Integrated Life Cycle Simulation and Assessment of Buildings

Frank Neuberg, Christian Ekkerlein, Ernst Rank, Martin Faulstich, Technische Universität München, Germany
{neuberg, ekkerlein, rank, faulstich}@bv.tum.de

Summary

Buildings require both for construction and, due to their comparatively long life cycle for maintenance, significant raw material and energy resources. So far available knowledge about resource consumption during an entire life cycle of a building is still quite rare, because various criteria affect each other and/or overlay mutually. In this contribution a model based software concept is presented using an integrated approach for life cycle simulation and assessment of buildings. The essential point of the development consists of connecting an IFC compliant product model of a building via the Internet with data bases for the resource and energy requirement of building materials. Furthermore, numerical simulations allow calculating and minimizing the energy consumption, the resource requirement, the waste streams and also the noxious emissions. In the context of this paper we present the first release of software programs for architects and engineers, which help them to evaluate their design decisions objectively in early planning steps. Additionally the usage of the software is demonstrated by a test case study for a real world building. By applying this software in practice a substantial contribution for saving energy and natural resources can be provided in the sense of sustainable and ecological building design.

1 Introduction

Within today's manufacturing sector and especially in the automotive industry, computer based project models are used as a basis for many design, production, marketing and controlling activities. These project models represent essential product life cycle information in a standardized way. Thus the electronic data exchange between the different computer applications of the involved parties can be performed easily. A lot of time and money can be saved in this way, as data input and calculation results of one party can be used by the next parties in the design process without the need for another manual data input.

The development and use of computer based project models within the AEC (Architecture, Engineering, Construction) industry has been discussed for a long time (IAI 2004 Eastman 1992; Gielingh 1988). Especially vendors of CAD applications like Autodesk, Nemetschek, Graphisoft and Bentley are joining the discussion and trying to gain new markets in this way. Recently, these vendors introduced the concept of a building information model (BIM) (Autodesk 2002; Bentley 2003; Graphisoft 2003). Unfortunately, most of these models can only be used to represent a building's three dimensional geometrical information. An application beyond those basic graphical representation tasks is only possible to a small extent up to now.

Main advantages of BIMs will yet lie in tasks beyond the 3D modeling and generation of drawings for a building. Engineers can use the geometric information contained in BIMs for their design tasks, e.g. for structural analysis, CFD simulation, energy simulation or life cycle assessment. In the bidding process information from BIMs can be used for the quantity take-offs needed for cost estimations. Within the production process BIMs can then be used for project management and controlling tasks. If updated throughout design and construction, BIMs continue to be useful during the occupancy phase for facility management and retrofit tasks.

Unfortunately the comprehensive use of project models within the construction sector is poor. One problem is a missing standard to exchange BIM's between different applications.

A promising approach is made by the International Alliance for Interoperability (IAI).They developed a standard for a product model in the building industry during the last years, the so called Industry Foundation Classes (IFC) (IAI 2004). The IFC define an object oriented schema of a product data model. This creates new possibilities for achieving interoperability for design software by use of a common object model of the building and its open data transfer standard. Now IFC is beginning to be widely accepted within the building industry. The CAD vendors like Autodesk, Nemetschek, Graphisoft and Bentley support with their current releases the import and export of building models according the IFC 2x (IFC 2x2) standard.

Another reason why project models are not widely used within the AEC industry yet is that there are almost no commercial software applications that work with and add to a BIM. The first problem described above has been discussed publicly for quite some time, relatively little attention has been paid to the second problem, and few formal approaches have been proposed in the past. Nowadays more and more non CAD vendors join the venture made by the IAI with the IFC product model definition. Primarily in the HVAC domain there are big efforts made to exchange the architectural model and the HVAC model via IFC files. It is important to proof that the IFC is not only a data exchange format for CAD systems. Therefore, this paper focuses on discussing the sharing of data through a BIM (focusing, for this paper, mostly on energy simulation and life cycle assessment) and the use of the shared data by engineering applications. In contrast, most of the design and simulation software currently applied in the construction process uses a stand-alone or application-specific data model. All of them offer user interfaces for data input, but project model interfaces to other applications within the design and production chain are rare. It is common practice to transfer data using paper based media in form of drawings or tables. This requires significant effort for data input: for most of the applications used within the design and construction process of a building, engineers have to enter the same data manually over and over again.

