A 3D CAD model of embodied energy for assessment of sustainable construction

S.N. Tucker
CSIRO Division of Building, Construction and Engineering, Melbourne, Australia, and Department of Building and Construction Economics, RMIT, Melbourne, Australia

M.D. Ambrose
CSIRO Division of Building, Construction and Engineering, Melbourne, Australia

C. Mackley
University of Technology, Sydney, Australia

Abstract

The concept of sustainable development of human activities has highlighted the environmental impacts of buildings, particularly the use of energy for construction and operation and the resulting contributions to carbon dioxide (CO$_2$) in the atmosphere from the burning of fossil fuels for energy generation. A system to estimate energy used in creating buildings, and the resultant CO$_2$ emissions, direct from 3D CAD drawings has been developed to calculate embodied energy, CO$_2$ emissions and mass for all materials in a building, and to provide graphing and tabulation functions which call upon CAD information to provide a wide variety of breakdowns of energy and CO$_2$ by element category, material category, and individual materials. The significance of initial embodied energy so estimated is compared with the operational energy over the whole life of a building calculated using other standard models based on heating and cooling loads. This paper discusses this example of integration of evaluation methods from CAD information as well as the operation, uses, limitations, benefits and future role for this type of analysis in designing and managing for sustainability of construction.

Keywords: Embodied energy, life cycle energy, sustainable construction, 3D CAD
1 Introduction

The concept of sustainable development of human activities has highlighted the environmental impacts of buildings, particularly the use of energy for construction and operation and the resulting contributions to carbon dioxide (CO₂) in the atmosphere from the use of fossil fuels for energy generation. A system to evaluate energy used in creating buildings, known as embodied energy, and the resultant CO₂ emissions is needed to complement the models for estimating operating energy of buildings.

To estimate the amount of energy embodied in a building; and the resultant greenhouse gas emissions generated through energy consumed in these processes, prototype software was developed for the CAD package APDesign to calculate the material quantities, embodied energy and greenhouse gas emissions directly from a 3D CAD model [1]. This model provides quantitative values to assist in determining the environmental impact of alternative designs and building materials at the design stage of a building. The ultimate aim of the software is to integrate it with an existing operating energy model to create a procedure which design professionals would use to assess alternative designs in terms of the amount of energy required to construct and operate a building and the resultant CO₂ emissions from that energy generation.

This paper discusses this example of integration of evaluation methods from CAD information as well as the operation, uses, limitations, benefits and future role for this type of analysis in designing and managing for sustainability of construction.

2 Embodied energy

Embodied energy is defined as the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in supporting functions. Buildings have a significant impact on the environment due to the energy embodied in construction materials.

To be able to quantify the energy embodied in the construction of a building, the quantities of materials must first be estimated through a process of disaggregation to a level of detail which allows for the separation of components into their principal materials. Energy intensities of each material can then be multiplied by the quantities of individual materials and the products aggregated to obtain the total for each material, element or whole building.

Embodied energy intensities were derived from input-output tables and other national and international studies. To obtain an accurate and reliable database of embodied energy and CO₂ intensities for all materials used in buildings is an enormous task in itself and is a necessity for detailed comparisons of materials. The main requirement of embodied energy calculations at the design stage is obtaining accurate and useable material quantities and then combining them with currently available embodied energy and CO₂ values.

Previous investigations have calculated the total embodied energy from individual houses (e.g. [2],[3],[4]) and Pullen [5] has formalised the process in a spreadsheet which links to a series of databases for embodied energy calculations for houses. The energy used in the construction process is not of a magnitude sufficient to effect the alternative choices but should be included in the total [6].
3 3D CAD model

The chosen approach to fast and practical estimates of embodied energy, CO₂ emissions and mass values directly from 3D CAD drawings at the design stage requires both 3D CAD and accurate quantity functions to calculate embodied energy values from a database of embodied energy intensities. To avoid duplicating the techniques for estimating quantities from first principles, an existing computer program which provided many of the required functions was selected and then extended. The chosen software was a program called APDesign, a CAD package developed and used extensively in Australia, Europe, Canada and the USA.

