Environmental Life Cycle Assessment in an Integrated CAD Environment: The Ecologue Approach

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Abstract: Construction and operation of buildings is a major cause of resource depletion and environmental pollution. Computational performance evaluation tools could support the decision making process in environmentally responsive building design and play an important role in environmental impact assessment, especially when a life cycle assessment (LCA) approach is used. The building domain, however, presents notable challenges to the application of LCA methods. For comprehensive environmental impact analysis to be realized in a computational support tool for the building design domain, such tools must *a*) have an analysis method that considers the life cycle of building construction, operation, and decommissioning, *b*) have a representation that is able to accommodate the data and computability requirements of the analysis method and the analysis tool, and c) be seamlessly integrated within a multi-aspect design analysis environment that can provide data on environmentally relevant building operation criteria.

This paper reviews the current state of assessment methods and computational support tools for LCA, and their application to building design. Then, the implementation of an application (ECOLOGUE) for comprehensive computational assessment of environmental impact indicators over the building life cycle is presented. The application is a component in a multi-aspect space-based CAD and evaluation environment (SEMPER). The paper describes the use and typical results of ECOLOGUE system via illustrative examples.

1. BACKGROUND

1.1 Introduction

ECOLOGUE was conceived to provide design decision support in environmental impact assessment. Computational tools can play an important role in the environmental impact assessment of a service, product or process especially when a life cycle assessment (LCA) approach is used. LCA requires extensive data collection for each component contained in or each process operating within the boundaries of the assessment. The typical building contains hundreds of products from different manufacturers, which are assembled in ways often unique to an individual building. The designer must be able to acquire, store, organize, and manipulate the data for the components such that it can be used in the required calculations for the situation in question. Computational support tools have the potential to expand the breadth and depth of the information easily available for an assessment. Applications, such as spreadsheets and databases that are stand-alone can be used to store and compute the impact values. To use them in an iterative design task, the designer must, most probably manually, modify and re-enter the building description as the design evolves. If multiple evaluation tools are required, the model must be converted into the respective format. The effort involved in input is a partial reason for the lack of substantive, widespread use of performance simulation applications in the building design industry.

A design environment with integrated evaluation modules would allow the designer to evaluate multiple aspects of a building's performance from the early design stages while describing the building's characteristics to a system only once. This is particularly important for a life cycle environmental impact assessment for the following reasons. A LCA that considers the building during operation can use integrated simulation modules that estimate loads for heating and cooling, lighting, and equipment. The impact assessment module can then determine the impacts of these loads. Alternative solutions, even if similar from a design standpoint, can have significantly different environmental effects. In an integrated environment, alternatives are more straightforward to compare, and evaluations can be accomplished expeditiously. The use of integrated evaluation tools that are able to provide feedback in early design stages can influence siting, orientation, and massing decisions that often effect environmental impact. These types of design changes are more difficult to carry out when the design is more resolved. The integrated analysis and CAD tools of the SEMPER environment allows the user to seamlessly step from design to LCA and back again, while having access to and input from operational phase analysis packages such as energy, airflow, HVAC, and lighting.

Considering the importance of the life cycle of buildings to environmental impact, the data collection and processing requirements, and the multi-disciplinary nature of the evaluations involved in building LCA, the development of integrated computational support tools is one way to provide meaningful design decision support.

1.2 Environmental Analysis Method Overview

The interest in the environmental impacts of products and processes has led to the development of various methods and software tools to assess these effects within the framework of LCA. Early work in this area with regard to buildings focused on the energy used in producing building products. Current assessment methods consider the emissions generated and energy used in the production of a product (from the raw material production to the eventual disposal of the product in a recycling or waste stream). The differences among the methods lie primarily in how the impacts from emissions are evaluated, commonly known as the impact assessment stage, and in the number and types of inventories performed over the product life cycle, commonly known as the inventory stage. The following is a brief description of selected assessment methods. The section is an overview, and is not intended to be an exhaustive review of the field.

