THE "ECOLOGUE" APPROACH TO COMPUTATIONAL BUILDING LIFE CYCLE ANALYSIS

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ABSTRACT

Construction and operation of buildings is internationally a major cause of resource depletion and environmental pollution. Computational performance evaluation tools could support the decision making process in the area of environmentally responsive building design and play an important role in environmental impact assessment, especially when a life cycle assessment (LCA) approach is used. LCA requires extensive data collection for each relevant component or process within the boundaries of the assessment. The typical building contains many products from different manufacturers which are assembled in ways often unique to an individual building. 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 describes the implementation of an application (ECOLOGUE) for comprehensive computational assessment of environmental impact indicators over the building life cycle. The application is embedded in a multi-aspect space-based building design and evaluation environment (SEMPER). The paper demonstrates the use and results of the ECOLOGUE system via illustrative examples.

BACKGROUND

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.

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).

SYSTEM OVERVIEW

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.

ECOLOGUE

ECOLOGUE'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.

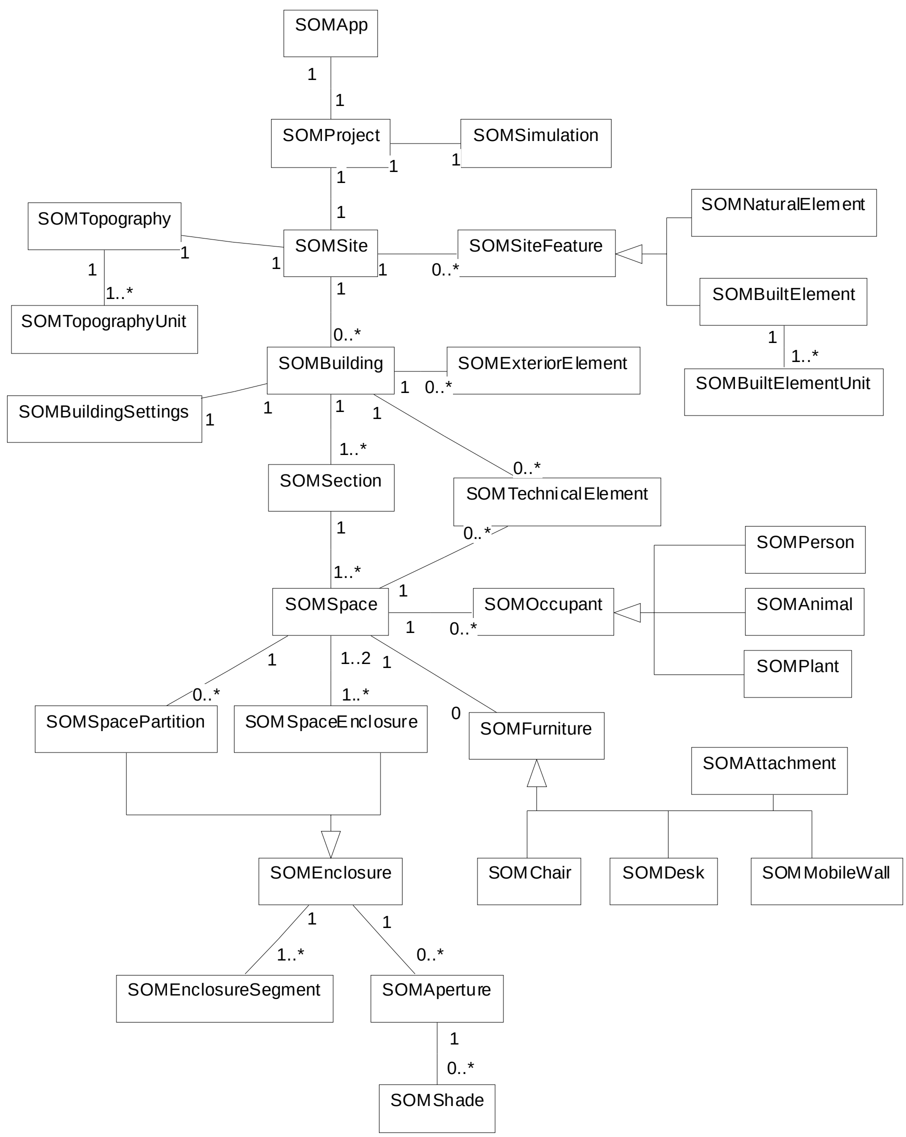

FIGURE 1. The primary elements of the shared building representation

ANALYSIS METHOD OVERVIEW

Currently, ECOLOGUE implements three environmental impact methods. These are the Critical Load and Eco-indicator methods, and a third method developed for ECOLOGUE, called "Affordance". 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. An overview of the methods is provided in the following sections.

