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Expansion in Number of Parameters - Simulation of Energy and Indoor Climate in Combination with LCA

Aleksander P. Otovic **Lotte M. B. Jensen** **Kristoffer Negendahl**

INTEGRATED ENERGY DESIGN WITH LCA

The Technical University of Denmark has been carrying out research in the energy balance of buildings in relation to indoor climate for decades. The last two decades have seen a major role played by research in the field of Integrated Energy Design (IED) focusing on the earliest design phases. The research has showed that the greatest effect in relation to achieving net-zero-energy buildings is achieved when indoor climate and energy simulation tools are applied from the very first architectural sketches, where geometry, façade design, orientation, etc. are determined. Large architectural offices and engineering consultancies in Scandinavia have invested in software and interdisciplinary design teams to carry out Integrated Energy Design (IED). Legislation has been altered and simulations of indoor climate and energy balance are now required to obtain building permits. IED has been rolled out extensively in the building industry. Having reduced the energy needed to operate the indoor environment to almost zero by designing with knowledge and optimizing systems, the energy needed to construct the building and its systems is now prominent in importance. The CO2 impact of buildings has become an important parameter because sustainability certification systems like the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) have taken the lead in Europe. The DGNB system includes Life Cycle Assessment (LCA), and the Danish government has stated that Denmark must be CO2 neutral by 2050. The focus in design is shifting from energy and indoor climate to CO2 impact. The experience from the decades of IED shows that the largest gains in reduction come from the early design phases. LCA in relation to buildings has to include the energy needed to operate the building's indoor climate as well as the CO2 embodied in the building. This makes the simulations far more complex. LCA thus tends to be placed in the last phases of design and used for certification, so that only a single iteration is needed. However, real-time LCA simulation tools are required if designers are to base design decisions not only on knowledge about indoor climate and energy balance but also on LCA. This paper presents the efforts at DTU's Department of Civil Engineering to develop a real-time LCA simulation tool, including indoor climate and energy balance simulation (based on Energy +) and the first round of implementing the tool at well-esteemed architectural offices in Scandinavia. The development of the real-time LCA-indoor climate- energy balance tool was funded by Nordic Built.

INTRODUCTION

For decades, it has been possible to design and build net-zero-energy buildings based on the design process of Integrated Energy Design (IED). The challenge was posed to the industry by UN reports which documented that close to 40% of the energy consumption of our societies was used for operating buildings (Laustsen et al. 2011). To meet the challenge, the building industry developed simulation/software tools with efficient interfaces with 3D-modelling software. Research demonstrated that time spent on informing the early stage design process about indoor climate and energy performance would result in buildings with better performance. However, IED is still not being used in all architectural studios in Scandinavia and is still considered with scepticism by parts of both the architectural and the engineering professions, while others are speeding ahead. To the latter group of professionals, the challenge

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of indoor climate and energy balance is no longer the main issue. A much broader but still quantifiable challenge is how to reduce CO2 emissions. How can the IED design process be made simpler and faster and at the same time integrate LCA information? The IED design process is facilitated by energy balance and indoor climate software tools (fig. 1), and if we are to address the research question presented above, new tools integrating LCA-parameters will pose both solutions and new challenges. To provide early design support, the tools must have the following features:

Visual: The tools must present the results of changes in a way that immediately shows the designer the consequences of the changes he makes. The tools should, as far as possible, allow the results to be visible at all times during modification of the model geometry.

Fast: To keep up with the rapid pace of design changes in the early stages, the tools must be able to deliver results almost instantaneously. This will obviously come at the cost of reduced accuracy, but as Hensen (2004) argues, simulation is much more effective as a comparative tool than it is for absolute predictions, and the value of using the minimum sufficient precision is commonly underestimated.

Flexible: The tools must facilitate a potential expansion of the system representations with innovative design concepts as the design progresses (Struck, 2012). In the case of LCA tools, they must be able to accommodate significant changes in the model design.

Scalable: The tools must be able to dynamically scale the resolution of interfaces to fit the different design stages (Struck, 2012).