The "classic" life cycle assessment (Fava et al. 1991) is defined by the Society for Environmental Toxicology and Chemistry (SETAC) as a three-phase process consisting of an inventory analysis, an impact analysis and an improvement analysis. The three phases are defined as follows:

- Life cycle inventory:
  A documentation of energy and raw material use, air and water emissions, solid waste, and any other releases to the environment throughout the life cycle of a product or process.
- Life cycle impact analysis:
  A quantitative and qualitative process, which characterizes and assesses the effects of the environmental loading of the inventory analysis.
- Life cycle improvement analysis:
  An evaluation of the environmental impacts identified in the previous stages of the analysis in order to determine the appropriate modifications to the product or process.

Impacts are grouped by the media in which they occur (i.e., air, water, and land). No attempt is made to aggregate these into a single indicator value.

Eco-balance (Etterlin et al. 1992, Müller-Wenk 1978) begins by defining the "balance domain", i.e. the parameters relevant for the evaluation, which is similar to many of the methods reviewed here. The data on emissions of pollutants to the air and water, energy and water consumption, and solid waste and residuals generation are grouped into energy consumption (in $MJ\text{-}kg^{-1}$ of material) as well as loads to water, air, and land (in $m^3 \cdot kg\text{-}^1$ of material). The loads to the air and water are converted from units that represent pollutant volume, into a unit that expresses the volume of air or water that would be contaminated to its legal threshold limit by the pollutant. This value is called the "critical volume", which is defined as:

$$\text{Critical volume} = E\ T^{-1} \qquad (1)$$

where E is the actual volumetric emission of the pollutant and T represents the legislated legal threshold limit for the pollutant.

Eco-points (Etterlin, et al. 1992) aggregate impacts from emissions by developing "eco-factors" for individual emissions. Eco-factors represent the relationship between the actual emissions of a pollutant, called the *effective load* or

F, and the legal threshold value, called the *critical load* or F_k for a given geographical location:

$$\text{Eco-factor} = C \cdot F_k^{-1} \cdot F \cdot F_k^{-1} \tag{2}$$

where C is a constant and Fk^{-1} represents the "sensitivity" of the environment to a given pollutant and will result in a large eco-factor for a low critical load. The eco-points of a material can be added together to give an estimation of the total environmental impact.

The Eco-indicator (Goedkoop 1995) is the result of a cooperative effort between government, industry, and research groups in the Netherlands, and is an extension to LCA. The goal of the project is to assist in the design of environmentally sound products. The method considers the damage to human and ecosystem health in the European region, and does not consider raw material depletion, the spatial impact of waste disposal, and the impact of land use.

The eco-indicator method involves the following steps: *a*) inventory of impacts (emissions and raw materials), *b*) classification of impacts into 10 effect categories, *c*) characterization of the emissions within an effect category, i.e.: weighting the effects of the different emissions within an effect category relative to each other, *d*) correlation of each effect category with one of three damage categories, *e*) normalization of the effect scores, and *f*) weighting the damage categories relative to one another in order to produce one eco-indicator value.

1.3 LCA Software Overview

There are many stand-alone packages that have a LCA-based assessment capability. The systems are generally built on a database of environmental information, and are used in industry for product analysis and process improvement. A typical example of a stand-alone package is TEMIS (Fritsche and Rausch 1993). The user constructs scenarios that contain one or more processes linked by their input and output types. The analysis results are documented in a text file of emissions, energy and resource use, with an optional graphical display. A comprehensive review of systems is given in (Menke et al. 1996). Examples of systems that are principally targeted toward the building industry are Building for Economic and Environmental Sustainability (BEES) (Lippiatt and Norris 1995) and ATHENA (Trusty et al. 1998). BEES combines economic evaluation and environmental impact with a multi-criteria decision analysis model. The level of analysis is at the product or component level. Plotting the performance results compares alternatives. ATHENA is a system that will calculate environmental impact for a schematic building description. Characteristics of alternative designs can be entered and the results compared.

