type 5 - LCA CAD based tools: These are integrated tools that can read material and component information from CAD drawings or other tools such as energy analysis software, and evaluate the environmental impacts of buildings. These tools may be applied when the building design is brought to higher level of detail.

Type 6 - Building assessment and rating schemes: These tools are used to assess the environmental performance of buildings and allocate them rating levels such as medals or a number of stars.

Figure 2.1. summarizes the typical use of the different types of LCA-based tools during the decision and design phases.

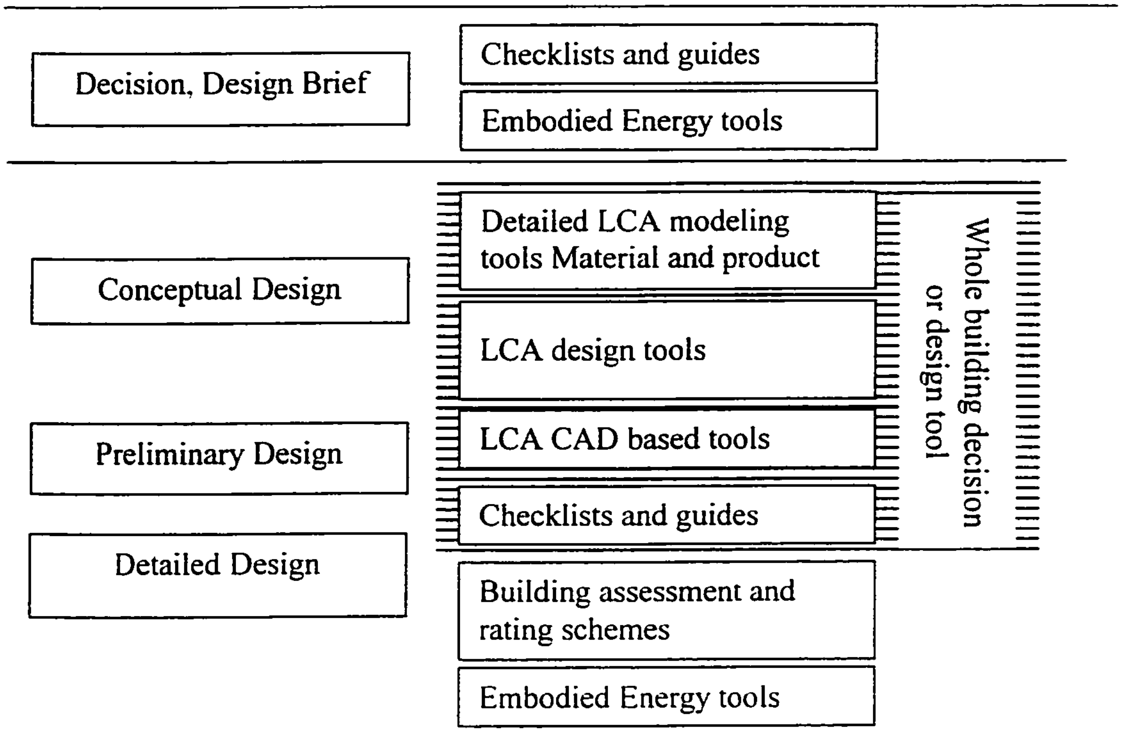


Figure 2.1. Use of LCA tools during the decision and design phases [13]

A list of the LCA tools used today in the building design is presented in Appendix A.

Four LCA-based tools using different approaches to the assessment of environmental impacts of buildings throughout their life cycle were selected as examples. BEES [6] and Athena [14] were chosen for their applicability to the North American context, and for their use of comprehensive inventory databases. EQUER [15] and LICHEE [16] are the most recently developed LCA CAD based tools and were selected for their interesting approaches. A general description of each tool is provided including features such as inputs, databases, methods of calculation, and outputs.

2.2.1. BEES

Building for Environmental and Economic Sustainability (BEES) is an American tool developed at the National Institute of Standards and Technology (NIST) [6]. It can be used by building designers for material and product selection based on a comparison of common building materials and products with respect to their environmental and economical performance.

- **Method**

The BEES model evaluates and compares the environmental and economical performance of common building materials and products using respectively the LCA method and ASTM's Life-Cycle Cost method [17].

Indexes or other self-explanatory measures are used in order to evaluate each environmental impact category based on direct use of the embedded inventory database. Ten environmental impact categories are evaluated including global warming, acid rain, eutrophication, resource depletion, indoor air quality, solid waste, smog, ozone layer depletion, and ecological and human toxicity. The calculated measures and indexes obtained are then, normalized using the Multi-Attribute Decision Analysis (MADA) [18], to scores on a scale from 1 to 100, where 100 is assigned to the worst performing material/product. Each environmental impact measure is normalized by dividing by the highest measure for the given impact category. This normalization allows combining the different impacts on the environment to a single score using user-defined or selected weights. BEES proposes three sets of weights for this purpose: The first set is an equal weight distribution on the different environmental impacts, the second is based on a study done by the U.S. Environmental Protection Agency [19], and the third by Harvard University [20].

In parallel, the economic performance of the alternative materials is also evaluated as the sum of its initial and future costs. Finally, an overall performance is calculated by weighting the environmental and economic performance as defined by the user.

- **Database**

In the BEES model, building materials are classified according to UNIFORMAT II, a classification system proposed by the ASTM. Materials covered include: site improvement materials and products, structural materials, interior finishes, exterior claddings, insulation and sheathing materials. Materials used in basement walls and slabs on grade are also covered.

Environmental inventory flows for a unit of a given building material or product include inputs (water, energy, and raw materials), outputs (air emissions, water effluents, and releases to land), and final product. Environmental data in BEES was mainly obtained from the Ecobalance LCA database [21] and adjusted to the American context. Economical data are based on first costs provided by the R.S. Means publications [22] and future costs based on data published by Whitestone Research [23].

- **Inputs**

The input module in BEES consists of a group of screens where the user makes a number of selections. The input process is divided in two steps. The first step consists in setting the parameters of the study such as the respective weights attributed to environmental and economical performance of the materials and products and individual weights corresponding to each environmental impact category. The second step enables the user to define the alternative building materials and products for comparison.

The tool compares the performance of materials per functional unit over 50 years of service life. For instance, 1 ft^2 of linoleum can be compared to 1 ft^2 of carpet used for floor covering throughout 50 years. Hence, no dimensional characteristics are defined as input.

- **Outputs**

A graphical representation of the calculation results illustrates a comparison of two or more building materials with respect to their environmental, economic, and overall performance. The following types of graphs can be viewed: (1) The environmental performance of each product by impact category and life-cycle stage; (2) The economical performance including a breakdown of initial and future costs; and (3) The overall performance combining the environmental and economical performances using user-defined weights.

2.2.2. ENVIRONMENTAL IMPACT ESTIMATOR

Environmental Impact Estimator is a Canadian tool developed by Athena The Sustainable Materials Institute. It is a whole building LCA-based tool that allows engineers and architects comparing different conceptual design alternatives. This model can be applied to different types of buildings including residential, commercial and light industrial buildings. A description of the tool's database, input module, calculations, and outputs are presented below based on the tool's help category.

- **Method**

The user of Environmental Impact Estimator defines the building location, life expectancy, and its constituting assemblies and materials. An estimate of the quantity of materials in the building is calculated by the software tool and is linked to the life-cycle inventory database. Some assumptions are set for these calculations. For instance, the volume calculation of lumber in a wood-stud wall, assumes 2 bottom plates and 1 sill plate but does not account for additional studs at corners and intersections or runs of blocking. Then, six environmental measures are calculated by the Athena model. The first two measures are self-explanatory since they use common units, and the four other measures are expressed using indices developed in order to facilitate interpretation of the inventory results:

- Embodied primary energy

This measure is given in Mega-joules (MJ) and accounts for direct and indirect energy used to extract raw materials, transport them and manufacture the final product. Indirect energy used accounts for processing and transport of fuel and energy.

- Solid waste

This measure is expressed in kilograms (Kg).

- Raw resource use

This measure is characterized using an index combining subjective scores that take into account the various effects of resource extraction such as effects on bio-diversity, ground water quality, and wildlife habitat. These scores are combined into a set of index numbers and are used as weights to the amount of raw material used to produce the final material or product. The different weighted resource use values of all the raw materials used to manufacture the given material. They are then, summed in order to provide coefficients or "ecologically weighted kilograms, where the weights reflect expert opinion about the relative ecological carrying capacity effects of extracting resources".

- Global warming

The amount of greenhouse gas emissions expressed in equivalent CO_2 emissions is evaluated in Athena. It accounts for the combustion of fossil fuel that can be either used directly or indirectly for material manufacturing and for the house operation when specified by the user. Global Warming Potentials (GWP) are used as a reference measure that enables comparing the global warming effect of the emission of one kg of a given gas to the effect of the emission of one kg of CO_2 over a 100-year time horizon as recommended by the International Panel on Climate change.

- Air and water pollution measures

Similar indexes are used to express the pollution and health effects of substances emitted to water or air. The indexes are developed using the critical volume method and estimate the volume of air or water necessary to dilute contamination to acceptable levels as defined by standards.

Athena calculates critical volumes measures based on "the worst offender, that is, the substance requiring the largest volume of air and water to achieve dilution to acceptable levels" [14].

- **Database**

The Athena database contains a set of regional North American life cycle inventory (LCI) databases for common building materials and products. The inventories include data of embodied energy and emission associated with the raw material extraction, material manufacturing and transport of 90 to 95% of the structural and envelope materials, that are typically used in residential, commercial, institutional, and light industrial buildings. The groups of materials include wood, steel and concrete products, cladding products, insulation and roofing materials. Other available data includes the energy use and process related emissions for on-site construction, maintenance, replacement, transportation of building materials, and end of life.

The Athena database is a relevant LCI database to the Canadian context and is being continually updated since 1997.

- **Inputs**

The user defines the building as a three-dimensional structure through a selection from a range of building assemblies or materials. The location of the building, its life expectancy, and area are also specified. The operating energy breakdown should also be entered to the model based on results provided by external energy analysis tool, to account for the energy and emissions related to the buildings operation.

To avoid the problem of estimating the bill of materials, the user can use pre-defined assemblies associated with material and product quantities. The user enters the assembly's description (size and composition) and the model will automatically calculate the quantity of materials and link it to the life cycle inventory databases of the model.

The pre-defined assemblies offered to the user include different types of foundations including concrete footings and slab on grade; walls; beams and columns; and floor and roof systems. For instance, the following wall assemblies are available: "Concrete blocks", "Concrete, cast in place", "Concrete, pre-cast cellular", "Concrete tilt-up", "Curtain wall", "Insulated concrete form wall", "Steel studs wall", and "Wood stud wall".

Another input option is also available for adding additional basic materials or products. However, the user should make hand calculations of the quantity of materials and input them to the model to account for their energy and emissions. When using this option, the user underestimates the total environmental load since the energy and emissions related to the construction, maintenance and end of life of the material are not accounted for.

- **Outputs**

The output of the model is a detailed life cycle inventory of the building design. The results are generated in tabular and graphical forms showing absolute and aggregated measures of: Aggregated ecologically weighted resource requirements, Embodied energy inputs, Global warming potential, index of water pollution effects, index of air pollution effects, and Solid wastes.

2.2.3. EQUER

EQUER is a French whole-building life cycle simulation tool developed at the "Ecole des Mines de Paris" [15] and is coupled with the thermal simulation tool COMFIE. The tool enables quantification of a number of environmental impacts and allows comparison of up to four design alternatives.

- **Approach**

EQUER receives data from COMFIE describing the operating energy consumption of the building and a detailed description of the building envelope including its geometric characteristics and its constitution. In addition, the user is asked to input other data necessary for the calculations such as water consumption. An estimate of the quantity of materials is generated and is linked to the database. Then, the environmental impact of the design alternative is assessed based on a number of indexes and measures. The different environmental impacts assessed by EQUER include abiotic resources depletion, primary energy consumption (in MJ), water consumption (in Kg), acidification (equivalent Kg SO_2), eutrophication (equivalent Kg PO_4^{3-}), global warming (equivalent Kg CO_2), non-radioactive waste (Kg), radioactive waste (Dm^3), odors (m^3), aquatic eco-toxicity (m^3), human eco-toxicity (Kg), and photochemical ozone (smog) (Kg C_2H_4 equivalent).

It is worth mentioning that each object of the modeled building has its own "age counter". This means that if the life duration of a material is shorter than the life duration of the building, the energy and associated emissions of the material will be counted for more than once.

- **Database**

The inventories used by EQUER are based on the Öekoinventare database [24] developed by the Polytechnic Federal School of Zurich. This last database comes in a Microsoft Excel format and is condensed for easy-to-use purposes. In fact, the elementary fluxes evaluated in the Swiss database are grouped by environmental impact category using aggregation coefficients proposed by the University of Leiden [25].

- **Inputs**

The building is modeled using an object-oriented modeling approach according to a formalism defined in the STEP standard proposed by ISO [26]. The objects included in the decomposition used are: building site, building, sub-systems such as walls, components such as windows, and products. Part of the information required such as the operating energy consumption and detailed description of the geometry of the envelope and its constitution are directly imported from the COMFIE thermal analysis software. Other necessary information should be input by the user.

- **Outputs**

The output from a simulation using EQUER is an eco-profile including the environmental impact indicators described above. The results can be visualized by different life cycle stages and a comparison of up to four different design alternatives can be performed.

2.2.4. LICHEE

LICHEE is an Australian prototype tool developed by the Commonwealth Scientific and Industrial Research Organization (CISRO) in order to help designers estimate the life cycle energy use in detached houses. The tool is in fact a group of intercommunicating programs including existing ones such the object-oriented architectural system ArchiCAD and the Australian Nationwide House Energy Rating Software (NatHERS).

- **Approach**

The LICHEE system is built as a series of intercommunicating programs using the Industry Foundation Classes (IFC). IFC provide a method for exchanging data about buildings and a structured building model. LICHEE imports object-oriented data from the architectural system ArchiCAD and uses additional information to calculate the embodied energy of the house. The embodied energy is calculated based on estimates of the quantities of materials constituting the building and values of embodied energy and lifetimes of building materials available in the database. In parallel, NatHERS is used to calculate the house operating energy. It is worth mentioning that the operating energy calculated by NatHERS include the energy required for space heating and cooling only, it does not account for the energy use for hot water, lighting, and electric appliances use.

The final result is the sum of the embodied energy and energy used for the operation of the house throughout its life cycle.

- **Database**

The database used by the LICHEE tool is based on a series of research studies undertaken at CSIRO and contains values of embodied energy derived from input-output tables and lifetimes of different building materials. A particular focus has been attributed to the estimation of the life expectancy of materials. In fact, durability effectiveness factors have been also developed in order to account for the reduction of lifetime of materials influenced by the life expectancy of other materials. For instance, a scenario such as the changing of glass in a window when the frame is changed is taken into consideration.

- **Inputs**

The automation of data entry allowed by the use of the IFCs reduces significantly the inputs to the program. In fact, the tool imports most of the information as object-oriented CAD data and asks the user to input additional information such as the house location.

- **Outputs**

The outputs generated by LICHEE include graphs and tables summarizing the life cycle energy use in the house and its breakdown per material groups and elements.

2.3. EVALUATION OF EMBODIED ENERGY AND EMISSIONS OF GREENHOUSE GASES OF BUILDINGS

Energy is used throughout a building's life cycle for space heating and cooling, lighting, and appliances use, and is also embodied in its constituting materials and products. This presupposes that the embodied energy in building materials and products includes all the energy used throughout their life cycle from raw materials extraction to their end of life. The combustion of the fossil fuel energy used at all stages of the building's life cycle is associated with emissions of greenhouse gases and contributes to the Earth's global warming.

Nowadays, the methods and data used in order to estimate a building's operating energy are well known and are implemented in a number of energy analysis software tools. However, the estimation of embodied energy and emissions of greenhouse gases remain less defined despite the abundance of literature on the topic.

The present section discusses the embodied energy data available in the literature the methods and data used for the estimation of greenhouse gases emissions.

2.3.1. EMBODIED ENERGY

A literature survey conducted within the framework of this study enabled collection of a large number of embodied energy values for more than 140 building materials [27].

These values were then classified in a Microsoft Access database. The embodied energy value of a given material is a coefficient that indicates the amount of energy used throughout its life cycle –or part of its life cycle- and is given per unit of material. Most of the embodied energy values found were given in MJ/Kg but can also be expressed in MJ/m^3 or MJ/m^2. Different definitions of embodied energy and diverse classifications of building materials were employed by different authors. In addition, many differences were observed between published values for the same building material.

Groups of definition

The embodied energy was defined in five different ways depending on the parts of the life cycle considered in the calculations. The five definitions include respectively the following parts of the material's life cycle:

Group 1 Raw material extraction, transport, and manufacturing of the final material.

Group 2 Raw material extraction and transport; and manufacturing and transport of the final material.

Group 3 Raw material extraction and transport; and manufacturing and transport of the final material and its construction.

Group 4 Whole life cycle.

Group 5 No definition is available to explain how the embodied energy was calculated.

Presentation of materials

Different classifications of building materials were used by different authors. Some classifications group the materials according to their use of the same raw material, for instance "clay products", while others gather materials used for the same function such as insulation or cladding materials. The detail in defining the groups and sub-groups varies as well. For example, some sources consider "paint" as a group of materials with no further sub-division, whereas others include sub-groups including "water-based and solvent-based paints". Also, some of the authors use additional parameters to qualify the materials such as "local" materials or "imported", or "virgin" material or "recycled".

Due to the differences in materials classification and the gap between the appellation of the material and its real characteristics –for instance, a brick may be made using different manufacturing process and different raw materials and may differ in dimensions–, the comparison of the different values was rather difficult.

Embodied energy values

Appendix B shows the embodied energy values collected from the literature survey grouped by group of definition. It can be noticed that most of the embodied energy values found belong to the first group, where only energy use associated with raw material extraction, transport, and manufacturing of the final material are accounted for.

A closer look shows differences between the values of embodied energy attributed by different authors to the same material. For instance, the embodied energy values of cement under the first group of definition, range from 0.08 [28] to 9.4 [29]. The differences can be explained by different parameters described below:

- Different groups of definition

Two values of embodied energy belonging to two different groups of definition should not be equal since energy is used at every stage of the material's life cycle. For instance, the "as built embodied energy" and "life cycle embodied energy" of "Asphalt building products" given in OPTIMIZE [30] are respectively equal to 3.26 and 7.14 MJ/Kg.

- Different methods of calculation

Four methods of calculation of embodied energy values are usually employed. These are: the statistical analysis, the input-output analysis, the process analysis, and hybrid analysis. Each method is briefly described below:

- The statistical analysis method uses published statistics in order to determine the energy consumed by a given industry.
- The input-output analysis method employs the economic input-output Tables of a given economy. By examining the monetary flow to and from the sectors of energy production, the energy consumption within the economy is traced, and the dollar output of each sector is equated with its energy usage.
- The process analysis method involves the systematic accounting of all the direct input and outputs of energy for a given process.
- The hybrid analysis method combines the best of the methods previously described, usually the input-output analysis and process analysis.

Using one method or another may lead to different values of embodied energy of the same building material. For instance, Baird and Chan [31] employed in 1983 the input-output analysis method based on New Zealand economic data in order to calculate the embodied energy of "copper". The value obtained is equal to 45.9 Mj/Kg. Alcorn [32] updated in 1998 the precedent results using the hybrid analysis method combining the input-output method analysis with the process analysis and statistical analysis methods.

The value obtained raised to 70.6 Mj/Kg. The observed difference is due to the fact that in 1983 Baird and Chan [31] accounted only for the energy used for processing the raw materials without actually considering the extraction of raw materials it-self since they are imported to New Zealand. Alcorn instead, integrated the energy used for raw material extraction.

- Different geographic origin

Values of embodied energy collected originate from different geographic locations where manufacturing techniques vary, transport means differ, and construction processes are dissimilar. All these parameters explain some of the differences observed.

- Different date of publication

Evolution in calculation methods and in techniques used to manufacture materials, build them into structure, or recycling them are important quality parameters that influence embodied energy values. A comparison between two sets of embodied energy values calculated by Alcorn illustrate some differences from 1995 [33] to 1998 [32] (See Appendix B)

Previous studies on the evaluation of embodied energy of buildings

A number of studies were carried out for the evaluation of the embodied energy of residential and office buildings.

Four studies on residential buildings were performed in Canada, New Zealand, and Sweden. A study under the Canadian Mortgage and Housing Corporation's Optimize program [30] provides the estimate that for a "standard house in Toronto with a 40-year life" the total embodied energy is 2,352 GJ [34]. A second Canadian study undertaken by

Cole [34] of the School of Architecture at University of British Columbia shows that the embodied energy of a "conventional" 3.750 ft^2 ranch-style home located in Vancouver or Toronto, the embodied energy is 1,000 GJ; whereas an "energy efficient" version of the same house has an embodied energy of 1,075 GJ. The third study performed by Buchanan and Honey in 1994 [35] for three types of houses in New Zealand (different material were used in floors, exterior walls, roof, framing, and window frames) shows an embodied energy range of 215 to 520 GJ. The last study by Thormark in 2001 [36] evaluates the embodied energy of "the most energy efficient apartment housing in Sweden" over 50-year lifetime and shows an embodied energy of 7.03 GJ/m^2 of floor area.

The results of a number of studies carried out on office buildings were also found. The first carried out by Cole and Kernan in 1996 [37] estimates the total embodied energy of a "4,620 m^2 three-storey, generic office building for alternative wood, steel and concrete systems, with and without underground parking". The calculated embodied energy of the office building with underground parking, is 4.54, 5.13, and 4.79 GJ/m2 respectively for wood, steel, and concrete construction; whereas, for the case of buildings without underground parking the embodied energy is estimated to 4.26, 4.86, and 4.52 GJ/m^2 respectively for wood, steel, and concrete construction. The results of other studies were also referred to in the same study for comparison. The first study by Stein et al. [38] evaluates the embodied energy of an office building located in the U.S. to 18.6 GJ/m^2. The second study performed by Buchanan and Honey in 1994 [35] on three to eight-storey office buildings in New Zealand respectively built on wood, steel, and concrete structures, shows a respective embodied energy of 3.7, 6.6, and 5.6 GJ/m^2. The third study, also carried out by Honey and Buchanan 1992 [39] evaluates the embodied energy of four buildings: two concrete-structure buildings of respectively three-storey and five-storey high (4.75 and 6.46 GJ/m^2), one three-storey wood-structure building (3.35 GJ/m^2), and one five-storey steel-structure building (7.75 GJ/m^2). The fourth study by Tucker and Treloar [40] estimates the embodied energy of a 15-storey office building in Australia built on a concrete structure to 8.23 GJ/m^2. The fifth study carried out in Japan on concrete and steel framed buildings by Oka et al. [41] shows embodied energy values ranging from 8.23 to 12.06 GJ/m^2 for concrete buildings and from 8.03 to 11.87 GJ/m^2 for steel buildings.

2.3.2. "EMBODIED" EMISSIONS OF GREENHOUSE GASES

A similar concept to the embodied energy is used to attribute the greenhouse gases emissions to the production and use of materials. A literature survey was conducted to collect values of "embodied emissions" of common building materials. Two types of values were obtained: one gives a breakdown of the emission for different greenhouse gases in kg of gas per unit of material and the other presents an aggregation of emissions of a number of gases using the Global Warming Potentials (GWPs) and expressed in kg of equivalent CO_2 per unit of material. GWPs are coefficients proposed by the Intergovernmental Panel on Climate Change that enable comparison of the effect of the emission of one kg of a given gas on the planet's global warming to the effect that would have 1 kg of emitted CO_2 throughout the same period of time, usually 100 years.

The number of values collected is relatively small compared to the abundance of embodied energy values since emissions of greenhouse gases is a new field of research. Appendix C shows the values collected.

2.3.3. EMISSIONS FROM BUILDING OPERATION

Greenhouse gases are emitted during the combustion of fossil fuels directly and indirectly used in buildings for space heating and cooling, lighting, appliances use, and also for the off-site production of electricity. A study undertaken by Liesen [42] for the U.S. Environmental Protection Agency proposed a method for the atmospheric pollution prediction related to building operation. The method is based on average values of pollution produced by the combustion of gas, oil and coal, and regional characteristics on how electricity is produced. The emission of six pollutants: carbon monoxide (CO), carbon dioxide (CO_2), Nitrogen oxides (NO_X), sulfur dioxide (SO_2), particulate matter (PM), and hydrocarbons (HC) are estimated in kilograms. The efficiency of combustion processes and transmission losses are accounted for in the method. The method proposes also to aggregate emissions of the different gases using the GWP coefficients.

2.4. CONCLUSIONS TO LITERATURE SURVEY

The LCA is a commonly used method for the evaluation of the environmental impacts of buildings. Many software tools were developed based on its principles in order to accompany designers in this task. Different approaches were used, but today's tendency is towarhds the development of tools that can be coupled with existing energy analysis and CAD tools, and therefore, avoid repetitive efforts to designers while providing accurate results. EQUER and LICHEE are two examples of such tools.

The selection of data to be used in the calculations is of major importance as well knowing the wide variability of data available in the literature. A number of parameters influence the quality of the data including geographic specificities that should be taken into account. Each tool should be developed for a particular geographic context and its calculations should be based on a database that is relevant to this same context. For the Canadian context, Athena provides thorough studies and a comprehensive database of embodied energy and emissions of commonly used building materials and construction processes.

A number of studies were undertaken across the world in order to evaluate the embodied energy of different residential and office buildings. The results obtained are limited in number and show wide variations due to differences in geographic contexts, construction techniques, and methods of evaluation.

2.5. OBJECTIVE OF THE PRESENT STUDY

The proposed research aims to provide designers with a methodology and an LCA-based prototype tool that estimate the energy use and greenhouse gases emissions throughout the life cycle of Canadian houses, and evaluate its associated life cycle cost. More specifically, the prototype tool is intended to help engineers and architects design building envelopes in such a way that the life cycle energy and emissions are minimized.

The prototype tool should be developed based on existing calculation methods and data, and should be coupled with an energy analysis software in order to facilitate its use.

The use of the prototype tool will be limited to low-rise wood-frame buildings located in four major Canadian cities: Montreal. Toronto. Vancouver. and Calgary. However, a section of this thesis will discuss additional features that must be covered by the tool in order to make it more comprehensive. In addition. the prototype tool should be employed to evaluate the environmental performance of different design alternatives of a case study house and the results obtained should be analyzed.

In order to achieve the proposed objective, the study should be composed of two parts: (1) the design of the prototype tool and its validation. and (2) the application of the tool to different design alternatives of a given house.

The design process should include the following:

- Determination of the methods and data to be used for calculations based on relevant literature to the Canadian context.
- Identification of data import from the energy analysis tool that will be coupled to the proposed prototype,
- Definition of the results to be generated by the prototype tool,
- Design of the user interface,
- Development of the computer program, and
- Validation of the prototype tool with results provided by other methods.

The application of the prototype tool should first provide an evaluation of the life cycle energy consumption and greenhouse gases emissions of a house and its life cycle cost. Then, an evaluation of different design alternatives of the house should also be performed given modifications of its level of insulation, different house location in Canada, and different types of heating systems. The results obtained should be compared and analyzed to assess the contribution of the modified design parameters on the environmental and economic performance of the house.

Chapter 3

DEVELOPMENT OF ENERGY & EMISSION ESTIMATOR

The proposed prototype tool, called Energy & Emission Estimator (EEE), applies the principles of the Life Cycle Assessment and Life Cycle Cost methods in order to help engineers and architects to design exterior envelopes of Canadian houses in such a way as to minimize the associated life cycle energy use and greenhouse emissions as well as the life cycle cost. For instance, the envelope design can be optimized using different building materials and/or by varying the dimensions of its components. This last application is particularly pertinent to achieving a "sustainable design" since the building envelope, by its embodied energy and influence on the operating energy consumption, has a major contribution to the life-cycle energy use and its associated emissions.

EEE calculations require information, such as the envelope description, from the energy simulation software tool HOT2000, and a built-in inventory database containing values of embodied energy, greenhouse gas emissions embodied in building materials and associated with the energy use for buildings' operation, and purchasing and installation cost of a number of common building materials. In the present version of the EEE, the life cycle calculations only account for the inventory flows associated with the construction and operation stages of a house's life cycle. Due to the lack of reliable inventory data associated with the maintenance, replacement and end of life of building materials, these stages are not considered yet but are planned for future work.

The results include life cycle estimations and breakdowns per life cycle stage of the energy use and its associated greenhouse gas emissions, as well as the life cycle cost of the proposed design.

The flowchart shown in Figure 3.1. summarizes the functioning of the proposed prototype tool.

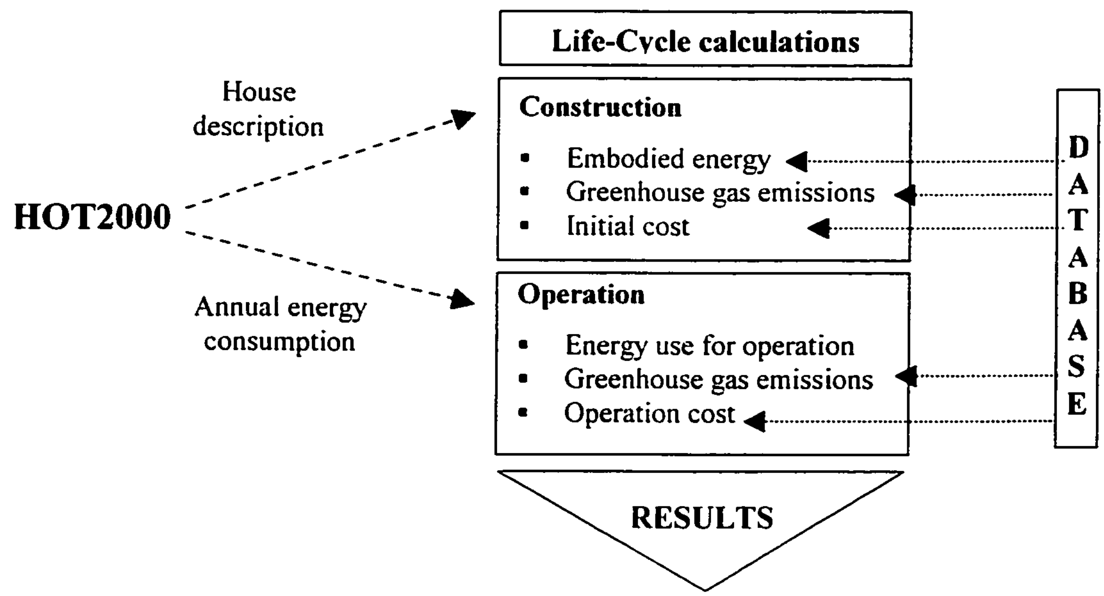


Figure 3.1. Flow chart of Energy & Emission Estimator

The present chapter gives a detailed description of the data import from HOT2000, the available databases, the calculation methods, the results obtained, and the validation of the EEE prototype tool.

3.1. DATA IMPORT FROM THE HOT2000 PROGRAM

HOT2000 program is an energy analysis tool developed by Natural Resources Canada [43]. It estimates monthly and annual operating energy consumption and cost of low-rise residential buildings, located in Canada or in the United States. The energy consumption includes the energy used for space heating and cooling, domestic hot water heating, lighting, and use of electric appliances. The calculations of the model take into account the thermal performance of the house and its components, the passive solar gains for the given building location, and the mechanical performance of the HVAC systems used.

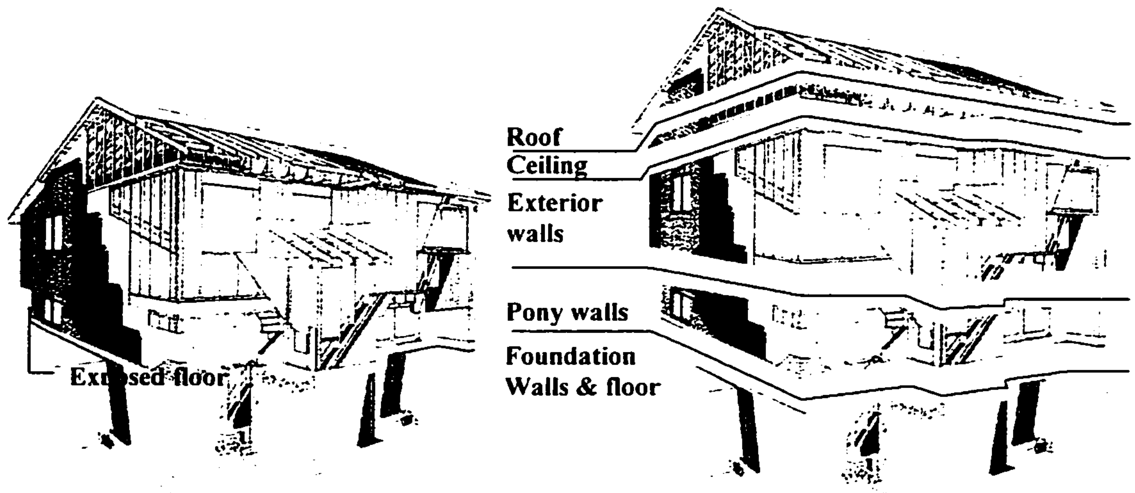
HOT2000 program has a weather database for 102 Canadian sites and 200 U.S. sites. It also provides economic data necessary for fuel cost calculations.