Critical Load

Critical Load (Etterlin et al. 1992, Müller-Wenk 1978) begins by defining the parameters relevant for the evaluation. 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 $MJ \cdot kg^{-1}$ of material) as well as loads to water, air, and land (in $m^3 \cdot kg^{-1}$ 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:

$$Critical\ volume = E \cdot T^{-1}$$

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

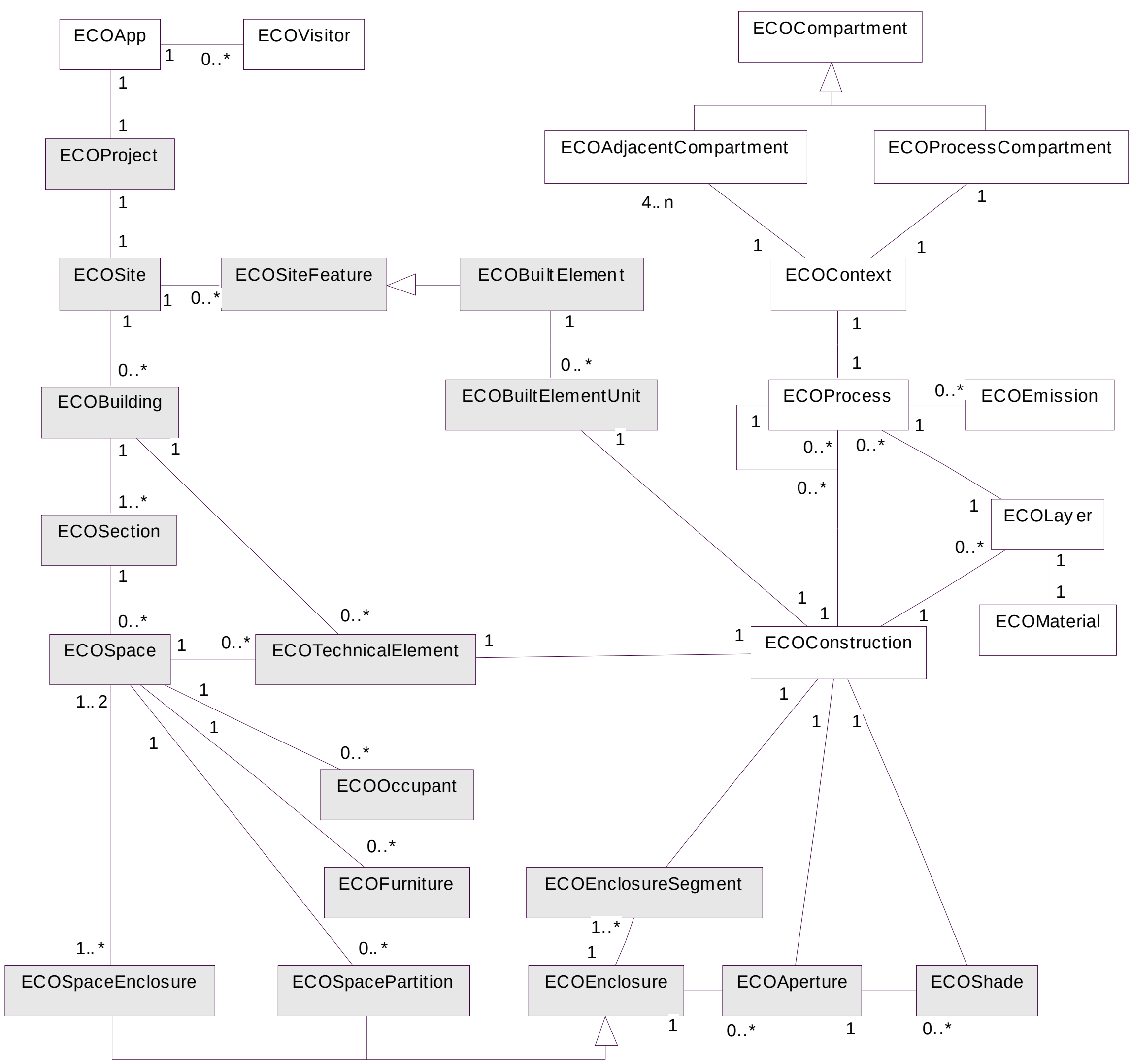

FIGURE 2. Elements of the ECOLOGUE domain model

Eco-indicator

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.

An eco-indicator analysis 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)

Affordance

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 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.