The LCA tools targeted toward the building industry have begun to address some of the drawbacks of using product- and component-based tools for building design. However, these systems lie outside of a computational design and evaluation environment. The user is required to calculate the quantity of materials and processes used in the building and then enter them into the LCA package for analysis. Operational building loads must be calculated outside of the program, either in other simulation packages or manually (ATHENA is planning links to energy simulation applications).

Integration of design and analysis applications allows the user to improve the scope of the analysis while reducing the effort required obtaining analysis results. This could lead to a wider use of LCA in building design. Another ongoing effort in the area of integrated LCA assessment and CAD is LEGOE (Hermann et al. 1998), a system incorporating quantity take-off, energy analysis, and LCA. A LCA module is also in the future plans for the Building Design Advisor (BDA) (Papamichael et al. 1997).

2. SYSTEM OVERVIEW

2.1 SEMPER

SEMPER is a spaced-based building design and evaluation environment (Mahdavi 1996, Mahdavi et al. 1996). The SEMPER environment consists of a user interface, a building representation that is shared among the application modules, domain specific evaluation modules, and a database for persistent storage.

The SEMPER domain modules currently focus on aspects of building performance; however, the system architecture is designed to be modular, so that additional applications can be added in the future. An object database is used for the persistent storage. This is used for elements of the shared representation, as well as additional attributes of materials and systems relevant for the analyses within individual domains.

The functional requirements for the shared object model (SOM, *see Figure 1*) in SEMPER are to contain the spatial information and the physical description of the project. The spatial information represents the geometry of the spaces in the project, and, in general, the physical description is the location and geometry of the site and building elements, and their type. The type information is selected by the user (such as a user-defined default wall type) and applied when the entity is instantiated. Individual modules provide additional data to their building representations by using type-associated database objects. An evaluation module may refine the type description when it is run and place that information in the database, where it becomes available for re-use or use by the other modules. Type can reference, for example, a representation of a construction method when the entity is a constructed or manufactured element, such as a wall, or it can simply be a reference to an object containing a set of attributes, for elements such as furniture or equipment.

2.2 ECOLOGUE

The ECOLOGUE module's task is to calculate relevant environmental parameters and environmental impact indicators for buildings and provide meaningful feedback to the designer. Minimal intervention from the user is required. The module can "automatically generate a proprietary building representation for use within its domain, derived from the shared representation, utilizing the inherent "isomorphic" relationship between the two representations. Additional environmental properties and characteristics of materials and components are accessed from the database through the type reference. The user can create or modify process and emission attributes and types, as well as context parameters.

The functional requirement for the domain object model (DOM) in ECOLOGUE is to provide a representation of the building and its context that can provide the information necessary for the calculation of the environmental impact indicators. The primary building representation is principally derived from the SOM model, and contains the basic building information. Additional domain specific requirements include the modeling of the building's context, processes, related emissions, and the implementation of the analysis methods. *Figure 2* shows the descriptive portions of the DOM. The areas of the representation with a correspondence to shared model are shaded.