APDesign is an AutoCAD based system, tailored to creating 3D models of building designs using a large inventory of standard and custom building items. All building items are entered into the drawing from an object database. Unlike the AutoCAD basis of the system, each line, or group of lines, on the drawing is a known building item, i.e. an identifiable object, with attached functions and associated attributes which relate to the drawing object. A typical detailed drawing is shown in Figure 1.

It was necessary to extend the capabilities of APDesign to further levels of detail beyond the bills of quantities approach which was successfully implemented in the original software. Every item needed to be further disaggregated into its component materials and a generic approach developed to achieve such extra detail with minimal effort. The resulting software makes it a very simple and straightforward procedure for users to access and utilise the embodied energy analysis techniques.

The embodied energy module is a specialist tool created to allow embodied energy values, CO₂ emission values and building mass to be calculated automatically from the 3D CAD drawing. The embodied energy, CO₂ and mass intensity values are stored in a material database which is linked back to the building item database of APDesign while the relationships (known as formula sets) are separate databases.

The building item database as found in APDesign consists of items used by the construction industry as 3D objects. The database comprises only the critical design information (mainly dimensional parameters) needed to create each item (walls, doors, windows, footings, etc).

The formulas are a crucial part of the process to calculate embodied energy. They are used to calculate the quantities of specific materials associated with each building item by using dimensional parameters from the detail of the items and the primary graphic, as held in the building item database. Each building item is made up of one or more materials, each of which has a separate embodied energy, CO₂ and mass value. Therefore, it is necessary to split each building item into a group of materials by associating with that building item a group of formulas, known as a formula set, from which the amount of each material can be calculated. The formula sets are generic, i.e. they can be used interchangeably for similar building items, thus reducing the number of formula sets needed.
The material database contains the materials and the embodied energy, CO₂ and mass data associated with them. At present, the materials database contains around 500 materials. These are divided into 20 material categories such as steel, aluminium, timber, plaster, and so on.

The prototype software is the first system which has attempted to design a framework for fast and useable estimations of embodied energy, CO₂ emissions and mass values directly from 3D CAD drawings at the design stage and the future possibility of simulating various design options for comparative purposes.

3.1 Results
The detailed calculated values, totals and percentages of the embodied energy, CO₂ and mass are tabulated and sorted in four ways: by description - the same fixed order as used for the element and material categories; by embodied energy - in descending order of estimated embodied energy values; by CO₂ emissions - in descending order of estimated CO₂ emissions values; and by mass - in descending order of mass values. The mass values are displayed because they are calculated as an essential step in the conversion from 3D CAD volumes to the units of mass in which embodied energy are normally expressed.

Graphs enable users to quickly see the relatiosivities of different building items and materials with regard to their embodied energy, CO₂ and mass values and also enable comparisons of different construction techniques and materials, e.g. Figure 2 shows the CO₂ emissions due to embodied energy by material category. The values shown are for a hypothetical project.

4 Operating energy
While the principles of energy efficient house designs have been known for some time, only a small proportion of new houses are energy efficient in Australia. Typical annual energy usage in Australian houses is shown in Table 1 [Table B.1 NS W/ACT Residential Sector Energy Use. 7, 8]. The annual heating and cooling loads are the most significant contributor and dependent upon the design of the dwelling.

<table>
<thead>
<tr>
<th>Usage</th>
<th>Annual energy consumption (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating and cooling</td>
<td>64.44</td>
</tr>
<tr>
<td>Water heating</td>
<td>34.53</td>
</tr>
<tr>
<td>Cookina</td>
<td>15.42</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>15.45</td>
</tr>
<tr>
<td>Appliances</td>
<td>7.67</td>
</tr>
<tr>
<td>Lighting</td>
<td>6.53</td>
</tr>
<tr>
<td>Other</td>
<td>13.26</td>
</tr>
<tr>
<td>Total</td>
<td>157.30</td>
</tr>
</tbody>
</table>

Table 1 Typical annual housing energy consumption
4.1 Nationwide House Energy Rating Scheme (NatHERS)

The Nationwide House Energy Rating Scheme rates the heating and cooling energy efficiency of a dwelling with a value from zero to five stars [9]. In at least one State of Australia, a four star rating is now mandatory, superseding the minimum insulation levels for walls, floors and ceiling. The dwelling rating takes into account the appropriate local climatic conditions, of which there are 27 zones in Australia. The NatHERS simulation software package predicts the temperature inside a dwelling 24 hours a day, 365 days a year, calculates the amount of energy needed to maintain temperatures within the desired comfort range and assigns a star rating.