METHOD

The question of how the IED design process can be made simpler and faster and at the same time integrate LCA information was investigated through an analysis of how a new simulation tool could address the challenge. Through an investigation of the various collaborative arrangements and levels of operator integration, a theoretical framework for the tool was identified in the 'integrated dynamic model'. Based on a number of sample applications, we then investigated whether the LCA tools currently available were able to deliver the necessary features. These observations set the stage for an attempt to propose a new tool specifically dedicated to supporting the early design stage within the framework of an 'integrated dynamic model'. The tool's potential was tested in two 'ideal' design situations and later compared with other commonly used LCA tools in an architectural studio.

RESULTS

The Integrated Dynamic Model

The integrated dynamic model was introduced by Negendahl (2014) as the centrepiece of his consequence-based design framework. An integrated dynamic model uses middleware consisting of a Visual Programming Language (VPL), which is a programming language that lets the user manipulate graphical elements to create programs instead of writing low-level code. VPLs are popular among architects due to their intuitive graphical user interfaces and their ability to create generative algorithms for 3D-geometry that let designers explore a range of design options within a parametric environment. In the integrated dynamic model, the VPL is dynamically coupled to the design tool on one side, and to the Building Performance Simulation (BPS) environment on the other. The dynamic couplings allow the model to function much like a combined model (see Figure 1), but without the restraint of having to work within a particular commercial software suite (Negendahl 2015). They also allow for different operators to control the different models, which makes the model better suited for the conventional design process.

"A fundamental part of an integrated dynamic model is the presence of parametric objects and variables. The consequence feedback from the linked BPS tool(s) is translated into direct visual input within the design tool, thus providing valid results in an integrated environment" (Negendahl 2014).

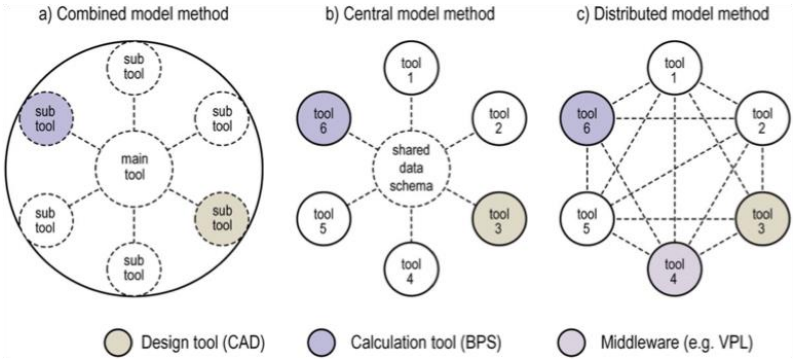

Figure 1 Methods for model integration. The integrated dynamic model is based on the distributed model method. From Negendahl (2015).

A parametric model allows the planner to change the design easily and quickly provide a range of variations (Hollberg & Ruth 2014). When combined with optimization algorithms, the automated generation of variations can also be used to optimize the design.

The integrated dynamic model seems to live up to the requirements. In the context of consequence-based design, the integrated dynamic model is able to sustain the design process through several levels of detail and precision from pre-conceptual design to detailed design (Negendahl 2014). Moreover, the dynamic couplings make sure that the results from the BPS environment are quickly transferred and visualized in the design tool:

Ideally, the integrated dynamic model requires that the geometry model is fully parametric to allow automatic updates between intermodel tools. This entails great potential but also necessitates strict modeling requirements from the operators. Nevertheless, when compared to the alternatives, the integrated dynamic model is superior in complying with the required features and therefore seems far better suited for the purpose of this project than the combined or central method.

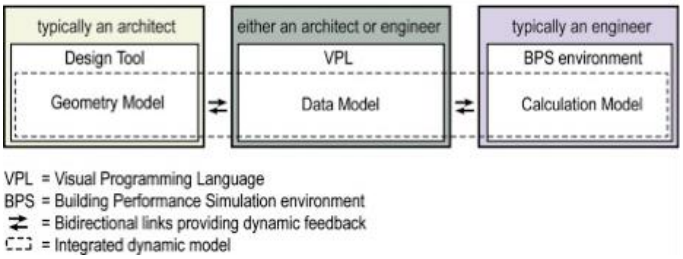

Figure 2 Definition of an integrated dynamic model. From Negendahl (2015).

