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Combining building thermal simulation methods and LCA methods

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SUMMARY:

This paper describes recent efforts made by the Danish Building Research Institute regarding the integration of a life cycle assessment (LCA) method into a whole building hygro-thermal simulation tool. The motivation for the work is that the increased requirements to the energy performance of buildings (as expressed in EU Directive 2002/91/EC), may in the future be supplemented by requirements to the environmental impact of buildings. This can be seen by the fact that EU recently has given CEN mandate to prepare standards for environmental assessment of buildings (CEN/TC 350).

Combining LCA methods with hygro-thermal simulation tools enables designers to assess both sets of requirements in one operation, without the need to input redundant data in different tools. Another advantage of combining the two tools is that it makes it possible to compare the environmental impact of buildings during the construction and operational phases. This is of particular interest for low-energy buildings, where a relatively large amount of resources is used during construction, compared to the amount of resources used during operation. The result of this is that the environmental impact during the two phases can easily be of the same order of magnitude.

The paper describes how the LCA method is integrated into the thermal simulation tool, and the prerequisites for using them. A case study regarding a single-family house is used to illustrate how the combination of the two methods can be used for generating design alternatives with high performance regarding energy use as well as environmental impact.

1. Introduction

This paper describes recent efforts made by the Danish Building Research Institute regarding the integration of the life cycle assessment (LCA) method by Petersen (1999), into the whole building hygro-thermal simulation tool BSim, Wittchen et al. (1999-2008).

The motivation for the work is that the increased requirements to the energy performance of buildings, as expressed in the EPBD Directive (2002), may in the future be supplemented by requirements to the

environmental impact of buildings. This can be seen by the fact that EU recently has given CEN mandate to prepare standards for environmental assessment of buildings.

Furthermore, assessing energy performance and environmental impact simultaneously is particularly important when considering low-energy buildings. The reduced amount of energy used for operating the building, combined with an increased use of renewable energy, reduces the environmental impact of the building during operation. On the other hand, more resources are required during construction and rehabilitation of low-energy buildings, especially for production of building materials. The result of this is that the environmental impact during construction becomes comparable with the environmental impact during operation. Sartori and Hestness (2007) present data for passive houses, for which the consumption of primary energy for construction and rehabilitation of buildings is 40-50% of the energy needed for operation. Besides, the use of building materials contribute significantly to a number of other environmental effects, related to e.g. dangerous substances and waste.

Combining LCA methods with hygro-thermal simulation tools enables designers to assess both sets of requirements in one operation, without the need to input redundant data in different tools. Designers can thereby easier investigate the compromise between the potentially conflicting goals of minimizing the amount of resources used during construction, and minimizing the energy use during operation.

This paper describes the LCA calculation methods, and the results. A case study regarding a single-family house illustrates how the tool can be used for generating design alternatives that support decision-making during the design phase. Further improvements of the tool are also discussed.

2. The life cycle assessment method

The Building Environmental Assessment Tool (BEAT) by Petersen (1999) is an LCA method based on the Environmental Design of Industrial Products (EDIP) method, which is described by Hauschild and Wenzel (1998). BEAT is intended for assessing the environmental impact of buildings, by providing quantifiable measures for environmental effects, caused by the construction of buildings.

2.1 Life cycle inventory analysis

The LCA calculation is based on a life cycle inventory (LCI) analysis, which provides detailed information about the amount of resources extracted from the environment, and the amount of pollutants emitted to the air, water and soil, during the production of building elements and construction of the building.

In order to perform the LCI analysis, the EDIP method uses a set of unit processes, each of which represent the process of producing one unit of a given product. It is assumed that the process requires other products as input, as well as natural resources, and has the considered product as output, as well as emissions to air, water and soil. Figure 1 shows a unit process.