The inputs to the HOT2000 program include a general presentation of the house location, shape, number of floors, a detailed description of the geometric characteristics of the house envelope and its constitution, and the mechanical systems.

An export program, specially developed by Natural Resources Canada for the needs of the present study [44], was integrated to the original HOT2000 program files. The program generates at the end of each HOT2000's simulation, a tab-separated export file containing a detailed description of the envelope and energy simulation results. Then, this file is converted to an Excel file in order to facilitate navigation.

The EEE tool uses the Excel export file in order to import three types of data from the HOT2000 program: the house location; the annual energy consumption and cost per fuel type, i.e. electricity, natural gas, oil, propane, and wood; and the detailed description of the exterior envelope.

The exterior envelope is defined by the user of the HOT2000 program as an assembly of a roof, ceilings, above grade and basement walls, exposed floors and foundation floors. This envelope decomposition is illustrated in Figure 3.2.



Picture of house cross-section from [44]

Figure 3.2. Envelope decomposition used in HOT2000

Each of these components may include elements such as floor headers, 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.

HOT2000 calculations require a description of each component of the exterior envelope and the dimensions and thermal properties of its constituting layers. The user of HOT2000 may use a "Code editor" or a "Code selector" in order to define each component of the house's envelope. The "Code editor" enables the user to define each component as a superposition of a user-specified number of layers, where each layer is defined by one or two selected materials and corresponding thickness depending on its layer type. With the "Code selector" the house components are only defined by selecting materials for a pre-defined number of layers. The use of the "Code editor" offers to the user a wider choice of materials and more flexibility in defining the house components. In the present version of the tool only data defined using the "Code selector" can be exported.

Some information used to define the envelope of the house in HOT2000 is exported to the EEE in order to estimate the life-cycle cost, embodied energy, and greenhouse gas emissions (see Table 3.1.).

Table 3.1. Information imported from HOT2000 for each building component and sub-component

House component	Sub-component	Imported information
Roof	Gable ends & sloped roof	- Area (m^2) - Layers of constituting materials
Ceilings		- Ceiling label - Roof type and slope - Ceiling length (m) - Ceiling area (m^2) - Total number of ceilings - Layers of constituting materials
Exterior walls & Floor headers		- Wall label - Wall length (m) - Wall height (m) - Wall area (m^2) - Number of corners - Number of intersections - Total number of walls - Layers of constituting materials
Exposed floors		- Floor label - Floor length (m) - Floor area (m^2) - Total number of floors - Layers of constituting materials

Table 3.1. Information imported from HOT2000 for each building component and sub-component (Continued)

House component	Sub-component	Imported information
Foundations		- Foundation label - Total number of foundations
	Walls	- Wall height (m) - Wall length (m) - Layers of constituting materials
	Floors	- Floor width (m) - Floor length (m) - Layers of constituting materials
	Pony walls	- Pony wall location - Pony wall height (m) - Pony wall length (m) - Pony wall net area (m^2) - Number of corners - Number of intersections - Total number of pony walls - Layers of constituting materials
	Floor headers	- Floor header location - Floor header height (m) - Floor header length (m) - Floor header net area (m^2) - Number of corners - Number of intersections - Total number of floors headers - Layers of constituting materials
Windows		- Window label - Window location - Number of windows of the same type - Window width (m) - Window height (m) - Window area (m^2) - Total number of windows - Window type - Frame and glazing materials
Doors		- Door label - Door location - Door area (m^2) - Total number of doors - Door type - Exterior and core materials

The description of different layers of materials depends on the layer type or the material use in the envelope. The information associated with each layer or other element such as windows and doors is shown in Table 3.2.

Table 3.2. Imported information for each layer of material and for other building elements

Layer type/Building element	Imported information
Wood frame, steel frame, and strapping	- Framing material - Framing thickness - Framing width - Framing spacing - Cavity material - Cavity thickness
Continuous insulation and continuous medium	- Material - Material thickness
Window: - Glazing and frame materials	- Material - Material thickness
Door: - Core and exterior materials	- Material - Material thickness
Lintels: - Studs and insulation	- Material - Material thickness
Roof: - Sheathing and exterior material in gable ends; and - Sheathing and roofing material in sloped roof	- Material - Material thickness

The research for data in the Excel file, which contains the imported data from HOT2000, is performed automatically by the tool. The EEE program uses keywords and horizontal and vertical displacements in order to locate each information. For instance, by searching for the words "# of Main Walls in column number 2 of a given export file (see example in Appendix D), the program will locate the beginning of the section where exterior walls are described. The cell located at the intersection of the same row number and in column number 1 will give the number of exterior walls. Then, each wall can be located by successive searches of the words "Number of Layers" in column number 3.

For each wall, the first row will include, successively from column 4 to 9, the number of corners of the given wall, its number of intersections with interior walls, its dimensions (perimeter and height), its area, and net area. The following rows provide a description of all the constituting layers of the wall. This part ends before the detection of the key word "Main Wall #, # of Windows, # of Doors" in column 4. The last part describing the given wall provides information concerning presence of openings (doors and walls) and their characteristics.

The keywords used and the layout of an example of converted import file is shown in Appendix D. This decoding technique of the imported file considers different particular cases such as situations where a given component (e.g. exposed floors) is not part of the house description.

3.2. DESCRIPTION OF DATABASE

The EEE database is composed of three groups of data required for the following activities: (1) to decode HOT2000 imports; (2) to calculate the embodied energy, embodied emissions and initial cost of the envelope; (3) and to evaluate the life-cycle energy use at the operation stage and its associated emissions and cost.

The database was created using the Microsoft Access program and is described in detail in this section.

3.2.1. DECODING THE HOT2000 IMPORTS

Building materials are coded in the HOT2000 program using two types of codes. The first coding system is used for most building materials and is an alphanumerical combination of five letters/numbers, e.g. "MLB32" is used to define "Type 1 expanded polystyrene". The second coding system uses a single or double-digit-number for materials used in the sloped part of the roof and its gable ends, and materials used as exterior layers of below-ground walls. These numerical codes are also used to refer to different characteristics of windows, doors and lintels.

Tables presented in Appendix E are used in the database in order to associate each building material with its HOT2000 code:

- Table E.1. provides alpha-numerical codes corresponding to materials available in the "Code selector",
- Tables E.2, E.3., E.4., and E.5. provide numerical codes respectively for roofing materials used in the sloped part of the roof; sheathing materials used both in the gable ends and sloped parts of the roof; materials used in the exterior layer of the foundation walls; and materials used as exterior cladding of gable ends, and
- Tables E.6., E.7., and E.8. show respectively numerical codes used to describe the characteristics of windows, doors and lintels.

The use of separate tables for the numerical coding system avoids confusion due to the use of the same code number for more than one material.

3.2.2. DATA FOR THE CALCULATION OF EMBODIED ENERGY, EMBODIED EMISSIONS, AND INITIAL COST

The database includes the following set of data necessary for the calculations of embodied energy, embodied emissions and material and installation cost of the house's envelope:

- Embodied energy in building materials,
- Embodied emissions in building materials,
- Material and installation cost, and
- Density of building materials.

3.2.2.1. Embodied energy

Embodied energy values of most common building materials have been collected from a number of sources. These values were obtained for different geographic locations, different manufacturing techniques of the given material, and were calculated using different methods of calculations. A discussion about the data available is provided in chapter 2.

All values of embodied energy, which were collected in the literature survey, were included in the database. They are presented in Appendix B. Each value is given in MJ/kg along with its bibliographical reference including original appellation of the material, authors, date of publication and location, and its category of definition.

Table F.1. of Appendix F presents another set of values, which were extracted from the Athena database [46]. It includes values of embodied energy corresponding to each of the building materials used in HOT2000's "Code selector". These values takes into account the energy used for the extraction of the raw material, manufacturing, and transport to the construction site. Since transportation is an important factor for the calculation of embodied energy, values are available in the database for the following locations: Montreal (Quebec), Toronto (Ontario), Vancouver (British Columbia), and Calgary (Alberta). The values were obtained using the Athena's Environmental Impact Estimator 2.0. [46] by calculating the embodied energy for a unit of each of the materials used in HOT2000's "Code selector", e.g. for 1 m^2 of gypsum board or 1m^3 of mortar.

EEE uses as default the values of embodied energy obtained from Athena's database. However, the user can select other values by performing a search giving access to all the collected values along with information on its associated bibliographic source (author, date of publication, journal...). The user may also directly input other values, for instance where a particular material is not available in the database.

3.2.2.2. Embodied emissions

Values of embodied emissions are available for a number of common building materials and are also presented in Table F.2. of Appendix F. They were extracted from Athena's database and are given for the same Canadian locations. The default values used by EEE for the calculations of greenhouse gas emissions are expressed in equivalent kg of CO_2 per unit of material and are obtained by combining emissions of different greenhouse gases such as methane, nitrogen oxide, and carbon dioxide. Individual emissions are expressed in kg of gas emitted per unit of material and are combined using the Global Warming Potentials (GWPs) for a 100-year-time-horizon. GWPs, developed by the

Intergovernmental Panel on Climate Change, enable comparison of the greenhouse effect due to the generation of different gases to the effect of 1 Kg of CO_2 over different time horizons. These coefficients are presented in detail in this chapter, in section 3.2.3.1.

For instance, according to Athena [46], the production and transport of 1 m^2 of 9mm-thick softwood plywood to a house located in Montreal emits 1 kg of CO_2, 2 g of CH_4, 10 g of CO, 13 g of SO_x, and 1g of particulates. The equivalent emission obtained is equal to 1.064 equivalent kg of CO_2 per m^2 of plywood. This value is obtained as the combination of emissions of two greenhouse gases the carbon dioxide, methane, and nitrogen oxide weighted by their associated GWP coefficients, respectively 1, 23, and 296 for a time horizon of 100 years. Other pollutants are not taken into account either because they are not greenhouse gases, e.g. particulate matter, or because their comparable effect to the effect of carbon dioxide is not yet available in the literature. e.g. sulfur dioxide and carbon monoxide.

3.2.2.3. Material and installation cost

Unit costs for building materials and associated labor were selected from the Means' Building Construction Cost Data [47], converted to metric units, and multiplied by a city factor to account for the impact of the local market (Appendix G). Values are available for Montreal, Toronto, Calgary, and Vancouver.

The unit costs take into account the particularity of certain materials. In fact, the same material with different dimensions and various uses may have different unit cost values. This is the case for instance, of wood used for framing and batt insulations.

3.2.2.4. Density

Values of density corresponding to the materials used in HOT2000 are either obtained from materials description given by the HOT2000 program or from ASHRAE Fundamentals Handbook [48] (Appendix H). Since most of the embodied energy values are given in MJ/kg, values of density are needed to convert the volume of materials calculated within the EEE into the mass of material in kg.

3.2.3. DATA REQUIRED FOR THE CALCULATION OF ENERGY, EMISSIONS, AND COST ASSOCIATED WITH THE OPERATION STAGE

3.2.3.1. Global Warming Potential (GWPs)

The database contains Global Warming Potential (GWP) values provided by the Intergovernmental Panel on Climate Change (IPCC) [49] for the greenhouse gases considered in the calculations (CO_2, HC, and N_2O) for 20, 100, and 500 years time horizons. It is assumed that the GWP coefficient of CH_4 is the same as the one for hydrocarbon. Other gases are not taken into account either because they do not have a significant effect on global warming or because respective GWP coefficients are not available in the literature. However, the database was designed to host values of GWP for other gases such as CO, SO_2, NO_x, and particulate matter.

Available GWP coefficients are presented in Table 3.3. It is worth mentioning that according to the IPCC, the uncertainty associated with the calculation of these coefficients is about ±35% [49].

Table 3.3. GWP coefficients [49]

Greenhouse gas	Time horizon		
	20 years	100 years	500 years
CO_2	1	1	1
HC	62	23	7
N_2O	275	296	156

3.2.3.2. Off-site electricity generation per energy source

The EEE database contains data for four Canadian provinces as well as average data for Canada, collected from provincial web sites and used in a study by Neuhann et Al. [50]. For each location, the contribution of the following energy sources to the off-site electricity generation is available: hydro-electricity, nuclear, natural gas, oil, coal, and "other sources"(Table 3.4.).

Table 3.4. Contribution of energy sources to the off-site electricity generation [50]

Province/ Country	Coal	Oil	Natural Gas	Nuclear	Hydro-Electricity	Other sources
British Columbia	2 %	2 %	2 %	0	94 %	0
Alberta	84 %	8 %	8%	0	0	0
Ontario	4.33 %	4.33 %	4.33 %	54 %	26 %	7 %
Quebec	0	1.1 %	1.1 %	1.1 %	96.7 %	0
Canada	19 %	3.5 %	3.5 %	12 %	62 %	0

For instance, in Quebec the hydro-electricity accounts for 96.7 % of the total generation of electricity while in Alberta 84% is generated in thermal plants using coal.

3.2.3.3. Conversion coefficients for greenhouse gas emissions

The database contains the coefficients of emission of CO2, SO2, NOx, CO, HC, and particulate matter generated by the use of 1 MJ of energy, for each fuel type [42]. These coefficients depend on the use of energy: either on-site use or off-site use for the generation of electricity and were originally expressed in kg/MWh. Table 3.5. and 3.6. show the emissions coefficients in grams of gas per MJ respectively for on-site and off-site of fossil fuel.

Table 3.5. Emission coefficient for on-site use of fossil fuels (g/MJ) [42]

Energy source	CO2	SO2	NOx	CO	HC	PM
Natural gas	49.4411	0.0002537	0.0588994	0.0146174	0.0002494	0.0012898
Oil	85.9845	1.2658641	0.2510748	0.0896647	0.0017928	0.0128977
Coal	73.0868	0.2949945	0.086766	0.0149197	0.0011186	0.0144811

Table 3.6. Emission coefficient for off-site use of fossil fuels (g/MJ) [42]

Fuel	CO2	SO2	NOx	CO	HC	PM
Hydro-electricity	0	0	0	0	0	0
Natural gas	49.4411	Regional	0.0859845	0.0168005	0.0007141	0.0012597
Oil	73.0868	Regional	0.1289768	0.0142627	0.0029665	0.0429923
Coal	85.9845	Regional	0.3009458	0.0124076	0.0020679	0.0429923
Nuclear	0	Regional	0	0	0	0
Other	0	Regional	0	0	0	0

It should be noticed that conversion coefficients for SO_2 emissions due to off-site energy use are regionally defined and are not available for Canadian locations. Therefore, these emissions are not automatically taken into account unless the user input them in the database.

3.2.3.4. Discount rates and escalation rates of energy

Discount rates and escalation rates for different fuel types are necessary to perform the life cycle calculation of the operating cost of the house. These coefficients depend on the province where the house is located. The reference values provided by the Model National Energy Code of Canada for Buildings were selected [51] (Table 3.7.).

Table 3.7. Discount rates and escalation rates for different Canadian provinces [51]

Province	Discount rate	Escalation rate for electricity	Escalation rate for oil	Escalation rate for natural gas
British Colombia	9 %	3.5 %	4 %	4.2 %
Alberta	9 %	2.94 %	4.74 %	7.03 %
Ontario	9 %	2.4 %	4.5%	4.5 %
Quebec	9 %	3 %	3 %	3 %

3.3. INTERFACE & PROGRAM

The EEE tool has a user-friendly interface and a program that links HOT2000 and the EEE database in order to perform life-cycle evaluation of the energy use, emissions and cost associated with the exterior envelope of a given house. In this section the interface of the EEE tool and the program used are presented.

3.3.1. PROGRAM

The program of the EEE tool is written using the Visual Basic programming language. This language offers the possibility of interacting with Excel files and Access databases and enables the design of a user-friendly Microsoft Windows interface. The program includes procedures that link different forms, import and decode data from export files, retrieve data in different tables of the database, perform the calculations and generate results.

3.3.2. INTERFACE

EEE tool users interact with five screens: two primary screens for data entry and display, two secondary screens to access database and select data, and an Excel workbook where results are presented. Each screen will be described in the following section.

3.3.2.1. Screens for data entry and display

Figures 3.3. and 3.4. show the screens used to enter and display data needed to perform calculations of energy use, emissions, and cost respectively at the construction and operation stages. They are also used to view intermediate results of the calculations.

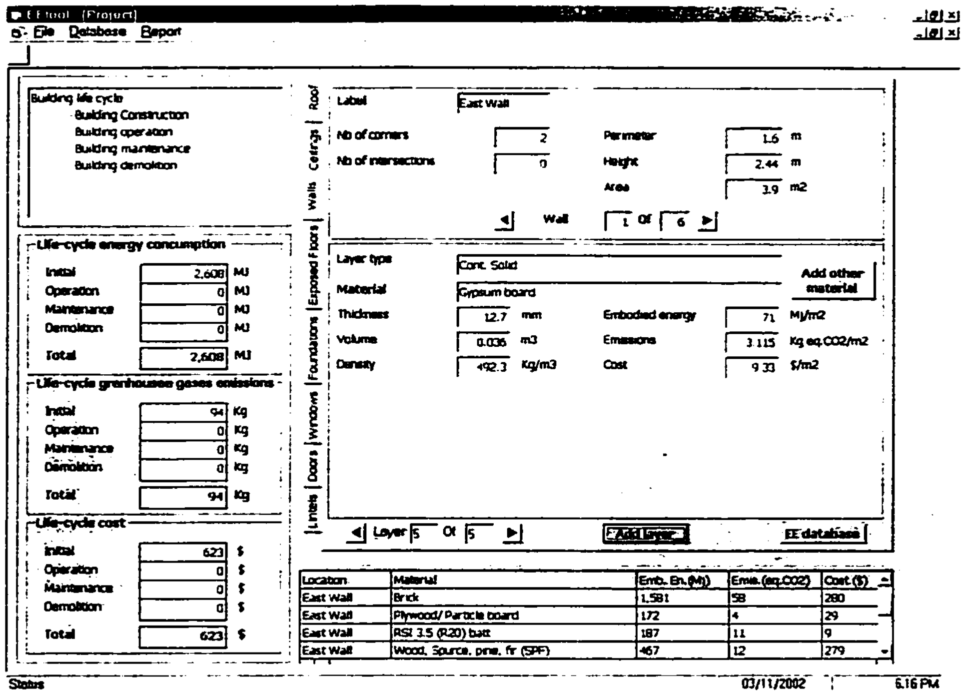


Figure 3.3. Screen: construction stage

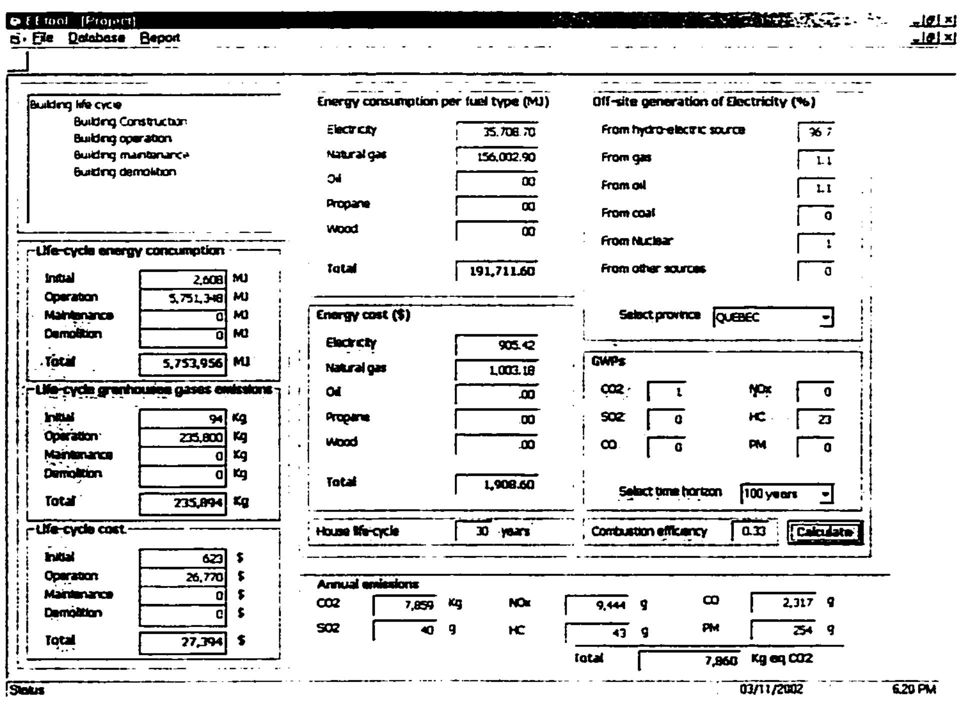
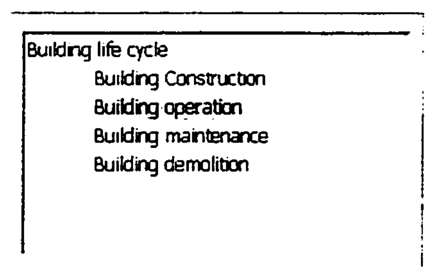


Figure 3.4. Screen: operation stage

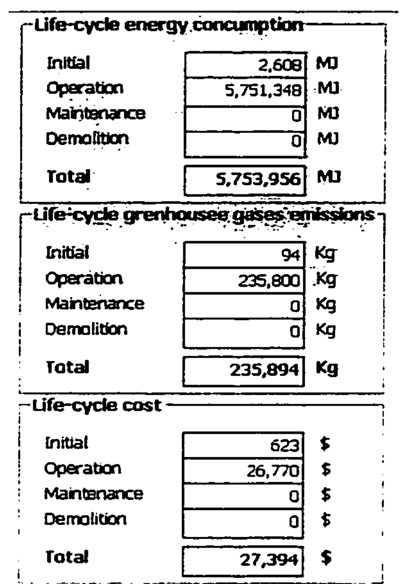
The two screens are composed of five main sections, three of which are commonly shared. These three sections consist of:

- A menu bar that enables the user to import files, browse databases and generate results files.

- A tree view that will enable the user to go from one life-cycle stage to the other, and



- A group of text boxes showing intermediate results of the calculations.



The two remaining sections enable the user visualize inputs and outputs to the EEE tool. Inputs include imported data, selected data form the database, and eventually user-defined data; and the outputs consist in the intermediate results generated by the tool at different stages of the use.

Screen associated with the construction stage

This screen is decomposed into four sections (Figure 3.5.). Section 1 is located on the left side of the "input" form and includes a number of tab strips that allow the user to switch from one building component to another. Section 2 includes the main information of the active building component and also enables the user to navigate between components of the same kind such as walls. Section 3 provides information about each layer of the active building component and allows the user to visualize precedent and sub-sequent layers of materials. Finally, Section 4 includes two buttons: one gives access to the database for data selection, and the second executes the calculations of embodied energy, embodied emissions and initial cost for the active layer of building component as presented in Figure 3.6.

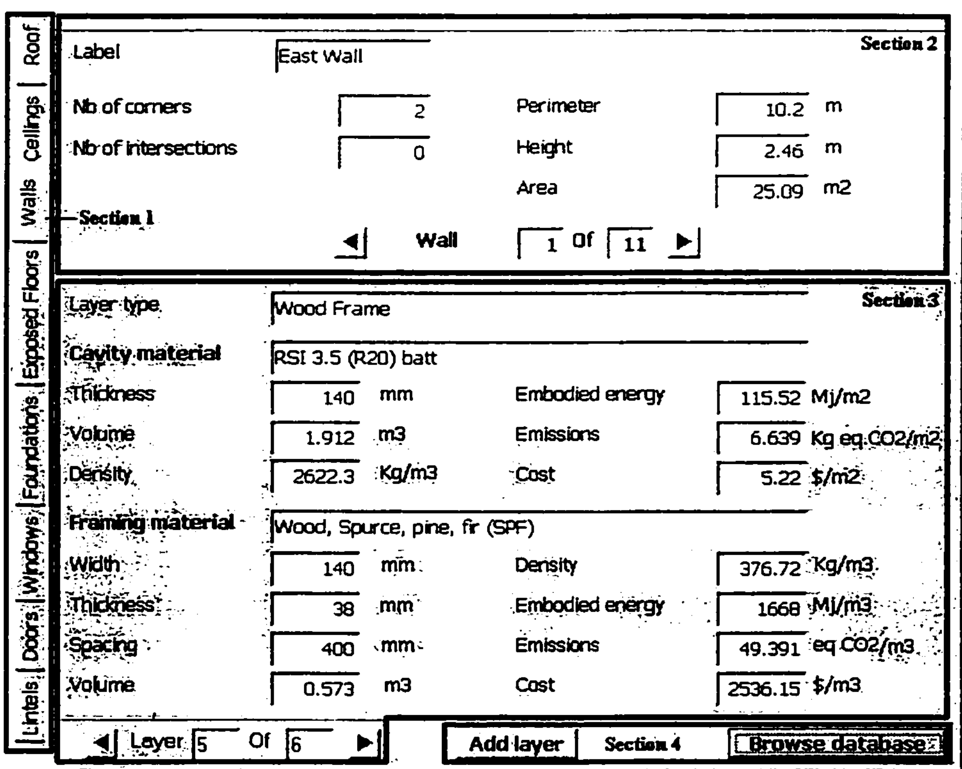


Figure 3.5. Screen showing inputs associated with the construction stage

The screen associated with the construction stage includes an "intermediate results" form as well. This form is shown in Figure 3.6. and provides the list of materials accounted for in the calculations and their respective location, embodied energy, embodied emissions and cost.

Location	Material	Emb. En.(MJ)	Emis.(eq.CO2)	Cost ($)
East Wall	Brick	1,581	58	280
East Wall	Plywood/ Particle board	172	4	29
East Wall	RSI 3.5 (R20) batt	187	11	9
East Wall	Wood, Spurce, pine, fir (SPF)	467	12	279

Figure 3.6. Screen showing intermediate results associated with the construction stage

Screen associated with the operation stage

This screen contains an "input" screen and an "intermediate results" screen. The "input" screen is shown in Figure 3.7. and contains seven sections. Sections 1 and 2 show respectively the imported annual energy consumption and cost from the HOT2000 program. Section 3 displays the province where the house under study is located, in order to obtain the percentile distribution of off-site generation of electricity per type of energy source. Section 4 enables the user to select the time horizon that should be considered in the calculations, and the corresponding Global Warming Potentials. Sections 5 and 6 contain cells where the user can input respectively the life expectancy of the house and the combined efficiency of combustion process and transmission losses in the generation of electricity off-site. Finally, section 7 includes a button that will initiate the calculations.

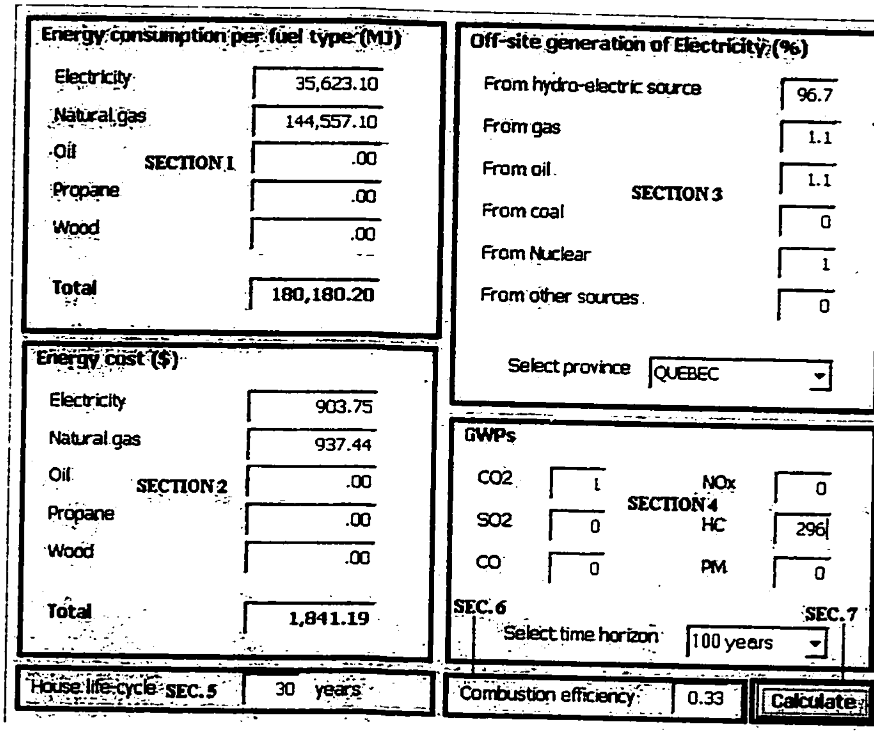


Figure 3.7. Screen showing inputs associated with the operation stage

The screen associated with the operation stage also includes a form that displays intermediate results. This form is illustrated in Figure 3.8. and shows a breakdown of the annual emissions of pollutants due to the energy use of fossil fuels for the house operation. It shows as well the combined emission expressed in kg of equivalent CO_2.

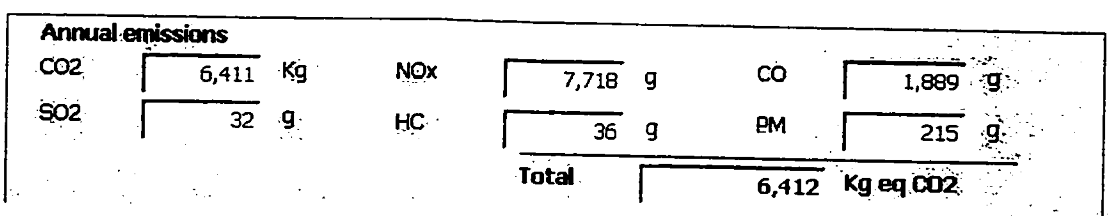


Figure 3.8. Screen showing intermediate results associated with the operation stage

3.3.2.2. Screens for database browsing and data selection

The user interacts with two secondary screens in order to select data from the database. One shown in Figure 3.9., is used to select values of embodied energy, embodied emissions based on the values collected from Athena and the second shown in Figure 3.10., is used to browse the complete database of embodied energy values.

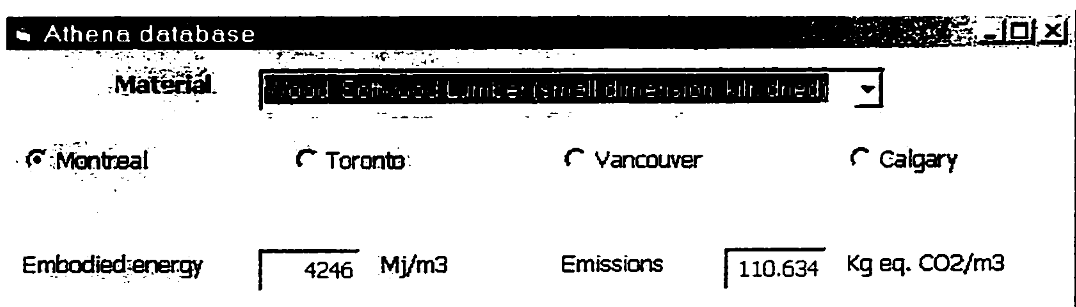


Figure 3.9. Database browser for Athena's values

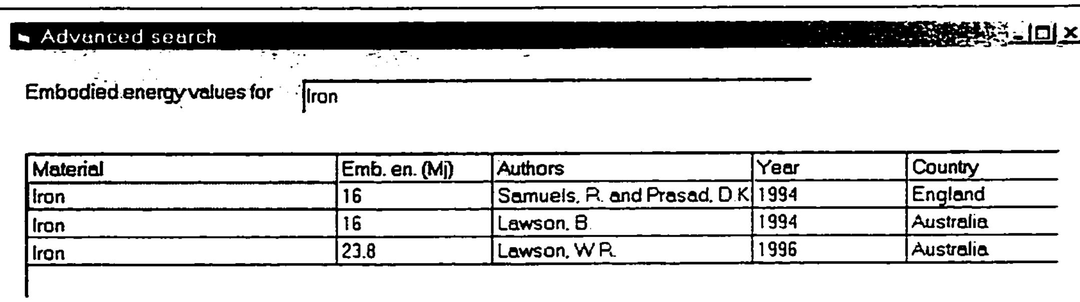


Figure 3.10. Examples of results obtained from an advanced search

3.3.2.3. Screens for results

An Excel file is generated by the EEE tool in order to summarize calculation results in an Excel workbook. An example of results file is given in Appendix I. The file includes two sheets. One sheet summarizes the calculations associated with the construction stage and the second with the calculations associated with the operation stage.