2 Model-based Software Concept

One widespread CAD software supporting the import and export of IFC compliant models is the present release of Architectural Desktop (ADT) from Autodesk. This type of software is expected to be used more and more by planners and architects to build three dimensional computer based product models from the beginning of the planning process. To make such models usable for life cycle referred simulation and assessment they have to be augmented by information e.g. about the materials and their ecological impact. Having once defined an extended product model it works as a database for further integrated simulation tools.

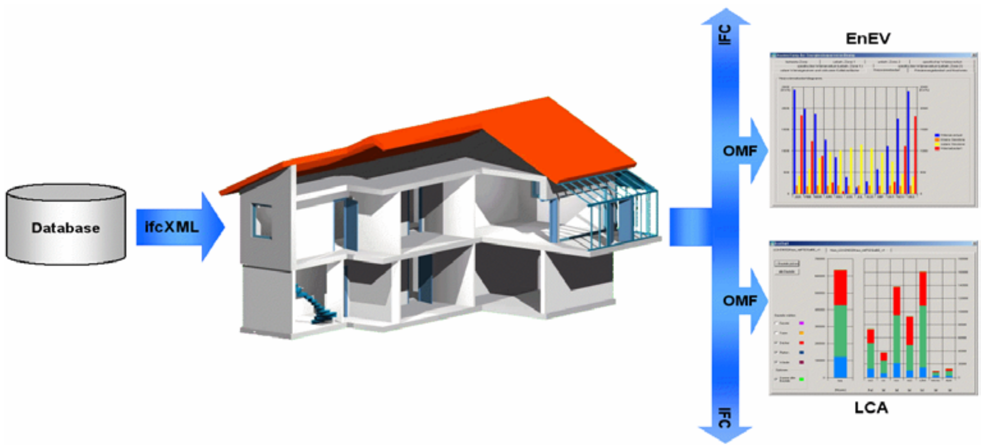

Figure 1. Model-based Software Concept

2.1 Internet based definition of the product model

Since these software tools work directly within ADT the extension of the project model with the required ecological data can be directly performed without exporting any project model data. The contents of the database are based on the available ecological data of the GEMIS project (GEMIS 2002). The GEMIS database provides a variety of ecological information about materials commonly used in construction.

The import feature uses the Object Modeling Framework (OMF 2002) programming interface to communicate with the current product model data of a building and is integrated by an internet browser window to connect to a central database server. This server provides extended product data, being transferred in ifcXML format.

Building components within ADT can be grouped by so called style objects. These style objects collect properties that can be assigned to a number of building components with different geometry. For example the different structural layers of a wall like the inner and outer plaster, the insulation, or the bearing layer can be defined. By assigning a wall style with defined layers to a collection of walls, the layers are assigned to all these walls independent of the walls' geometry.

The developed software extends the definition of these style objects with the necessary ecological data definitions (Figure 2), which are used afterwards by the energy simulation (EnEV) and life cycle assessment (LCA) program. A variety of different styles can be defined using miscellaneous ecological material data for each of the various building components (such as the walls, slabs, columns or piles). These styles can be assigned to the building components and the input model needed by the simulation program is created automatically from ADT's project model. Engineers can easily create design alternatives for case studies, by interchanging the styles for different building components.