5 Life cycle energy

The embodied energy of different types of dwelling construction and energy efficiency in the Australian Capital Territory have been compared to the annual operational energy as calculated by the Nationwide House Energy Rating Scheme. The basic dwelling was that of a single family house with changes made only to accommodate the differences between timber cladding, standard brick veneer and cavity brick construction and the specific requirements necessary to meet zero to five star ratings as defined by the NatHERS software. Many elements remained constant throughout the options; e.g. roof, windows, wall, floor and ceiling finishes, sanitary fixtures and plumbing, water supply, space heating, electric light and power. The ratings were increased largely by insulative measures (Table 2).

<table>
<thead>
<tr>
<th>Starring</th>
<th>Timber</th>
<th>Brick veneer</th>
<th>Cavity brick</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No insulation</td>
<td>No insulation</td>
<td>No insulation</td>
</tr>
<tr>
<td>1</td>
<td>PLUS R1.0 insulation to underside of floor, R2.0 entire ceiling</td>
<td>PLUS R1.0 insulation to entire ceiling</td>
<td>PLUS R1.0 insulation to entire ceiling</td>
</tr>
<tr>
<td>2</td>
<td>PLUS R1.5 to external walls</td>
<td>PLUS R0.5 to external walls</td>
<td>CHANGE ceiling to R2.5</td>
</tr>
<tr>
<td>3</td>
<td>CHANGE underfloor to R1.5, ceiling to R2.0, external wall to R2.5, PLUS external blinds, seal 85% of windows</td>
<td>CHANGE ceiling to R1.5, external wall to R1.5</td>
<td>PLUS R1.0 to external walls</td>
</tr>
<tr>
<td>4</td>
<td>CHANGE underfloor to R3.0, external walls to R3.0, and ceiling to R3.5</td>
<td>CHANGE external walls to R2.0, ceiling to R2.5, ADD R1.0 to around slab</td>
<td>CHANGE external walls to R2.0, ADD R1.0 to ground slab</td>
</tr>
<tr>
<td>5</td>
<td>CHANGE to double glazing all windows, re-orient dwelling to north, seal downlights</td>
<td>CHANGE to double glazing all windows, ceiling to R3.0</td>
<td>CHANGE to double glazing all windows, ceiling to R3.5, ADD external blinds</td>
</tr>
</tbody>
</table>

Table 2 Insulative measures to achieve star ratings in a single family dwelling

5.1 Comparison of embodied and operating energies

Initial results show that

- it is not necessary to have heavy construction to achieve increases in operational energy efficiency for a dwelling (Figure 3, Figure 4),
- the timber dwelling required the greatest increase in embodied energy to achieve a 5 star rating (42% increase) from a 0 star rating (Figure 3),
the largest incremental increases in embodied energy occurred when stepping up from a 4 star rating to a 5 star rating (Figure 3),

conversely, very little additional embodied energy is required to raise the star rating from 0 or 1 to the next highest rating (Figure 3),

the ratio of embodied energy to annual operating energy increased dramatically as the star rating increased mainly because of the rapid decline in operating energy (Figure 4), and

the importance of embodied energy in a life cycle model of energy becomes significant (equal to 20 years of operating energy and 20% of life cycle energy for a dwelling life of 80 years) for 4 star rating and above (Figure 4).

**6 Uses**

The embodied energy model has been developed as an evaluative tool for assessing the comparative embodied energy impacts of alternative materials to assist in determining the overall environmental impact (as measured by embodied energy or CO₂ emissions due to energy use) of alternative design and building materials at the design stage of a building. It provides a designer with a measure of the total environmental impact of a building or component from a perspective never before undertaken.