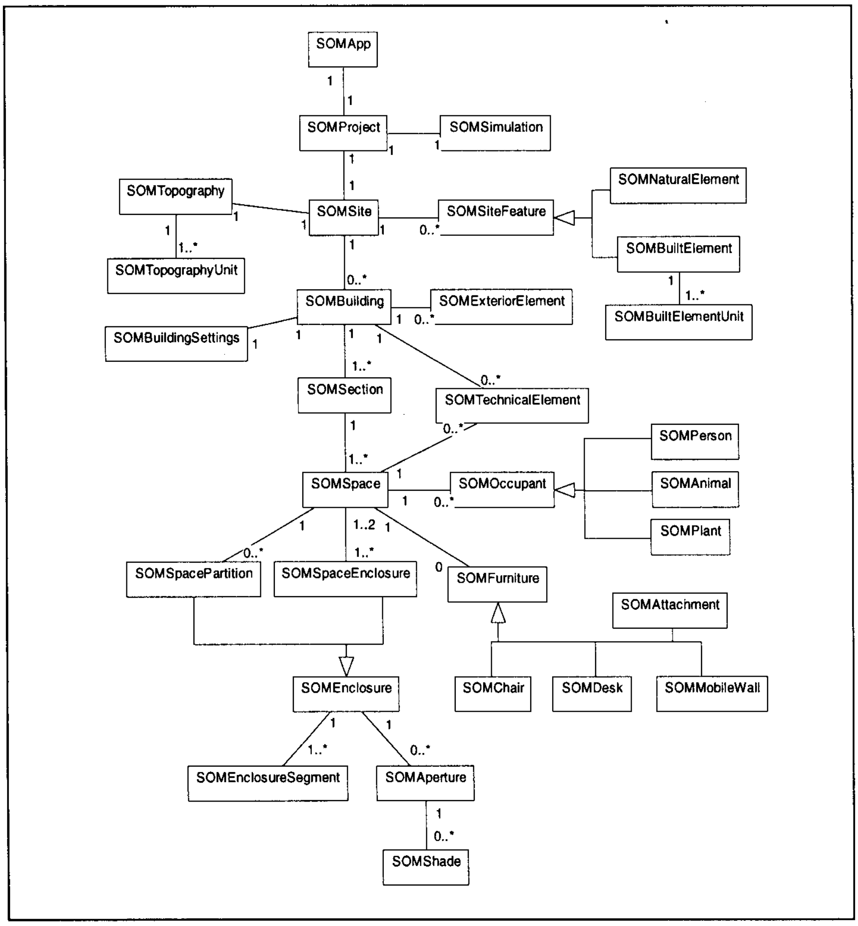

Figure 1. The primary elements of the shared building representation

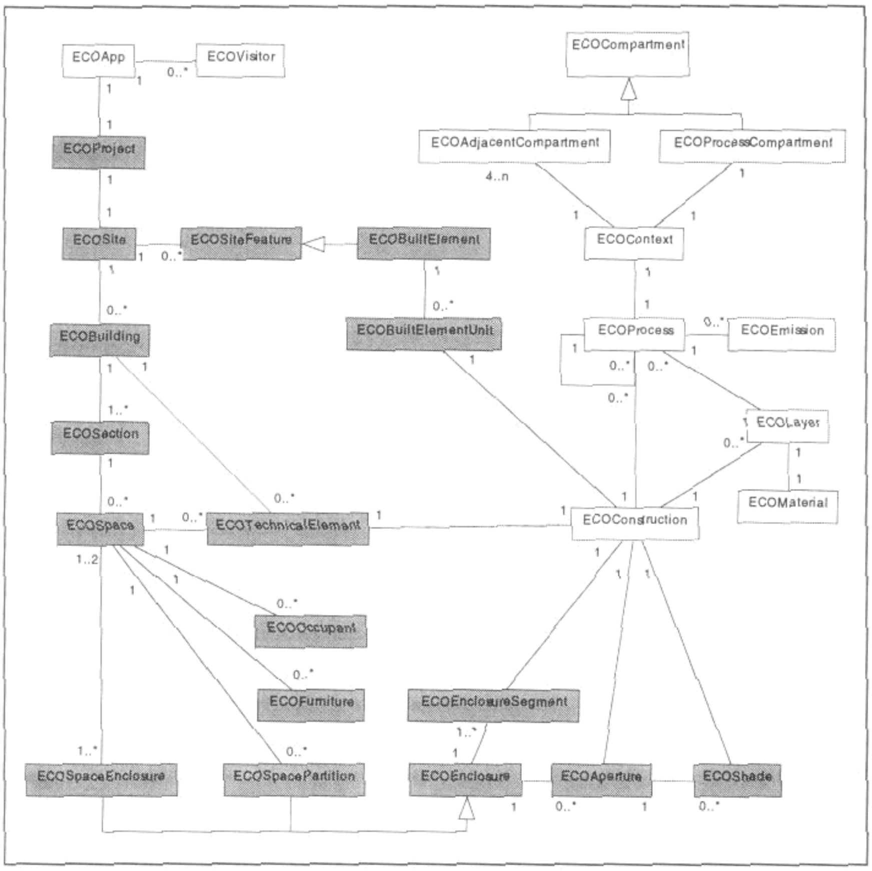

Figure 2. Elements of the ECOLOGUE domain model

2.3 ECOLGUE Analysis

2.3.1 Method Overview

Currently, ECOLOGUE implements three environmental impact methods. These are the Critical Load and Eco-indicator methods described earlier, and a third method developed for ECOLOGUE, called "Affordance". This method is described in more detail in the following section. A code structure was implemented, through the use of Visitor classes (*see Figure 2*) (Gamma et al. 1994) that will allow the addition of future functionality, such as another analysis method, with minimal alteration of the core classes.

Rather than the comparison of alternatives, the goal of affordance is to provide an indicator that will express the performance of a building design in relation to a context. In this way, for the given design and site being considered, the indicator would determine whether the impacts generated by the solution meet or are below the allowable level for the context or contexts effected by the proposed building construction. The advantages of this type of indicator are that when emissions commonly expressed in mass terms are related to a context or eco-system type over a period of time, the ability of the ecosystem to sustain the impacts from the emissions can be included in the indicator. Examples of how such an indicator could be used are:

- Evaluation of the impacts of building materials.
  Using the affordance indicator, environmental evaluation of building material production could be more context-specific. The ecological sensitivity of the region where production processes occur can be considered.
- Land use planning
  When the affordance of a regional area is determined, the spatial allocation and distribution of the load would represent the region's carrying capacity when fully developed. Also, using an affordance indicator for planning would allow for the explicit definition of an area's sensitivity to disturbance.
- Resource planning
  Allocation and use of resources, for example water, could also be expressed in terms of an affordance indicator. Areas with low water availability would have a lower affordance.