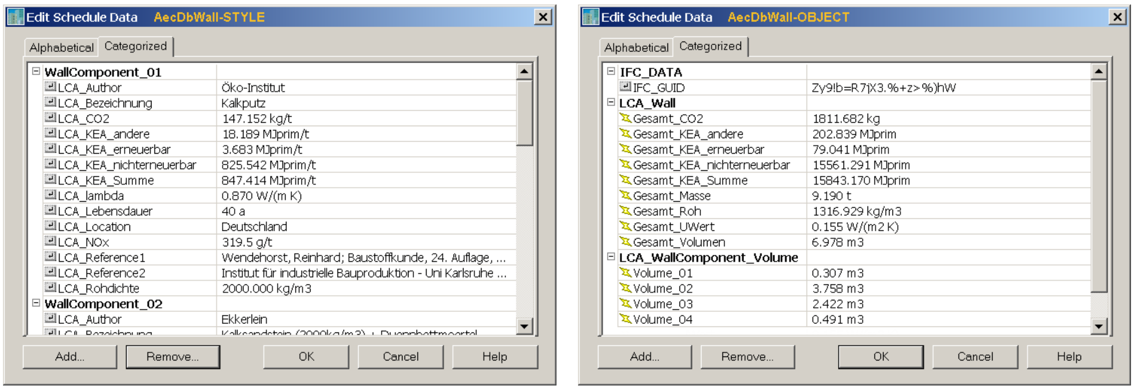

Figure 2. Static and automatic (dynamic) property sets for building elements and styles within the ADT

The interface to the materials database is completely integrated within the graphical user interface of ADT. Planners can use an Internet browser to easily access the database server of the Technische Universität München containing the ecological information (Figure 3). This framework is extendable to transfer any property data (e.g. costs) to the model. The upper section of the window contains a fully featured web browser control. The user can navigate through the database and select the required data. The contents of the tables are created dynamically from a relational database server (MySQL: http://www.mysql.com) using the scripting language PHP. The transferred extended data are then attached to style objects being linked to building parts (e.g. walls). This enables the user with a few internet database requests to define the styles in a building model. Due to the direct integration of the interface into ADT, designers can extend the product model within their familiar working environment.

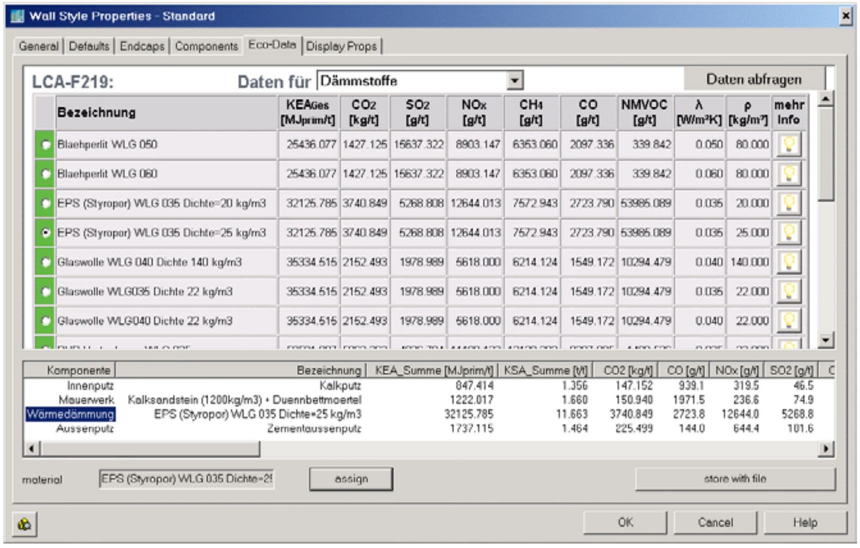

Figure 3. Integrated web-interface to the ecological database server within ADT

2.2 Analysis of the product model

Once having created an extended product model, it can be used as a database for further simulation tools. Up to now two applications have been developed, one performing an energy simulation due to the German Energy Saving Ordinance - EnEV (EnEV 2001), the other one allowing life cycle assessment studies (Figure 4). Using the IFC format enables other tools to be easily integrated into this software concept. Examples are the integration of CFD simulations (Treeck and Rank 2004) and 3D Finite Element Methods (Romberg et al. 2004) or cost planning and schedules (Seidenfad 2002).