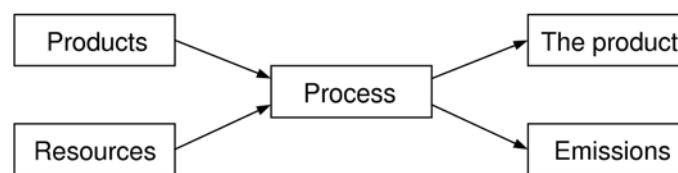


FIG. 1: A unit process.

All products and resources used for constructing a building form a product system, as shown in Figure 2. In order to perform a LCI analysis, the product system is traced backwards from the building over the manufacturing of the components to the processes where resources are extracted from the environment. During these calculations, the extracted resources and emitted pollutants are added up. Given the lifetime of the constructions used in the building, the average annual amount of extracted resources and emitted pollutants is calculated.

The building model in the BSim simulation tool contains (among others) information about the geometry and constructions used in the building. The BSim database contains information about the constructions and materials, such as lifetimes and the amount of materials used in the constructions. This information is used for performing an inventory analysis on the construction and material levels of the product system.

In order to trace the product system further back, each material in the BSim database must be related to a corresponding product in the BEAT database. When this relation is known, the product system can be traced from the building to the processes where natural resources are extracted from the environment.

The entries (material or product) in both databases are associated with a Sfb index. The Sfb classification system is described by Ray-Jones and Clegg (1991). For each material in the BSim database, a relation is established by locating the first product in the BEAT database with a corresponding Sfb index.

This correspondence is, however, not unique, since there are usually many products in the BEAT database with the same Sfb index. Future versions of the BEAT tool will provide more flexibility for the user to establish relations between the two databases.

The LCI analysis method described above requires an acyclic product system. A depth-first search (DFS) is performed in order to locate cycles in the product system. DFS is an algorithm for analysing a graph consisting of vertices and edges, such as a product system. The DFS algorithm provides a spanning tree of the graph, which can be used for classifying the edges belonging to graph as being either (1) tree edges, (2) back edges, (3) forward edges or (4) cross edges. The graph contains cycles if one or more back edges is found. In this case, the LCI analysis is aborted. see Cormen et al. (2001) for further details regarding the DFS algorithm.

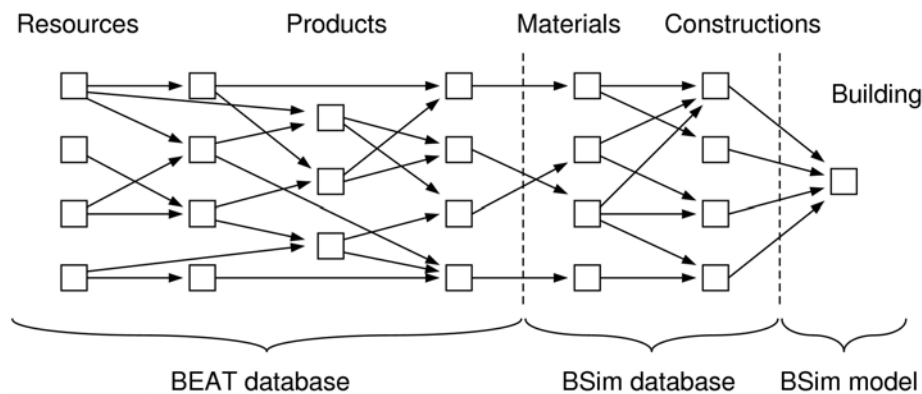


FIG. 2: A product system for constructing a building. The emissions resulting from the processes are omitted. The arrows indicate directions of the material flows.

2.2 Calculating the environmental effects

Each extracted resource and emitted pollutant contribute to one or more environmental effect, such as global warming, water pollution, depletion of rare resources, etc. The environmental effects are calculated with the EDIP method, described by Hauschild and Wenzel (1998), using the expression:

$$\text{environmental effect} = \frac{\sum \text{amount} \cdot \text{effect factor}}{\text{normalizing factor}} \cdot \text{weighting factor} . \quad (1)$$

The effect factors are used for calculating an equivalent amount of reference resource or pollutant. For instance, for all pollutants that contribute to global warming, an equivalent amount of CO₂ is calculated, and the sum of these contributions is used for calculating the environmental effect.