- Indoor environmental quality
  Emissions from in-place building materials can effect indoor environmental quality. Given the characteristics of the building, an affordance method could evaluate the potential indoor conditions.

2.3.2 Formulation and Calculation

The characteristics of the preliminary formulation developed to date are an ecosystem classification that has a spatial allocation or affordance for substances expressed in $kg \cdot m^{-2} \cdot yr^{-1}$ (Mahdavi 1998). In the following equation, w_i is the weight for emission e_i, and the product is summed from 1 to n emissions.

$$\text{Impact} = \sum w_i \cdot e_i \tag{3}$$

A zeroeth approximation of w_i can be expressed as:

$$w_i = (e_{i,\,max} \cdot n)^{-1} \tag{4}$$

and, as a first approximation:

$$w_i = (e_{i,max} \cdot \sum e_{j,\,max})^{-0,5} \cdot n^{-1} \tag{5}$$

In ECOLOGUE, the affordance value of an emission in a context is calculated through the use of an evaluative environment. The fate and transport model is based on fugacity concept (Mackay 1991). The evaluative environment is modeled as compartments, each of which contain four media - air, water, soil, and sediment. The concentration of an emission in the system of compartments is calculated at runtime. With each iteration, the emission rates to the principal and adjacent compartments are incrementally increased until a compartment or compartments reach the threshold concentration level for that emission. This emission rate for the compartment divided by the land area that will potentially be developed, is the affordance for the emission in the compartment. An evaluation of the actual emission rate from the building process can then occur.

3. 3. ILLUSTRATIVE EXAMPLE

3.1 Introductory Remark

To illustrate the operation of SEMPER-ECOLOGUE, the computational life cycle assessment of a building is described below. The example project is a single-family residential house of 2 1/2 stories located in suburban central Pennsylvania (Lee 1997, NAHB 1997). The schematic of the partial representation of the floor construction in the project (*Figure 3*) shows how a portion of the building is described in ECOLOGUE.