Designers and quantity surveyors are familiar with the elemental cost planning approach to building de-composition and, as it is an accepted analytical approach to building design, the same approach facilitates comparisons between embodied energy impacts and building costs of elements of building, not individual materials. The effect of “trade-offs” should become apparent. For example, a particular insulating material may incur high embodied energy impacts in terms of product manufacture, but require little energy to install and maintain and it may enable greater energy savings to be achieved in the operation of air cooling or heating systems.

Embodied energy impacts are best studied at an early stage in the design process of buildings and should focus on the combinations of the main contributors to the totals for the building. The effect of using alternative materials on the total embodied energy and annual operating energy of a building, can most readily be investigated at this design stage, preferably before any major design decisions are taken.
The ability to perform any analysis work direct from CAD drawings is a relatively new concept and one that will probably be utilised more as systems are developed with more analysis and detailed studies. Likewise, the concept of embodied energy is relatively new and this program is one of the first to attempt to provide a simple and effective methodology for performing embodied energy calculations. The program is the first, as far as is known, to attempt to calculate quantities of every material in a building (rather than items which can be costed) and thus the first to estimate embodied energy direct from a 3D CAD drawing.

7 Benefits

The provision of fast environmental evaluations of embodied and operating energies and CO$_2$ of whole buildings is a major benefit in evaluation of alternative designs. It requires little additional effort by designers, architects and quantity surveyors to perform embodied energy and CO$_2$ calculations. The 3D CAD model also allows users to compare the embodied energy and CO$_2$ for parts of a building, if required.

This approach identifies the main contributors of embodied energy and CO$_2$, by element and material categories so that designers can concentrate on the areas where gains are likely to be most easily achieved and provides detailed material breakdown of building elements for other environmental assessment procedures. The various multi-level analysis options provide users with a highly flexible method for obtaining the data required for analysis and decisions.

The embodied energy total provides an energy value for the whole building on the same basis as operating energy for life cycle energy assessments and provides a method of assessing trade-offs between more energy intensive materials and less energy requirements for heating and cooling over the life of a dwelling.

There are a number of steps to be undertaken before a practical life cycle energy model can be made available to industry practitioners, and these steps include:

- development of the prototype embodied energy and CO$_2$ emission module to a commercial version, as has been done with the NatHERS software.
- expansion of the embodied energy and CO$_2$ database to cover construction energy and most materials and items commonly found in buildings.
- linking of the embodied energy module to the operational energy model in order to represent a total life-cycle (or ‘cradle to grave’) view of the energy impacts of dwellings.

8 Integration of evaluation methods

The embodied energy module in 3D CAD is an example of integration of a new analysis need (embodied energy) with an existing need (quantities of materials) based on an object oriented approach to specification of building items. Additional databases were created and additional analytical tools were developed to complete the integration. The effort required by users to apply such models is then only minimal. This is but a first step to implementing a life cycle energy model (and other applications) which includes the existing operating energy models.
9 Conclusion

Embodied and operating energy and CO$_2$ emissions are becoming important factors in the built environment and with the possibility of legislative requirements and standards, the ability to perform accurate calculations is essential. The prototype embodied energy software is the first example of a simple, yet effective CAD based tool to perform these calculations directly from quantities of individual components of a building. The complementary NatHERS operating energy model is an excellent example of a practical tool for analysis of an environmental impact of a dwelling. The two models both allow designers to undertake a sophisticated analysis on their designs and to compare alternative design solutions, quickly and effectively. There is an enormous potential for using 3D CAD based tools for analysis work, not only for embodied and operating energy, but for a range of environmental areas as well.

10 Acknowledgments

The prototype embodied energy software would not have been possible without the participation and guidance from a dedicated team of developers and researchers from the CSIRO Division of Building, Construction and Engineering in partnership with Cedar Enterprises, RMIT University and Wilde and Woollard and with financial support from the Energy Research and Development Corporation (ERDC).

11 References