In Figure 4 the results of a monthly energy simulation according to the EnEV and a life cycle assessment study are shown. Planners can easily change the underlying model and recalculate the different design variants. This supports them to find an optimized design of the building envelope and the building service systems (HVAC).

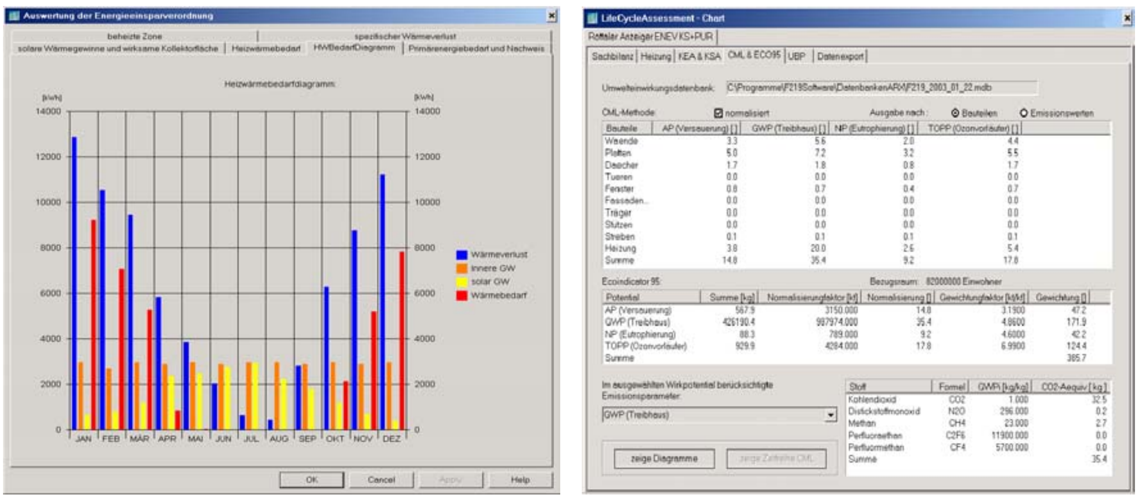

Figure 4. Results of a monthly energy simulation (left) and life cycle assessment (right)

The results of the energy simulation are stored back to the product model and can be used as input data for the LCA software tools. The planner can simulate the resource requirement of the building over its life cycle. For evaluation of the life cycle inventory (LCI) results different assessment methods have been implemented: The cumulated energy expenditure (KEA), the CML method (Heijungs 1992), the EcoIndicator95 method (Goedkoop 1995) and the Swiss UBP method (BUWAL 1990, 1998). Due to the available ecological data in GEMIS (GEMIS 2002) and the chosen reference area (Germany) these methods were adapted within the presented project.

The CML method was developed in 1992 by the Center of Environmental Science of the Leiden University (**C**entrum voor **M**ilieukunde **L**eiden). The CML method summarizes the LCI results into a set of environmental impact categories. This set of category indicators describes the environmental profile of the analyzed product or process. Within the presented project four impact categories have been chosen: the Global Warming Potential (GWP), the Acidification Potential (AP), the Nutrification Potential (NP) and the Tropospherical Ozone Precursor Potential (TOPP).