3.4. METHODS OF CALCULATION

Figure 3.11. summarizes the calculations performed by EEE. In this section, each method of calculation is presented in details.

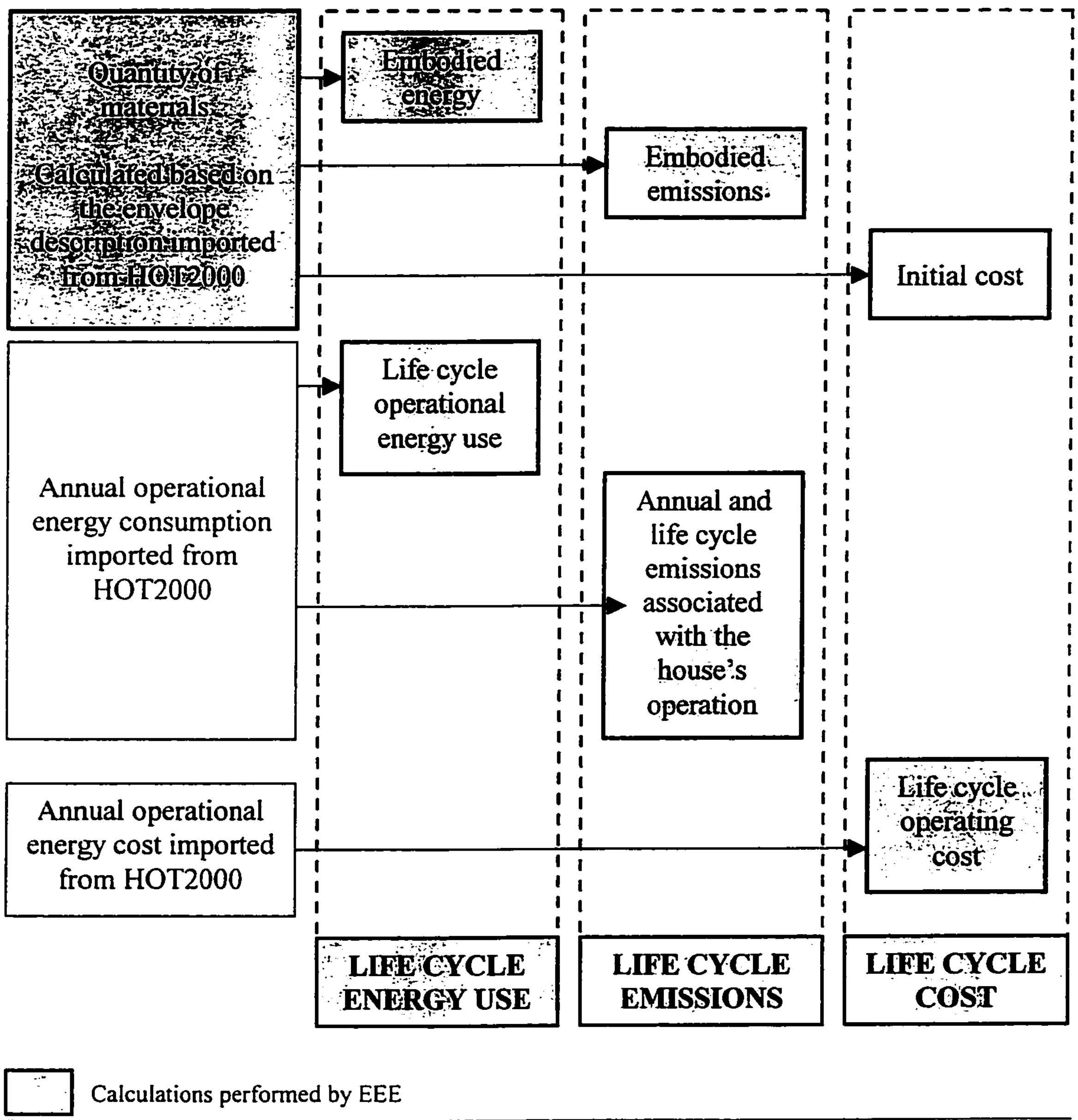


Figure 3.11. Summary of calculations performed by EEE

3.4.1. Energy use, emissions and cost of the construction stage

3.4.1.1. Quantity of materials

The quantity of each material used for the construction of the envelope is required in order to calculate its embodied energy, embodied emissions and initial cost. This amount is either expressed as volume, area or mass.

The area of material used in the envelope is directly imported from the HOT2000 program, and the volume (m^3) and mass (Kg) of each material is then calculated considering material thickness and construction practices. The formulas used for the volume calculation are described in Appendix J for materials used in roof, ceiling, above and below-grade walls, exposed floors, and foundation floors. The calculation of mass consists in a simple multiplication of volume by values of density.

In the present version of the EEE prototype tool, the calculation of framing material quantities are limited to wood-stud structures only. Other available structures in HOT2000 can be imported to the EEE tool, however the user has to input the associated quantity of materials.

3.4.1.2. Embodied energy in the exterior envelope

Embodied energy in building components and sub-systems is accounted for in the "construction" stage and is summed in order to obtain the total energy embodied in the house envelope. For each layer of each building component, the embodied energy is calculated by multiplying the respective embodied energy value for the given material by its volume, weight or area depending on the unit of the embodied energy value selected from the database.

It is worth mentioning that most values of embodied energy available in the database account only for the two first stages of the life cycle, i.e. the raw material extraction, material manufacturing, and transport. Hence, the energy used to build the envelope is neglected. In other cases such as when the user opts for an advanced search in the database, the selected values may also take into consideration the maintenance and end of life of the material, and therefore account for more energy than what is associated with the construction stage.

3.4.1.3. "Embodied" emissions in the house's envelope

Similarly to the calculations of embodied energy, "embodied emissions" in each layer of material are obtained as the product of "embodied" emission coefficients available in the database by the quantity of material used. The total "embodied emission" in the exterior envelope is obtained as the sum of each individual "embodied emission".

3.4.1.4. Initial cost

The initial cost of the house envelope is calculated using unit price of materials provided by the Means catalogue. The cost of a material and its associated labor is calculated as the product of the volume, area, or mass of the material by the corresponding unit price.

3.4.2. ENERGY USE, EMISSIONS AND COST OF THE OPERATION STAGE

3.4.2.1. Life cycle operating energy consumption

The annual operating energy consumption is directly imported from the HOT2000 program. The life-cycle operating energy consumption is obtained by multiplying the annual consumption by the house life expectancy entered by the user. The default house physical life is set to 30 years.

3.4.2.2. Annual and life cycle emissions due to the house operation

Emission of pollutants is associated with the combustion of fossil fuels used directly for the operation of the house and indirectly for the off-site generation of electricity. The EEE tool calculates the amount of emitted pollutants primarily associated with fuel combustion. These are: carbon dioxide (CO_2), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). The parameters used for the calculations are the following:

- Distribution of the annual energy consumption per fuel type,
- Emission coefficients available in the database, expressing the amount of pollutants that are generated when one unit of fossil fuel energy is used respectively for on-site use and off-site generation of electricity,
- Percentile distribution of electricity production per energy source for a given Canadian province, and

- Combined efficiency accounting for the efficiency of combustion process when producing electricity and the transmissions losses; the default value of combined efficiency is set to 0.33 [52, 53] but can be modified by the user.

The annual consumption of each type of fuel is calculated as the sum of its annual consumptions on-site and off-site. The off-site annual energy consumption for generating electricity is calculated by dividing the annual on-site electricity consumption by the combined efficiency.

For each type of fuel, the annual emissions of different pollutants are calculated by multiplying the corresponding emission coefficient for each gas (in kg/MJ) by the annual energy consumption of the fuel. This calculation is made for on-site and off-site use of the fuel.

The emission of each pollutant due to the combustion of each fuel type are then summed in order to get the total annual emissions per emitted pollutant. This result is displayed on the user interface along with the annual emission expressed in equivalent CO_2 –obtained using the Global Warming Potential coefficients for a selected time horizon. The final result shows the life cycle emissions of greenhouse gases as the product of the annual combined emission given in equivalent CO_2, by the house life expectancy.

3.4.2.3. Operating energy cost

Annual cost of energy used for the house operation is directly imported from HOT2000. In order to calculate the life cycle operating energy cost, the Present Worth Value method is used in order to express the life-cycle cost in "today's money".

The formula used for the calculations is recommended by the Model National Energy Code of Canada for Buildings and takes into account the escalation rate of energy, i.e. "the rate ate which energy costs are expected to increase (including inflation)" and the "discount rate or cost of money (including inflation)" [51]:

$$PW = C \times \frac{1-(1+a)^{-n}}{a}$$

Where,

PW is the present worth of energy costs

C is the annual energy cost in the first year

a is the effective interest rate and is equal to $\frac{i-e}{1+e}$

e is the rate at which energy costs are expected to increase

i is the discount rate of the cost of money (including inflation), and

n is the life-cycle duration

3.4.3. LIFE CYCLE ENERGY USE, EMISSIONS, AND COST

The life cycle energy use is given in MJ and is obtained as the sum of the embodied energy in the house envelope and the life cycle operating energy use. The life cycle emissions are given in tons of equivalent CO_2 and are calculated as the sum of the embodied emissions in the envelope and the emissions generated from the operation of the house. The life cycle cost, given in Canadian dollars, is the sum of the initial cost of the envelope and the life cycle cost of the energy used for the house operation.

3.5. RESULTS

The EEE provides as results the life cycle estimations and breakdowns per life cycle stage of the energy used in the house and its associated emissions and cost. The results are displayed in two different forms: (1) on the user interface, and (2) in an Excel file.

The results shown on the user interface are displayed and updated along with the advancement of the data entry and selection process. It enables the user to visualize intermediate results of the calculations and appreciate the contribution of different materials or life cycle stages to the final results.

The results exported to Excel are intended to provide the user with detailed results of the calculations. This practical format is particularly useful for the generation of graphical representations of the results. Appendix I shows an example of an Excel results file.

3.6. VERIFICATION OF EEE'S CALCULATIONS

A base case was used for the verification of the results of volume calculation generated by the EEE tool. The results of volume calculations provided by Timberline's Precision Estimating [54] and hand calculations were used for comparison. Comparison of volumes calculated by the EEE program to those obtained from the Environmental Impact Estimator program was not possible due to the discovery of a conversion bug in Athena's program. The developer of Environmental Impact Estimator was contacted, and the work is in progress to eliminate the error.

3.6.1. Verification of quantity of materials using Precision Estimating

The Precision Estimating software is a construction cost estimating tool that uses an RS Means database and formulas for the calculations of material quantities or "take-offs" in order to enable cost estimators evaluate the cost of different building assemblies and items.

A comparison between the take-off results of a wall wood frame given by Precision Estimating and the corresponding volume calculations performed by the EEE tool showed some differences. A comparison of the methods used respectively by EEE and Precision Estimating showed similarities. This can be illustrated through an example of calculation of a wood-stud wall.

The wall has the following characteristics:

- Height = 2.4384 m = 8 ft
- Perimeter = 10.516 m = 34.5 ft
- Number of corners = 2
- Number of intersections with an interior wall = 0
- Number of studs at corners = 3
- Number of studs at intersections = 3
- Number of top and bottom plates = 3

Table 3.8. summarizes the quantities that were calculated using EEE and Precision Estimating.

Table 3.8. Comparison of the estimation of quantities of materials in EEE and Precision Estimating

Quantity	EEE	Precision Estimating
Number of vertical studs	33 including 6 studs used in both corners	32 studs including 3 studs at each corner (used as default by the cost estimating program)
Volume of vertical studs	0.43 m^3	0.6 m^3
Length of top and bottom plates	31.55 m	33.125 m

The differences observed are mainly due to the assumptions used by the EEE tool and the Precision Estimating software respectively. In fact. EEE tool evaluates the exact volume of materials as built in the house, whereas Precision Estimating considers the volume of material purchased and takes into account of wastes. For instance, if a given wood-stud wall measures more than 9 feet high, take-off calculations in Precision Estimating assume that 12-foot-long boards are purchased in order to obtain 9-foot-long boards; also, bottom and top plates calculations include 5% of waste in the calculated volume. Another reason is the difference in defining the size of dimension lumber in both tools. For example, in Precision Estimating, a 2" by 4" (50.8mm by 101.6mm) size is used in calculations instead of 38mm by 89 mm. Finally, due to the use of metric units in EEE and imperial units in Precision Estimating, some differences may arise due to units conversion such as in the counting of vertical wood studs in the last example (Round (10.5156 mm/ 0.4 mm) + 1 = 27 whereas Round (34.5' / 16") + 1 = 26) .

This comparison shows that the formulas and algorithms used for volume calculations in EEE are correct and give results that are comparable with those given by Precision Estimating.

3.6.2. VERIFICATION OF QUANTITY OF MATERIALS USING HAND CALCULATIONS

All the volume calculations performed by the EEE tool for different layers of each house component i.e. roof, ceilings, walls, and floors were compared to similar results given by hand calculations. The formulas described in Appendix J were used for hand calculations. The results proved that the implementation of code algorithms was correct and the numerical values calculated by the EEE program and hand calculations are equal.

Chapter 4

APPLICATION

Energy & Emission Estimator was used in order to evaluate the life cycle energy use and emissions of an existing house and its associated life-cycle cost. In addition, a study was carried out in order to evaluate the impact of different design parameters such as material use, fuel type use, and location on the house environmental and economical profiles. This chapter provides a presentation and an analysis of the results obtained.

4.1. CASE STUDY

4.1.1. DESCRIPTION

The case study used for the present study is based on information collected during an energy audit of an existing house located in Dollard-des-Ormeaux, near Montreal [55]. The house was built in 1967 and is a one-story single-detached house with 258 m^2 of heated floor area. The house has a pseudo-rectangular shape and encompasses 14 rooms distributed on two floors including a heated basement floor.

4.1.2. EXTERIOR ENVELOPE OF THE HOUSE

The house has a wood-frame envelope. The characteristics of each part of the envelope are presented below.

4.1.2.1. Roof and ceiling

The house has a gable roof with a 1/3 slope. It is supported by a 47.3 meters long ceiling that has an area of 128.6 m^2. The area of the sloped part of the roof is equal to 200.21 m^2 and the area of the gable ends is 14.27 m^2. 38 mm x 89 mm (2"x4") joists and rafters make the frame of both the ceiling and roof and are spaced by 600 mm (24"). Additional building materials are also used:

- In the sloped parts of the roof a 12.7 mm thick plywood layer is used for sheathing, and the exterior layer is covered with asphalt shingles.
- Gable ends include a 12.7 mm thick plywood layer used for sheathing and a layer of brick used for exterior cladding.
- The ceiling includes two layers of fiberglass insulation -one is placed in the cavity between the studs and the second is continuous-. and a 12.7 mm thick gypsum board as an interior finish.

The overall thermal resistance of the ceiling is equal to 5.42 RSI.

4.1.2.2. Above ground walls

The above-ground perimeter of the house can be decomposed into six above-ground walls. The dimensions of each wall are presented in Table 4.1.

Table 4.1. Walls dimensions

Wall	Height (m)	Width (m)	Wall net area (m^2)	Thermal resistance (RSI)
East wall 1	2.44	1.6	2.86	2.1
East wall 2	2.44	8.68	21.18	2.28
North wall	2.44	6.24	7.96	2.19
North wall 2	2.44	6.72	16.4	2.23
South wall	2.44	13.11	24.27	2.24
West wall	2.44	10.52	24.59	2.22

A cross section of above-ground walls shows the following sequence of layers of materials:

- layer of brick,
- 12 mm of air space,
- 12.7 mm thick layer of plywood sheathing,
- 38 mm x 89 mm (2" x 4") wood studs frame spaced at 400 mm (16") with a RSI 3.4 batt cavity insulation, and
- 6 mil thick polyethylene sheet
- 12.7 mm thick layer of gypsum board.

At each corner or intersection with an interior wall, three studs are used for the wood frame.

Windows and doors contained in each wall and their respective characteristics are presented in Table 4.2.

Table 4.2. Window characteristics in above-grade exterior walls

Window/Door	Location	Width (m)	Height (m)
Small bedroom window	East wall	1.08	0.97
Front door	North wall 1	0.91	2.13
Door window	North wall 1	0.38	0.76
Living room bay	North wall 1	3	1.68
Patio door	South wall	1.74	1.93
Dinning room window	South wall	1.41	0.97
Kitchen window	South wall	1.06	0.97
Main bathroom window	South wall	0.56	0.51
Master bedroom window	South wall	1.74	0.97
Large bedroom window	West wall	1.11	0.97

All the windows have an aluminium frame and a double-glazing. The front door is wooden with a hallow core.

4.1.2.3. Basement walls

Basement walls are 2.28 m high with a 1.52 m depth below grade and a total length of 46.94 m.

Below grade walls are composed of the following layers of materials:

- 15 cm thick concrete layer,
- 38 mm x 89 mm (2" x 4") wood studs frame spaced by 400mm (16") with a RSI 4.9 batt cavity insulation, and
- 6 mil thick polyethylene sheet,
- 12.7 mm thick layer of gypsum board.

In every corner and intersection with an interior wal!, two studs are used in basement walls.

Basement walls also encompass windows. Each has an aluminum frame and double-glazing. Other characteristics of basement windows are presented in Table 4.3.

Table 4.3. Characteristics of windows in basement

Window	Orientation	Width (m)	Height (m)
Basement window	South	0.79	0.3
Bathroom window	South	0.79	0.3
Bedroom window	East	0.79	0.3
Bedroom window	East	0.79	0.3
Basement window	West	0.79	0.3
Basement window	West	0.79	0.3

The thermal resistance of basement walls is equal to 2.08 RSI.

4.1.2.4. Basement floor

The basement floor has an area of 128.6 m^2 and a perimeter of 46.9 m. The composition of the floor is as follows:

- 15 cm thick concrete layer,
- 38 mm x 140 mm wood studs frame spaced by 305 mm with a no cavity insulation,
- wood flooring layer, and
- 6 mil thick polyethylene sheet,
- 12.7 mm thick layer of plywood.

The thermal resistance of the basement floor is equal to 1 RSI

4.1.3. MECHANICAL SYSTEMS AND OPERATION PARAMETERS

The house is occupied by four adults 50 % of the time and is heated only. A temperature of 19 degrees Celsius is maintained in the house's first floor whereas the temperature in the basement is set to 18 degrees Celsius.

An infiltrometry test (also known as blower-door test) was performed by Abraham [55]. It evaluated the air change rate (ACH) in the house to 7.76 at 50 Pa and the equivalent leakage area was estimated to 1641.29 cm^2 at 10 Pa.

A forced-air natural gas furnace heating system is used in the house except in one of the rooms located in the basement where an independent baseboard heater is used. The furnace used is a Lincoln NTC6-75 and has a capacity of 75000 Btu/hr. A total volumetric flow rate was estimated to 210 liters per second.

Domestic hot water is heated at 51 degrees Celsius using natural gas. A conventional tank of 151.4 liters (40 US gallons) is used and is located in basement.

4.2. ANNUAL OPERATING ENERGY CONSUMPTION

The characteristics of the house's envelope and mechanical systems as well as its operation parameters were entered in the HOT2000 program in order to evaluate its annual operating consumption. The operating energy consumption includes all the energy used in the house for space heating, domestic hot water supply, lighting, and use of electric appliances. The output file presented in Appendix I summarizes the data input to the HOT2000 program and the results obtained.

A summary of the results generated by the HOT2000 tool in terms of annual energy consumption and cost are presented in Table 4.4. Natural gas is used for space heating and domestic hot water supply whereas electricity is utilized for lighting and electric appliances use.

Table 4.4. Summary of annual operating energy use of the house

Electricity	9,725 kWh (20.9 %)	718.97 $ (40.8 %)
Natural gas	3,561.3 m^3 (79.1 %)	1,045 $ (59.2 %)
Annual energy consumption	**167,701.4 MJ** (100 %)	**1,764.11 $** (100 %)

The results of annual operating energy consumption obtained from the HOT2000 program were compared to the normalized annual energy consumption derived from the house utility bills of electricity and natural gas. The weather normalization is used in order to correct the annual energy consumption of a given building for weather effects that differ from one year to the other. The PRInceton Scorekeeping Method (PRISM) [56] tool was used for this purpose and generated the results provided in Table 4.5.

Table 4.5. Comparison of the annual operating energy consumption calculated respectively by the HOT2000 and PRISM programs.

Fuel	Annual energy cons. from HOT2000	Normalized annual energy cons. using PRISM	Difference / PRISM results
Electricity	9,725 kWh	10,612.68 kWh	**- 8.4 %**
Natural gas	3,561.3 m^3	3,105 m^3	**+ 14.7 %**

It can be noticed that the results obtained from the HOT2000 simulation are close to those obtained after weather normalization.

The normalized annual energy consumption of the studied house can be expressed as 180.5 kWh/m^2 of heated floor area and be compared to those of similar houses based on the results of a study carried out by Zmeureanu et al. [57]. In this last study, the normalized annual energy consumption of 12 houses located in Montreal and built between 1961 and 1970 was estimated. The average heated floor area of these houses is equal to 212 ± 8 m^2. The results obtained showed that the average normalized annual energy consumption of the houses is equal to 167.6 kWh/m2 with a standard deviation of 41.5 kWh/m2. This comparison shows that the studied house has a higher annual energy consumption than an average house in Montreal.

4.3. LIFE CYCLE ENERGY USE, EMISSION AND COST

The Energy & Emissions Estimator tool was used to evaluate the embodied energy of the exterior envelope as well as the house's life cycle energy use, emissions and life cycle cost. The results found are provided in Appendix I and are summarized in this section.

4.3.1. EMBODIED ENERGY

4.3.1.1. Embodied energy of the house's exterior envelope

The embodied energy of the house exterior envelope calculated by the EEE tool is equal to 330,136 MJ. The breakdown of the calculation for each layer of material used in the envelope is shown in Table M.1 of Appendix I. The total embodied energy can be reported as 1279.6 MJ/m^2 of heated floor area, and is equivalent to two years of operating energy consumption.

It is important to notice that: (1) the calculated embodied energy is not the total embodied energy of the house but the embodied energy of the exterior envelope and (2) it does not account for the energy used for maintenance and end of life.

The distributions of the embodied energy of the exterior envelope per material type and component are respectively shown in Figures 4.1. and 4.2.

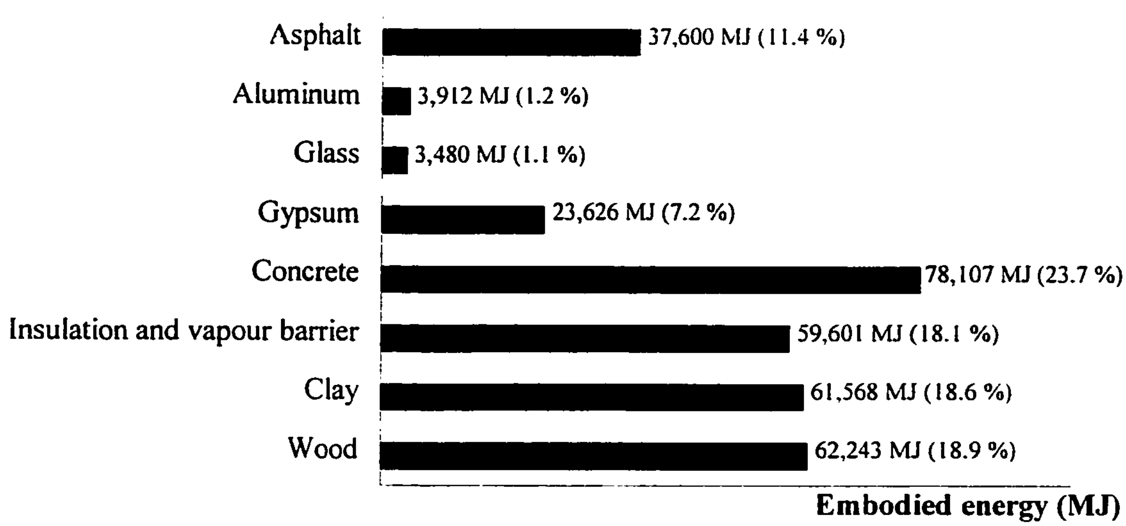
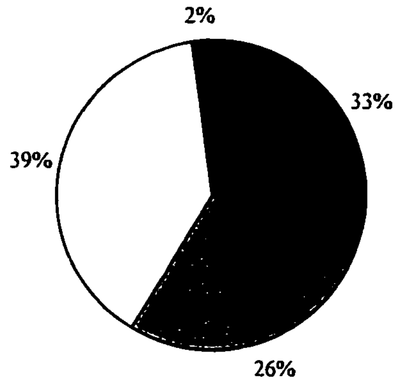


Figure 4.1. Distribution of embodied energy of the exterior envelope per material type



Building component	Embodied energy MJ	MJ/m² of component area
Roof & ceilings	107,958	315
Above-ground walls	85,726	881
Foundations	128,667	549
Doors & windows	7,785	420
Total	**330,136**	**476**

Figure 4.2. Distribution of the embodied energy of the exterior envelope per envelope component

It can be noticed that the foundations contributes the most to the embodied energy of the exterior envelope (39%), followed by the roof and ceiling (33%), and the exterior walls (26%). The contribution of windows and doors to the embodied energy of the envelope is insignificant compared to the other envelope components.

The contribution to the embodied energy of the envelope of these same elements can also be compared per unit area of components, e.g. per m^2 of roof area, m^2 of wall area. On this basis, the walls show the highest embodied energy (881 MJ/m^2), followed by the foundations –including walls and floors- (549 MJ/m^2), the windows and doors (420 MJ/m^2), and finally the roof and ceiling (315 MJ/m^2). The average embodied energy of the envelope is estimated to be 476 MJ/m^2.

The high embodied energy of exterior walls per unit of area is mainly explained by the use of bricks that have a relatively high embodied energy (552 MJ/m^2). Other building components do not include a layer of brick. The foundations also have a relatively high embodied energy due to the use of 15 cm of concrete for both the walls and slab. The embodied energy of 15 cm thick concrete layer is 334 MJ/m^2. Figure 4.1. shows that the use of concrete contributes the most to the embodied energy of the envelope (23.7 %).

4.3.1.2. Embodied energy of exterior walls

Based on the breakdown calculation provided as part of the EEE results, the average embodied energy of exterior walls of the studied house –not including windows and doors- is estimated to be 881 MJ/m^2 of wall area. This result can be compared to those of two studies done by Baird and Chan in 1983 [31] and Pierquet in 1998 [58], respectively (see Table 4.6.).

Table 4.6. Comparison of the embodied energy of exterior walls to previous studies

Wall	Embodied energy (MJ/m^2 of wall area)	Source
Timber frame wall with veneer cladding	1284	[31]
Timber frame wall with vinyl siding	470	[58]
Wood frame wall with brick siding	860	Present case study

Differences observed are mainly due to the values of embodied energy utilized by each authors. For instance, the embodied energy value of "kiln dried framing lumber used by Pierquet [58] is equal to 1554 MJ/m^3 and by Baird and Chan [31] is equal to 1200 MJ/m^3, whereas in the present study the respective value is equal to 4246 MJ/m^3 [46].

4.3.1.3. Total embodied energy of the house

The total embodied energy of the house can be estimated by extrapolation of the embodied energy of the envelope using the results of a study done by Samuels and Prasad in 1995. In this study, the authors provide the following distribution of the total embodied energy in a house per component type:

Table 4.7. Distribution of the embodied energy of a house per house component [29]

House component	Contribution to the total embodied energy
Floors	17.4 %
Walls	14 %
Roof	18.5 %
Joinery	17.4 %
Plumbing	7.8 %
Electrical	1.4 %
Finishes	16 %
Insulation	4.5 %
Preliminaries	3 %
Total	**100%**

Knowing that the embodied energy of the exterior envelope calculated by Samuels and Prasad (1995) –not including plumbing and electrical installation- represents 53% of the total house embodied energy, the total embodied energy of the house under study is by extrapolation, about 623 GJ. This represents 3.7 years of operating energy of the house.

This result can be compared to those obtained in other studies of houses located in Canada, New Zealand, and Sweden (See Table 4.8.).

Table 4.8.Comparison of the embodied energy of the case study to results from other studies

House	Total embodied energy (GJ)	Embodied energy per floor area (GJ/m^2)	Source
Conventional house, Vancouver	948	2.72	[34]
Conventional house, Toronto	948	2.72	[34]
Energy-efficient house, Vancouver	1019	2.92	[34]
Energy-efficient house, Toronto	1019	2.92	[34]
Standard house with 40-year life in Toronto	2352	-	[34]
Houses in New Zealand with different construction types	215-520	-	[35]
Energy-efficient apartments in Sweden with 50-year life	-	7.03	[36]
Case study, Montreal	*600*	*2.41*	

The comparison is not easy to do since the houses have different dimensions, constructions and locations. The embodied energy of the houses per unit of floor area can be used for comparison in order to get round the differences in dimensions. Also, comparison should be made for houses that are close in terms of geographic location and thus, having similar weathers. Hence, the most appropriate comparison is with houses located in Toronto studied by Cole [34]. The result obtained for the "conventional house, located in Toronto" is close to the upper limit of embodied energy calculated for the case study house (6.25 % higher), whereas the "energy-efficient house located in Toronto" presents an embodied energy 14.1 % higher.

4.3.2. LIFE-CYCLE ENERGY CONSUMPTION

The total life cycle energy consumption of the studied house is calculated as the sum of its embodied energy and the operating energy consumption over 30 years. It is equal to 5361 GJ and can be broken down as shown in Figure 4.3.

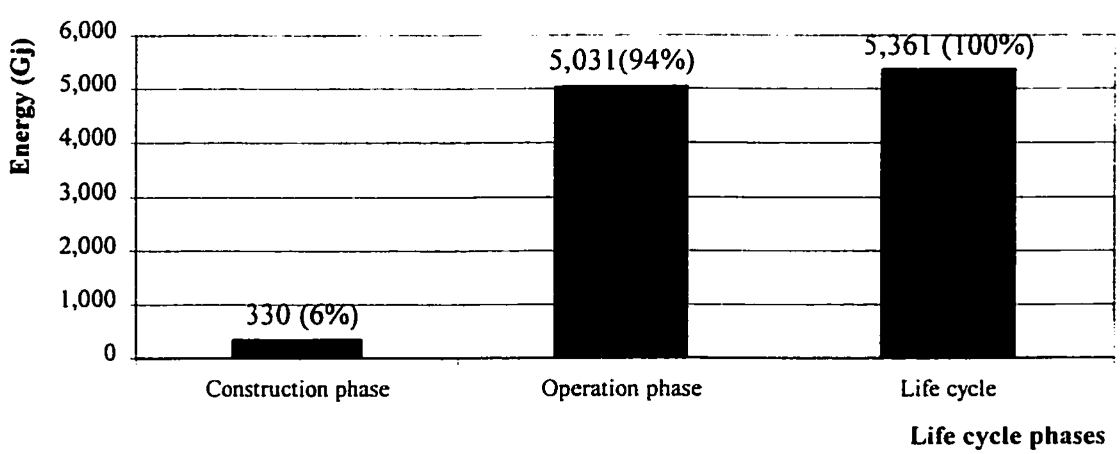


Figure 4.3. Life cycle energy consumption of the case study

4.3.3. EMISSIONS FROM OPERATION AND EMBODIED

The emissions of greenhouse gases associated with the embodied energy of the house's exterior envelope and its operation during 30 years was also estimated. The embodied emissions were evaluated to be 20,752 kg of equivalent CO_2. The emissions due to the annual operation were calculated taking into account the generation of electricity in Quebec and a combined efficiency of production and transmission of 0.33. It is equal to 6704 kg of equivalent CO_2 and may be broken down as shown in Table 4.9. per pollutant type.

Table 4.9. Distribution of annual operating emissions per pollutant type

Emission of gas (kg)					
CO2	SO2	NOx	HC	CO	PM
6,703	34	8.066	37	1,976	223

The life cycle emissions of greenhouse gas emissions is illustrated in Figure 4.4 per life cycle stage.