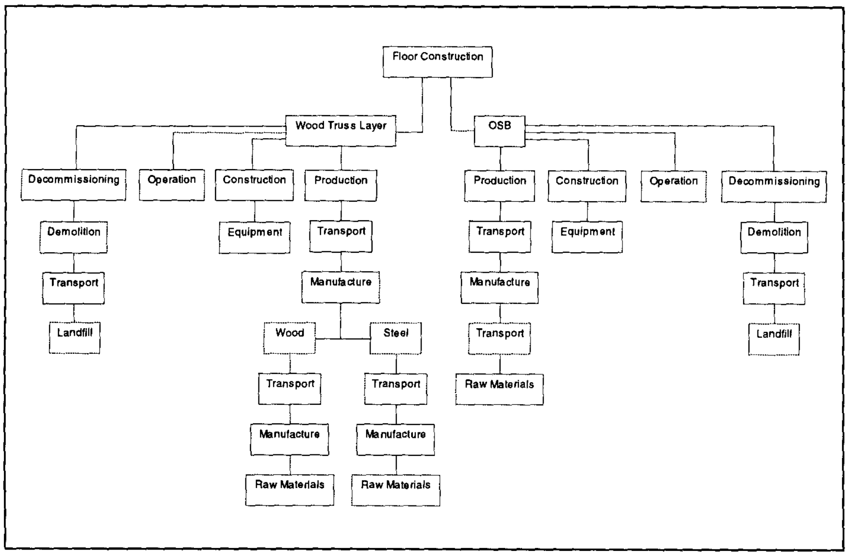

Figure 3. Partial representation of a floor construction in ECOLOGUE

3.2 Results

Figure 4 through *Figure 7* show the summary of the distribution of environmental loads in two media and energy use for the building systems included in the ECOLOGUE analysis in each of the four life cycle phases. The indicator method used is the Critical Load method.

The production and construction life cycle phases include the manufacturing of the materials used in the building, and the assembly of the materials and systems into the finished building. The material production phase includes raw material extraction, transportation of raw materials to the manufacturing facility, and the manufacturing process itself.

The construction phase includes the transportation of the materials or manufactured systems to the building site, the manufacture, transportation, and operation of the equipment used in construction, and the transportation of the required labor force to the site.

The operation and maintenance phase of the building includes all of the activities that occur during the occupancy phase. Included in this area are the estimated loads resulting from the heating and air conditioning of the building, the energy used for lighting, the maintenance (repair or replacement) of building systems, and the energy used for transportation by the building's occupants. Although the inclusion of transportation energy use for the occupants' daily activities is normally not included in environmental analyses of buildings, it is an important aspect, from an environmental perspective, of the loads during the operation of the building. Including this aspect partially addresses the regional issues, such as the location of a development, which contributes to the environmental impacts resulting from building construction.

Decommissioning is defined here as the process of removing the building materials to a local landfill. The two processes included are an estimate of the machinery required to dismantle the structure and transportation to the landfill. It is assumed that all of the material is removed with the exception of the aggregate, and that no material is recycled.