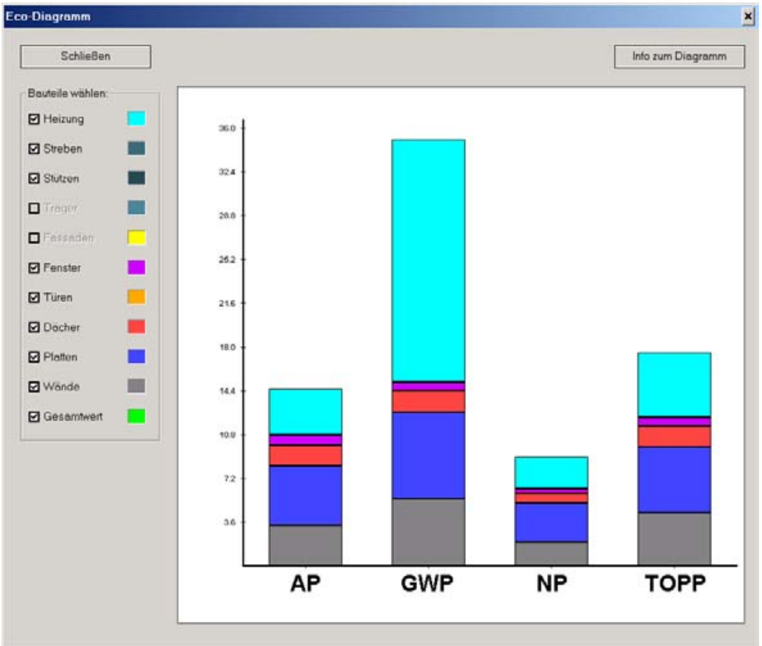

Figure 5. LCA results (normalized category indicators) using the CML method

In analogy to the scarcity in economical fields (supply to demand ratio), the Swiss UBP method calculates ecopoints for different emissions based on the ratio between the current and target (critical) flows of a substance (= distance to target principle). These ecopoints are then added up to one single value: the higher this value, the larger the environmental impact of the examined product. Within the presented project new ecopoints have been calculated, based on actual data for Germany.

The EcoIndicator95 method was developed in the Netherlands in 1995. Thereby the steps of LCI analysis and impact assessment are based on the CML method. In addition to the CML method the EcoIndicator95 method introduces an additional weighting step to convert and aggregate the indicator results across the impact categories to one single value: the EcoIndicator. Like the UBP method the EcoIndicator95 method was adapted for our project concerning the chosen categories indicators and reference area.

3 Test case study

The 3D product model of a real world building is shown in Figure 6. The building consists of three floors, whereby the heated zone is defined by the external building components. The volume of the heated zone amounts to 2.500 m³.

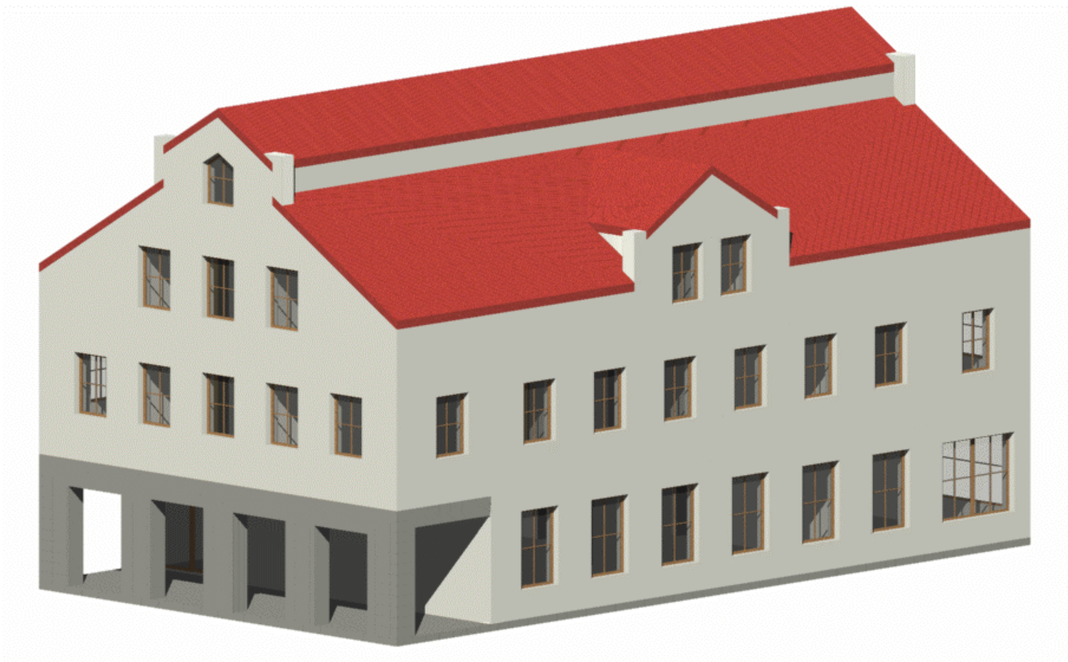

Figure 6. 3D product model for the test case studies

3.1 Description of the design variants

The basic geometric characteristics, like the volume of the heated zone and the orientation remain the same throughout all design variants. On the other hand the used building materials, the insulation characteristics and the heating technology are changed. The simulation period is set to 50 years. At first a calculation of the annual heat use with the ENEV module is performed for all variants. The results are used as an input for the calculations with the LCA module.