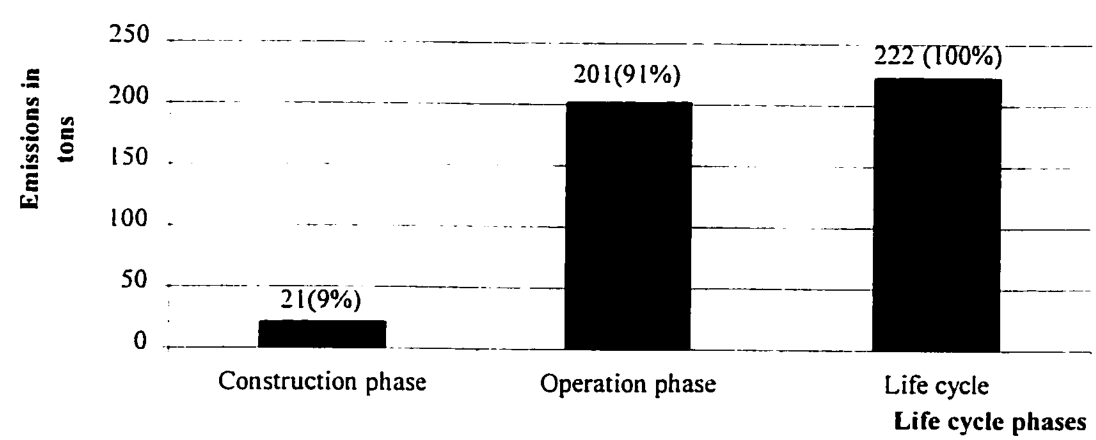


Figure 4.4. Distribution of life cycle emissions per life cycle stage

In spite of the fact that the embodied energy of the envelope represents only 6 % of the total life cycle energy use, the embodied emissions represents 9 % of the life cycle emissions. This means that overall, the energy used to manufacture materials and transport them is associated with more emissions per unit of energy than the energy used for the house operation.

4.3.4. LIFE CYCLE COST

The life cycle cost calculated by the EEE program includes the initial cost of the exterior envelope, i.e. construction and material costs, and the operating cost of the house over 30 years. It is equal to CAN $ 85,827 and can be broken down as shown in Table 4.10.

Table 4.10. Life cycle cost distribution per life cycle stage

Life cycle stage	Life cycle cost ($CAN)	Percentage compared to the life cycle cost
Construction stage	61,083	71 %
Operation stage	24,744	29 %
Life cycle	**85,827**	100%

The results obtained show a major contribution of the initial cost of the envelope (71 % of the life cycle cost). It can be also observed that the cost associated with the house operation has a low impact on the life cycle cost (29 %) compared with the significant impact on the life cycle energy use (94 %) and greenhouse gas emissions (91 %).

4.3.5. SUMMARY OF THE RESULTS

The results obtained are summarized in Table 4.11.

Table 4.11. summary of the life cycle profile of the case study house

		Construction stage	Operation stage	Life cycle
Life cycle energy use	(MJ)	330,136	5,031,042	**5,361,178**
	%	6	94	**100**
	Years of operation	2	30	**32**
Life cycle emissions	(kg of eq. CO_2)	20,752	201,120	**221,872**
	%	9	91	**100**
	Years of operation	3	30	**33**
Life cycle cost	(Canadian $)	61,083	24,744	**85,827**
	%	71	29	**100**
	Years of operation	35	14	**49**

4.4. OTHER DESIGN PARAMETERS

The original design of the case study house was modified in order to evaluate the effect of different insulation levels of the exterior envelope, house locations, and heating systems on the life cycle energy use, equivalent CO_2 emissions and cost.

4.4.1. IMPROVEMENT OF THE THERMAL PERFORMANCE OF THE EXTERIOR ENVELOPE

The thermal resistance of the exterior envelope of the case study house was upgraded to four different levels of insulation in order to study the associated impacts on the life cycle energy use, emissions and cost. The design alternatives include three upgrades to the minimum prescriptions according to the Quebec Energy Code [59], the Model National Energy Code of Canada for Houses (MNECCH) [60], and Novoclimat [61], a Quebec labelling system promoted by Hydro-Quebec. The fourth alternative, called "maximum insulation", is obtained by choosing the maximum insulation level allowed to be input by the HOT2000 program for each component of the exterior envelope. Table 4.12. summarizes the overall thermal resistance of each component of the envelope for all the studied design alternatives. The overall thermal resistance of the whole envelope was also calculated for the base case and the four proposed design alternatives.

Table 4.12. Summary of the overall thermal resistance of the exterior envelope for each design alternative [m^2 °C/W]

		Design alternatives			
House component	**Base case**	**Quebec energy code**	**MNECCH**	**Novoclimat**	**Maximum insulation**
Ceiling/roof	5.42	5.42	7.42	7.42	7.42
Above grade walls	2.23	3.54	4.34	4.44	4.86
Foundation walls	2.08	2.23	3.15	3.15	4.33
Foundation floors	1	2.33	2.33	1	6.53
Overall thermal resistance	**2.72**	**3.43**	**4.36**	**4.03**	**5.88**

The thermal resistance of each component of the envelope was obtained using different insulation materials. Table 4.13. summarizes the material and associated thickness used for each component and design alternative. Proposed design alternatives were established in such a way to respect the minimum resistance required by the code. Other design alternatives can also be selected.

Table 4.13. Insulation material used in each envelope component and design alternative

	Ceiling/roof	Exterior wall	Basement wall	Basement floor
Base case	RSI 3.5 fiberglass batt 152 mm	RSI 4.9 fiberglass batt 89 mm	RSI 4.9 fiberglass batt 89 mm	No insulation
	RSI 3.5 fiberglass batt 152 mm			
Quebec code	RSI 3.5 fiberglass batt 152 mm	RSI 3.5 fiberglass batt 89 mm	EPS II 89 mm	RSI 1.4 fiberglass batt 65 mm
	RSI 3.5 fiberglass batt 152 mm	EPS I 50.8 mm		
MNECCH	23.7 RSI/m blown cellulose 380 mm	RSI 3.5 fiberglass batt 89 mm	RSI 1.4 fiberglass batt 65 mm	RSI 1.4 fiberglass batt 65 mm
	23.7 RSI/m blown cellulose 380 mm	EPS II 76.2 mm	RSI 1.4 fiberglass batt 65 mm	
Novoclimat	23.7 RSI/m blown cellulose 380 mm	RSI 3.5 fiberglass batt 89 mm	RSI 1.4 fiberglass batt 65 mm	No insulation
	23.7 RSI/m blown cellulose 380 mm	XTPS IV 63.5 mm	RSI 1.4 fiberglass batt 65 mm	
Max. insulation	23.7 RSI/m blown cellulose 380 mm	XTPS IV 63.5 mm	XTPS IV 63.5 mm	XTPS IV 150 mm
	23.7 RSI/m blown cellulose 380 mm	XTPS IV 89 mm	RSI 7.0 fiberglass batt 89mm	XTPS IV 140 mm

Using the HOT2000 program and the EEE tool, the life cycle energy use, emissions and cost were evaluated for each design alternative (Table 4.14).

Table 4.14. Reduction [%] of life cycle profiles due to the improvement of the thermal performance of the exterior envelope of the base case house

		Annual operation			Construction stage			Life cycle		
		Energy	Emissions	Cost	Embodied energy	Embodied emissions	Initial Cost	Energy	Emissions	Cost
Base case		167,701 MJ	6,704 kg	1,764 $	330,136 MJ	20,752 kg	61,083 $	5,361,178 MJ	221,872 kg	85,827 $
Design alternatives	Quebec code	6.7 %	8.2 %	4.3 %	- 4.1 %	- 2.8 %	- 3.2 %	6.1 %	7.2 %	- 1.1 %
	MNECCH	11.9 %	14.5 %	7.5 %	- 2.0 %	2.3 %	- 13.3 %	11.1 %	13.4 %	- 7.3 %
	Novoclimat	11.1 %	13.6 %	7.0 %	- 0.7 %	3.5 %	- 11.7 %	10.4 %	12.6 %	- 6.3 %
	Max insulation	14.9 %	18.2 %	9.4 %	- 51.3 %	- 34.8 %	- 33.6 %	10.8 %	13.2 %	- 21.2 %

N.B. Negative percentages indicate the increase compared with the base case house

All design alternatives gave savings in terms of energy consumption and cost and reduction of greenhouse gas emissions associated with the annual operation of the house (See Figure 4.5.).

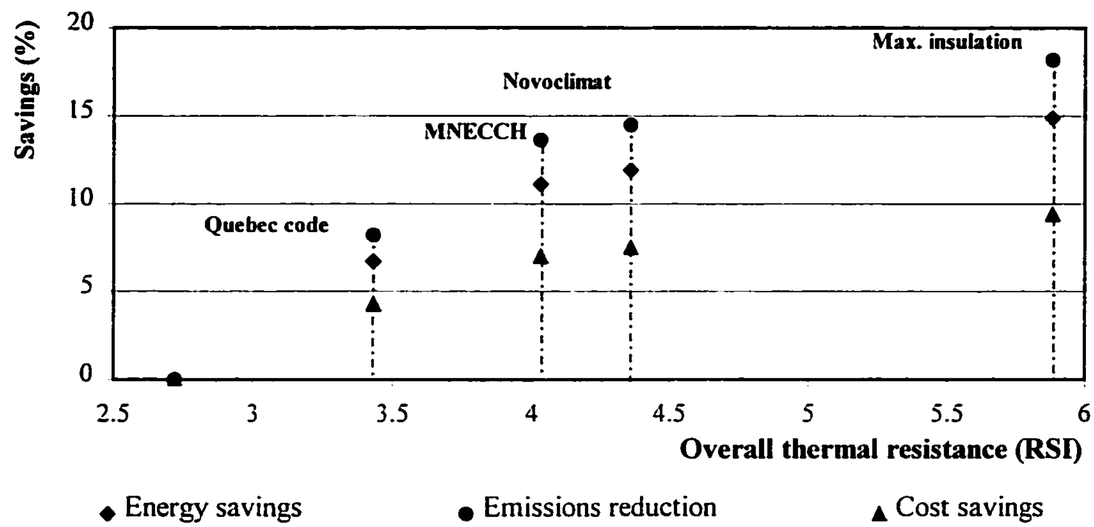


Figure 4.5. Reduction of annual operating energy, emissions and cost compared with the base case

The efficiency of adding insulation diminishes with the thermal resistance of the exterior envelope. The most significant reductions are those for greenhouse gas emissions whereas cost savings are the least important. Table 4.15. shows the differences between each design alternative with respect to the original design in terms of embodied energy, embodied emissions, and initial cost.

Table 4.15. Reduction of embodied energy, embodied emissions, and initial cost compared with the base case

Design alternative	Thermal resistance (RSI)	Embodied energy increase (%)	Embodied emissions increase/decrease (%)	Initial cost increase (%)
Quebec code	3.43	- 4.1	- 2.8	- 3.2
Novoclimat	4.03	- 0.7	3.5	- 11.7
MNECCH	4.36	- 2	2.3	- 13.3
Max. insulation	5.88	- 51.3	- 34.8	- 33.6

The variations of embodied energy, emissions and initial cost is not dependent –or, not strictly dependent– on the increase/decrease of the overall thermal resistance of the house. The type of material used to insulate each envelope component for each design alternative has a major impact on the variation observed. Indeed, different materials that provide the same level of insulation may have different costs, embodied energy, and embodied emissions. Table 4.16. shows an example comparing three alternative insulation materials that can provide the same resistance of 3.25 RSI [60].

Table 4.16. Comparison of different insulation materials with respect to embodied energy, embodied emissions, and cost

Insulation material	Fiberglass batt (140 mm)	EPS I (125 mm)	Sprayed cellulose (135 mm)
Embodied energy (MJ/m^2)	106.4	210	10
Embodied emissions (Kg eq. CO_2/m^2)	6.64	10.23	0
Cost ($ CAN/m^2)	5.22	23.54	5.76

Based on this example, it can be understood that in the case of the design alternative with the "maximum insulation", the increase by 51.3 % of the embodied energy is mainly due to the use of polystyrene insulation in most of envelope components. Also, in the case of the design alternatives where the insulation of the envelope was upgraded to the level required by the MNECCH and Novoclimat, the decrease in the embodied emissions can be explained by the use of cellulose insulation in the ceiling, which does not have any associated emissions. The examples presented underline the importance of material selection, which should be optimized given various material characteristics such as thermal resistance, embodied energy, embodied emissions, cost, and durability (number of replacement of the material during the house life time). Reduction of the life cycle energy, emissions and cost associated with each upgrade of the base case study house is presented in Figure 4.6.

		Life cycle energy use	Life cycle emissions	Life cycle cost
Base case		*5,361,178 MJ*	*221,872 kg*	*85,827 $*
Altenatives	**Quebec code**	6.1 %	7.2 %	- 1.1 %
	Novoclimat	10.4 %	12.6 %	- 6.3 %
	MNECCH	11.1 %	13.4 %	- 7.3 %
	Max insulation	10.8 %	13.2 %	- 21.2 %

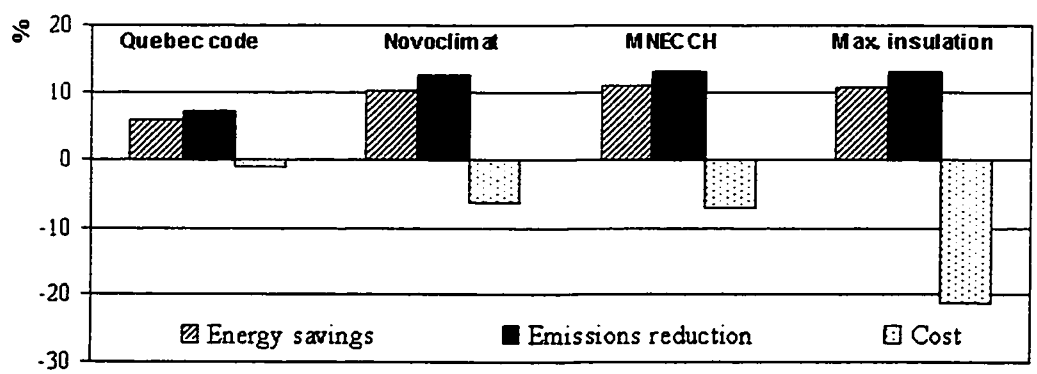


Figure 4.6. Reduction of life cycle energy use, emissions, and cost for the different design alternatives

It can be noticed that for the design alternatives where the thermal resistance level of the envelope was upgraded to the level of the MNECCH and Novoclimat and where the insulation is "maximum", approximately the same energy savings and emissions reduction were obtained but variable cost investments were necessary. This is mainly due to the significant contribution of the initial cost to the life cycle cost and the little contribution of the embodied energy and emissions to the life cycle energy use and emissions.

4.4.2. DIFFERENT LOCATIONS ACROSS CANADA

An evaluation of the life cycle energy use, emissions, and cost of the base case study house was performed assuming that the house is located in four Canadian cities: Montreal (Quebec), Toronto (Ontario), Vancouver (British Columbia), and Calgary (Alberta). Table 4.17. summarizes the results obtained.

Table 4.17. Comparison of life cycle energy use, emissions, and cost of the case study house for different geographic locations

		Annual operation				Construction stage				Life cycle			
		Montreal	Toronto	Vancouver	Calgary	Montreal	Toronto	Vancouver	Calgary	Montreal	Toronto	Vancouver	Calgary
Energy use	MJ	167,701	147,859	113,532	178,282	330,136	416,553	540,019	502,869	5,361,178	4,852,320	3,945,988	5,851,341
	%*	**0**	**- 11.8**	**- 32.3**	**+ 6.3**	**0**	**+ 26.2**	**+ 50.4**	**+ 32.0**	**0**	**- 9.5**	**- 26.4**	**+ 9.1**
Emissions	kg	6,704	6,531	4,331	15,519	20,752	23,875	30,894	30,516	221,872	219,805	160,824	496,086
	%*	**0**	**- 2.6**	**- 35.4**	**+ 131.5**	**0**	**+ 15.0**	**+ 42.5**	**+ 31.6**	**0**	**- 0.9**	**- 27.5**	**+ 123.6**
Cost	$	1,764	1,458	1,446	1,903	61,083	65,293	59,863	55,784	85,827	86,209	82,370	92,971
	%*	**0**	**- 17.4**	**- 18.0**	**+ 7.9**	**0**	**+ 6.9**	**- 1.9**	**- 8.9**	**0**	**+ 0.4**	**- 4.0**	**+ 8.3**

(*) expresses the difference compared to the original case study located in Montreal in percentage

A comparison of the embodied energy associated with each house is illustrated in Figure 4.7.

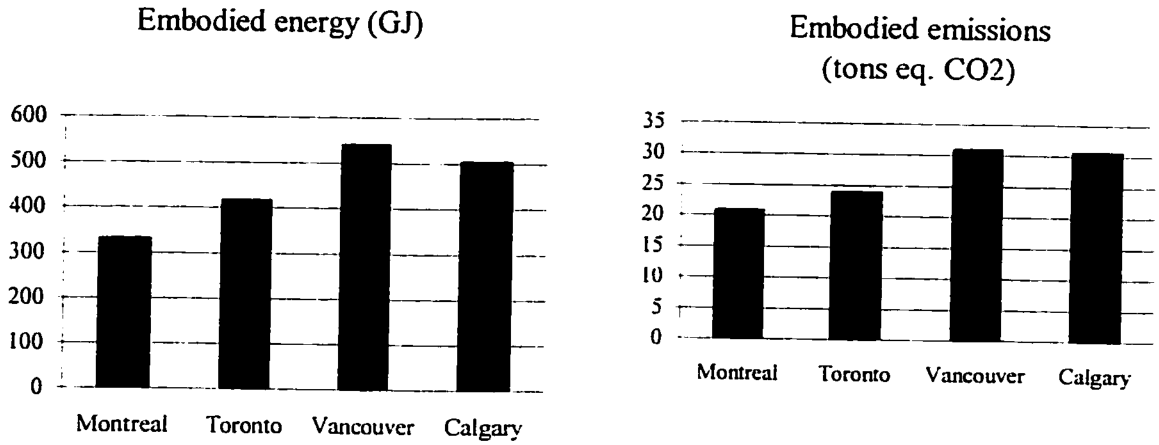


Figure 4.7. Comparison of embodied energy and emissions of the case study located in four different Canadian locations

It can be noticed that despite the fact that the construction of the exterior envelope is unchanged, the embodied energy and its associated greenhouse gas emissions vary depending on the house location. The variation observed is mainly due to differences in materials manufacturing processes, use of different energy sources for the generation of electricity, as well as differences in the distances and transportation means necessary to bring raw materials to the factory and final products to the construction site. For instance, Table 4.18. shows a comparison of the energy necessary for the manufacturing of "30 MPa, average flyash concrete" in Montreal, Toronto, Vancouver, and Calgary [62]. The breakdown of energy use associated with raw material transport and material production (including raw material extraction) illustrates the individual differences in the manufacturing processes and transportation effects depending on the geographic location.

The percentage presented between brackets expresses the difference with respect to the material when it is manufactured in Montreal.

Table 4.18. Differences in energy use for "30 MPa, average flyash concrete" manufacturing depending on the geographic location [62]

	Montreal	Toronto	Vancouver	Calgary
Raw material transport	127	107 (**-15.7 %**)	94 (**-26 %**)	215 (**+62.3 %**)
Raw material extraction & manufacturing processing	2031	2482 (**+22.2 %**)	2418 (**+19 %**)	3302 (**+62.5 %**)

The initial cost of the exterior envelope varies differently from what was observed for embodied energy and emissions (See Figure 4.8.). Its variation is dictated by the general local market. Indeed, according to RS MEANS [47], the location index for the cost of materials and their installation in buildings in Montreal, Toronto, Vancouver, and Calgary is on average 101.2, 110.9, 106.3, and 96.4 respectively, compared with the corresponding U.S. national average cost index of 100. This means that by comparison to Montreal, average material and installation costs in Toronto and Vancouver are respectively 9.6% and 5% higher whereas in Calgary they are 4.7% lower. The variation observed in the present cost study does not exactly follow RS MEANS tendency due to different individual cost variations of different types of materials. For instance, material and installation cost of masonry products in Toronto are 44.3% higher than U.S. national average whereas thermal protection products are only 6.5 % higher than U.S. average.

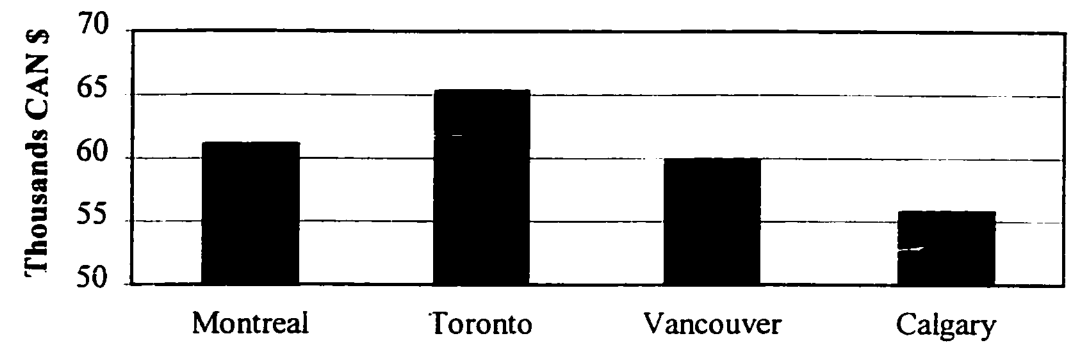


Figure 4.8. Comparison of the exterior envelope initial cost for different house locations

Different weather conditions influence the annual operation of the house and more importantly its space heating. Figure 4.9. shows the variation of the annual operating energy consumption of the case study house depending on its geographic location.

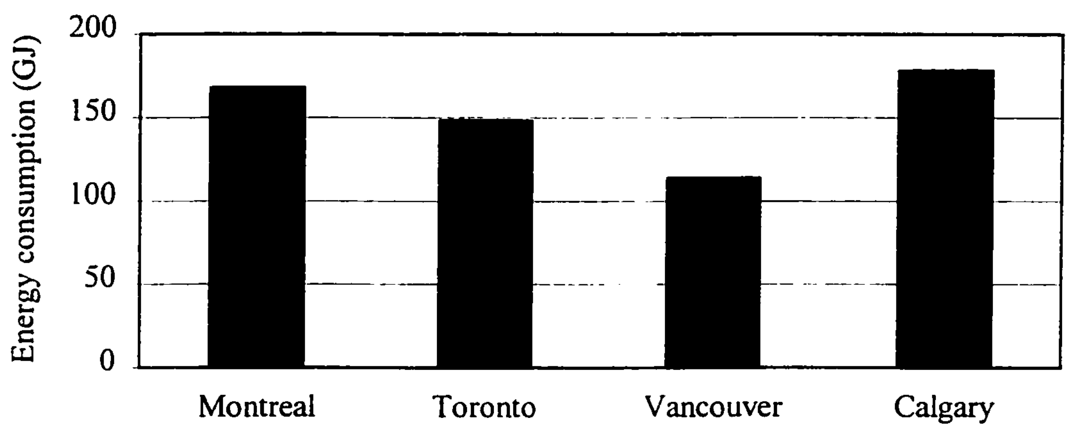


Figure 4.9. Annual operating energy consumption for different house locations

The variation observed was expected knowing the climate of the four Canadian locations (The number of heating degree days below 18°C is 4575, 3589.7, 2926.5, and 5108.4 for Montreal, Toronto, Vancouver, and Calgary respectively [63]). For instance, since Vancouver has a milder weather than the three other locations, the heating loads of a house located in Vancouver and its energy consumption are much lower than those of the other houses.

The greenhouse gas emissions associated with the annual operating energy use of the house (see Figure 4.10.) shows a similar variation to the one of the annual energy consumption, with a distinct peak for the house located in Calgary.

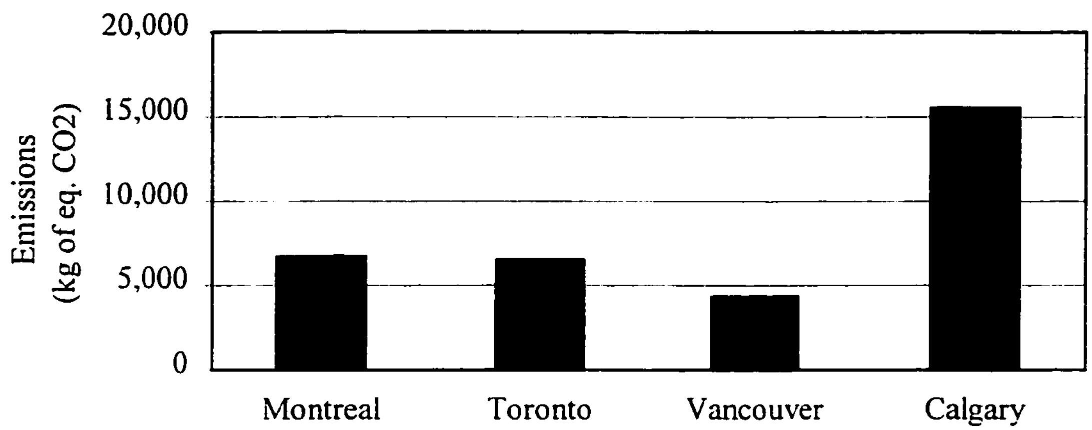


Figure 4.10. Comparison of annual greenhouse gas emissions from the house operation for different locations

The variation observed is mainly attributable to the way electricity is generated in different geographic locations. In fact, in Alberta, electricity is essentially produced from fossil fuels (84% from coal, 8 % from oil, and 8% from nuclear sources) which by combustion, generates significant amounts of greenhouse gas emissions. However, in the three other provinces the electricity is largely produced from hydro-electric and/or nuclear sources with no associated greenhouse gas emissions. A comparison between the house operation in Toronto and Montreal illustrates as well the impact of electricity generation on the emissions associated with the house operation. The house located in Toronto consumes 11.8 % less energy than the house located in Montreal but emits only

2.6% less greenhouse gas. This is due to the fact that in Quebec 96.7 % of the electricity is generated from a hydro-electric source whereas in Toronto 20 % of the electricity is generated from combustion of fossil fuels.

The annual operating cost associated with the four geographic locations is associated with the amount of energy consumed as well as the corresponding residential utility rating. The utility rating which are defined by utility firms in each city and for each type of energy source used (electricity and natural gas), were obtained from Hydro Quebec [64] and Gaz Metropolitain [65] for Montreal; Toronto Hydro Electric System Limited [66] and Embridge Gas Distribution [67] for Toronto; BC Hydro [68] and BC Gas [69] for Vancouver, and ATCO Electric [70] and ATCO Gas [71] for Calgary. The rating schemes were defined in HOT2000 for the needs of the calculations. Figure 4.11. shows a comparison of the annual operating cost for each location.

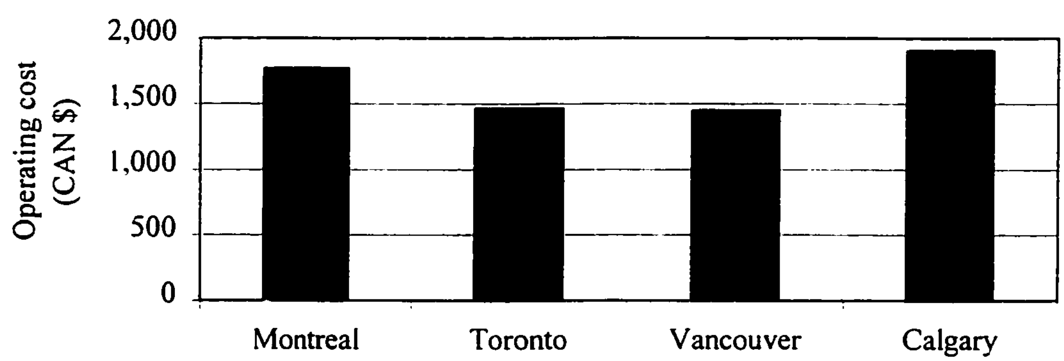


Figure 4.11. Comparison of annual operating cost for different house locations

An analysis of the results of life cycle energy use and its associated emissions for each house location points up the major influence of the operation stage of the life cycle. The embodied energy of the envelope only accounts for 6.2 to 13.7 % of the total life cycle energy use and the corresponding embodied emission represents only 9.3 to 19.2 % of the total life cycle emissions.

A comparison of the results associated with each location shows that the most energy-consuming and greenhouse gas-emitting house is the one located in Calgary (See Figure 4.12.). This is mainly due to the cold climate in this location which implies more energy for space heating in the house, and also to the major use of fossil fuel energy sources. For the three remaining locations the influence of the weather conditions are the most significant.

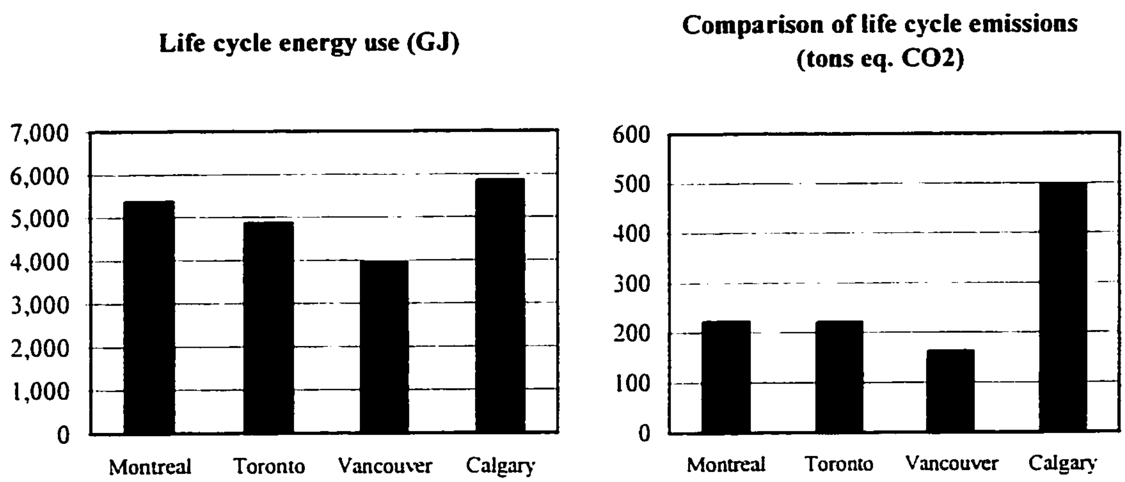


Figure 4.12. Life cycle energy use and emissions of the house depending on its location

For the life cycle cost of the house, the scenario differs. In fact, the construction cost or initial cost represents from 60 to 75.7 % of the life cycle cost. Figure 4.13 shows a comparison of the life cycle costs of the house in the different Canadian locations.

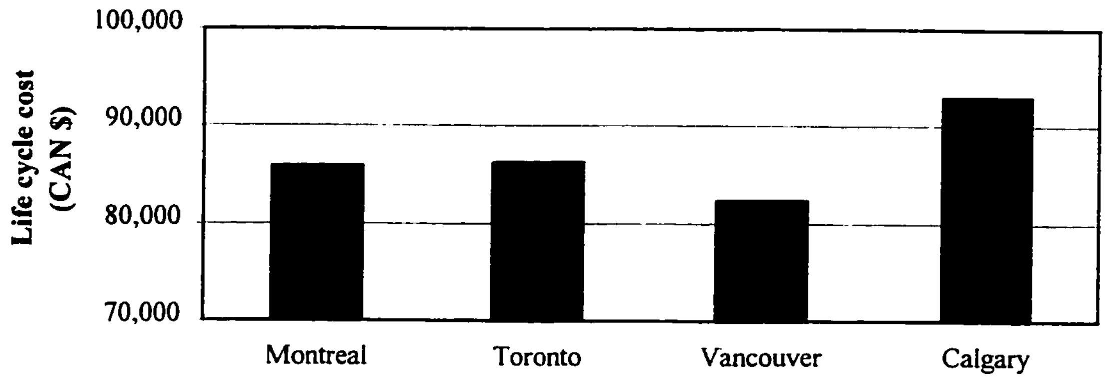


Figure 4.13. Comparison of life cycle cost for different house locations

4.4.3. DIFFERENT HEATING SYSTEMS

Based on the results discussed in the previous sections, it can be concluded that the operation of a given house contributes significantly to its life cycle energy use and emissions. Therefore, it is important to study the influence of the use of different heating systems and fuel types on the annual operation.

The present study compares the use of electricity, natural gas, or oil for space heating and domestic hot water supply in the case study house given four different geographic locations: Montreal, Toronto, Vancouver, and Calgary.

The annual energy consumption of the case study house covers all the energy used for space heating, domestic hot water supply, lighting, and use of appliances. Given that electricity is usually used for lighting and use of appliances, three alternatives were considered for each geographic location, where respectively electricity, natural gas, or oil are used for space heating and domestic hot water supply.

In this study, the steady-state efficiency of the furnace used as part of the heating system is assumed to be equal to 100%, 85%, and 80% when electricity, oil, and gas are used, respectively [43].

A comparison of the annual energy use for each alternative is illustrated in Figure 4.14.