The normalization factor is the average amount of extracted resource or emitted pollutant per person. Extracted resources are weighted with the inverse of the supply period. This means that highly demanded rare resources, which have short supply periods, have large weights. Weights for emitted pollutants are often politically decided.

3. Case study

The combination of BEAT and BSim is demonstrated by using a beta version of the combined tool in a case study regarding the single-family house shown in Figure 3. The aim of the study is to illustrate the impact of either increasing or reducing the amount of insulation in the building envelope. Intuitively, increasing the amount of insulation will decrease the energy use during operation, but increase the environmental impact during

construction, since a larger amount of natural resources is used for producing insulation material. Reducing the amount of insulation should have the opposite effect.

The study is conducted by parameter variations of the insulation thickness used in the external walls, slab on ground and ceiling. The contribution to global warming and the annual amount of energy required for heating the building are treated as dependent parameters. The contribution to global warming only includes the construction phase, and therefore only includes emissions related to the production of building materials. Emissions related to the use of natural resources during operation are disregarded.

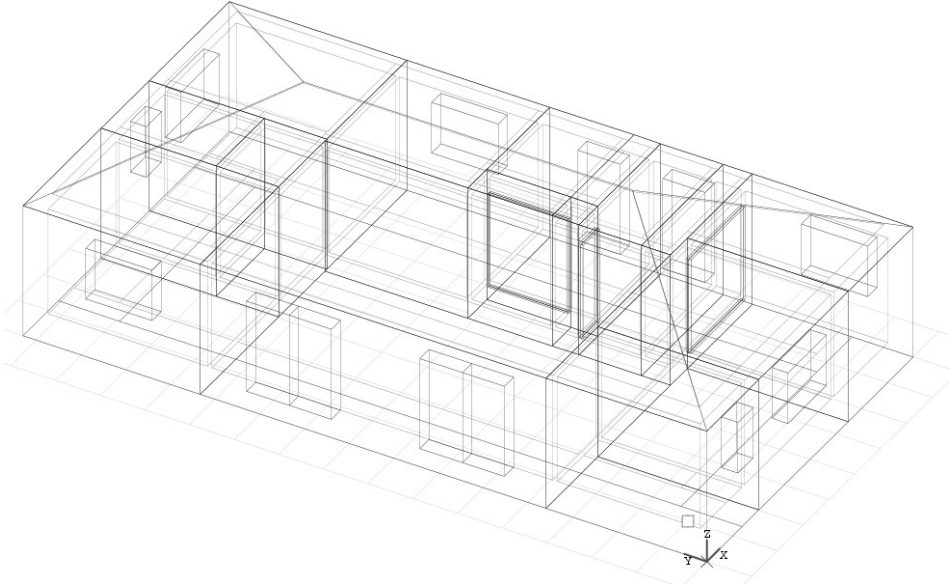


FIG. 3: BSim wire frame representation of the considered single-family house.

The LCA calculations are based on the lifetimes shown in Table 1, which are consistent with the values provided by Nielsen et al. (1985).

TABLE. 1: Lifetimes for the constructions used in the case study.

Construction	Lifetime
External walls	60 years
Internal walls	60 years
Floors, including ground slab	60 years
Ceiling	60 years
Roof construction	60 years
Windows and doors	40 years

Variations of the insulation thicknesses in the external walls, slab on ground and ceiling are calculated by scaling them relative to their original values. The scaling is performed in the range from 50 % to 150 %. Table 2 show the insulation thicknesses, the resulting annual energy use for heating the house, as well as the contribution to global warming due to the production of construction materials.