The first variant complies with the formalities of the EnEV regarding the annual heat use (Q_h) and primary energy consumption (Q_P). In consequence a comparison of different building material combinations under condition of the same insulation standard takes place. Further on the insulation is optimized so that Q_P stays below the limit of 60 kWh/(m²a). This meets the requirements of the German "Kreditanstalt für Wiederaufbau" (KFW) for a financial governmental aid. In a last step an optimized heating technology is combined with the high insulation standard. Table 1 gives an overview of the examined variants. The denotation of the variants is made up to the energy standard, the heating technology and materials.

Table 1: Design variant overview

Variant	Energy standard	heating technology	material combination
E-G-C	**E**nEV	**G**as fired condensing boiler	Wall material: **c**lay brick
E-G-S/P	**E**nEV	**G**as fired condensing boiler	Wall material: **s**and-lime brick Insulating material: **P**UR
E-G-S/E	**E**nEV	**G**as fired condensing boiler	Wall material: **s**and-lime brick Insulating material: **E**PS
60-G-S/P	KFW**60**	**G**as fired condensing boiler	Wall material: **s**and-lime brick Insulating material: **P**UR
60-G/S/V-S/P	KFW**60**	**G**as fired condensing boiler **S**olar collector **V**entilation system with heat recovery	Wall material: **s**and-lime brick Insulating material: **P**UR

A comparison of the first three variants investigates the effect of different building materials on the overall ecological balance of the building. Therefore the three variants must have the same heating system and achieve an identical insulation standard (U-value). The variants two and four aim to estimate the influence of a very high insulation standard on the LCA results. Again the heating system must be identical but the U-value changes instead of the building material. With the last variant the combination of high insulation standard and a multivalent heating system is examined. Thereby the design of the single heating system components follows the standard values given in DIN V 4701-10. In Table 2 the configuration of the structural elements is described. Vapor barriers and water vapor open layers are not explicitly mentioned but have been considered in the LCA study.

Table 2: Configuration of the structural elements

	E-G-C	E-G-S/P	E-G-S/E	60-G-S/P 60-G/S/V-S/P
Outside walls	15 mm lime plaster 365 mm clay brick no insulation 20 mm cement plaster	← 175 mm sand-lime brick 62 mm PUR^{WLG035} ←	← ← 62 mm EPS^{WLG035} ←	← ← 280 mm EPS^{WLG035} ←
	*U = 0,45 W/(m^2*K)*			*U = 0,12 W/(m^2*K)*
Ground slab	50 mm cement screed 30 mm PUR^{WLG035} 200 mm reinforced concrete 20 mm PUR^{WLG030}	←	←	← ← ← 140 mm PUR ^{WLG030}
	*U = 0,31 W/(m^2*K)*			*U = 0,13 W/(m^2*K)*
Roof	tiled roof 180 mm PUR^{WLG035} wooden rafter	←	← 180 mm EPS^{WLG035} ←	← 240 mm PUR ^{WLG030} ←
	*U = 0,18 W/(m^2*K)*			*U = 0,14 W/(m^2*K)*
Windows	PVC frame and 3x glazing	←	←	←
	*U = 1,20 W/(m^2*K)*			*U = 0,80 W/(m^2*K)*
Inside loadbearing walls	15 mm lime plaster 240 clay brick 15 mm lime plaster	← 175 mm sand-lime brick ←	←	←
Inside walls	15 mm lime plaster 115 clay brick 15 mm lime plaster	← 115 mm sand-lime brick ←	←	←
Floor slabs	200 mm reinforced concrete	←	←	←

3.2 Results

In Figure 7 the LCA results of all design variants for a simulation period of 50 years are compared. For a better presentation the absolute LCA results have been transformed into relational results. Therefore the design variant E-G-C was set to an ecological load of 100% and used as reference. As one can see no remarkable difference between the material combinations concerning the overall ecological load of the whole building can be found (E-G-C, E-G-S/P and E-G-S/E). Thereby is has to be taken into account that there is an uncertainty in the basic ecological data of GEMIS.