Formulation

The characteristics of the preliminary formulation developed to date are an eco-system classification that has a spatial allocation or affordance for substances expressed in kg · m^{-2} · yr^{-1} (Mahdavi 1998). In the following equation, w_i is the weight for emission e_i.

$$I_e = w_i \cdot e_i \qquad (2)$$

A zeroeth approximation of w_i can be expressed as:

$$w_i = e_{i_{max}}^{-1} \qquad (3)$$

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 1979, Mackay 1991, Mackay et al. 1997). Fugacity is a property of a substance that is used in a calculation procedure for predicting mass and concentration distributions, reaction characteristics, and persistence of a chemical released into a model or evaluative environment. The evaluative environment is not intended to simulate the real environment, but is intended to provide behavioral information characteristic of the substance. The media in the environment. Fugacity is an "escaping tendency" or "driving force" with units of pressure [Pa]. When the escaping tendencies from two phases are equal, they are in equilibrium. Fugacity is linearly proportional to concentration, and one molecule exerts one-tenth the escaping tendency of ten.

The fugacity-based environmental fate models of have been developed in four levels. The Level III model is non-equilibrium steady-state: a system with non-equilibrium distribution in which each phase may have a different fugacity. Emissions may occur in one or more media. The media in this level are air, soil, water, biota and suspended solids, and sediment. The processes modeled are transfers between media (diffusion, deposition, runoff), reaction, and advection. Reaction is the chemical process that changes the form of one chemical into another. Advection is the process of movement that occurs when a substance is in a medium that is flowing. Examples of advective processes are air or water flows that carry substances from one area to another.

Implementation

Processes and the related components (see Figure 2) are the principal elements that contain environmentally relevant information. Processes model activities in the environment. Processes are related to an element of the domain building model. Each process can be composed of multiple processes, each with a set of related emissions and one related context. A context is defined as a set of five compartments that have advective and diffusive flows between them. A context can correspond to a geographical region such as a watershed. Compartments are evaluative environments wherein the tendencies of the distribution of a substance in media can be estimated (Mackay 1991). The compartment is defined by its physical characteristics, such as the area and volumes of the media, rates of advective flow, and mass transfer coefficients. Emission are defined by their chemical and physical characteristics. The combination of these compartment characteristics, the emission properties, and the emission rates are what drives the partitioning by media of the substance in the simulation.

Each compartment can have an emission profile for individual substances. The emission profile determines the relative distribution of the emission rate among air, water, and soil. The emission limit for a substance is typically based on the threshold concentration limit for each media. However, a compartment can set an allowable emission concentration limit as a percentage of the threshold limit. This allows individual compartments to be defined that are either more or less sensitive than the average environment to any particular substance. Also, to determine the emission rate allocation, each compartment can specify the percentage of land area that is currently developed or open for development in the future.

Calculation procedure

The affordance method is based on the evaluation of an emission-context pair. To calculate the affordance, the first step is to parse the domain building representation, calculate the quantities of each process that will be required, and organize the processes by their context. For each pair, an interative affordance simulation is run. For each iteration, one emission rate is used for the system of compartments. Each iteration of the calculation determines the distribution of the emission in the media in each compartment. For the next iteration, the emission rate changes by a ratio of the target concentration and a selected concentration resulting from the previous iteration. The selection of the concentration from among the media in all of the compartments is determined by whether the target concentration has or has not been exceeded. The allowable emission rate is determined when the target concentration level for the emission is reached in any media in any of the compartments.

The allowable emission rate is the divided by the developable area, resulting in the allocation of the emission rate per unit area. The impact of the emission is then calculated as per equation 1. The impact of a process that contains a set of n number of emissions is calculated as:

$$I_p = \sqrt{\frac{\sum I_{e_i} \cdot w_{e_i}}{n}} \qquad (4)$$

where w_i is the ratio of the actual emission impact and the target impact I_t:

$$w_{e_i} = \frac{I_{e_i}}{I_{t_i}} \qquad (5)$$

In this case, $I_t = 1$, and equation 3 can be re-written as:

$$I_p = \sqrt{\frac{\sum I_{e_i}^{\;2}}{n}} \qquad (6)$$

Similarly, for a process consisting of a set of n number of processes, impact I_p is calculated as:

$$I_p = \sqrt{\frac{\sum I_{p_i}^{\;2}}{n}} \qquad (7)$$

ILLUSTRATIVE EXAMPLE

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.

RESULTS

Figures 4 and 5 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.