Figure 4 shows a plot of the environmental impact and energy use against the scaling factor for the insulation thicknesses. When the amount of insulation is increased, the environmental impact increases, and the annual energy use decreases, which is expected.

Figure 5 shows a plot of the environmental impact against the energy use, also known as a Pareto plot (see Pareto (1969) for details), since two objective functions are plotted against each other. This type of plot is particularly useful for investigating the compromise between objectives, and is therefore often used as a tool for supporting decisions.

Figure 5 thus shows the compromise between the objectives of minimizing the environmental impact and minimizing the energy use. It indicates that reducing the energy use during the operational phase of the building can only be done by increasing the environmental impact during the construction phase.

TABLE 2: Impact of scaling the insulation thicknesses on the energy use and the environmental impact. The insulation thicknesses are rounded to the nearest mm.

Scaling [%]	50.0	62.5	75.0	87.5	100.0	112.5	125.0	137.5	150.0
Walls [mm]	75	94	113	132	150	169	188	206	225
Slab on ground [mm]	63	78	94	109	125	141	156	172	188
Ceiling [mm]	150	188	225	263	300	338	375	413	450
Energy use [kWh]	8682	7616	6848	6251	5780	5382	5054	4773	4531
Environmental impact [10 ⁻² CO ₂ equivalents]	5.30	5.51	5.71	5.91	6.10	6.28	6.46	6.63	6.79

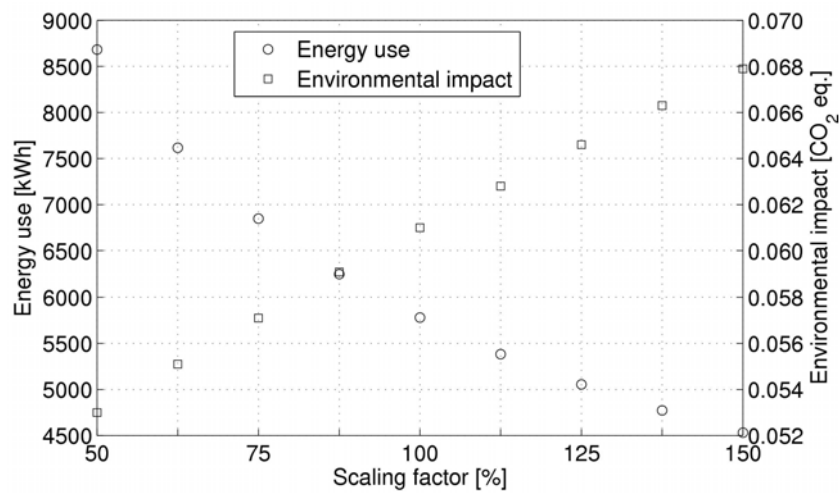


FIG. 4: Environmental impact and energy use plotted against the scaling factor.

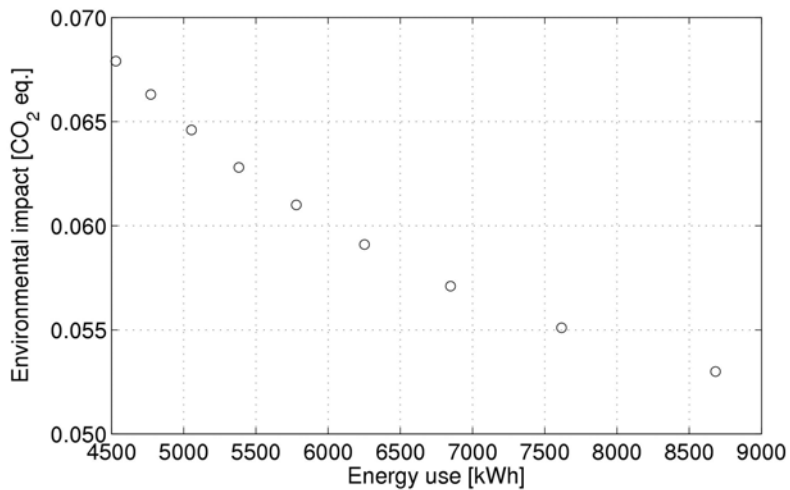


FIG. 5: Environmental impact plotted against energy use.