Comparing the design variants E-G-S/P and 60-G-S/P shows the effect of a high insulation standard on the LCA results. Following the EnEV criteria Q_P of the heating system, variant 60-G-S/P is classified about 30 % better than variant E-G-S/P. If additionally the building material is taken into account this advantage decreases to 25 % (KEA_{nE} = Cumulated Energy Expenditure of non renewable resources). Performing an impact assessment with the EcoIndicator95 and UBP method, where both emissions of building material production and operation of the heating system are considered, the difference decreases to about 10 %. This means that the building material has a very large influence on the ecological balance of the overall building (see also Figure 8). As a consequence it can be stated that an ecological ranking of buildings on basis of the EnEV (Q_P) is insufficient, because only energetic parameters of the heating system are taken into account. Building materials and emissions are not considered at all. The combination effect of high insulation standard and modern multivalent heating system is illustrated by design variant 60-G/S/V-S/P. Compared to variant 60-G-S/P the ecological load is reduced for another 20 %.

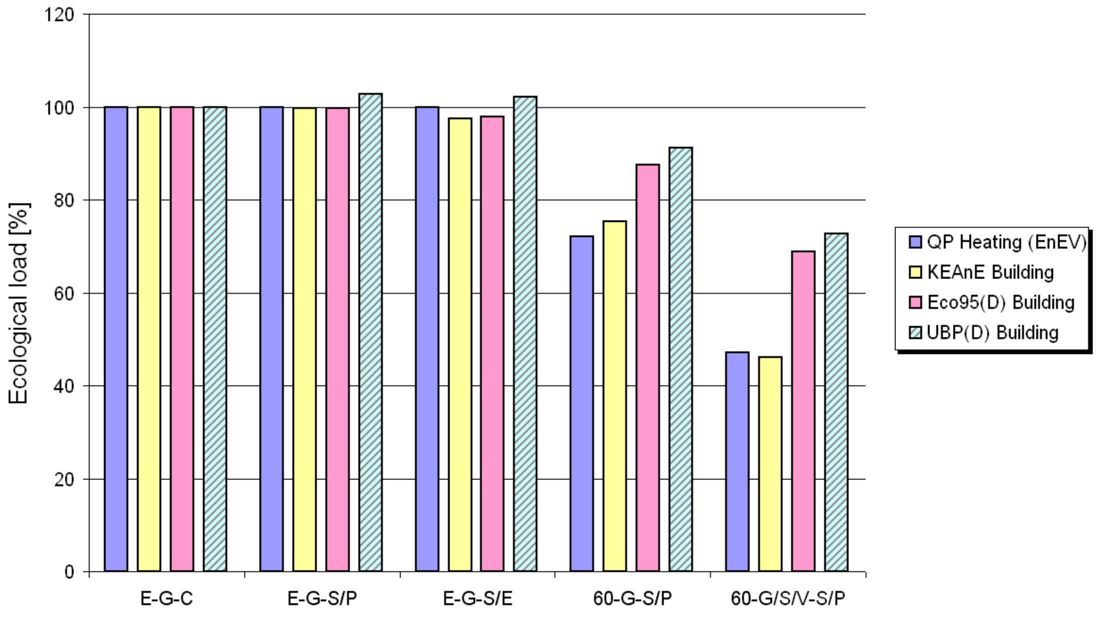

Figure 7. Comparison of all design variants with variant E-G-C as 100 % reference level

Figure 8 presents the influence of the building materials on the LCA results, again over a simulation period of 50 years. It is shown that for the EnEV conforming variants the building materials already have a portion of 40 % on the overall result. This increases up to 55 % with variant 60-G-S/P and even 70 % with variant 60-G/S/V-S/P. Especially walls and slabs have a large influence. A further investigation with the LCA module points to the NO_X and CO_2 emissions from the production of concrete (cement) and sand-lime brick (not the PUR insulation). Minimizing the usage of concrete and sand-lime brick and/or replacement by other materials would therefore be a possible approach to optimize the overall LCA result.