	Electricity [MJ]	Natural gas [MJ]	Oil [MJ]
Montreal	119,592	167,701	146,575
Toronto	103,974	147,202	127,551
Vancouver	78,337	112,875	96,816
Calgary	125,193	177,625	154,312

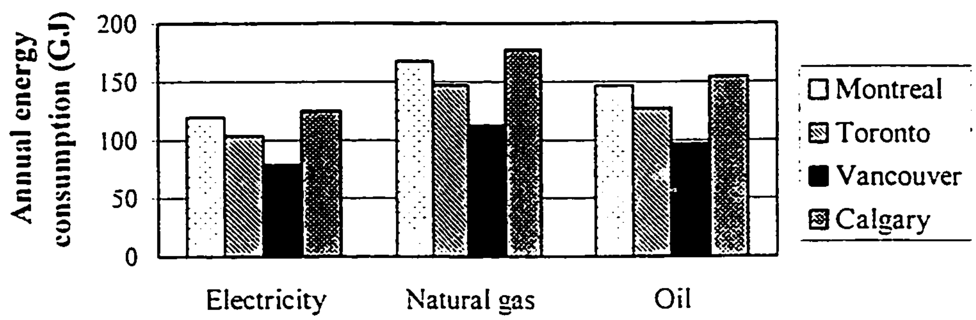


Figure 4.14. Comparison of the annual energy used for each location and fuel type use

Besides the effect of weather on the annual operating energy consumption, it can be noticed that the use of different types of fuel also plays a significant role. This is due to the efficiency associated with the heating system used. For instance, the efficiency of the furnace used in the case study house is equal to 100%, 85%, or 80% respectively, depending if the fuel used is electricity, natural gas or oil. Also, efficiencies of other equipments of the systems used for space heating and domestic hot water supply enter into account.

Assuming that space heating and domestic hot water systems using electricity have an efficiency of 100 %, it can be calculated that the combined efficiency of the systems using natural gas and oil are respectively less than 70% and 80 %.

Figures 4.15. and 4.16. illustrate the amounts of emissions and costs associated with the annual operation of the house depending on its location and the fuel type used for its space heating and domestic hot water supply.

	Electricity (kg)	Natural gas (kg)	Oil (kg)
Montreal	488	6,704	9,746
Toronto	2,849	6,513	8,939
Vancouver	991	4,323	5,821
Calgary	29,636	15,363	18,558

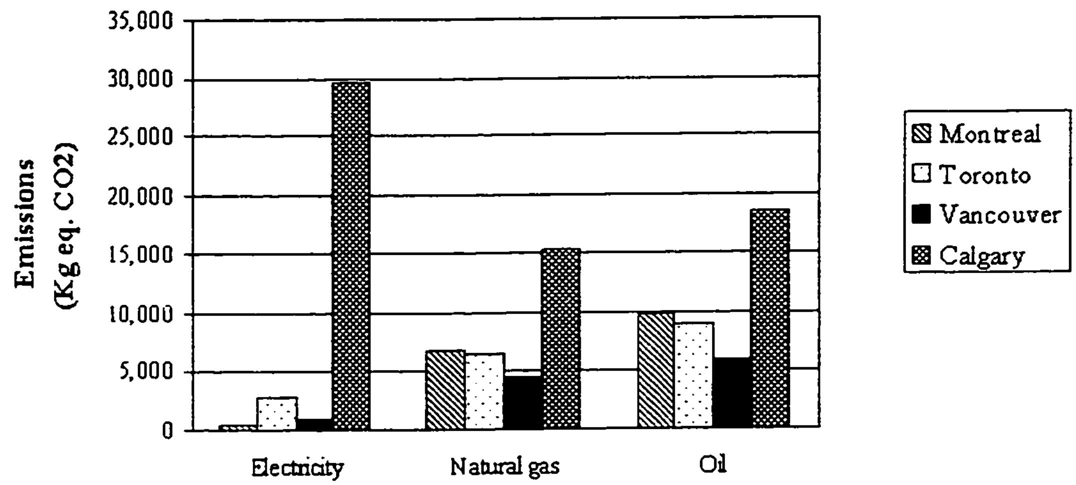


Figure 4.15. Annual greenhouse gas emissions for each location and fuel type used for space heating and domestic hot water supply

	Electricity ($ CAN)	Natural gas ($ CAN)	Oil ($ CAN)
Montreal	2,122	1,764	2,013
Toronto	2,482	1,443	2,040
Vancouver	1,297	1,435	1,369
Calgary	1,859	1,895	2,078

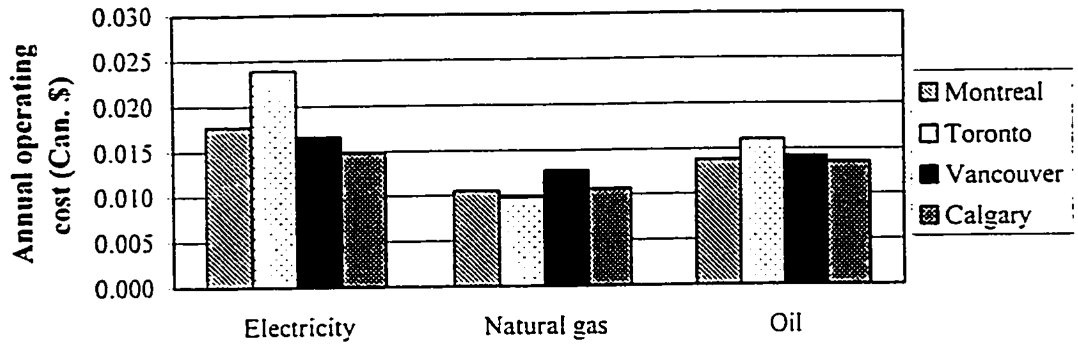


Figure 4.16. Annual operating costs for each location and fuel type used for space heating and domestic hot water supply

It can be noticed that in terms of emissions, electricity use in Montreal, Toronto, and Vancouver present the lowest amount of greenhouse gases whereas the highest is in Calgary for electricity use. This is mainly due to the major use of coal in Alberta for electricity generation. On the other hand, electricity appears as the most expensive alternative for all geographic location.

Figure 4.17. compares the emissions and cost per mega Joules used in each location and for each fuel type. This way of representation helps identifying the best alternatives where the emissions and costs can be minimized.

The alternatives presenting the best ratio emissions/cost can be identified for each location. For Montreal and Vancouver, use of electricity or natural gas can be considered as good alternatives where electricity is less-emitting whereas natural gas is less expensive. Depending on the importance given to economical and environmental aspects, the designer can decide which alternative is more appropriate. For Toronto and Calgary, natural gas presents the best alternative since electricity in Calgary is associated with significant emissions whereas in Toronto, electricity is expensive.

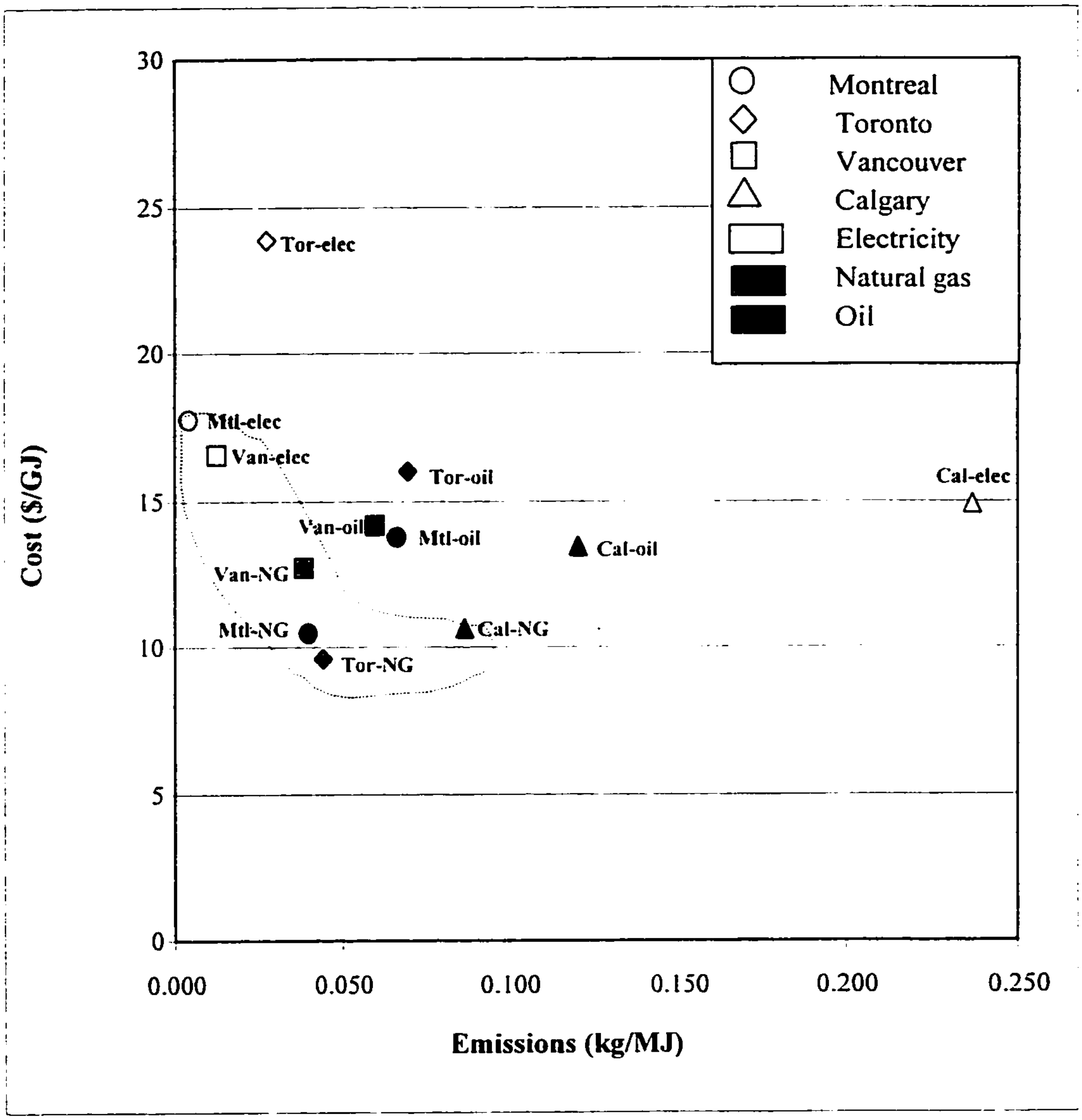


Figure 4.17. Comparison of different design alternatives in different locations and using various types of fuel with respect to emissions and cost

4.5. CONCLUSIONS

The EEE tool was applied to a one-storey single-detached house located in Montreal and built in 1967. The house presents a slightly higher operating energy consumption comparatively to those of other houses of the same type. The estimated embodied energy of its exterior envelope is 330,136 MJ and represents 2 years of operating energy consumption. The exterior walls have the highest embodied energy per floor area but the foundations have the major contribution to the total embodied energy due to the use of concrete. The emissions associated with the exterior envelope were also estimated as well as the emissions due to the house operation. The embodied emissions represent 9 % of the life cycle emissions. The initial cost of the envelope (61,083 CAN $) was also evaluated and represents 71 % of the total life cycle cost. This contribution varies from the one of life cycle energy use and emissions since the embodied energy and emissions represent respectively 6 % of the life cycle energy use and 9 % of the life cycle emissions.

Different design alternatives of the house were also studied for different insulation levels, locations, and heating systems. The results obtained show that the increase of the thermal resistance of the exterior envelope of the house is not automatically accompanied by an increase of the embodied energy or emissions. The choice of insulation materials is very important since different insulation systems may have the same thermal resistance but different embodied energy and emissions and different cost. The study of the house in different locations illustrated mainly the expected influence of the weather on the house operation and the influence of the way electricity is generated in different Canadian provinces on the emissions of the house. Calgary where most of the electricity is generated from coal, showed very high emissions. The choice of heating systems and the fuel type is therefore very important and should be balance between the cost and environmental impacts.

Chapter 5

CONCLUSION AND FUTURE WORKS

5.1. CONCLUSION

The present research project led to the development of a prototype tool that can be used by engineers and architects in order to design environmental friendly and cost effective houses in Canada. More precisely, the proposed tool enables the evaluation of the energy use, greenhouse gas emissions, and cost associated with the life cycle operation of a house and the construction of its exterior envelope.

The tool has a user-friendly interface. It is also time and effort effective since it is coupled with HOT2000, an existing energy analysis tool, and requires only few data input. The data used as default for the calculations are based on available databases and literature sources that best apply to the Canadian context. As for the methods of calculation, they are defined or selected in such way as to provide with accurate and comprehensive results. These results are generated along with their intermediate details in an Excel file format in order to allow flexibility of interpretation to the users.

The present study illustrates one way to answer the needs of engineers and architects for simplified and efficient life cycle analysis tools for building design. The example included in this thesis suggests some of the possible applications of the tool.

5.2. RESEARCH CONTRIBUTION

This research project brought the following contributions:

- Development of a database of values of embodied energy,
- Analysis of the existing embodied energy values and definition of the parameters that affect their quality,
- Development of a database describing existing LCA-based tools,
- Development of an LCA tool applicable to the Canadian context and that is coupled with the HOT2000 energy analysis software, and
- Implementation of methods to calculate emissions associated with buildings operation in a computer tool.

5.3. FUTURE WORK

Various research works are planned for the improvement of the EEE prototype. They include:

- Further development of calculation methods

Calculations will be extended to the evaluation of a whole house including its mechanical and electrical systems, rather than the exterior envelope only. Also, other environmental impacts will be calculated in addition to energy use and greenhouse gas emissions (acidification, ozone layer depletion…etc) and methods of aggregation will be defined in order to combine them along with economical parameters. Sustainability indicators will be developed as well in order to help designers interpret impact assessment results. The life expectancy of materials will be accounted for in the calculation.

- User-friendliness and coupling with CAD tools

The prototype tool will be coupled with a CAD software so that quantities of materials can be evaluated more precisely and automatically. In addition, the interface will be designed in such way to dynamically and simultaneously reflect changes on CAD drawings, HOT2000 models, and calculations performed by the developed tool. Graphical representations of the generated results will be included as well.

- Database improvement

Data concerning the energy use and emissions associated with the maintenance and end of life of common building materials as well as their life expectancies will be collected and included in the database. Also, materials' life cycle inventories will be completed by accounting for all relevant releases to air, water, and soil as well as water consumption.

The planned tool can be then, applied to assess the environmental and economical performance of a number of houses of different construction types, age, size in Canada and the United States.

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APPENDICES

Appendix A: List of LCA tools used in the building design field

Acronym	Country	Developer	Category of LCA tool
LICHEE	Australia	Commonwealth Scientific and Industrial Research Org.	
BEES	U.S.A.	National Institute of Standards and Technology	Detailed LCA modeling tools
BRI-LCA Japan	Japan		Detailed LCA modeling tools
Athena	Canada	The Athena Sustainable Materials Institute	Detailed LCA modeling tools
BEE	Finland	VTT Building Technology	Building assessment schemes
ECO Methods	France		Detailed LCA modeling tools
EcoQuantum	Netherlands	IVAM Environmental Research	Detailed LCA modeling tools
LISA	Australia		Detailed LCA modeling tools
Optimize	Canada	Canada Mortgage and Housing Corporation	Detailed LCA modeling tools
SIADO123	Switzerland		Detailed LCA modeling tools
Envest	U.K.	British Research Establishment	LCA design tools
BDA	U.S.A.	Lawrence Berkley National Laboratory	LCA CAD tools
Ecopro	Germany	Institut für Industrielle Bauproduktion (ifib), Univ Karlsruhe	LCA CAD tools
Ecotect	Australia		LCA CAD tools
Energy 10	U.S.A.	National Renewable Energy Laboratory	LCA CAD tools
ENER-RATE	Australia		LCA CAD tools
EPCMB	U.K.		LCA CAD tools

Acronym	Country	Developer	Category of LCA tool
EQUER	France	Ecole des Mines de Paris	Detailed LCA modeling tools
Green Building Advisor	U.S.A.	SHAI	Detailed LCA modeling tools
LCAid	Australia	Department of Public Works and Services	LCA CAD tools
Legoe	Germany	Institut für industrielle Bauproduktion (ifib) Univ Karlsruhe	LCA CAD tools
PAPOOSE		TRIBU	LCA CAD tools
SBI	Danemark	Danish Building Research Institute	Detailed LCA modeling tools
TEAM	France	Ecobalance, Inc.	Detailed LCA modeling tools
BEPAC	U.K.		Green product guides and checklists
EPM-Checklist	Netherlands		Green product guides and checklists
ECDG	Japan		Green product guides and checklists
Green housing A-Z	Japan	BIO City Co., Ltd.	Green product guides and checklists
EcoSpecifier	Australia		Green product guides and checklists
BUNYIP	Australia		Building assessment schemes
DOE 2.2	U.S.A.	Environmental Protection Agency	Building assessment schemes
Beaver/ESPII			Building assessment schemes
Okoprogfile	Norway	Norwegian Building Research Institute	Building assessment schemes
BREEAM	U.K.	British Research Establishment	Green product guides and checklists
GB tool	Canada	Natural Resources Canada	Building assessment schemes
NatHERS	Australia	Commonwealth Scientific and Industrial Research Org.	Building assessment schemes

Acronym	Country	Developer	Category of LCA tool
SEDA	Australia		Building assessment schemes
E2000	Switzerland	Basler & Hofmann	Building assessment schemes
LEED	U.S.A.	US Green Building Council	Building assessment schemes
Energy certification for buildings	Finland	VTT Building Technology	Building assessment schemes
Boustead	U.K.	Boustead	Detailed LCA modeling tools
Gabi	Germany	Institut für Kunststoffprüfung und Kunststoffkunde	Detailed LCA modeling tools
KCL-ECO	Finland		Detailed LCA modeling tools
LCAiT	Sweden	Chalmers Industriteknik	LCA design tools
PEMS	U.K.	Pira International	Detailed LCA modeling tools
SimaPro	Netherlands	PRé Consultants	Detailed LCA modeling tools
EcoScan	Netherlands	Philips	LCA design tools
ECOit	Netherlands	Pré Consultants	LCA design tools
Carnegie Melon I/O model	U.S.A.	Carnegie Melon	Embodied energy tools
NIRM	Japan		Embodied energy tools
OGIP	Switzerland	ETH Zürich, Laboratory for Technical Chemistry	LCA CAD tools

Appendix B: Embodied energy values (MJ/kg)

	Material	Value	Ref	original name	Group
Aggregate general	***Aggregate, general***	0.1	1	Aggregate, general	Group 1
		0.1	2	Aggregate, general	Group 1
		0.3	22	Aggregate	Group 1
		0.05	7	Sable et gravier	Group 1
		0.04	8a	Sand and gravel	Group 3
		<0.5	18	Sand, aggregate	Group 3
		0.07	8b	Sand and gravel	Group 4
		0.03-0.12	9	Natural aggregate	Group 5
	Crushed stone	0.05	26	Crushed stone	Group 1
		0.11	26	Crushed stone	Group 2
	virgin rock	0.04	1	Virgin rock	Group 1
	river aggregate	0.02	1	River	Group 1
	Sand	0.04	22	Sand	Group 1
		0.005	26	Sand	Group 1
		0.1	1	Sand	Group 1
		<0.5	18	Sand, aggregate	Group 3
		0.044	26	Sand	Group 2
Aluminum	***Aluminum, virgin***	54-130	3	Aluminum	Group 1
		65-211	3'	Aluminum	Group 1
		96	3"	Aluminum	Group 1
		129.5	22	Aluminum, general	Group 1
		145	14	Aluminum	Group 1
		191	1	Aluminum, virgin	Group 1
		241	6	Aluminum, virgin	Group 1
		170	4	Aluminum, virgin	Group 1
		198	20	Primary aluminum	Group 1
		150-240	13	Aluminum (primary)	Group 2
		200	23	Aluminum	Group 2
		97.18	8a	Aluminum and aluminum alloy fabricated materia	Group 3
		200-500	18	Aluminum	Group 3
		97	10	Aluminum	Group 3
		238	18	Aluminum	Group 3
		108.92	8b	Aluminum and aluminum alloy fabricated materia	Group 4
		180-240	12	Aluminum	Group 4
		207.70	16d	Aluminum	Group 5
	Extruded	201	1	Aluminum, virgin, extruded	Group 1
		166	2	Aluminum, virgin, extruded	Group 1
	Extruded, anodised	227	1	Aluminum, virgin, extruded, anodised	Group 1
	Extruded, factory painted	218	1	Aluminum, virgin, extruded, factory painted	Group 1
	Aluminum, virgin, products				
	foil	204	1	Aluminum virgin, foil	Group 1
		154	22	Aluminum foil	Group 1
	sheet	199	1	Aluminum virgin, sheet	Group 1
		145	22	Aluminum sheets	Group 1
	Aluminum, recycled	8.1	1	Aluminum, recycled	Group 1
		12.6	20	Secondry aluminum	Group 1
	Extruded	17.3	1	Aluminum, recycled, extruded	Group 1
		17.3	2	Aluminum, recycled, extruded	Group 1
	Extruded, anodised	42.9	1	Aluminum, recycled, extruded, anodised	Group 1
	Extruded, factory painted	34.3	1	Aluminum, recycled, extruded, factory painted	Group 1
		11-40	12	Aluminum (recycled)	Group 2

Al.	***Aluminum, recycled, products***				
	Foil	20.1	1	Aluminum, recycled, foil	Group 1
	sheet	14.8	1	Aluminum, recycled, sheet	Group 1
Asbestos	Asbestos cement	8.2	22	Asbestos cement	Group 1
	Asbestos: others	8.2	22	Asbestos: others	Group 1
Asphalt	Asphalt	3.4	1	Asphalt (paving)	Group 1
		3.26	8a	Asphalt building products	Group 3
		7.14	8b	Asphalt building products	Group 4
	Bitumen	44.1	1	Bitumen	Group 1
		44.1	2	Bitumen	Group 1
		38	22	Bitumen felt	Group 1
		31	22	Asphalt felt	Group 1
		2.45	7	Materiaux pour revetement d'asphalte, enduits d'asphalte et emulsion d'asphalte	Group 1
	Asphalt shingles	31.7	28	Asphalt shingles	Group 1
		33	24	Asphalt shingles	Group 1
Brass	Brass	62	1	Brass	Group 1
		62	2	Brass	Group 1
		49.3	22	Brass	Group 1
Carpet	Carpet	72.4	1	Carpet	Group 1
		10	24	Tufting carpet	Group 1
	felt underlay	18.6	1	Carpet, felt underlay	Group 1
		18.6	6	Carpet, felt underlay	Group 1
	Nylon	148	1	Carpet, nylon	Group 1
		148	6	Carpet, nylon	Group 1
		2.7	24	Nylon carpet	Group 1
	Polyester	53.7	1	Carpet, polyester	Group 1
		54	6	Carpet, polyester	Group 1
		2.7	24	Recycled polyester carpet	Group 1
	Polyethylterephthalate (PET)	107	1	Carpet, polyethylterephthalate	Group 1
		107	6	Carpet, polyethylterephthalate	Group 1
	Polypropylene	95.4	1	Carpet, polypropylene	Group 1
		95.4	6	Carpet, polypropylene	Group 1
	wool	106	1	Carpet, wool	Group 1
		106	2	Carpet, wool	Group 1
		4.86	24	Wool carpet	Group 1
Cement	***Cement***	7.8	1	Cement	Group 1
		9.4	6	Cement	Group 1
		7	4	Cement	Group 1
		0.08	7	Ciment	Group 1
		7.8	2	Cement	Group 1
		9	3	Cement	Group 1
		9.4	3'	Cement	Group 1
		5.9	3"	Cement	Group 1
		6.04	26	Cement	Group 1
		4.3-5.24	29b	Cement	Group 1
		5.75	24	Cement Portland	Group 1
		6.64	26	Cement	Group 2
		4.5-5.48	29b	Cement	Group 2
		7.18	8a	Cement	Group 3
		5-8	18	Cement	Group 3
		8	10	Cement	Group 3
		10.2	8b	Cement	Group 4
		4.3-7.8	9	Cement	Group 5

Cement	***Cement products***				
	cement mortar	2	1	Cement mortar	Group 1
		2	4	Cement mortar	Group 1
		22	33	Mortar	Group 1
		1.46-1.87	29b	Cement mortar	Group 1
		2.88	24	Brick and mortar	Group 1
		2	5	Cement mortar	Group 4
	cement render	2	5	Cement render	Group 4
	fibre cement	9.5	1	fibre cement board	Group 1
		13.1	2	fibre cement board	Group 1
		44	24	filber cement shingles	Group 1
	soil-cement	0.42	1	soil-cement	Group 1
		0.7	4	soil-cement	Group 1
		0.42	2	Soil-cement pressed brick	Group 1
	stucco	3.02	24	Stucco	Group 1
Clay	***Clay***	10.70	20	Clay	Group 1
		6.3	15	Vitrified clay	Group 1
	Clay products	200	22	Other clay products	Group 1
	brick	2.5	1	Ceramic brick	Group 1
		2.14	7	Brique d'argile	Group 1
		9.3	6	Ceramic brick	Group 1
		1.7	4	Ceramic brick	Group 1
		2.5	2	Ceramic brick	Group 1
		2.88	24	Brick and mortar	Group 1
		7.2	1	Ceramic brick, glazed	Group 1
		5.8	23	Common bricks	Group 2
		1.64	8a	Bricks and other clay building products	Group 3
		2-7	18	Clay bricks and tiles	Group 3
		2	11	Clay bricks and tiles	Group 3
		3	10	Clay bricks and tiles	Group 3
		2.8	18	Brick	Group 3
		2.37	8b	Bricks and other clay building products	Group 4
		2	5	Clay brick	Group 4
		3-4	12	Fired clay bricks	Group 4
		1-9.4	9	Bricks	Group 5
	pipe	6.3	1	Ceramic pipe	Group 1
		6.3	15	Ceramic pipe	Group 1
	tile	2.5	1	Ceramic tile	Group 1
		19.5	6	Ceramic tile	Group 1
		2.1	7	Ceramic tile	Group 1
		7.2	19	Tiles and clinkers	Group 1
		6.3	24	Clay tile	Group 1
		4.19	24	Ceramic tile	Group 1
		2-7	18	Clay bricks and tiles	Group 3
		2	11	Clay bricks and tiles	Group 3
		3	10	Clay bricks and tiles	Group 3
		2	5	Clay tile	Group 4
	shingles	10.23	29d	Glass shingles	Group 1
	structural clay	6.9	3	Structural clay	Group 1
		7.2	3'	Structural clay	Group 1
		2	3"	Structural clay	Group 1
		6.9	22	Structural clay	Group 1
Concrete	***Concrete***	24	6	Concrete	Group 1
		2	3	Concrete	Group 1
		1	3'	Concrete	Group 1
		1.7	3"	Concrete	Group 1
		1.63	20	Concrete	Group 1

Concrete		0.86	26	Concrete	Group 1
		0.756	19	Concrete, plain	Group 1
		4.4	20	Light concrete	Group 1
		0.72	18	Mass concrete	Group 3
		1	12	Concrete	Group 4
		0.51	16b	Concrete	Group 5
		0.51	16c	Concrete	Group 5
	In-situ concrete	0.84	23	In-situ concrete	Group 2
		0.8-1.5	18	Concrete in situ	Group 3
		1.2	10	Concrete in situ	Group 3
		2	5	Concrete in situ	Group 4
	ready mix	0.54	7	Beton prepare	Group 1
		0.42	8a	Ready mix concrete	Group 3
		0.65	8b	Ready mix concrete	Group 4
	ready mix 15 MPa	1.26-1.51	29b	Ready mix 15 Mpa	Group 1
	ready mix 17.5 MPa	1	1	ready mix 17.5 MPa	Group 1
		2.3	4	ready mix 17.5 MPa	Group 1
		0.54	7	ready mix 17.5 MPa	Group 1
	ready mix 20 Mpa	1.38-1.6	29b	20 Mpa ready mix	Group 1
	ready mix 30 Mpa	1.3	1	ready mix 30 Mpa	Group 1
		1.4	2	Concrete, 30 Mpa	Group 1
		1.83-2.25	29b	30 Mpa Ready mix	Group 1
	ready mix 40 Mpa	1.6	1	ready mix 40 Mpa	Group 1
	ready mix 60 Mpa	2-2.57	29b	60 Mpa ready mix	Group 1
	Concrete products	0.81	7	Produits de base en beton	Group 1
		0.65	8a	Concrete products	Group 3
		0.83	8b	Concrete products	Group 4
	Reinforced concrete	2.016	19	Concrete, reinforced	Group 1
		6.06	20	Armoured concrete	Group 1
		8.3	18	Reinforced concrete	Group 3
		2.5	12	Reinforced concrete	Group 4
	Concrete block	0.94	1	Concrete block	Group 1
		2.2	6	Concrete block	Group 1
		0.81	7	Concrete block	Group 1
		0.86	2	Concrete block	Group 1
		0.022-0.024	29b	Concrete block	Group 1
		0.81	7	blocs de construction en beton	Group 1
		0.8-3.5	18	Concrete: blocks	Group 3
		3.5	5	Autoclaved aerated concrete block	Group 4
		0.8	12	Concrete blocks	Group 4
	Concrete panel	5.4	5	Autoclaved aerated concrete panel	Group 4
	Concrete brick	0.97	1	Concrete brick	Group 1
	Glass Reinforced Concrete (GRC)	7.6	1	GRC	Group 1
		3.4	2	Concrete, glass reinforced	Group 1
	Concrete paver	1.2	1	Concrete paver	Group 1
	Pre-cast concrete	2	1	Pre-cast concrete	Group 1
		2	2	Concrete, pre-cast	Group 1
		1.5-8	18	Concrete: pre-cast	Group 3
	Concrete pipe	0.81	7	tuyaux en beton	Group 1
	Concrete roofing tile	0.81	1	Concrete roofing tile	Group 1
		9	7	Concrete roofing tile	Group 1
Copper	***copper***	70.6	1	Copper	Group 1
		70.6	2	Copper	Group 1
		100	4	Copper	Group 1
		66-106	3'	Copper	Group 1
		45	3"	Copper	Group 1
		45.9	22	Copper	Group 1

Copper		70.2	19	Copper	Group 1
		70	20	Copper	Group 1
		71-85	13	Copper (primary)	Group 2
		108.24	8a	Copper fabricated materials	Group 3
		100+	18	copper	Group 3
		114.5	8b	Copper fabricated materials	Group 4
	copper recycled	40-50	13	Copper (recycled)	Group 2
	Copper products				
	Copper sheet	100	5	Copper sheet	Group 4
	Copper pipe	29.46	7	Tyuaux de cuivres	Group 1
	Copper wire	71.208	19	Electric wires, copper	Group 1
		29.46	7	Fils de cuivre	Group 1
Earth, raw	**Earth, raw**				
	adobe block, straw stabilised	0.47	1	Earth, raw, adobe block, straw stabilised	Group 1
	adobe, bitumen stabilised	0.29	1	Earth, raw, adobe, bitumen stabilised	Group 1
		0.29 - 4.4	6	Earth, raw, adobe, bitumen stabilised	Group 1
	adobe, cement stabilised	0.42	1	Earth, raw, adobe, cement stabilised	Group 1
	rammed soil cement	0.8	1	Earth, raw, rammed soil cement	Group 1
	pressed block	0.42	1	Earth, raw, pressed block	Group 1
Fabric	Cotton	143	1	Cotton	Group 1
		143	6	Cotton	Group 1
	polyester	53.7	1	Polyester	Group 1
		53.7	6	Polyester	Group 1
Felt		13.51	29d	Felt shingle	Group 1
		36.53	29d	#15 felt	Group 1
		36.96	29d	#30 felt	Group 1
		38	22	Bitumen felt	Group 1
Glass	Glass	15	6	Glass	Group 1
		31.5	3	Glass	Group 1
		8.4	3'	Glass	Group 1
		22	3"	Glass	Group 1
		31.5	22	Glass	Group 1
		31.5	14	Glass	Group 1
		26.028	19	Glass	Group 1
		21.55	7	Verre (vitres de fenetre)	Group 1
		12-30	13	Glass (primary)	Group 2
		27.01	8a	Miror and glass household products	Group 3
		12-25	18	Glass	Group 3
		33	10	Glass	Group 3
		34.67	8b	Miror and glass household products	Group 4
		13-31	9	Glass	Group 5
		16.60	16d	Glass	Group 5
	recycled glass	10	13	Glass (recycled)	Group 2
	float	15.9	1	Glass, float	Group 1
		14.9	2	Glass, float	Group 1
	miror	27.23	7	miroir	Group 1
		27.01	8a	Miror and glass household products	Group 3
		34.67	8b	Miror and glass household products	Group 4
	toughened	26.2	1	Glass, toughened	Group 1
		25.3	2	Glass, toughened	Group 1
	tinted	16.3	1	Glass, laminated	Group 1
	laminated	14.9	1	Glass, tinted	Group 1
Ins.	***Batt insulation***				
	Glass fibre	30.3	1	Fibreglass	Group 1
		30.3	6	Fibreglass	Group 1
		18.3	7	Fibreglass	Group 1
		150	22	Fiberglass batts	Group 1