The LCA Tool Embedded In An Integrated Dynamic Model – IDGB

The proposed Integrated Dynamic Grasshopper Based (IDGB) tool utilizes the framework of an integrated dynamic model (see Figure 2) to connect sustainability data from an external LCA database to the Rhinoceros (Rhino) design tool (Robert McNeel & Associates 2015) using the VPL Grasshopper (Rutten 2015). The tool calculates the Global Warming Potential (GWP) in kg CO2eq over three phases:

1) The geometry model has constructions assigned to it, and the sustainability data is used to calculate the Embodied Carbon of the construction materials used.

2) The Grasshopper plugin Honeybee (Roudsari 2015) is used to communicate with EnergyPlus (U.S. Department of Energy 2015), which calculates the annual energy usage of the proposed geometry model. When

combined with the database, this provides information on the lifetime energy use and the environmental impact of the Use phase.

3) Finally, based on a simple model of reuse or dispose, the environmental impact of the End of Life phase is calculated.

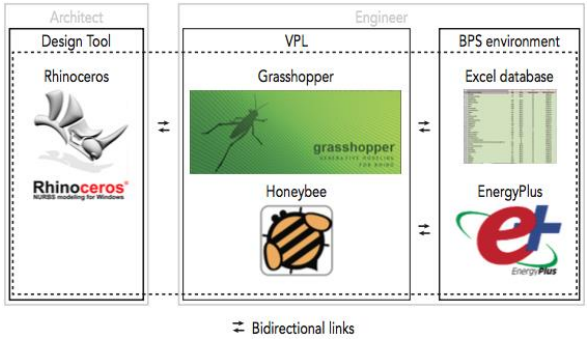

Figure 3 Framework for the proposed LCA tool. Based on the model by Negendahl (2015)

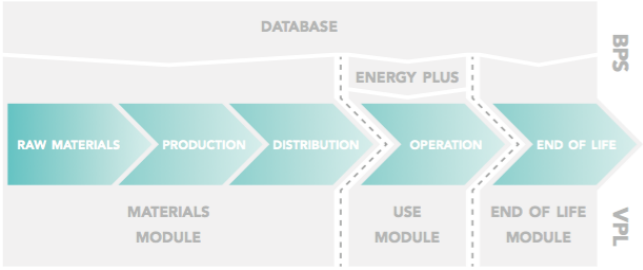

Figure 4 The data flow of the tool. The external database contains information on all levels of the building life cycle, but the energy consumption of the building is needed for the Use module.

The lower part of Figure 4 outlines the central parts of the tool's VPL interface, as the life cycle stages are applied in the three modules, which are further elaborated upon below. The upper part of the figure shows the BPS environment, which contains the external calculation model. The next section goes through the underlying elements of this calculation model.

BPS environment: Database and EnergyPlus. The Grasshopper model is dynamically connected to an external database, which is located in a customized Excel sheet and comprises environmental data on materials, use and disposal. The database can be edited to include new, project-specific data by copying from other databases, but the structure of the data sheets must remain the same for the link to remain intact.

The Grasshopper model is also connected to EnergyPlus, an energy analysis and thermal load simulation program from the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE). EnergyPlus calculates the annual heating and electricity demand for the building based on a user's description of a building from the perspective of the building's physical make-up and associated systems. (U.S. Dept. of Energy 2015).

VPL: The Grasshopper Interface. Figure 5 shows the interface of the Grasshopper model, which consists of eight interconnected modules, each performing a specific task. Essentially, the modules are used to transform the architect's geometry into visualizations of the sustainability of the design. Three of the modules are dedicated specifically to calculating the environmental impact (see Figure 4). The modules serve to:

Calculate environmental impact (*Materials, Use and End of Life Modules*)

Import/generate model geometry (*Geometry Module*)
Import environmental data (*LCA Database Module*)
Assign constructions (*Constructions Module*)
Calculate energy (*Energy Demand Module*)
Visualize results (*Column Graph Module and Materials Module*)