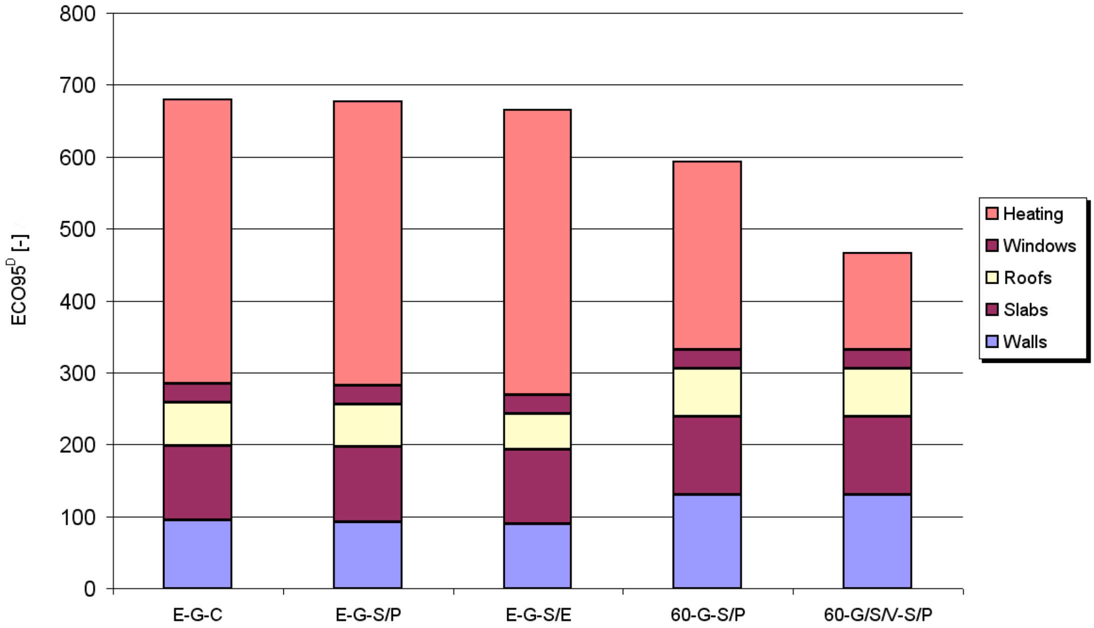

Figure 8. Comparison of all design variants based on the EcoIndicator95

4 Conclusion

In this paper a software concept was presented using an integrated approach for ecological life cycle simulation and assessment of buildings. The basic idea is to link LCI databases and simulation tools together by using a common product model (BIM). The LCI database server is designed as an open platform for product model data exchange using the ifcXML format and the 'IFCPropertySet' concept. This creates new possibilities for achieving interoperability for design software through the use of a common object model of the building and its open data transfer standard (ISO/PAS 16379). The general software framework is extendable to other analysis and simulation methods used in the AEC domain, e.g. project management or 4D simulations (Fischer et al. 2004).

The evaluation of the presented design studies shows that an ecological optimization of buildings on basis of the EnEV is insufficient, because building materials and noxious emissions are not taken into account. More detailed evaluation methods (e.g. LCA) have to be carried out to recognize the mutual interaction and ecological impact of building materials and building systems over the whole life cycle. The presented software tools enable planers to perform integrated LCA and energy simulations on several design variants during early design stages in a fast and easy way. By applying this software in practice a substantial contribution for saving energy and natural resources can be provided in the sense of sustainable and ecological building design.

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