4. Discussion

Integration of the BSim and BEAT tools seems to be useful for supporting decisions during the design phase, e.g. investigating compromises between design objectives. There are, however, some details that must be addressed.

The current version does not include heating, ventilation and air-conditioning (HVAC) systems in the LCA calculations, since these systems do not have geometrical representations in the BSim model. It is therefore not possible to calculate the amount of materials attributed to these systems. Furthermore, the BEAT database needs an extension to include environmental data for these systems, which complicates the problem further in terms of collecting relevant data.

Assuming that environmental data for the HVAC systems can be found – which is a far from trivial task to undertake – the issue regarding the missing geometry can be resolved by using average material amounts for the different systems, related to the heated floor area and simulated energy demand. For instance, the average length of ventilation ducts in different building types per unit of heated floor area can be used for estimating the total amount of materials used for producing the ventilation ducts.

The current version of the BEAT tool only calculates the environmental impact of constructing the building, and omits the impact of operating and maintaining the building. The impact of operating the building can be handled by making the results from thermal simulations of the building available to the BEAT tool, and by requiring that the user specifies the method used for producing the required heat and electricity.

The impact of maintaining the building can be handled by relating each construction type in the BSim database with processes needed for its maintenance, representing for instance cleaning, reparation, or replacement processes. These relations need though to be defined in the BEAT database.

The LCI calculation method currently used is not able to handle product systems with cycles; however, there are methods that resolve this issue. For instance, the IO-based LCI calculation method described by Suh and Huppes (2005) is able to handle systems with cycles. This method furthermore performs LCI calculations using matrix operations, which most likely will speed up the calculations and reduce the requirements to the data provided by the user.

Using the current beta version of the tool requires that the user specifies lifetimes for the constructions in the BSim database, as well as relations between materials in the BSim database and products in the BEAT database. This process can be quite time-consuming, especially for buildings consisting of many different materials.

Providing default lifetimes in the BSim database, and default relations between the two databases may reduce the time needed for specifying these parameters. In case the user adds new materials to the BSim database, it may be necessary to add the same material in the BEAT database and create the required relation. This should be done in an integrated user interface, allowing access to both databases.

5. Conclusion

This paper describes a prototype integration of a LCA method into a whole building hygro-thermal simulation tool. The life cycle inventory calculations are described and a case study is performed in order to demonstrate the tool on a realistic example. A number of issues need to be addressed in future versions of the tool to make it usable outside the academic society.

The case study indicates that the results obtained with the tool are useful for supporting energy- or environmentally oriented building design. The tool can be used for highlighting the compromise between the environmental impact during the construction phases of the building, and the energy required during the operational phase. The tool is thus suitable for addressing the increased requirements to the energy performance of buildings, which in the future are likely to be supplemented with requirements to the environmental impact of buildings.

A number of issues need to be addressed in order to ensure that all contributions to the environmental impact during the construction and operational phases of the building are accounted for, and to make the tool easier to use:

The HVAC systems must be included in the calculations. This requires environmental data for these systems, and an estimate of their use of materials, which for instance can be accomplished by

using statistical data for the average system size per unit of heat floor area in different building and system types.

The processes needed for operating and maintaining the building must be included in the calculations, which can be done by relating the constructions in the BSim database to relevant processes in the BEAT database, and make sure that the BEAT tool includes these relations when performing the LCI calculations.

Implementation of an IO-based LCI calculation method will enable the BEAT tool to handle product systems with cycles, which reduces the requirements to the data provided by the user.

The graphical user interface needs further development in order to make it easier for the user to specify the required relations between the two databases and analyse the results.

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