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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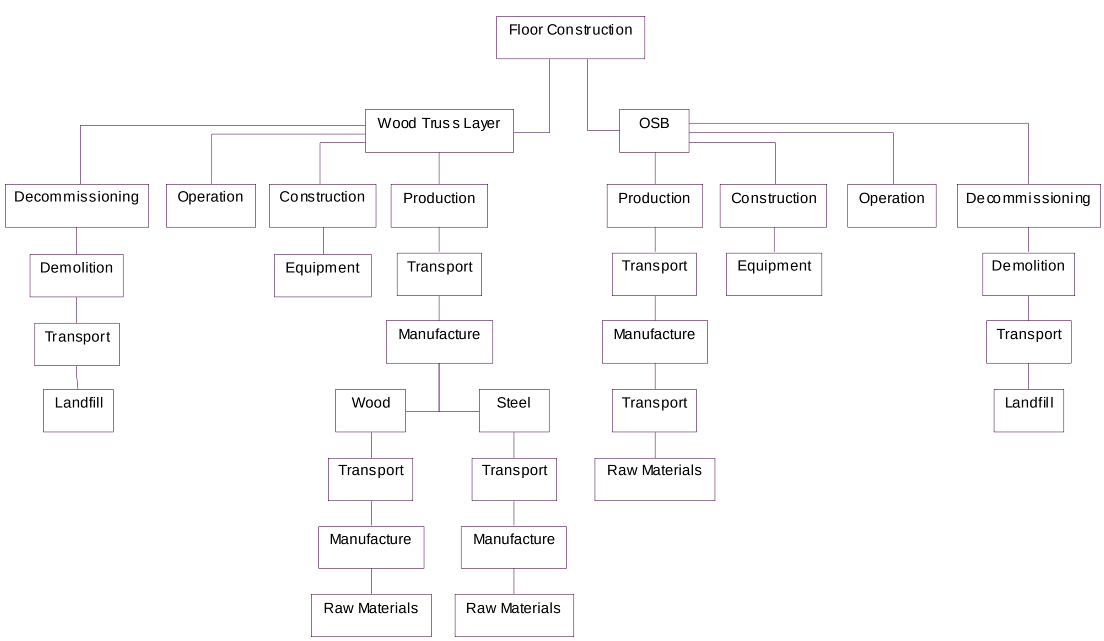

FIGURE 3. Partial representation of a floor construction in ECOLOGUE

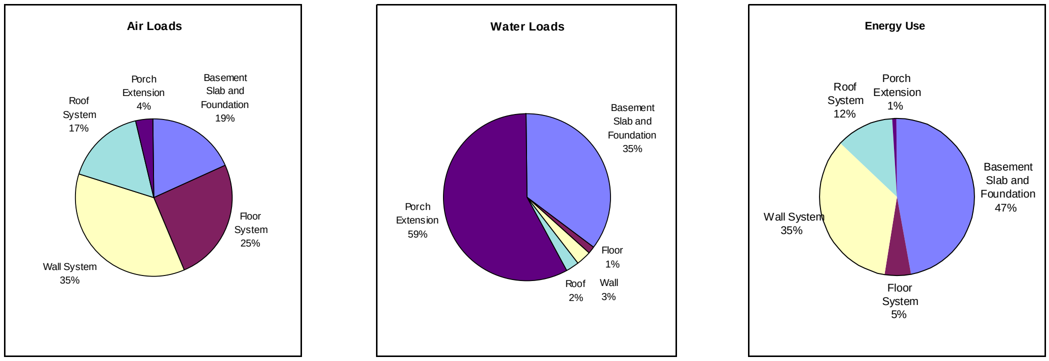

FIGURE 4. Distribution of environmental loads for material production

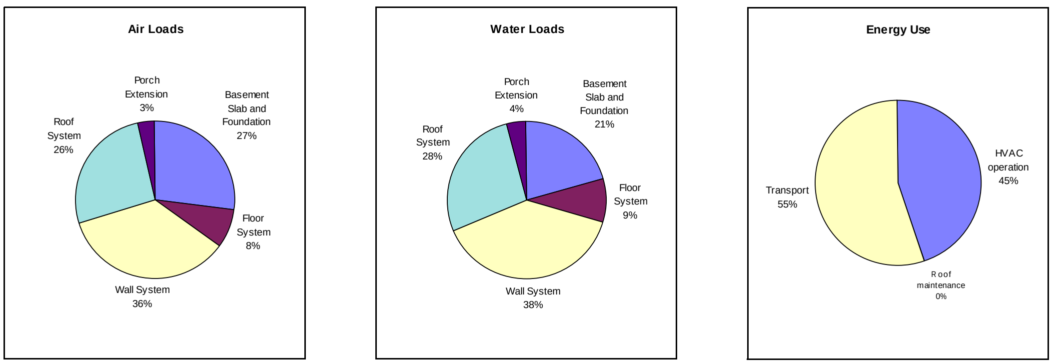

FIGURE 5. Distribution of loads for the construction phase

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