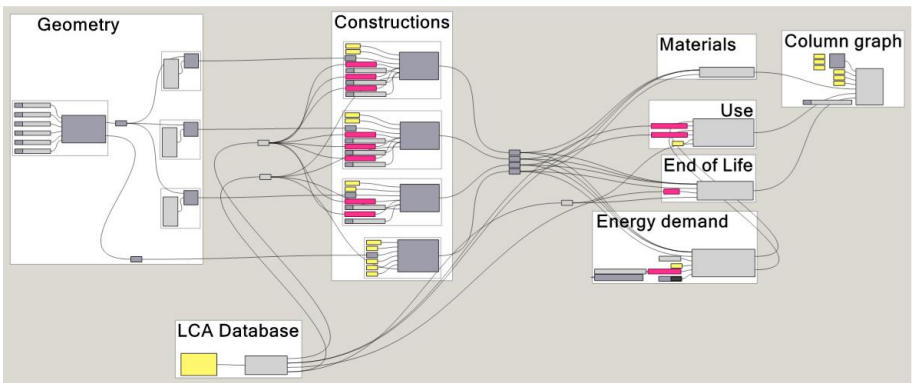

Figure 5 Full Grasshopper interface of the LCA tool with the 8 modules. The content of the Geometry module is project-dependent.

The Geometry module contains the dynamic coupling between Grasshopper and Rhino. It can receive geometry from Rhino for use in Grasshopper, but it can also construct its own parametric geometry, which is then visualized in Rhino. The *LCA Database Module* uses the LCA Database component to read the external database and outputs the database in a format that the other components can read. It also enables the user to choose from a selection of materials, energy sources and possible end-of-life scenarios. The *Constructions Module* connects the building geometry with the LCA database by letting the user define construction types and window attributes to each part of the design model geometry. The *Materials Module* takes the assigned constructions and windows and calculates the Carbon Footprint of each construction layer in kg CO2eq based on the type and weight of the material. It then divides the result by the surface area of the construction and visualizes the result in the Rhino model by assigning a colour to the surface on a scale from red to green, depending on the size of the Carbon Footprint. The *Energy Demand Module* uses the plugin Honeybee, externally connected to EnergyPlus, to calculate the energy demand of the proposed geometry model based on the assigned constructions and windows. The *Use Module* essentially converts the energy demand result from the Energy Demand Module into a measure of the environmental impact of the Use phase. The user is allowed to try out different sources of energy to see what environmental effect they have. The *End of Life Module* lets the user choose between various methods of disposal for the assigned materials. The *Column Graph Module* visualizes the environmental results of all the other modules.

Dynamic Visualization. As mentioned, the Rhino design tool receives feedback visualization on two fronts:

Surface Colouring: If required, the walls of the model geometry can be coloured depending on the Embodied Carbon per m^2 of surface. The scale can be adjusted to the ambitions of the project, but the default is set to a range from 50 to 300 kg CO2eq per m^2.

Column Graph: The main objective of the Column graph is to communicate the proportions of the Embodied Carbon in the various constructions.

The Potential of the IDGB tool

Case Study 1: Building Component. The first Case Study proposes three wall elements, all 4m long and 3m

tall, but with different types of windows. Constructions of different types and weight classes can be assigned to the elements, e.g. a very heavy one with a regular brick exterior wall and a concrete back wall, a lighter one with a cladding of tiles fastened with steel plates to a concrete back wall, and a very light one made of steel plate elements with a cement plate as wind barrier. A profound difference in the Embodied Carbon of the constructions will be immediately visible from the Rhino model colouring; the lightweight element will have the least environmental impact from a materials perspective. The windows in the elements also differ slightly; differences in the area of glass and length of the frames mean that they also have different levels of Embodied Carbon.

It is possible to compare the three elements side by side. The Embodied Carbon of the widows seems to be significantly reduced when the number of mullions is decreased. The two windows with mullions have about the same impact, while the impact of the window without mullions is only half that of the others. It would have been possible to make the width and height of the elements parametric, which would have added a new dimension to the analysis because it would then have been possible to compare the effect of the size of the element against the effect of the size and type of the window.

Case Study 2: Building Extension. The second Case Study uses the tool to support design on a whole building scale: a simple, one-story extension to an existing office building. The building already exists as a simple geometry model in Rhino, which makes it easy to impose parametric dependencies upon the new building extension. These parametric dependencies will enable the tool to perform calculations for many different geometry variations very quickly – e.g. the parametric model can be capable of varying the length and height of the building extension as well as varying the window sizes.