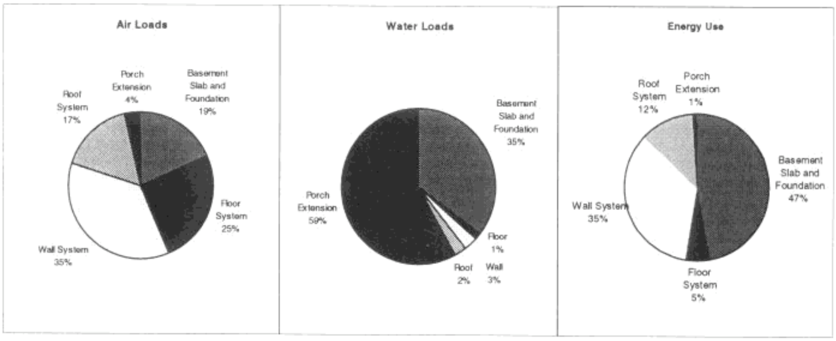

Figure 4. Distribution of environmental loads for material production

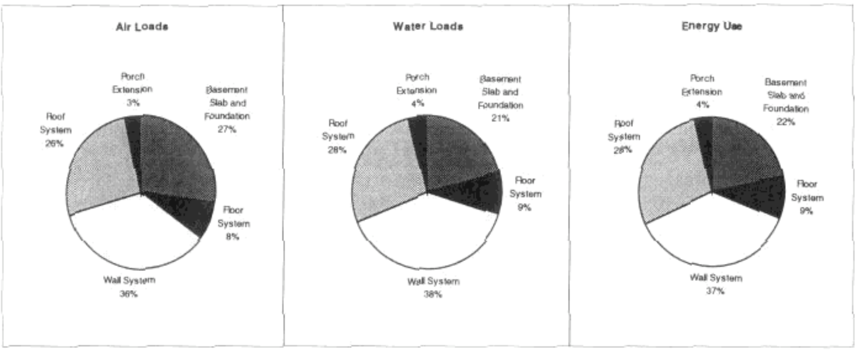

Figure 5. Distribution of loads for the construction phase

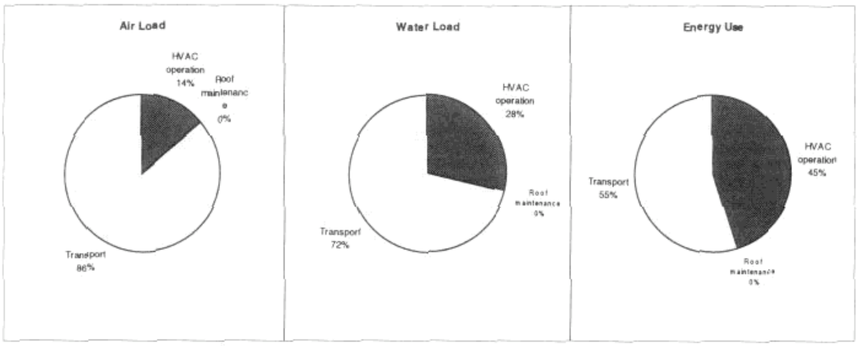

Figure 6. Distribution of loads in the operation and maintenance phase

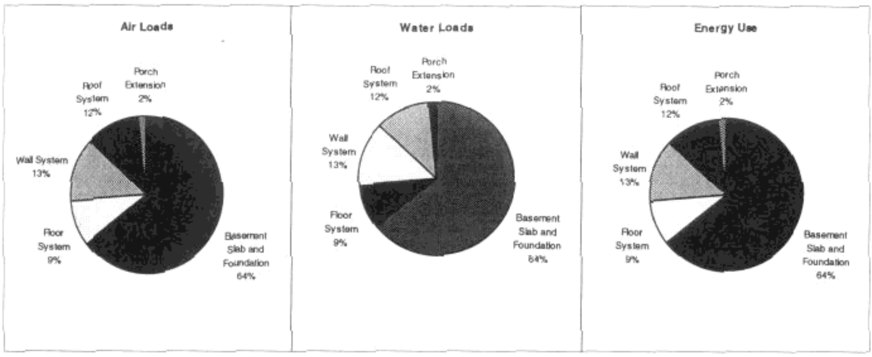

Figure 7. Distribution of loads in the decommissioning phase

4. CONCLUSION

This paper has presented an environmental impact application, ECOLOGUE, within a multi-aspect design environment, SEMPER. The paper has argued that computational design support tools would assist in the effective management and calculation of life cycle environmental impact, and may encourage the use of environmental assessment tools early in the design process. It has shown the relevance of a multi-aspect design environment to life cycle assessment, and has provided an example of the characteristic building model used and the results of an illustrative evaluation.

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