Insulation		18.35	7	Fibre de verre d'isolation	Group 1
		150	14	Fiberglass batts	Group 1
		27.9	15	Fiberglass	Group 1
		6.13	24	Fiberglass batt insulation	Group 1
		29.10	16d	Fiberglass	Group 5
	Mineral fibre	19.188	19	Mineral wool	Group 1
		18.35	7	Laine minerale et fibre de verre d'isolation	Group 1
		15.1	26	Mineral wool	Group 2
		8.11	8a	Mineral wool products	Group 3
		11.91	8b	Mineral wool products	Group 4
	Loose/fill insulation				
	Glass fibre	30.3	1	Fibreglass	Group 1
		30.3	6	Fibreglass	Group 1
		18.3	7	Fibreglass	Group 1
		23	22	Insulation: fibre	Group 1
		27.9	15	Fiberglass	Group 1
		6.13	24	Blown fiberglass insulation	Group 1
		29.10	16d	Fiberglass	Group 5
	Mineral wool	14.6	1	Wool (recycled)	Group 1
		16.1	2	Insulation, wool	Group 1
		19.188	19	Mineral wool	Group 1
		7.38	24	Blown mineral wool insulation	Group 1
		18.35	7	Laine minerale d'isolation	Group 1
		15.1	26	Mineral wool	Group 2
		8.11	8a	Mineral wool products	Group 3
		11.91	8b	Mineral wool products	Group 4
	Cellulose	3.3	1	Cellulose	Group 1
		4.3	7	Cellulose	Group 1
		4.36	7	isolant en cellulose	Group 1
		0.35	6	Cellulose	Group 1
		4.4	2	Insulation, cellulose	Group 1
		0.35	24	Blown cellulose insulation	Group 1
		1.75	26	Cellulose	Group 2
	Wood shavings	11.34	19	Timber: Shingles and shavings	Group 1
	Board insulation				
	Glass fibre board	30.3	1	Fibreglass	Group 1
		30.3	6	Fibreglass	Group 1
		18.3	7	Fibreglass	Group 1
		18.35	7	Fibre de verre d'isolation	Group 1
		27.9	15	Fiberglass	Group 1
		29.10	16d	Fiberglass	Group 5
	Polystyrene	117	1	Polystyrene	Group 1
		189	7	Polystyrene	Group 1
		188.59	7	Panneau isolant en polystyrene	Group 1
		111	15	Polystyrene	Group 1
		100	22	Polystyrene	Group 1
		106.74	19	polystyrene	Group 1
	Expanded polystyrene	117	1	Ploystyrene, expanded	Group 1
		117	6	Ploystyrene, expanded	Group 1
		111.6	15	Expanded polystyrene	Group 1
	Polyurethane board	74	1	Polyurethane	Group 1
		72.2	6	Polyurethane	Group 1
	Polyisocyanurate board	69.8	15	Polyiso	Group 1
	Expanded rubber	110	1	Synthetic rubber	Group 1
	Spray-type				
	Polyurethane foam	74	1	Polyurethane	Group 1
		72.2	6	Polyurethane	Group 1

Insulation	Ureaformoldehyde foam	78.2	1	Urea formaldehyde sealant	Group 1
	Cellulosic fibre	3.3	1	Cellulose	Group 1
		4.3	7	Cellulose	Group 1
		4.36	7	isolant en cellulose	Group 1
		0.35	6	Cellulose	Group 1
		4.4	2	Insulation, cellulose	Group 1
		1.75	26	Cellulose	Group 2
	Sprayed asbestos	8.2	22	Asbestos: others	Group 1
Iron	***Iron***	16	3	Iron	Group 1
		16	3'	Iron	Group 1
		23.8	3"	Iron	Group 1
		37	22	Galvanized iron	Group 1
	Iron pipe	34.64	15	Cast iron	Group 1
		28.23	7	tuyaux et raccord en fonte et en fer forge	Group 1
		38.15	8a	Other iron and steel pipes and tubes	Group 3
		67.44	8b	Other iron and steel pipes and tubes	Group 4
Lead	Lead	35.1	1	Lead	Group 1
		11 - 30	4	Lead	Group 1
		35.1	2	Lead	Group 1
		26	3'	Lead	Group 1
		25	3"	Lead	Group 1
		25.3	22	Lead	Group 1
		25+	18	Lead, zinc	Group 3
Lime	Lime	10.4	22	Lime: hydrated	Group 1
		3-5	18	Lime	Group 3
Linoleum	Linoleum	116	1	Linoleum	Group 1
		116	6	Linoleum	Group 1
		7.8	24	Linoleum flooring	Group 1
Paint	Paint	90.4	1	Paint	Group 1
		76.8	6	Paint	Group 1
		40.3	7	Paint	Group 1
		40.34	7	Peinture et produits connexes	Group 1
		25.2	19	Coatings: paints andlacquers	Group 1
		19.84	8a	Paints and related products	Group 3
		75.87	8b	Paints and related products	Group 4
	solvent based	98.1	1	Paint, solvent based	Group 1
		96.8	6	Paint, solvent based	Group 1
		98.1	2	Paint, solvent based	Group 1
	water based	88.5	1	Paint, water based	Group 1
		53 - 76.8	6	Paint, water based	Group 1
		88.5	2	Paint, water based	Group 1
		7.5	22	Paints: water soluble	Group 1
Paper	***Paper***	36.4	1	Paper	Group 1
		26	3	Paper	Group 1
		61	3'	Paper	Group 1
		42	3"	Paper	Group 1
		4.36	7	Papier trans. Gom. Cire ou d'im.	Group 1
	Building paper	25.5	1	Paper, building	Group 1
		12	7	Paper, building	Group 1
		25.5	2	Paper, building	Group 1
		12.01	7	Papier construction	Group 1
		7.63	8a	Building board and paper	Group 3
		12.32	8b	Building board and paper	Group 4
	kraft	12.6	1	Paper, kraft	Group 1
		12.6	2	Paper, kraft	Group 1

Paper	Wall paper	36.4	1	Wall paper	Group 1
		36.4	6	Wall paper	Group 1
		4.4	7	Wall paper	Group 1
	Recycled paper	23.4	1	Paper recycled	Group 1
		23.4	6	Paper recycled	Group 1
Plaster, gypsum	Plaster	6.7	3	Plaster	Group 1
		5.9	3'	Plaster	Group 1
		3.2	3"	Plaster	Group 1
		6.7	22	Plaster: solid and Plaster:fibrous	Group 1
		4.48	7	Platre et autres produits gypse	Group 1
		2.94	8a	Plaster and gypsum products	Group 3
		4.78	8b	Plaster and gypsum products	Group 4
		1.1-6.7	9	Plaster	Group 5
	Plaster, gypsum	4.5	1	Plaster, gypsum	Group 1
		3.4	4	Plaster, gypsum	Group 1
		1-4	18	Gypsum plaster	Group 3
		6.70	16g	Gypsum	Group 5
	Plaster board	6.1	1	Plaster board	Group 1
		9.4	6	Plaster board	Group 1
		4.4	4	Plaster board	Group 1
		6.1	2	Plaster board	Group 1
		2.7	23	Plasterboard	Group 2
		8-10	18	Plasterboard	Group 3
		3	10	Plasterboard	Group 3
		4.5	5	Plaster board	Group 4
	Gypsum board	8.64	19	Gypsum wallboard	Group 1
Plastics	**Plastics**	159	3"	Plastics - general	Group 1
		160	22	Plastics: general	Group 1
		31.82	7	Tuiles, plastique	Group 1
		72.26	8a	Plastic film and sheet	Group 3
		79.37	8a	Foamed and expansed plastic	Group 3
		57.74	8a	Plastic building supplies	Group 3
		50-100	18	Plastics	Group 3
		162	10	Plastics	Group 3
		81.71	8b	Plastic film and sheet	Group 4
		85.17	8b	Foamed and expansed plastic	Group 4
		86.4	8b	Plastic building supplies	Group 4
	ABS	111	1	ABS	Group 1
		111	15	ABS	Group 1
	Polyethylene	112	3	Polyethylene	Group 1
		163	3'	Polyethylene	Group 1
		104	3"	Polyethylene	Group 1
		112	22	Polyethylene	Group 1
		87	33	Polyethylene vapour barrier	Group 1
		188.59	7	Feuille de polyethylene	Group 1
	High density polyethelene	103	1	High density polyethelene (HDPE)	Group 1
		98.2	15	High density polyethelene (HDPE)	Group 1
	Low density polyethelene	103	1	Low density polyethelene (LDPE)	Group 1
		90	4	Low density polyethelene (LDPE)	Group 1
	polyester	53.7	1	polyester	Group 1
		53.7	6	polyester	Group 1
	polystyrene	117	1	polystyrene, expanded	Group 1
		117	6	polystyrene, expanded	Group 1
		189	7	Polystyrene	Group 1
		111	15	Polystyrene	Group 1
		140	3'	Polystyrene	Group 1
		96	3"	Polystyrene	Group 1

Plastics		100	22	Polystyrene	Group 1
		106.74	19	polystyrene	Group 1
		188.59	7	Panneau isolant en polystyrene	Group 1
	polyurethane,	74	1	polyurethane	Group 1
		72.2	6	polyurethane	Group 1
	Polyvinyl chloride (PVC)	70	1	PVC	Group 1
		189	7	PVC	Group 1
		63.3	6	PVC	Group 1
		96	3	PVC	Group 1
		87	3'	PVC	Group 1
		85	3"	PVC	Group 1
		96	22	PVC	Group 1
		88.74	19	Polyvinyl chloride (PVC)	Group 1
		66.8	20	PVC	Group 1
		79.1	15	PVC	Group 1
	PVC pipe	188.59	7	raccord de tuyauterie CPV	Group 1
		125.53	7	tuyau en CPV	Group 1
		79	5	PVC u/g pipe	Group 4
	PVC floor tiles	79	5	PVC floor tiles	Group 4
	polypropylene	64	1	polypropylene	Group 1
		64	6	polypropylene	Group 1
		157	3'	polypropylene	Group 1
		171	3"	polypropylene	Group 1
		175	22	polypropylene	Group 1
	Polythene	59.04	19	Polythene	Group 1
Rubber	Rubber, natural latex	67.5	1	Rubber, natural latex	Group 1
		67.5	6	Rubber, natural latex	Group 1
	Rubber, synthetic	110	1	Synthetic rubber	Group 1
		148	22	Rubber, synthetic	Group 1
	Rubber tile	31.82	7	Tuiles, caoutchouc	Group 1
Sealants	Sealants and adhesives	110.56	7	Joint, garniture d'etancheite	Group 1
	phenol formaldehyde	87	1	Phenol formaldehyde sealant	Group 1
	urea formaldehyde	78.2	1	Urea formaldehyde sealant	Group 1
Steel	***Steel, virgin, general***	32	1	Steel, virgin, general	Group 1
		32	2	Steel, virgin, general	Group 1
		10.4 - 45	6	Steel, virgin, general	Group 1
		35-50	3	Steel	Group 1
		35-100	3'	Steel	Group 1
		37-47	3"	Steel	Group 1
		35	22	Steel: general	Group 1
		32.004	19	Steel	Group 1
		32	20	steel	Group 1
		34.8	1	Steel, virgin, galvanised	Group 1
		35	1	Steel, virgin, imported structural	Group 1
		25-40	13	Steel (primary)	Group 2
		25.5	23	Primary steel	Group 2
		100+	18	stainless steel	Group 3
		75	11	stainless steel	Group 3
		30-60	18	steel	Group 3
		50	11	steel	Group 3
		48	10	steel	Group 3
		43	18	steel	Group 3
		6.70	16c	Steel, electric furnace	Group 5
		6.70	16e	Steel, electric furnace	Group 5
		16.80	16c	Steel, blast furnace	Group 5
		16.80	16e	Steel, blast furnace	Group 5

Steel	***Structural steel***	59	14	Structural steel	Group 1
		25.5	23	Structural steel	Group 2
	Steel beam	20.78	7	poutres et solives d'acier	Group 1
	trusses	41.6	29g	Heavy trusses	Group 1
		38.5	29g	Open web joists	Group 1
	Steel products				
	steel sections	26	12	Hot-rolled steel sections	Group 4
		31	12	Cold-formed steel sections	Group 4
		24-59	9	Steel (steel sections)	Group 5
	Steel sheet	22.5	26	Galvanized sheet steel	Group 1
		28.51	29g	Galvanized sheet	Group 1
		25.8	29g	Hot rolled sheet	Group 1
		28.78	29g	Cold rolled sheet	Group 1
		22.5	26	Galvanized sheet steel	Group 1
		38	5	Basic oxygen steel, coated sheet	Group 4
	Steel plates	58.08	8a	Fabricated steel plates	Group 3
		73.37	8b	Fabricated steel plates	Group 4
	Steel pipes	28.74	29g	tubing	Group 1
		38.91	7	Tubes et tuyaux d'acier	Group 2
		38.15	8a	Other iron and steel pipes and tubes	Group 3
		67.44	8b	Other iron and steel pipes and tubes	Group 4
	Steel, stud	29.08	32	Steel studs, galvanized	Group 1
		29.24	29g	Galvanized studs	Group 1
		5.6	24	Steel framing	Group 1
		38	5	Basic oxygen steel, stud	Group 4
	Steel, rod	36.41	28	Steel reinforcing bar	Group 1
		36.52	29g	Rebar, rod light sections	Group 1
		17.90	7	barres et tiges d'acier	Group 2
		28.65	8a	Reinforcing bars and rods	Group 3
		19	5	Electric arc furnace steel, reinforcing rod	Group 4
		30.16	8b	Reinforcing bars and rods	Group 4
	Steel cladding	109.15	29c	Steel cladding (30 ga)	Group 1
		146.69	29c	Steel cladding (26 ga)	Group 1
	Steel, recycled	10.1	1	Steel, recycled	Group 1
		9	6	Steel, recycled	Group 1
		9-12	13	Steel (recycled)	Group 2
		17.3	23	Recycled or secondary steel	Group 2
	reinforcing, sections	8.9	1	Steel, recycled, reinforcing, sections	Group 1
		8.9	2	Steel, recycled, sections	Group 1
		59	22	Steel: sections	Group 1
	wire rod	12.5	1	Steel, recycled, wire rod	Group 1
		12.5	2	Steel, recycled, wire rod	Group 1
		35	22	Steel: rods	Group 1
	Steel pipes	57	22	Steel pipes	Group 1
Stone		0.79	2	Stone, dimension	Group 1
		0.3	22	Masonry, stone	Group 1
		0.37	7	Pierres de construction faconnées ou travaillées	Group 1
		0.79	1	Stone, dimension, local	Group 1
		5.9	4	Stone, dimension, local	Group 1
		0.37	7	Stone, dimension, local	Group 1
		6.8	1	Stone, dimension, imported	Group 1
		13.9	7	Stone, dimension, imported	Group 1
		1.3	6	Stone, dimension, imported	Group 1
		0.14	7	Pierre non taillee	Group 1
		0.2	8a	Natural stone products	Group 3
		0.5	8b	Natural stone products	Group 4

Straw	straw, baled	0.24	1	Straw, baled	Group 1
Wood	***Wood***	6.7	3	Finished timber	Group 1
		4.3	3'	Finished timber	Group 1
		6.4	3"	Finished timber	Group 1
		5.184	19	Timber: rough saw	Group 1
		8.064	19	Timber: planned	Group 1
		13	23	Timber	Group 2
		0.1-5	18	timber	Group 3
		0.7	10	timber (local air dried)	Group 3
		1.17	18	timber (sawn)	Group 3
		0.7	12	Timber in round from local source	Group 4
		7.8	12	Microlaminated timber	Group 4
	**Timber, hardwood*				
	air dried, roughsawn	0.5	1	Timber, hardwood, air dried, roughsawn	Group 1
	kiln dried, roughsawn	2	1	Timber, hardwood, kiln dried, roughsawn	Group 1
	**Timber, softwood*	7.4	7	Timber, softwood	Group 1
		6.1	6	Timber, softwood	Group 1
		4.21	26	Softwood lumber	Group 1
		6.31	29f	Kiln dried softwood lumber	Group 1
		0.52-7.1	9	Timber (prepared softwood)	Group 5
	air dried, roughsawn	0.3	1	Timber, softwood, air dried, roughsawn	Group 1
	kiln dried, roughsawn	1.6	1	Timber, softwood, kiln dried, roughsawn	Group 1
		3.4	4	Timber, softwood, kiln dried, roughsawn	Group 1
	air dried, dressed	1.16	1	Timber, softwood, air dried, dressed	Group 1
	kiln dried, dressed	2.5	1	Timber, softwood, kiln dried, dressed	Group 1
		2.5	2	Timber, kiln dried, dressed	Group 1
		4	6	Timber, softwood, kiln dried, dressed	Group 1
	Lumber	2.795	29a	Dry lumber	Group 1
		1.138	29a	Green lumber	Group 1
		7.38	7	Sciage et bois d'oeuvre	Group 1
		9.87	7	bois d'oeuvre brut	Group 1
		6.3	8a	Treated lumber	Group 3
		6.07	8a	Lumber	Group 3
		8.8	8b	Lumber	Group 4
		6.64	8b	Treated lumber	Group 4
		12.5	16a	lumber	Group 5
	Dimension lumber	5.6	24	Wood framing	Group 1
		7.38	7	Bois de construction	Group 1
		3.5	5	Timber, softwood stud	Group 4
	Pannels	14.62	7	Placages et contre-plaques	Group 1
	Plywood	10.4	1	plywood	Group 1
		14.6	7	plywood	Group 1
		10.01	29f	plywood	Group 1
		0.35	24	plywood	Group 1
		11.16	8a	Plywood and veneer	Group 3
		18.06	8b	Plywood and veneer	Group 4
		8.8	16f	Plywood	Group 5
	Hardboard	24.2	1	hardboard	Group 1
		24	5	Timber hardboard (hardwood)	Group 4
	Oriented Strandboard/Waferboard	6.87	29f	OSB/WB sheathing	Group 1
		0.612	24	OSB	Group 1
	Particleboard	8	1	particle board	Group 1
		8.96	7	Paneaux de particules	Group 1
		8	5	Timber particleboard (softwood)	Group 4
	Fibreboard	11.9	1	MDF	Group 1
		11.9	2	Timber, medium density fibreboard	Group 1

Wood	***Other lumber products***	8.96	7	Divers produits de bois	Group 1
	siding	5.6	24	Cedar siding	Group 1
		7.14	29c	Cedar siding (Bevel, green)	Group 1
		15.18	29c	Cedar siding (Bevel, dry)	Group 1
		10.74	29c	Cedar siding (T&G, green)	Group 1
		22.83	29c	Cedar siding (T&G, dry)	Group 1
		11.19	29c	Cedar siding (Shiplap, green)	Group 1
		23.8	29c	Cedar siding (Shiplap, dry)	Group 1
		8.8	29c	Pine siding (Bevel, green)	Group 1
		18.7	29c	Pine siding (Bevel, dry)	Group 1
		13.17	29c	Pine siding (T&G, green)	Group 1
		28	29c	Pine siding (T&G, dry)	Group 1
		13.71	29c	Pine siding (Shiplap, green)	Group 1
		29.14	29c	Pine siding (Shiplap, dry)	Group 1
		8.1	29c	Spurce siding (Bevel, green)	Group 1
		17.23	29c	Spurce siding (Bevel, dry)	Group 1
		11.88	29c	Spurce siding (T&G, green)	Group 1
		25.12	29c	Spurce siding (T&G, dry)	Group 1
		12.24	29c	Spurce siding (Shiplap, green)	Group 1
		26.02	29c	Spurce siding (Shiplap, dry)	Group 1
	flooring products	7.38	7	Carreaux de plancher, lames de parquet	Group 1
	shingles	9	1	Wood shingles	Group 1
		9	7	Wood shingles	Group 1
		11.34	19	Timber: Shingles and shavings	Group 1
		8.96	7	bardeaux et bardeaux fendus en bois	Group 1
	mouldings, etc	3.1	1	Wood mouldings	Group 1
	Engineered wood products	0.9-13.2	29f	Engineered wood products	Group 1
		11.86	7	Materiaux fabriques en bois pour structure	Group 1
		11	5	Timber hardwood engineered products	Group 4
	glulam	4.6	1	Glulam	Group 1
		4.6	2	Glulam	Group 1
		11	4	Glulam	Group 1
Vinyl	**vinyl**	79.1	1	Vinyl flooring	Group 1
		79.1	6	Vinyl flooring	Group 1
		31.8	7	Vinyl flooring	Group 1
		2.21	24	Vinyl composition tile	Group 1
		30.13	8a	Vinyl floor and wall covering	Group 3
		188.59	7	Parement en vinyl	Group 1
		125.53	7	Tuyaux en vinyl	Group 1
		164.91	8b	Vinyl floor and wall covering	Group 4
Zinc	**Zinc**	51	1	Zinc	Group 1
		51	4	Zinc	Group 1
		38	3'	Zinc	Group 1
		67	3"	Zinc	Group 1
		68.4	22	Zinc	Group 1
		13.75	8a	Zinc and zinc alloy fabricated materials	Group 3
		25+	18	Lead, zinc	Group 3
		14.38	8b	Zinc and zinc alloy fabricated materials	Group 4

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Appendix C: Embodied emissions in building materials

Material	Values (Ton/Kg)	Original name	Ref.
Wood products	1644	Timber	23
	376.72	Timber	26
	1084.1	Lumber	16
	376.72	Softwood lumber	26
	518.495	Klin dried softwood lumber	29f
	70.5	Log	29f
	77547.21	Dry lumber products	29a
	30131.22	Green lumber products	29a
	587	Plywood	16
	588.5	Plywood	29f
	591.7	Waterboard/Oriented strand board	29f
	124.373	Green siding (Harvesting, Forest mgt, trans + manuf.)	29c
	91.611	Dry siding (Harvesting, Forest mgt, trans + manuf.)	29c
Fiberglass	2622.3	Fiberglass	16d
Concrete products	78.8	Concrete	16b,c
	119	In-situ concrete	23
	160-280	Concrete 160	20
	160-280	Light concrete 280	20
	160-280	Armoured concrete 400	20
Gypsum products	492.3	Gypsum plaster	16 g
	180	Plasterboard	23
Steel products	1775.4	Steel	26
	1955.69	Steel	29f
	1910	Steel	20
	440	Steel, electric furnace	16
	1467	Steel, blast furnace	16
	1775.39	Galvanized sheet steel	26
	2030	Structural steel	23
Glass	1061.7	Glass	16
	770	Glass	20
Clay products	660	Clay	20
	490	Common bricks	23

Appendix D: Example of key words used to read export file

Row/ Col.	1	2	3	4	5	6	7	8	9	10	
1	ExportEE	CaseStudy	Sep 8/02	17:24:44							Energy consumption and cost
2	MONTREAL	QUEBEC	Yes								House location
3	35637	145447.8	0	0	0	181084.8	"Annual fuel cons. EGOPW, Total MJ"				
4	904.02	942.54	0	0	0	1846.56	"Annual Fuel Cost $. EGOPW, Total"				
5	1	"# of Ceilings"									
6	Ceiling	Attic/Gable	21STDCLG	0.333	0.13	47.24	128.58				Ceilings description
7	1	0	"Ceiling #, # of Windows"								Roof description
8	1	0	4	3	4	2	4	14.27	0.17		
9	0.11	200.21	0.17	0.08	0.15	93.36	0.5	"<-- Attic data"			
10	4	"# of Main Walls"									Walls description starts here
11	East Wall	112x4R12	N/A	2	0	2.44	10.52	[illegible]	24.54		
12	112x4R12	6	"Number of Layers"								Description of "East Wall" (rows 11–28)
13	1	5	Cont. Solid								
14	MLA21	0.00113	19								
15	2	5	Cont. Solid								
16	MLA15	0.0165	12.7								
17	3	2	Wood Frame								
18	1	2	1	Lumber fra	Standard	Primary					
19	MLC15	0.0085	89	38	400	MLB15	0.023	152			
20	3	3	3	1	Yes						
21	4	5	Cont. Solid								
22	MLA11	0.0062	12.7								
23	5	5	Cont. Solid								
24	MLA30	0.01417	12								
25	6	6	Cont. Insulation								
26	MLB15	0.023	0								
27	1	1	0	"Main Wall #, # of Windows, # of Doors"							
28	small bedroom	500000	1	1.14	0.97	1.1					
29	North Wall	112x4R12	N/A	4	3	2.44	6.77	16.5	8.43		"North Wall" : Dimensions and Descritption of constituting layers (rows 29–44)
30	112x4R12	6	"Number of Layers"								
31	1	5	Cont. Solid								
32	MLA21	0.00113	19								
33	2	5	Cont. Solid								
34	MLA15	0.0165	12.7								
35	3	2	Wood Frame								
36	1	2	1	Lumber fra	Standard	Primary					
37	MLC15	0.0085	89	38	400	MLB15	0.023	152			
38	3	3	3	1	Yes						
39	4	5	Cont. Solid								
40	MLA11	0.0062	12.7								
41	5	5	Cont. Solid								
42	MLA30	0.01417	12								
43	6	6	Cont. Insulation								
44	MLB15	0.023	0								

45	2	2	1	"Main Wall #, # of Windows, # of Doors"						"North Wall" :
46	door window	500000	1	0.2	0.76	0.15				Descritption of
47	living room bay	200000	1	3.56	1.68	5.96				windows and doors
48	Front Door	M2	Wood hollow	1	2.13	0.91	1.95	0		
49	South Wall	112x4R12	N/A	2	3	2.44	13.11	30.47	22.77	
50	112x4R12	6	"Number of Layers"							
51	1	5	Cont. Solid							
52	MLA21	0.00113	19							Description of "South Wall"
53	2	5	Cont. Solid							
54	MLA15	0.0165	12.7							
55	3	2	Wood Frame							
56	1	2	1	Lumber fra	Standard	Primary				
57	MLC15	0.0085	89	38	400	MLB15	0.023	152		
58	3	3	3	1	Yes					
59	4	5	Cont. Solid							
60	MLA11	0.0062	12.7							
61	5	5	Cont. Solid							
62	MLA30	0.01417	12							
63	6	6	Cont. Insulation							
64	MLB15	0.023	0							
65	3	5	0	"Main Wall #, # of Windows, # of Doors"						
66	Patio Door	500040	1	1.75	1.93	3.38				
67	dining room	500000	1	1.45	0.97	1.4				
68	kitchen	500000	1	1.14	0.97	1.1				
69	main bathroom	500000	1	0.84	0.51	0.43				
70	master bedroom	500000	1	1.45	0.97	1.4				
71	West Wall	112x4R12	N/A	2	1	2.44	10.52	25.64	24.24	
72	112x4R12	6	"Number of Layers"							
73	1	5	Cont. Solid							Description of "West Wall"
74	MLA21	0.00113	19							
75	2	5	Cont. Solid							
76	MLA15	0.0165	12.7							
77	3	2	Wood Frame							
78	1	2	1	Lumber fra	Standard	Primary				
79	MLC15	0.0085	89	38	400	MLB15	0.023	152		
80	3	3	3	1	Yes					
81	4	5	Cont. Solid							
82	MLA11	0.0062	12.7							
83	5	5	Cont. Solid							
84	MLA30	0.01417	12							
85	6	6	Cont. Insulation							
86	MLB15	0.023	0							
87	4	1	0	"Main Wall #, # of Windows, # of Doors"						
88	large bedroom	500000	1	1.45	0.97	1.4				
89	0	"# of Exposed Floors"								← Exposed floors description

90	1	"# of Foundations"								
91	1	Foundation -	2	1	1	1.56	0	0	6	0
92	2.29	46.94	210501	0	14.76	8.71	0	0	4.21E+09	
93	1221501000	2	"Number of Layers"							
94	1	2	Wood Frame							
95	1	1	1	Lumber fra	N/A	Primary				
96	MLC15	0.0085	89	38	400	MLB17	0.0243	89		
97	2	2	2	1	Yes					
98	2	5	Cont. Solid							
99	MLA11	0.0062	12.7							
100	3000000000	0	"Number of Layers"							
101	4210006600	3	"Number of Layers"					**Foundations description**		
102	1	2	Wood Frame							
103	1	1	Lumber fram	N/A						
104	MLC15	0.0085	140	38	305	UserDef	1E-06	0.01		
105	2	5	Cont. Solid							
106	MLA14	0.0087	15.5							
107	3	5	Cont. Solid							
108	MLA56	0.00632	19							
109	Window - base2	500000	1	0.79	0.3	0.24				
110	Window - bsmba	500000	1	0.79	0.3	0.24				
111	Window - bdr4	500000	1	0.79	0.3	0.24				
112	Window - bdr5	500000	1	0.79	0.3	0.24				
113	Window - base1	500000	1	0.79	0.3	0.24				
114	Window - base2	500000	1	0.79	0.3	0.24				
115	0	"# of Pony Walls"								
116	0	"# of Basement Floor Headers"								

Appendix E: Material codes used in HOT 2000

Table E.1. Alphanumerical codes

HOT2000 Code	Building Material
MLC10	Wood, Oak
MLC11	Wood, Birch
MLC12	Wood, Maple
MLC13	Wood, Ash
MLC14	Wood, Southern pine
MLC15	Wood, Spurce, pine, fir (SPF)
MLC16	Wood, West coast cedar
MLB10	Glass/Mineral fibre, 65 mm RSI 1.4
MLB11	Glass/Mineral fibre, 70 mm RSI 1.4
MLB12	Glass/Mineral fibre, 89 mm RSI 1.7
MLB13	Glass/Mineral fibre, 89 mm RSI 2.1
MLB14	Glass/Mineral fibre, 89 mm RSI 2.4
MLB15	Glass/Mineral fibre, 152 mm RSI 3.5
MLB16	Glass/Mineral fibre, 140 mm RSI 3.9
MLB17	Glass/Mineral fibre, 202 mm RSI 4.9
MLB18	Glass/Mineral fibre, 222 mm RSI 5.4
MLB19	Glass/Mineral fibre, 254 mm RSI 5.4
MLB1A	Glass/Mineral fibre, 250 mm RSI 6.1
MLB1B	Glass/Mineral fibre, 254 mm RSI 6.1
MLB1C	Glass/Mineral fibre, 280 mm RSI 6.1
MLB1D	Glass/Mineral fibre, 265 mm RSI 7.0
MLB1E	Glass/Mineral fibre, 280 mm RSI 7.0
MLB20	Blown glass fibre
MLB21	Blown mineral fibre
MLB22	Blown cellulose, high density
MLB23	Blown cellulose, low density
MLB24	Vermiculite
MLB25	Wood fibre
MLB26	Wood shavings
MLB30	Semi-rigid glass fibre sheathing
MLB31	Rigid glass fibre sheathing
MLB32	Type 1 expanded polystyrene
MLB33	Type 2 expanded polystyrene
MLB34	Type 4 extruded polystyrene
MLB35	Urethane/isocyanurate board
MLB36	Phenolic board
MLB37	Fibreboard
MLB38	Mineral aggregate board
MLB39	Natural cork
MLB40	Polyurethane
MLB41	Cellulosic fibre
MLB42	Glass fibre
MLB43	Sprayed asbestos
MLB44	Icynene

Table E.1. Alphanumerical codes (Continued)

HOT2000 Code	Building Material
MLA10	Asbestos board
MLA11	Gypsum board
MLA12	Plywood
MLA13	Hardboard
MLA14	Particle board
MLA15	Reg. density fibreboard sheathing
MLA16	Int. density fibreboard sheathing
MLA17	Waferboard/Oriented strand board
MLA18	Floor header
MLA20	Brick, fired clay (2240 kg/m3)
MLA21	Brick, fired clay (1920 kg/m3)
MLA22	Brick, fired clay (1600 kg/m3)
MLA23	Concrete (sand & gravel) (2240 kg/m3)
MLA24	Concrete (sand & gravel) (1920 kg/m3)
MLA25	Concrete (sand & gravel) (1600 kg/m3)
MLA26	Concrete block: sand & gravel, 3 oval core (200 mm)
MLA27	Concrete block: sand & gravel, 3 oval core (300 mm)
MLA28	Concrete block: sand & gravel, no insulation in core (140 mm)
MLA29	Concrete block: sand & gravel, no insulation in core (190)
MLA2A	Concrete block: sand & gravel, vermiculite in core (140 mm)
MLA2B	Concrete block: sand & gravel, vermiculite in core (190 mm)
MLA2C	Insulated concrete block
MLA2D	Mortar
MLA2E	Stucco
MLA30	Air space
MLA31	Air space
MLA32	Air space
MLA40	Wood siding, 20x200 mm
MLA41	Wood siding, bevel, 19x250 mm
MLA42	Hardboard siding
MLA43	Fibreboard siding
MLA44	Hollow-backed metal/ Vinyl cladding
MLA45	Hollow-backed metal/ Vinyl cladding
MLA46	Horizontal clapboard profile with backing
MLA50	Gypsum plaster (720 kg/m3)
MLA51	Gypsum plaster (1680 kg/m3)
MLA52	Carpet: fibrous underlay
MLA53	Carpet: rubber underlay
MLA54	Resilient floor covering
MLA55	Terrazzo
MLA56	Wood finish
MLA57	Tile- Linoleum, vinyl, rubber, ceramic
MLA58	Architectural glass block
MLA59	Log

Table E.2. Codes for roofing materials

HOT2000 Code	Building Material
1	User defined
2	Asphalt shingles
3	Metal roofing
4	Built-up membrane
5	Asphalt roll roofing
6	Wood shingles
7	Crushed stones (not dried)
8	Clay tile

Table E.3. Codes for sheathing materials used for roofs

HOT2000 Code	Building Material
1	Waferboard/Oriented strand board
2	Waferboard/Oriented strand board
3	Waferboard/Oriented strand board
4	Plywood/ Part. Bd
5	Plywood/ Part. Bd
6	Plywood/ Part. Bd
7	Plywood/ Part. Bd
8	Fibreboard
9	Fibreboard
10	Gypsum board
11	Gypsum board
12	User defined

Table E.4. Codes for materials used in the

HOT2000 Code	Building Material
1	Type 1 expanded polystyrene
2	Type 2 expanded polystyrene
3	Type 2 expanded polystyrene
4	Type 2 expanded polystyrene
5	Type 4 extruded polystyrene
6	Type 4 extruded polystyrene
7	Type 4 extruded polystyrene
8	Semi-rigid glass fibre sheathing
9	Urethane/isocyanurate board
10	Rigid glass fibre sheathing
11	User defined

Table E.5. Codes for materials used as exterior cladding of gable ends

HOT2000 Code	Building Material
1	User defined
2	Wood
3	Hollow-backed metal/ Vinyl cladding
4	Insulated Metal/ Vinyl cladding
5	Brick
6	Mortar
7	Stucco

Table E.6. Codes for windows

Code	Glazing type	Coatings/tints	Fill type	Spacer type	Window type	Frame type
0	-	Clear	13 mm Air	Metal	Picture	Aluminum
1	Single (SG)	(Soft)	9 mm Air	Fused glass	Hinged	thermal break
2	with 1 coat	(Soft)	6 mm Air	Insulating	sash	Wood
3	1 coat	(hard 1)	13 mm Air	-	Patio door	wood
4	coatings	(hard 2)	Argon	-	Skylight	Vinyl
5	Double acrylic	Tint	Argon	-	-	vinyl
6	mirror 66	0.04	Krypton	-	-	-
7	mirror 88	0.10	-	-	-	-
8	mirror 88	0.20	-	-	-	-
9	-	0.35	-	-	-	-
A	-	Reflective	-	-	-	-
B	-	Tint	-	-	-	-

Table E.7. Codes for doors

Door type	Exterior material	Core material
Wood hallow core	Wood	Air
Solid wood	Wood	Wood
Steel fibreglass core	Steel	Fibreglass
Steel polystyrene core	Steel	Polystyrene
Steel polyurethane core	Steel	Polyurethane
Fibreglass polystyrene core	Fibreglass	Polystyrene
Fibreglass polyurethane core	Fibreglass	Polyurethane
User specified	User specified	User specified

In the case of doors, we can import the door type directly from HOT2000 without using a code. This table serves more to identify the exterior and core materials in a door.

E.8. Codes for lintels

Code	Lintel type	Material	Insulation	Thickness (mm)
0	Single	Wood	None	
1	Double	Steel	framing cavity	
2	Triple		EPSI	50
3			EPSII	38
4			EPSII	76
5			XTPS IV	19
6			XTPS IV	38
7			XTPS IV	64
8			Semi-rigid	25
9			Polyisocyanurate	19

Appendix F: Values obtained from Athena

Table F.2. Embodied energy in building materials

	Material	Embodied energy values				
		Montreal	Toronto	Vancouver	Calgary	Unit
Wood	Softwood Lumber (small dimension, green)	1668.00	1420.00	1701.00	2598.00	Mj/m3
	Softwood Lumber (small dimension, kiln dried)	4246.00	3563.00	4311.00	7323.00	Mj/m3
	Softwood Plywood (9mm basis)	43.00	42.00	36.00	44.00	Mj/m2
	Oriented Strand Board (9mm basis)	45.00	63.00	45.00	67.00	Mj/m2
	Parallel Strand Lumber	7538.00	7412.00	6703.00	6876.00	Mj/m3
	Laminated Veneer Lumber	6077.00	6086.00	11773.00	6383.00	Mj/m3
	Glulam Beams	3384.00	3327.00	3273.00	4157.00	Mj/m3
	Softwood Lumber (large dimension, green)	2618.00	2390.00	1254.00	2869.00	Mj/m3
	Softwood Lumber (large dimension, kiln dried)	5021.00	4793.00	3657.00	5599.00	Mj/m3
Concrete	20 Mpa, Average Flyash	1688.00	2056.00	1952.00	2618.00	Mj/m3
	30 Mpa, Average Flyash	2224.00	2675.00	2611.00	3495.00	Mj/m3
	60 Mpa, Average Flyash	2409.00	2879.00	2833.00	3796.00	Mj/m3
	20 Mpa, 25% Flyash	1589.00	1960.00	1874.00	2473.00	Mj/m3
	30 Mpa, 25% Flyash	1984.00	2418.00	2339.00	3120.00	Mj/m3
	60 Mpa, 25% Flyash	193.00	193.00	193.00	193.00	Mj/m3
	20 Mpa, 35% Flyash	1508.00	1881.00	1761.00	2350.00	Mj/m3
	30 Mpa, 35% Flyash	1847.00	2281.00	2190.00	2914.00	Mj/m3
	60 Mpa, 35% Flyash	193.00	193.00	193.00	193.00	Mj/m3
	Concrete/Masonry	26.00	32.00	29.00	37.00	Mj/Block
	Mortar	2046.00	2464.00	2506.00	3354.00	Mj/m3
Cladding materials	Brick Type 2	0.00	0.00	0.00	0.00	Mj/Kg
	Cedar Wood Bevel Siding	13.00	25.00	11.00	11.00	Mj/m2
	Cedar Wood Shiplap Siding	18.00	39.00	17.00	17.00	Mj/m2
	Cedar Wood Tongue and Groove Siding	18.00	38.00	17.00	17.00	Mj/m2
	Commercial (26 ga.) Steel Cladding	429.00	427.00	439.00	436.00	Mj/m2
	Concrete Brick	262.00	320.00	263.00	340.00	Mj/m2
	Metric Modular (Modular) Brick	552.00	1078.00	1621.00	1247.00	Mj/m2
	Ontario (standard) Brick	615.00	1218.00	1768.00	1405.00	Mj/m2

	Material	Montreal	Toronto	Vancouver	Calgary	Unit
Cladding materials	Pine Wood Bevel Siding	15.00	30.00	15.00	35.00	Mj/m2
	Pine Wood Shiplap Siding	25.00	51.00	27.00	56.00	Mj/m2
	Pine Wood Tongue and Groove Siding	25.00	52.00	28.00	59.00	Mj/m2
	Residential (30 ga.) Steel Cladding	216.00	215.00	220.00	219.00	Mj/m2
	Spurce Wood Bevel Siding	15.00	29.00	15.00	32.00	Mj/m2
	Spurce Wood Shiplap Siding	21.00	42.00	22.00	47.00	Mj/m2
	Spurce Wood Tongue and Groove Siding	21.00	42.00	22.00	47.00	Mj/m2
	Stucco over metal mesh	56.00	56.00	52.00	70.00	Mj/m2
	Stucco over porous surface	7.00	5.00	7.00	7.00	Mj/m2
	Vinyl	121.00	120.00	130.00	128.00	Mj/m2
Gypsum board	1/2" Fire-Rated Type Gypsum Board	71.00	77.00	70.00	82.00	Mj/m2
	1/2" Gypsum Fibre Gypsum Board	101.00	99.00	115.00	112.00	Mj/m2
	1/2" Moisture Resistant Gypsum Board	74.00	81.00	73.00	86.00	Mj/m2
	1/2" Regular Gypsum Board	71.00	77.00	69.00	82.00	Mj/m2
	5/8" Fire-Rated Type Gypsum Board	86.00	93.00	85.00	100.00	Mj/m2
	5/8" Gypsum Fibre Gypsum Board	126.00	122.00	143.00	140.00	Mj/m2
	5/8" Moisture Resistant Gypsum Board	89.00	96.00	90.00	104.00	Mj/m2
	5/8" Regular Gypsum Board	86.00	93.00	85.00	100.00	Mj/m2
Insulation	Batt. Fiberglass (25 mm)	19.00	21.00	24.00	23.00	Mj/m2
	Batt. Rockwool (25mm)	38.00	38.00	38.00	38.00	Mj/m2
	Blown Cellulose (25mm)	2.00	2.00	3.00	2.00	Mj/m2
	Expanded Polystyrene (25 mm)	42.00	44.00	42.00	44.00	Mj/m2
	Extruded Polystyrene (25mm)	86.00	89.00	90.00	90.00	Mj/m2
	Foam Polyisocyanurate (25mm)	0.00	0.00	3.00	2.00	Mj/m2
Roofing	#15 Organic Felt	33.00	36.00	34.00	37.00	Mj/m2
	# 30 Organic Felt	66.00	72.00	67.00	73.00	Mj/m2
	4-Ply-fiberglass felts roof membrane	0.41	0.39	1.11	0.27	Mj/Kg
	4-Ply-organic felts roof membrane	0.41	0.39	1.11	0.27	Mj/Kg
	Asphalt BUR application	0.00	0.00	0.00	0.00	Mj/Kg
	Ballast (aggregate stone)	0.00	0.00	0.00	0.00	Mj/Kg
	Clay tile	602.00	575.00	696.00	666.00	Mj/m2
	Concrete tile	88.00	105.00	88.00	111.00	Mj/m2
	EPDM membrane	167.00	167.00	170.00	170.00	Mj/Kg
	Glass Based shingles 20 yr	124.00	123.00	126.00	129.00	Mj/m2

	Material	Montreal	Toronto	Vancouver	Calgary	Unit
Roofing	Glass Based shingles 25 yr	142.00	141.00	144.00	146.00	Mj/m2
	Glass Based shingles 30 yr	0.00	0.00	0.00	0.00	Mj/m2
	Min. Surface roll	88.00	95.00	98.00	98.00	Mj/m2
	Mod. Bit. Membrane	49.00	52.00	55.00	55.00	Mj/m2
	Organic Felt shingles 20 yr	160.00	171.00	160.00	175.00	Mj/m2
	Organic Felt shingles 25 yr	175.00	186.00	175.00	191.00	Mj/m2
	Organic Felt shingles 30 yr	188.00	200.00	188.00	206.00	Mj/m2
	Polyester felt	0.64	0.15	1.14	0.95	Mj/Kg
	PVC membrane	93.00	93.00	94.00	93.00	Mj/Kg
	Roofing Asphalt	129.00	133.00	83.00	47.00	Mj/Kg
	Rubberized Asphalte Membrane	0.00	0.00	0.00	0.00	Mj/Kg
	TPO Membrane	0.00	0.00	0.00	0.00	Mj/Kg
	Type III Glass Felt	21.00	21.00	18.00	21.00	Mj/m2
	Type IV Glass Felt	15.00	15.00	15.00	15.00	Mj/m2
Steel	Nails	25.49	29.82	25.74	31.21	Mj/Kg
	Welded Wire Mesh Ladder Wire	47.54	47.24	52.05	51.32	Mj/Kg
	Screws, nuts, bolts	30.51	34.34	31.49	36.31	Mj/Kg
	Wide Flange Sections	29.83	29.79	30.71	30.49	Mj/Kg
	Open Web Joists	27.44	29.56	29.05	31.78	Mj/Kg
	Rebar Rod Light Sections	20.07	21.80	20.62	22.64	Mj/Kg
	Hollow Structural Steel	26.10	26.06	26.98	26.75	Mj/Kg
	Steel Tubing	27.92	28.13	31.58	31.62	Mj/Kg
	Hot Rolled Sheet	23.74	23.77	27.71	27.43	Mj/Kg
	Cold Rolled Sheet	26.00	26.20	29.93	29.88	Mj/Kg
	Galvanized Sheet	26.24	26.20	27.12	26.90	Mj/Kg
	Galvanized decking	25.79	27.15	28.84	30.35	Mj/Kg
	Galvanized studs	25.24	25.20	26.12	25.90	Mj/Kg
Other	3 mil Polyethylene	9.00	9.00	9.00	9.00	Mj/m2
	6 mil Polyethylene	17.00	17.00	17.00	18.00	Mj/m2
	Aluminium	58.48	59.03	59.55	58.69	Mj/Kg
	Aluminium Frame	69.00	68.00	1275.00	71.00	Mj/m
	Concrete block	35.00	42.00	35.00	45.00	Mj/block
	Glazing Panel	6.32	17.94	6.93	20.73	Mj/Kg
	Joint Compound	0.46	1.22	0.76	0.93	Mj/Kg

	Material	Montreal	Toronto	Vancouver	Calgary	Unit
Other	Low E Silver Argon Filled Glazing	119.00	298.00	128.00	340.00	Mj/m2
	Low E Tin Argon Filled Glazing	105.00	283.00	114.00	326.00	Mj/m2
	Low E Tin Glazing	105.00	283.00	114.00	325.00	Mj/m2
	Paper Tape	21.19	29.71	24.77	31.56	Mj/Kg
	Polyethylene Filter Fabric	0.64	0.15	1.14	3.50	Mj/Kg
	Polypropolene	95.40	94.90	95.90	98.29	Mj/Kg
	PVC Clad Wood Frame	168.00	106.00	6.00	102.00	Mj/m
	PVC Frame	0.00	0.00	0.00	0.00	Mj/m
	Solvent Based Alkyd Paint	0.05	0.05	0.04	0.05	Mj/m3
	Solvent Based Varnish	0.03	0.03	0.03	0.03	Mj/m3
	Spandrel Panel	0.55	0.55	0.55	0.55	Mj/ton
	Split-faced Concrete block	29.00	26.00	32.00	40.00	Mj/block
	Standard Glazing	105.00	283.00	113.00	324.00	Mj/m2
	Water Based Latex Paint	0.03	0.03	0.03	0.03	Mj/m3
	Wood frame	16.00	10.00	14.00	10.00	Mj/m

Table F.2. Embodied emissions in building materials

	Material	Values of embodied emissions				
		Montreal	Toronto	Vancouver	Calgary	Unit
Wood	Softwood Lumber (small dimension, green)	49.391	118.907	56.943	103.102	Kg eq. CO2/m3
	Softwood Lumber (small dimension, kiln dried)	110.634	201.162	120.370	365.364	Kg eq. CO2/m3
	Softwood Plywood (9mm basis)	1.046	1.046	1.046	1.069	Kg eq. CO2/m2
	Oriented Strand Board (9mm basis)	1.023	1.046	1.023	2.092	Kg eq. CO2/m2
	Parallel Strand Lumber	120.623	120.623	120.623	120.623	Kg eq. CO2/m2
	Laminated Veneer Lumber	96.289	96.289	575.096	114.669	Kg eq. CO2/m3
	Glulam Beams	108.830	108.830	112.014	175.139	Kg eq. CO2/m3
	Softwood Lumber (large dimension, green)	51.874	51.874	51.874	137.942	Kg eq. CO2/m3
	Softwood Lumber (large dimension, kiln dried)	110.025	110.025	110.025	223.585	Kg eq. CO2/m3
Concrete	20 Mpa, Average Flyash	218.895	221.976	202.045	235.161	Kg eq. CO2/m3
	30 Mpa, Average Flyash	312.999	313.448	287.678	328.369	Kg eq. CO2/m3
	60 Mpa, Average Flyash	344.367	343.448	316.207	359.151	Kg eq. CO2/m3
	20 Mpa, 25% Flyash	201.688	204.723	186.473	217.747	Kg eq. CO2/m3
	30 Mpa, 25% Flyash	271.516	272.781	249.965	286.380	Kg eq. CO2/m3
	60 Mpa, 25% Flyash	0.000	0.000	0.000	0.000	Kg eq. CO2/m3
	20 Mpa, 35% Flyash	187.527	191.493	173.220	203.402	Kg eq. CO2/m3
	30 Mpa, 35% Flyash	248.240	249.413	228.551	262.805	Kg eq. CO2/m3
	60 Mpa, 35% Flyash	0.000	0.000	0.000	0.000	Kg eq. CO2/m3
	Concrete/Masonry	2.046	2.069	2.069	3.092	Kg eq. CO2/Block
	Mortar	319.999	318.402	293.747	355.780	Kg eq. CO2/m3
Cladding materials	Brick Type 2	0.000	0.000	0.000	0.000	Kg eq. CO2/Kg
	Cedar Wood Bevel Siding	0.023	1.046	0.023	0.023	Kg eq. CO2/m2
	Cedar Wood Shiplap Siding	0.023	1.046	0.023	0.023	Kg eq. CO2/m2
	Cedar Wood Tongue and Groove Siding	0.000	1.046	0.023	0.023	Kg eq. CO2/m2
	Commercial (26 ga.) Steel Cladding	46.127	46.127	46.127	46.127	Kg eq. CO2/m2
	Concrete Brick	17.506	19.598	18.529	23.782	Kg eq. CO2/m2
	Metric Modular (Modular) Brick	20.150	39.024	71.700	75.976	Kg eq. CO2/m2
	Ontario (standard) Brick	22.311	43.300	81.206	86.528	Kg eq. CO2/m2
	Pine Wood Bevel Siding	0.023	1.046	0.023	2.092	Kg eq. CO2/m2
	Pine Wood Shiplap Siding	0.023	1.069	1.023	3.138	Kg eq. CO2/m2
	Pine Wood Tongue and Groove Siding	0.023	1.069	1.023	3.138	Kg eq. CO2/m2
	Residential (30 ga.) Steel Cladding	22.552	22.552	22.552	22.552	Kg eq. CO2/m2

	Material	Montreal	Toronto	Vancouver	Calgary	Unit
Cladding materials	Spurce Wood Bevel Siding	0.023	1.046	0.023	2.092	Kg eq. CO_2/m^2
	Spurce Wood Shiplap Siding	0.023	1.069	0.023	3.115	Kg eq. CO_2/m^2
	Spurce Wood Tongue and Groove Siding	0.000	1.046	0.023	3.115	Kg eq. CO_2/m^2
	Stucco over metal mesh	5.092	5.115	5.092	6.138	Kg eq. CO_2/m^2
	Stucco over porous surface	0.000	0.000	0.000	0.000	Kg eq. CO_2/m^2
	Vinyl	7.460	7.460	7.460	7.460	Kg eq. CO_2/m^2
Gypsum board	1/2" Fire-Rated Type Gypsum Board	3.115	3.138	2.115	3.161	Kg eq. CO_2/m^2
	1/2" Gypsum Fibre Gypsum Board	5.207	3.184	5.207	5.207	Kg eq. CO_2/m^2
	1/2" Moisture Resistant Gypsum Board	3.138	3.138	3.138	3.161	Kg eq. CO_2/m^2
	1/2" Regular Gypsum Board	3.115	3.138	2.115	3.161	Kg eq. CO_2/m^2
	5/8" Fire-Rated Type Gypsum Board	3.161	3.161	3.138	4.184	Kg eq. CO_2/m^2
	5/8" Gypsum Fibre Gypsum Board	6.276	4.230	6.276	6.276	Kg eq. CO_2/m^2
	5/8" Moisture Resistant Gypsum Board	3.161	4.161	3.161	4.207	Kg eq. CO_2/m^2
	5/8" Regular Gypsum Board	3.161	3.161	3.138	4.184	Kg eq. CO_2/m^2
Insulation	Batt. Fiberglass (25 mm)	1.092	1.092	1.115	1.115	Kg eq. CO_2/m^2
	Batt. Rockwool (25mm)	3.092	3.092	3.092	3.092	Kg eq. CO_2/m^2
	Blown Cellulose (25mm)	0.000	0.000	0.000	0.000	Kg eq. CO_2/m^2
	Expanded Polystyrene (25 mm)	2.046	2.046	2.046	2.046	Kg eq. CO_2/m^2
	Extruded Polystyrene (25mm)	4.092	4.092	4.092	4.115	Kg eq. CO_2/m^2
	Foam Polyisocyanurate (25mm)	0.000	0.000	0.000	0.000	Kg eq. CO_2/m^2
Roofing	#15 Organic Felt	0.023	1.023	0.023	1.046	Kg eq. CO_2/m^2
	# 30 Organic Felt	1.046	1.046	1.046	1.069	Kg eq. CO_2/m^2
	4-Ply-fiberglass felts roof membrane	0.001	0.001	0.002	0.000	Kg eq. CO_2/Kg
	4-Ply-organic felts roof membrane	0.001	0.001	0.002	0.000	Kg eq. CO_2/Kg
	Asphalt BUR application	0.000	0.000	0.000	0.000	Kg eq. CO_2/Kg
	Ballast (aggregate stone)	0.000	0.000	0.000	0.000	Kg eq. CO_2/Kg
	Clay tile	30.472	30.472	30.472	30.472	Kg eq. CO_2/m^2
	Concrete tile	5.161	6.184	5.161	7.230	Kg eq. CO_2/m^2
	EPDM membrane	6.207	6.207	6.207	6.207	Kg eq. CO_2/Kg
	Glass Based shingles 20 yr	1.069	1.069	2.092	2.092	Kg eq. CO_2/m^2
	Glass Based shingles 25 yr	1.069	1.069	2.092	2.092	Kg eq. CO_2/m^2
	Glass Based shingles 30 yr	0.000	0.000	0.000	0.000	Kg eq. CO_2/m^2
	Min. Surface roll	1.046	1.046	2.069	2.069	Kg eq. CO_2/m^2

	Material	Montreal	Toronto	Vancouver	Calgary	Unit
Roofing	Mod. Bit. Membrane	0.023	1.046	1.046	1.046	Kg eq. CO2/m2
	Organic Felt shingles 20 yr	2.069	2.092	2.069	3.138	Kg eq. CO2/m2
	Organic Felt shingles 25 yr	2.092	2.092	2.092	3.138	Kg eq. CO2/m2
	Organic Felt shingles 30 yr	2.092	2.115	2.092	3.138	Kg eq. CO2/m2
	Polyester felt	0.001	0.000	0.000	0.000	Kg eq. CO2/Kg
	PVC membrane	3.230	3.230	3.230	3.230	Kg eq. CO2/Kg
	Roofing Asphalt	4.023	4.046	4.023	0.000	Kg eq. CO2/Kg
	Rubberized Asphalte Membrane	0.000	0.000	0.000	0.000	Kg eq. CO2/Kg
	TPO Membrane	0.000	0.000	0.000	0.000	Kg eq. CO2/Kg
	Type III Glass Felt	0.023	0.023	0.023	1.023	Kg eq. CO2/m2
	Type IV Glass Felt	0.023	0.023	1.023	1.023	Kg eq. CO2/m2
Steel	Nails	0.939	1.096	0.956	1.380	Kg eq. CO2/Kg
	Welded Wire Mesh Ladder Wire	1.334	1.342	1.341	1.363	Kg eq. CO2/Kg
	Screws, nuts, bolts	1.048	1.190	1.064	1.446	Kg eq. CO2/Kg
	Wide Flange Sections	0.985	0.985	0.985	0.985	Kg eq. CO2/Kg
	Open Web Joists	0.881	0.964	0.893	1.117	Kg eq. CO2/Kg
	Rebar Rod Light Sections	0.700	0.765	0.709	0.879	Kg eq. CO2/Kg
	Hollow Structural Steel	0.633	0.633	0.633	0.633	Kg eq. CO2/Kg
	Steel Tubing	0.696	0.717	0.703	0.762	Kg eq. CO2/Kg
	Hot Rolled Sheet	0.752	0.768	0.760	0.804	Kg eq. CO2/Kg
	Cold Rolled Sheet	0.775	0.797	0.783	0.843	Kg eq. CO2/Kg
	Galvanized Sheet	0.736	0.736	0.736	0.736	Kg eq. CO2/Kg
	Galvanized decking	0.790	0.850	0.800	0.964	Kg eq. CO2/Kg
	Galvanized studs	0.676	0.676	0.676	0.676	Kg eq. CO2/Kg
Other	3 mil Polyethylene	0.000	0.000	0.000	0.000	Kg eq. CO2/m2
	6 mil Polyethylene	1.023	1.023	1.023	1.023	Kg eq. CO2/m2
	Aluminium	1.894	1.895	1.896	1.894	Kg eq. CO2/Kg
	Aluminium Frame	4.184	4.184	100.850	4.184	Kg eq. CO2/m
	Concrete block	2.069	3.069	2.069	3.092	Kg eq. CO2/block
	Glazing Panel	1.665	2.091	1.712	2.853	Kg eq. CO2/Kg
	Joint Compound	0.011	0.024	0.019	0.033	Kg eq. CO2/Kg
	Low E Silver Argon Filled Glazing	26.805	33.104	26.851	44.610	Kg eq. CO2/m2
	Low E Tin Argon Filled Glazing	25.759	32.058	25.805	43.587	Kg eq. CO2/m2
	Low E Tin Glazing	25.759	32.058	25.805	43.587	Kg eq. CO2/m2

	Material	Montreal	Toronto	Vancouver	Calgary	Unit
Other	Paper Tape	0.799	1.101	1.074	1.638	Kg eq. CO2/Kg
	Polyethylene Filter Fabric	0.001	0.000	0.000	0.006	Kg eq. CO2/Kg
	Polypropolene	1.296	1.295	1.295	1.301	Kg eq. CO2/Kg
	PVC Clad Wood Frame	0.000	0.000	0.000	0.000	Kg eq. CO2/m
	PVC Frame	0.000	0.000	0.000	0.000	Kg eq. CO2/m
	Solvent Based Alkyd Paint	0.001	0.001	0.001	0.001	Kg eq. CO2/m3
	Solvent Based Varnish	0.001	0.001	0.001	0.001	Kg eq. CO2/m3
	Spandrel Panel	0.001	0.001	0.001	0.001	Kg eq. CO2/ton
	Split-faced Concrete block	2.046	2.046	2.069	3.092	Kg eq. CO2/block
	Standard Glazing	25.759	32.058	25.805	43.587	Kg eq. CO2/m3
	Water Based Latex Paint	0.001	0.001	0.000	0.000	Kg eq. CO2/m3
	Wood frame	0.000	0.000	0.000	0.000	Kg eq. CO2/m2

Appendix G: Material and installation cost

Material	Montreal	Toronto	Vancouver	Calgary	Unit
1/2" Regular gypsum board	707.68	779.96	743.09	659.82	$/m3
18.6 RSI/m (R2.7/in) mineral fibre	5.76	6.08	5.79	5.29	$/m2
23.7 RSI/m (R3.4/in) blown cellulose	5.76	6.08	5.79	5.29	$/m2
25.3 RSI/m (R3.6/in) blown cellulose	4.67	4.93	4.7	4.29	$/m2
Asphalt roll roofing	1.07	1.13	1.07	0.98	$/m2
Asphalt shingles	0.73	0.77	0.73	0.67	$/m2
Brick	95.83	115.33	104.3	94.39	$/m2
Built-up membrane	1.29	1.36	1.29	1.18	$/m2
Clay tile	5.71	6.02	5.74	5.24	$/m2
Gypsum board	8.99	9.91	9.44	8.38	$/m2
Hollow-backed metal/ Vinyl cladding	17.72	18.69	17.81	16.26	$/m2
Insulated metal/ Vinyl cladding	18.48	19.49	18.57	16.96	$/m2
Lath & plaster	8.66	9.38	8.93	7.93	$/m2
Mortar	190.96	229.83	207.85	188.1	$/m3
Plywood/ Particle board	9.9	10.06	8.93	8.57	$/m2
RSI 1.7 (R10) batt	4.13	4.36	4.15	3.79	$/m2
RSI 2.1 (R12) batt	4.46	4.7	4.48	4.09	$/m2
RSI 3.5 (R20) batt	5.22	5.5	5.24	4.79	$/m2
RSI 4.9 (R28) batt	9.13	9.63	9.18	8.38	$/m2
Slate	7.2	7.59	7.23	6.61	$/m2
Stucco	1.52	1.67	1.59	1.42	$/m2
Type 1 expanded polystyrene	188.33	198.58	189.26	172.85	$/m3
Type 2 expanded polystyrene	188.33	198.58	189.26	172.85	$/m3
Type 4 extruded polystyrene	273.93	288.85	275.28	251.42	$/m3
Urethane/isocyanurate board	6.63	6.99	6.66	6.09	$/m2
Vermiculite	30.88	32.56	31.03	28.34	$/m3
Wood (lapped)	46.31	48.83	46.54	42.51	$/m2
Wood shingles	2.69	2.83	2.7	2.46	$/m2
Wood, Spurce, pine, fir (SPF), Ceiling 38x89	3529.69	3587.04	3185.65	3055.03	$/m3
Wood, Spurce, pine, fir (SPF), Ceiling 38x140	3046.00	3095.48	2749.09	2636.38	$/m3
Wood, Spurce, pine, fir (SPF), Ceiling 38x184	3163.65	3215.05	2855.28	2738.22	$/m3
Wood, Spurce, pine, fir (SPF), Wall 38x89	2536.15	2577.35	2288.95	2195.10	$/m3
Wood, Spurce, pine, fir (SPF), Wall 38x140	2523.08	2564.07	2277.15	2183.78	$/m3
Wood, Spurce, pine, fir (SPF), Floor 38x89	2706.10	2750.06	2442.33	2342.19	$/m3
Wood, Spurce, pine, fir (SPF), Floor 38x140	2353.13	2391.36	2123.76	2036.69	$/m3
Wood, Spurce, pine, fir (SPF), Floor 38x184	2447.26	2487.01	2208.71	2118.16	$/m3
Wood, Spurce, pine, fir (SPF), Floor 38x235	2679.95	2723.49	2418.73	2319.56	$/m3
Wood, Spurce, pine, fir (SPF), Floor 38x286	2847.29	2893.54	2569.75	2464.39	$/m3

Appendix H: Density of building materials

Material type	Density (Kg/m3)
Oak	750
Maple	720
Ash	690
Southern pine	430
Spurce, pine, fir (SPF)	420
West coast cedar	52
Glass/Mineral fibre	52
Glass fibre	9.6-32
Mineral fibre	9.6-32
Cellulose	37-51
Cellulose	26.4
Vermiculite	112-131
Natural cork	86
Gypsum board	1200
Brick, fired clay	2240
Brick, fired clay	1920
Brick, fired clay	1600
Concrete (sand & gravel)	2240
Concrete (sand & gravel)	1920
Concrete (sand & gravel)	1600
Mortar	1920
Stucco	1850
Gypsum plaster	720
Gypsum plaster	1680
Carpet: rubber underlay	1100-1190
Steel	1500-7380

Appendix I: Result files

Table I.1. Breakdown of the results of embodied energy calculations

Material	Location	Type of location	Volume (m3)	Thickness (mm)	Embodied energy (Mj)	Emissions (eq. Kg of CO2)	Cost ($CAN)	Density (Kg/m3)
Plywood/ Particle board	Roof	Roof & Ceilings	0.221	15.5	1,056	26	141	660
Brick	Roof	Roof & Ceilings	1.45	101.6	7,878	288	1,368	0
Plywood/ Particle board	Roof	Roof & Ceilings	3.103	15.5	14,825	361	1,982	0
Asphalt shingles	Roof	Roof & Ceilings	0.2	1	37,600	418	146	0
RSI 3.5 (R20) batt	Ceiling	Roof & Ceilings	19.547	152	14,856	854	671	2622.3
RSI 3.5 (R20) batt	Ceiling	Roof & Ceilings	18.291	152	13,901	799	628	2622.3
Wood, Spurce, pine, fir (SPF)	Ceiling	Roof & Ceilings	1.538	38	6,530	170	5,429	376.72
Gypsum board	Ceiling	Roof & Ceilings	1.633	12.7	9,129	401	1,156	492.3
Other, 6 mil Polyethylene	Ceiling	Roof & Ceilings	0.77	6	2,182	131	2,051	0
Brick	East Wall	Exterior walls	0.291	101.6	1,581	58	274	660
Air space	East Wall	Exterior walls	0.034	12	0	0	0	0
Plywood/ Particle board	East Wall	Exterior walls	0.036	12.7	172	4	28	0
RSI 3.5 (R20) batt	East Wall	Exterior walls	0.144	89	187	11	8	2622.3
Wood, Spurce, pine, fir (SPF)	East Wall	Exterior walls	0.11	38	467	12	279	376.72
Gypsum board	East Wall	Exterior walls	0.036	12.7	201	9	25	492.3
Brick	East Wall -cntd	Exterior walls	2.152	101.6	11,692	427	2,030	660
Air space	East Wall -cntd	Exterior walls	0.254	12	0	0	0	0
Plywood/ Particle board	East Wall -cntd	Exterior walls	0.269	12.7	1,285	31	210	0
RSI 3.5 (R20) batt	East Wall -cntd	Exterior walls	1.566	89	2,033	117	92	2622.3
Wood, Spurce, pine, fir (SPF)	East Wall -cntd	Exterior walls	0.319	38	1,354	35	809	376.72
Gypsum board	East Wall -cntd	Exterior walls	0.269	12.7	1,504	66	190	492.3
Brick	North Wall	Exterior walls	0.809	101.6	4,395	160	763	660
Air space	North Wall	Exterior walls	0.096	12	0	0	0	0
Plywood/ Particle board	North Wall	Exterior walls	0.101	12.7	483	12	79	0
RSI 3.5 (R20) batt	North Wall	Exterior walls	0.442	89	574	33	26	2622.3
Wood, Spurce, pine, fir (SPF)	North Wall	Exterior walls	0.266	38	1,129	29	675	376.72
Gypsum board	North Wall	Exterior walls	0.101	12.7	565	25	71	492.3
Brick	North Wall-Cnt	Exterior walls	1.666	101.6	9,051	330	1,571	660
Air space	North Wall-Cnt	Exterior walls	0.197	12	0	0	0	0
Plywood/ Particle board	North Wall-Cnt	Exterior walls	0.208	12.7	994	24	162	0
RSI 3.5 (R20) batt	North Wall-Cnt	Exterior walls	1.177	89	1,528	88	69	2622.3
Wood, Spurce, pine, fir (SPF)	North Wall-Cnt	Exterior walls	0.283	38	1,202	31	718	376.72

Gypsum board	North Wall-Cnt	Exterior walls	0.208	12.7	1,163	51	147	492.3
Brick	South Wall	Exterior walls	2.466	101.6	13,398	489	2,326	660
Air space	South Wall	Exterior walls	0.291	12	0	0	0	0
Plywood/ Particle board	South Wall	Exterior walls	0.308	12.7	1,472	36	240	0
RSI 3.5 (R20) batt	South Wall	Exterior walls	1.609	89	2,088	120	94	2622.3
Wood, Spurce, pine, fir (SPF)	South Wall	Exterior walls	0.551	38	2,340	61	1,397	376.72
Gypsum board	South Wall	Exterior walls	0.308	12.7	1,722	76	218	492.3
Brick	West Wall	Exterior walls	2.498	101.6	13,572	495	2,356	660
Air space	West Wall	Exterior walls	0.295	12	0	0	0	0
Plywood/ Particle board	West Wall	Exterior walls	0.312	12.7	1,491	36	243	0
RSI 3.5 (R20) batt	West Wall	Exterior walls	1.732	89	2,248	129	102	2622.3
Wood, Spurce, pine, fir (SPF)	West Wall	Exterior walls	0.457	38	1,940	51	1,159	376.72
Gypsum board	West Wall	Exterior walls	0.312	12.7	1,744	77	221	492.3
Other, 6 mil Polyethylene	West Wall	Exterior walls	0.58	6	1,643	99	1,545	0
RSI 4.9 (R28) batt	Foundation - 1	Foundation	8.267	89	14,260	820	848	2622.3
Wood, Spurce, pine, fir (SPF)	Foundation - 1	Foundations	1.258	38	5,341	139	3,190	376.72
Gypsum board	Foundation - 1	Foundations	1.359	12.7	7,598	333	962	492.3
Other, 6 mil Polyethylene	Foundation - 1	Foundations	0.63	6	1,785	107	1,678	0
Concrete, 30 Mpa, Average Flyash	Foundation - 1	Foundations	15.84	150	35,228	4,958	1,807	0
User-defined	Foundation - 1	Foundation	0.001	0.01	0	0	0	0
Wood, Spurce, pine, fir (SPF)	Foundation - 1	Foundations	2.271	38	9,643	251	5,344	376.72
Plywood/ Particle board	Foundation - 1	Foundations	1.633	12.7	7,802	190	1,273	0
Wood flooring	Foundation - 1	Foundations	0.13	1	1,950	3	4,806	0
Other, 6 mil Polyethylene	Foundation - 1	Foundations	0.77	6	2,182	131	2,051	0
Concrete, 30 Mpa, Average Flyash	Foundation - 1	Foundations	19.28	150	42,879	6,035	2,199	0
Double acrylic, Clear	small bedroom	Windows	0 -		218	54	148	0
Aluminum	small bedroom	Windows	4.1 -		283	17	137	0
Double acrylic, Clear	door window	Windows	0 -		61	15	41	0
Aluminum	door window	Windows	2.28 -		157	10	38	0
Double/double with 1 coat, Clear	living room bay	Windows	0 -		1,056	259	714	0
Aluminum	living room bay	Windows	9.36 -		646	39	664	0
Double acrylic, Clear	Patio Door	Windows	0 -		706	173	477	0
Aluminum	Patio Door	Windows	7.34 -		506	31	443	0
Double acrylic, Clear	dining room	Windows	0 -		286	70	193	0
Aluminum	dining room	Windows	4.76 -		328	20	180	0
Double acrylic, Clear	kitchen	Windows	0 -		214	53	145	0
Aluminum	kitchen	Windows	4.06 -		280	17	135	0
Double acrylic, Clear	main bathroom	Windows	0 -		59	14	40	0
Aluminum	main bathroom	Windows	2.14 -		148	9	37	0
Double acrylic, Clear	master bedroom	Windows	0 -		353	87	238	0

Aluminum	master bedroomWindows		5.42 -		374	23	222	0
Double acrylic, Clear	large bedroom	Windows	0 -		225	55	152	0
Aluminum	large bedroom	Windows	4.16 -		287	17	141	0
Double acrylic, Clear	Window - base	Windows	0 -		50	12	34	0
Aluminum	Window - base	Windows	2.18 -		150	9	32	0
Double acrylic, Clear	Window - bsmtWindows		0 -		50	12	34	0
Aluminum	Window - bsmtWindows		2.18 -		150	9	32	0
Double acrylic, Clear	Window - bdr4	Windows	0 -		50	12	34	0
Aluminum	Window - bdr4	Windows	2.18 -		150	9	32	0
Double acrylic, Clear	Window - bdr5	Windows	0 -		50	12	34	0
Aluminum	Window - bdr5	Windows	2.18 -		150	9	32	0
Double acrylic, Clear	Window - base	Windows	0 -		50	12	34	0
Aluminum	Window - base	Windows	2.18 -		150	9	32	0
Double acrylic, Clear	Window - base	Windows	0 -		50	12	34	0
Aluminum	Window - base	Windows	2.18 -		150	9	32	0
Wood	Front Door	Doors	0.15 -		393	8	457	0
Air	Front Door	Doors	0 -		0	0	0	0
RSI 3.5 (R20) batt	East Wall	Lintels	0.009	89	12	1	1	376.72
Wood, Spurce, pine, fir (SPF)	East Wall	Lintels	0.007	38	30	1	18	376.72
RSI 3.5 (R20) batt	North Wall	Lintels	0.034	89	44	3	2	376.72
Wood, Spurce, pine, fir (SPF)	North Wall	Lintels	0.029	38	123	3	74	376.72
RSI 3.5 (R20) batt	South Wall	Lintels	0.052	89	67	4	3	376.72
Wood, Spurce, pine, fir (SPF)	South Wall	Lintels	0.044	38	187	5	112	376.72
RSI 3.5 (R20) batt	West Wall	Lintels	0.009	89	12	1	1	376.72
Wood, Spurce, pine, fir (SPF)	West Wall	Lintels	0.008	38	34	1	20	376.72
					330,136	20,752	61,083	

Table I.2. Summary of the results

OPERATION: ANNUAL ENERGY CONSUMPTION & COST

Total	Electricity	Natural gas	Oil	Propane	Wood	
167,701.40	35,010.70	132,690.70	0.00	0	0	Energy use (Mj)
1,764.11	718.97	1,045.14	0.00	0	0	Cost ($CAN)

EMISSION GENERATED FROM ANNUAL OPERATION

CO2	SO2	NOx	HC	CO	PM	
6,703	34	8,066	37	1,976	223	(ton)

EMISSION IN EQUIVALENT CO2

6,704 (ton)

LIFE CYCLE ANALYSIS

	Life cycle energy use (MJ)	Life cycle emisson (eq. Ton of CO2)	Life cycle cost ($CAN)
Construction phase	330,136	20,752	61,083
Operation phase	5,031,042	201,120	24,744
Life cycle	5,361,178	221,872	85,827

Appendix J: Formulas used for volume calculations of materials

The present Appendix presents the mathematical formulas used to calculate the volumes of materials in EEE. Different formulas are used depending on the material use, i.e. in the roof, ceiling, above or below-grade walls, exposed floors, and foundation floors.

In order to facilitate presentation of formulas, each parameter imported from HOT2000 and used in the calculation is presented in italic font, e.g. *Wall height*.

1. ROOF & CEILINGS

Quantity of materials used in the construction of the roof and ceilings is calculated differently for wood frame layers compared to other continuous layers. They also depend on the type of roof construction. The volume of wood studs shown in the ceiling screen of the EEE tool accounts for all the studs used in the different ceilings, the sloped part of the roof and the gable ends. Wood studs used in lintels are considered separately in a different section. Quantities of other continuous materials such as roofing and cladding materials are calculated independently and are shown in different windows.

In the following section, the formulas used in order to calculate quantities of different materials are presented following their order of appearance in the EEE user interface.

1.1. Sheathing and cladding materials used in gable ends

EEE imports from HOT2000 the following data:

- *Area of gable ends* (m^2)

- *Thickness of sheathing material* (mm)

- *Thickness of cladding material* (mm)

The volume of materials is calculated as follows:

$$\text{Volume of sheathing material} = \textit{Area of gable ends} \times \frac{\textit{Thickness of sheathing material}}{1000}$$

$$\text{Volume of cladding material} = \textit{Area of gable ends} \times \frac{\textit{Thickness of cladding material}}{1000}$$

1.2. Sheathing and roofing materials used in sloped roof

EEE imports from HOT2000 the following data:

- *Area of sloped roof* (m^2)

- *Thickness of sheathing material* (mm)

- *Thickness of roofing material* (mm)

The volume of materials is calculated as follows:

$$\text{Volume of sheating material} = \textit{Area of sloped roof} \times \frac{\textit{Thickness of sheathing material}}{1000}$$

$$\text{Volume of roofing material} = \textit{Area of sloped roof} \times \frac{\textit{Thickness of roofing material}}{1000}$$

1.3. Continuous layer of materials used in ceilings

The following data is imported from the HOT2000 program:

- *Ceiling net area* (m^2)

- *Material thickness* (mm)

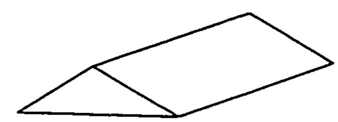
The volume of continuous materials such as gypsum board is calculated as follows:

$$\text{Volume} = \textit{Ceiling net area} \times \frac{\textit{Material thickness}}{1000}$$

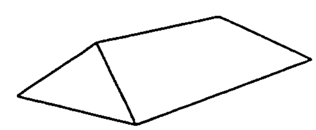
1.4. Wood studs and cavity insulation used in roof and ceilings

Formulas used in order to calculate the volume of wood studs depend on the roof construction type. Five types of roofs are used by the HOT2000 program. These are [43]:

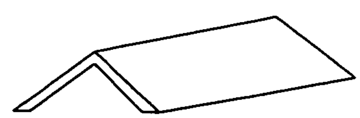
- Attic/Gable, which is a ceiling with an attic above it where two opposite sides of the roof are sloped and the two ends are vertical.



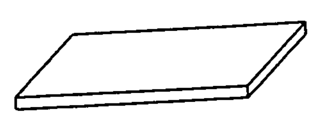
- Attic/Hip, which is a ceiling with an attic above it where all four sides of the roof are sloped.



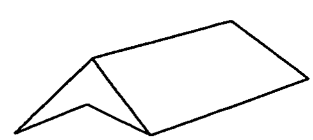
- Cathedral, which has a high, sloped ceiling with no attic space, just a vent along the roof surface. The roof surface and the ceiling surface are parallel.



- Flat, which has no slope.



- Scissor, which has a high, sloped ceiling generally with an air cavity. The roof surface and the ceiling surface are not parallel.



The volume of wood studs calculated includes the volume of studs used in ceilings, sloped roof and gables ends. The data required in order to perform calculations is the following:

- *roof construction type* and *roof slope*
- *ceiling length* (m) and *ceiling area* (m^2)
- *studs spacing* (mm), *studs thickness* (mm), and *studs width* (mm)
- *total number of windows* and their characteristics (*window width* (m), *window height* (m) and *number of windows* of the same type)

Some of these parameters are differently defined in HOT2000 depending on the *roof construction type*. For all roof types (cathedral, attic, etc.) the *ceiling area* defined as input in HOT2000 by the user, is the ceiling area, not the roof area. For cathedral and scissor roofs, the *ceiling area* is the actual area, not the horizontal projection of the ceiling area. The *ceiling length*, is one of two lengths depending on.the *roof construction type*. If the *roof construction type* selected is cathedral or flat, the required *ceiling length* is the base length (perpendicular to the joists). If the *roof construction type* selected is attic gable, attic hip, or scissor, the required *ceiling length* is "the total length of the eave along which there may be compression of the insulation" [43]. For each *roof construction type*, except flat roof, the *roof slope* is greater than 0.

a- The calculation procedure starts first by counting the number of studs in the ceiling, composed of: (N) the number of studs which have a length equal to the ceiling width, and (Nw_i) the number studs located at the level of each window i (with a length equal to the ceiling width minus the height of the given window).

$$\text{N} = \text{Rnd}\left(\frac{\left(\text{Base lenght} - \sum_i Width\ of\ window_i\right) - \left(\frac{Stud\ thickness}{1000}\right)}{\frac{Stud\ spacing}{1000}}\right) + 1$$

$$\text{Nw}_i = \text{Rnd}\left(\frac{Width\ of\ window_i - \left(\frac{Stud\ thickness}{1000}\right)}{\frac{Stud\ spacing}{1000}}\right) + 1$$

Where, the base length of the ceiling is perpendicular wood studs and Rnd (23.1) + 1 = 24 for instance.

The volume of studs installed in the ceiling is calculated as follows:

$$\text{Studs volume}_{\text{ceiling}} = \left(\text{N} \times \text{Ceiling width} \times \frac{Studs\ width}{1000} \times \frac{Studs\ thickness}{1000}\right) +$$
$$\sum_i \left[\text{Nw}_i \times \left(\text{Ceiling width} - Window\ width - \frac{Studs\ width}{1000}\right) \times \frac{Studs\ width}{1000} \times \frac{Studs\ thickness}{1000}\right]$$

Table 1.1. shows the formulas used to calculate the base length and ceiling width for each *roof construction type*.

Table 1.1. Formulas used to calculate the base length and ceiling width for each *roof construction type*.

Roof type	**Base length**	**Ceiling width**
Flat	*Ceiling length*	$\frac{Ceiling\ area}{Ceiling\ length}$
Cathedral	*Ceiling length*	$\frac{Ceiling\ area}{Ceiling\ length}$
Gable	$\frac{Ceiling\ length}{2}$	$2 \times \frac{Ceiling\ area}{Ceiling\ length}$
Scissor	$\frac{Ceiling\ length}{2}$	$2 \times \frac{Ceiling\ area}{Ceiling\ length}$
Hip	Base length is obtained from equation (E)	$\frac{Ceiling\ area}{\text{Base length}}$

$$\text{Base length}^2 \times (\frac{\textit{Ceiling length}}{2}) \times \text{Base length} + \textit{Ceiling area} = 0 \qquad \text{(E)}$$

Equation (E) was obtained by combining the following formulations:

$$\textit{Ceiling area} = \text{Base length} \times \text{Ceiling width} \qquad \text{, and}$$

$$\text{Ceiling width} + \text{Base length} = \frac{\textit{Ceiling length}}{2}$$

Equation (E) always have a solution since Δ is always positive. Where,

$\Delta = \textit{Ceiling length}^2 - 4 \times \textit{Ceiling Area}$

$\Delta \geq 0$ since the biggest area of a square and a rectangle having the same perimeter is the one of the square.

b- The second stage in the calculations accounts for the wood studs used in the sloped roof.

The sloped roof is defined by its *sloped roof area Asr* and the *roof slope RS.*

The following general formula is used in order to count the number of studs Nsr used in the sloped part of the roof.

$$\text{Nsr} = \text{Rnd}\left(\frac{\text{Base length} - \frac{\textit{Studs thickness}}{1000}}{\frac{\textit{Studs spacing}}{1000}} \right) + 1$$

Where, the base length is the length of the roof perpendicular to the studs.

The corresponding volume of studs constituting the roof is obtained as follows:

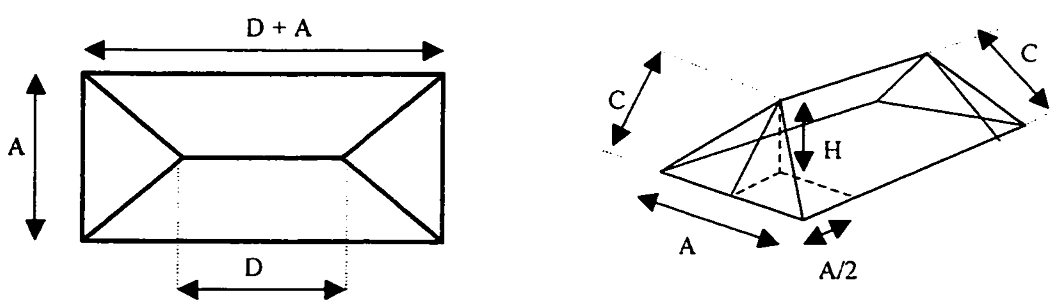
$$\text{Studs volume}_{\text{Sloped Roof}} = \text{Nsr} \times \text{Roof width} \times \frac{\textit{Studs thickness}}{1000} \times \frac{\textit{Studs width}}{1000}$$

The base length and roof width depend of the *roof construction type* and are calculated as shown in Table 1.2.

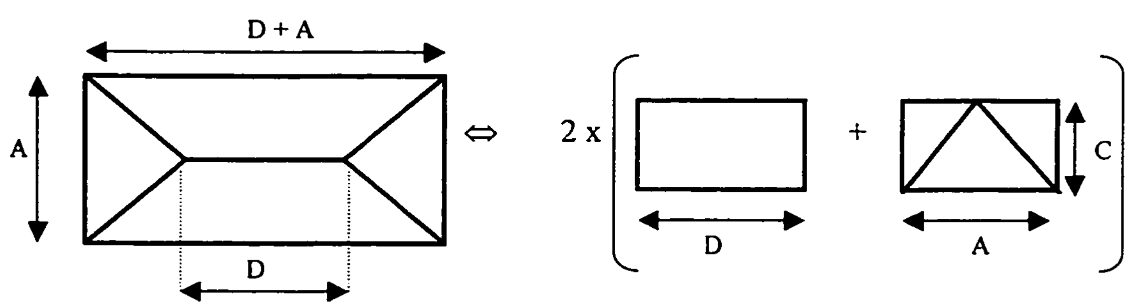
Table 1.2. Formulas used to calculate the base length and roof width depend of the *roof construction type*

Roof type	**Base length**	**Roof width**
Gable	$\frac{Ceiling\ length}{2}$	$\frac{2 \times Ceiling\ area}{Ceiling\ length} \times \sqrt{(1 + RS^2}$
Scissor	$\frac{Ceiling\ length}{2}$	$\frac{2 \times Ceiling\ area}{Ceiling\ length} \times \sqrt{(1 + RS^2}$
Hip	$\frac{Ceiling\ length}{2} + D$	$\frac{A}{2} \times \sqrt{1 + RS^2}$

Where D and A are defined as shown in the following Figure for a hip roof.



The area of the sloped roof can be obtained using the following geometric equivalency:



A and D can be determined using the following equalities:

(1) $$2 \times A + D = \frac{Ceiling\,length}{2}$$

(2) $$C = \frac{A}{2} \times \sqrt{1 + RS^2}$$

(3) $$Asr = 2 \times C \times (A + D)$$

By substituting D and A in equation (3), the following 2nd degree equation in A is obtained:

(E) $$\sqrt{1 + RS^2} \times A^2 - \frac{Ceiling\,length}{2} \times \sqrt{1 + RS^2} \times A + Asr = 0$$

Equation (E) always have solutions since $\Delta \geq 0$. In fact,

$$\Delta = \frac{Ceiling\,length^2}{4} \times (1 + RS^2) + \left(4 \times \sqrt{1 + RS^2} \times Asr\right)$$

$$\Leftrightarrow \Delta = 4 \times (1 + RS^2) \times \left[\frac{Ceiling\,length^2}{16} - \frac{Asr}{\sqrt{1 + RS^2}}\right]$$

Δ is always positive since $\frac{Ceiling\,length^2}{16}$ is always superior to $\frac{Asr}{\sqrt{1 + RS^2}}$. In fact, the area of a rectangular ceiling corresponding to the given sloped roof is equal to $\frac{Asr}{\sqrt{1 + RS^2}}$ and its perimeter is equal to *Ceiling length*. This area is always inferior to the area of a square of the same perimeter, i.e. of area equal to $\frac{Asr}{\sqrt{1 + RS^2}}$.

The resolution of this equation provides the value of A. Then, D can be obtained using equality (1) linking A to D. Then Base length and Roof width can be calculated.

- The calculations of the roof width for gable and scissor roofs are as follows:

Figures 1.1. and 1.2. show respective sections of a gable roof and a scissor roof. In the Figures, Wsr represents the Roof width, E the roof height, RS the roof slope, and F the ceiling width or its horizontal projection in the case of a scissor roof.

In HOT2000, it is assumed that the ceiling slope in a scissor roof is half the roof slope. This same assumption is maintained for the proposed volume calculations.

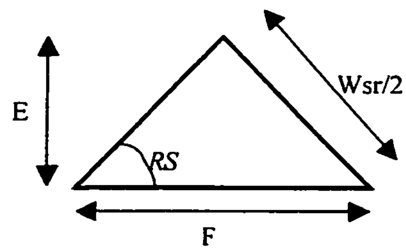


Figure 1.1. Section of a gable roof

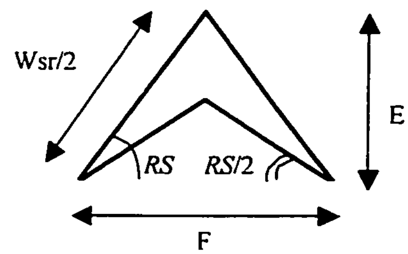


Figure 1.2. Section of a scissor roof

Since,

$$F = \frac{2 \times Ceiling\ area}{Ceiling\ length} \qquad \text{and,}$$

$$\frac{Wsr}{2} = \frac{F}{2} \times \sqrt{1 + RS^2}$$

Wsr can be expressed as follows:

$$Wsr = \frac{Ceiling\ area}{\frac{Ceiling\ length}{2}} \times \sqrt{1 + RS^2}$$

c- The final step in wood studs calculations accounts for the studs used in gable ends in the case of cathedral, gable and scissor roofs.

For this calculation we assume that if only one ceiling is defined by the user then the roof has two gable ends. Otherwise, if more than one ceiling is defined by the user, then the number of gable ends is equal to the *number of ceilings*. This assumption takes into account the intersection of different parts of the roof. In flat and hip roofs there are no gable ends and therefore the corresponding area in nil.

The calculation of wood studs in gable ends starts by counting the number of studs N in the gable ends, using the following general formula:

$$N = \frac{F - \frac{\textit{Studs thickness}}{1000}}{\frac{\textit{Studs spacing}}{1000}}$$

The volume is then obtained as follows:

$$\text{Studs volume}_{\text{Gable ends}} = N \times \frac{E}{2} \times \text{Number of gable ends} \times \frac{\textit{Studs thickness}}{1000} \times \frac{\textit{Studs width}}{1000}$$

Where E and F are defined as shown in Figures 1.3. and 1.4. respectively for a scissor roof and a cathedral or gable roof.

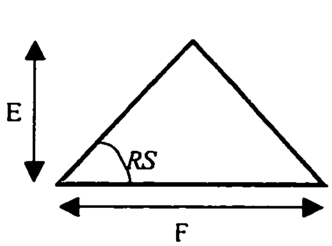


Figure 1.3. Section of a cathedral or gable roof

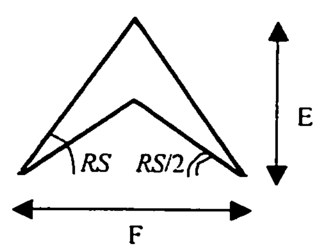


Figure 1.4. section of a scissor roof

Values of E and F depend on the *roof construction type* and are obtained as shown in Table 1.3.

Table 1.3. Formulas used to calculate E and F depending on the *roof construction type*

Roof type	**E**	**F**
Cathedral	$RS \times \dfrac{Ceiling\ area}{Ceiling\ length}$	$\dfrac{Ceiling\ area}{Ceiling\ length}$
Gable	$RS \times \dfrac{Ceiling\ area}{Ceiling\ length}$	$2 \times \dfrac{Ceiling\ area}{Ceiling\ length}$
Scissor	$\dfrac{Ceiling\ area}{Ceiling\ length} \times \dfrac{RS}{\sqrt{1+RS^2}}$	$2 \times \dfrac{Ceiling\ area}{Ceiling\ length}$

The values of E and F were obtained as follows:

- For cathedral and gable roofs,

$$\left.\begin{aligned} F &= \frac{Ceiling\ area}{Ceiling\ length} \\ RS &= \frac{E}{\frac{F}{2}} \end{aligned}\right\} \quad E = RS \times \frac{F}{2} = RS \times \frac{Ceiling\ area}{Ceiling\ length}$$

- For scissor roofs,

$$\left.\begin{aligned} F &= \frac{Ceiling\ area}{\frac{Ceiling\ length}{2} \times \sqrt{1+RS^2}} \\ RS &= \frac{E}{\frac{F}{2}} \end{aligned}\right\} \quad E = RS \times \frac{F}{2} = \frac{RS}{\sqrt{1+RS^2}} \times \frac{Ceiling\ area}{Ceiling\ length}$$

The volume of cavity materials can be obtained as follows:

$$\text{Volume} = \textit{Ceiling net area} \times \left(\frac{\text{Studs volume}_{\text{ceiling}}}{\frac{\textit{Studs thickness}}{1000}} \right) \times \frac{\textit{Material thickness}}{1000}$$

2. WALLS, FLOOR HEADERS, FOUNDATION WALLS, AND PONY WALLS

A wall is defined in HOT2000 given its *height*, *perimeter* (or length), its *area*, and *net area* and also the *number of intersections* with an interior wall, and the *number of corners*. Information about each opening (window or door) in the wall is also provided, i.e. *width*, *height* and *number of openings* of the same type (for windows only).

The volumes of wood studs in exterior walls, foundation walls, and pony walls are differently calculated depending on the layer type. The formulas used for the calculations are detailed in this section.·

2.1. Volume calculations of wood studs and cavity insulation used in walls, floor headers

Volumes of framing material and cavity material are calculated as follows:

The wood frame layer is defined in HOT2000 given the *thickness of the cavity material*, the *thickness and width of studs* used and their *spacing*, the *number of top and bottom plates*, the *number of studs at corners and intersections* with interior walls, and the *number of studs at the level of windows*. The *type of lintels* and their *dimensions* are also described.

a- In order to calculate the volume of wood studs used in a wood frame layer, the number of studs in the wall is first determined. This number is the sum of the number of studs located at the windows and doors level (Nw) as well as the number of studs of length equal to the wall height and located elsewhere (N). The following formula is used to calculate N.

$$N = \frac{Wall\ Perimeter - \sum_i Window\ width_i - \frac{Stud\ thickness}{1000}}{\frac{Stud\ spacing}{1000}}$$

Nw is calculated for each window i as follows:

$$Nw_i = \frac{Window/door\ width_i - \frac{Stud\ thickness}{1000}}{\frac{Stud\ spacing}{1000}}$$

Hence, the volume of studs in the wall can be calculated as follows:

$$\text{Studs volume} = \left[N \times \frac{Stud\ thickness}{1000} \times \frac{Stud\ width}{1000} \times Wall\ height\right] +$$
$$\sum_i Nw_i \times \frac{Stud\ thickness}{1000} \times \frac{Stud\ width}{1000} \times \left[Wall\ height\ -(Window/door\ height_i + \frac{stud\ width}{1000})\right]$$

b- Second, the volume of studs used as top and bottom plates, at the corners and intersections, and at the level of openings are accounted for.

- The volume of studs used as top and bottom plates is obtained as:

$$\text{Studs volume} = Nbr\ of\ top\ \&\ bottom\ plates \times Wall\ perimeter \times \frac{Stud\ thickness}{1000} \times \frac{Stud\ width}{1000}$$

- The volume of studs at corners and intersections is calculated as follows:

$$\text{Studs volume} = \left[(\textit{Ns/corners} \times \textit{Nbr of corners}) + (\textit{Ns/intersections} \times \textit{Nbr of intersections}) \right] \times \textit{Wall height} \times \frac{\textit{Stud width}}{1000} \times \frac{\textit{Stud thickness}}{1000}$$

Where *Ns/corners* represents the number of studs at corners, and *Ns/intersections* the number of studs at intersections with interior walls.

At the level of windows and doors, the studs may be doubled. In that case, the additional studs are calculated as follows:

$$\text{Studs volume} = \textit{Number of windows} \times 2 \times \textit{Wall height} \times \frac{\textit{Stud thickness}}{1000} \times \frac{\textit{Stud width}}{1000}$$

c- The total volume of studs is hence obtained as the sum of all the volumes calculated including additional studs in bottom and top plates, at the corners and intersections with an interior wall, and at the level of windows if double studs are used.

The volume of cavity material is calculated as follows:

$$\text{Volume} = \left[\textit{Wall net area} - \left(\frac{\text{Studs volume}_{\text{wall}}}{\frac{\textit{Stud thickness}}{1000}} \right) \right] \times \frac{\textit{Material thickness}}{1000}$$

2.2. Volume calculations of material used in continuous layers

The volume of continuous layers of materials along the wall is obtained as the product of the *wall net area* by the *thickness of the given material.*

Floor headers can be attached to a given wall or foundation. In both cases, the volumes of corresponding materials are calculated assuming the floor header as a wall. In reality the floor header is the continuity of an intermediate floor which means that the framing of floor headers is horizontal. The assumption used for this estimation is intended to into account for materials used in floor headers in an approximate way, since the import from HOT2000 does not give any information about intermediate floors and since the height and the depth of floor headers are of the same range.

3. EXPOSED FLOORS AND FOUNDATION FLOORS

Each exposed floor or foundation floor is defined as a superposition of layers of materials, and given its *length* (m) and *area* (m^2). The *length* is perpendicular to the studs run. The methods used to calculate volume of materials used in each layer of a floor are similar to the one used for walls and ceilings. They are detailed below:

3.1. Volume calculations of wood studs and cavity insulation

A wood frame layer is defined given the cavity material and its *thickness*, and the framing material and its *thickness*, *width*, and *spacing*.

The volume calculations start by counting the number of studs (N) used along the floor length.

$$\mathrm{N} = \frac{\mathit{Floor\ length} - \dfrac{\mathit{Stud\ thickness}}{1000}}{\dfrac{\mathit{Stud\ spacing}}{1000}}$$

The studs volume is therefore obtained as follows:

$$\text{Studs volume} = \mathrm{N} \times \frac{\mathit{Floor\ area}}{\mathit{Floor\ length}} \times \frac{\mathit{Stud\ thickness}}{1000} \times \frac{\mathit{Stud\ width}}{1000}$$

The volume of cavity material is calculated as :

$$\text{Cavity volume} = \left[\textit{Floor area} - \frac{\text{Studs volume}}{\frac{\textit{Stud thickness}}{1000}} \right] \times \frac{\textit{Material thickness}}{1000}$$

3.2. Volume calculations of materials used in continuous layers

Volume of a material is obtained as the product of the *floor area* by the *thickness of the material.*

4. LINTELS

Volume of materials used in lintels are calculated as follows:

The volume of insulation is calculated as the product of the *lintel area* by the *insulation thickness*.

The volume of wood studs is obtained as the product of the *number of layers of wood studs* (double, triples..etc) by the *lintel area* and the *stud thickness*.

5. OTHERS

Other house components such as windows and doors are taken into account in the calculations of embodied energy, embodied emissions and initial cost. The volume calculations are not performed by the EEE tool though. This is due to the lack of precise dimensional information that would enable the estimation of the bill of materials used in window frames, window glazing, door cavity material and materials used in exterior sides of the door. The user must enter the volume of these materials and select the appropriate values of embodied energy, embodied emissions and unit cost in order to account for these house components.