The wall, floor and roof surfaces of the parametric model can all be connected to different Construction components, while the window surfaces can be connected to a Window component. This allows the IDGB tool to instantly visualize the Embodied Carbon of each construction in Rhino through colouring. The wall constructions seem to have the highest Embodied Carbon, so several alternatives could be tried out to determine the best solution. Finally, it is possible to investigate the effect of using alternative heating and electricity sources. In this simple case, it was (not surprisingly) discovered that using solar heating instead of district heating and using electricity from wind turbines instead of power plants could significantly reduce the environmental impact of the Use phase.

Testing the IDGB Tool In An Architectural Studio

Since most LCA programs include indoor climate and energy from a secondary source only – meaning that the indoor climate and energy performance is analysed in a different program and key factors subsequently entered in the LCA program, it was decided to compare only the LCA part of the integrated dynamic LCA tool with three existing LCA tools used in Scandinavian architectural studios. Architects Jan Kauschen and Søren Nielsen, together with Kikki Lambert, Regitze Zimmerman and Louise Pedersen, carried out a test of the tools in the autumn of 2015 at the architectural studio of Vandkunsten.

To promote sustainable building in Denmark, the Green Building Council (DK-GBC) has chosen to implement the German DGNB evaluation system in Denmark. Our integrated dynamic Grasshopper-based tool (the IDGB tool) was compared with the results of the LCA part of the DGNB system and the closely related software, LCAbyg, and another design-oriented LCA tool, OpenLCA. The comparison was done by analysing a case of two different façade systems and their required fire protection systems. The architectural studio Vandkunsten had designed the façade and the analysis was performed in collaboration with the architects in the studio. The first façade system had an outer cover of larch, which resulted in a requirement for an automatic sprinkler system; the second façade system had an outer cover of steel plates and the load-bearing structure could be protected by fire-resistant plaster. The architects wanted to know which of the two options was the most sustainable. The two façades had the same U-value. The materials and processes assumed to be the same were left out of the analyses and only the materials that changed when changing the façade cover and fire protection system were taken into account.

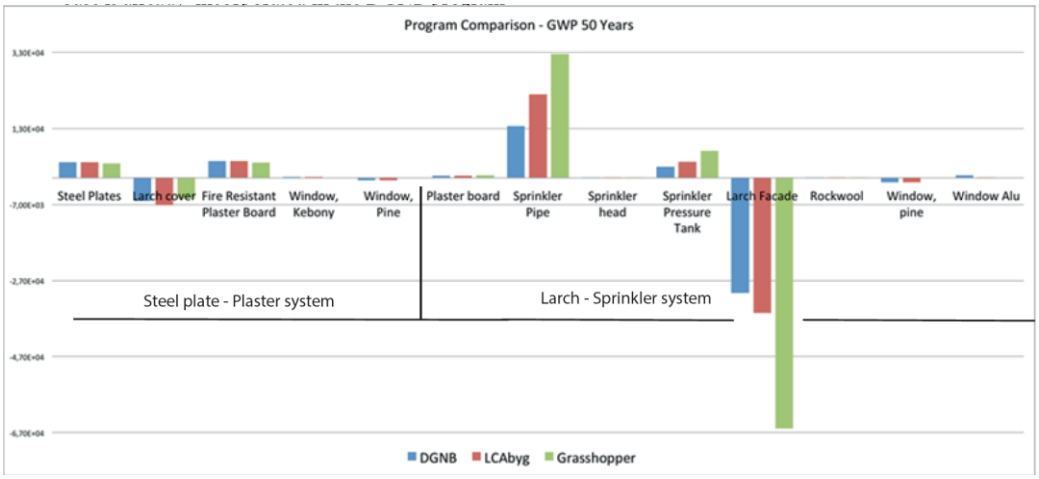

Figure 6 Results for the DGNB, LCAbyg and IDGB (Grasshopper) tool for the 50-year GWP analysis.

LCA Tool Comparison. Figure 6 shows a comparison of the DGNB's Excel sheet, LCAbyg and the IDGB tool for the GWP over 50 years. For the Steel plate/Plaster system, the values are relatively similar, especially those from the DGNB's Excel sheet and LCAbyg. These values are approximately 10% higher than the results from the IDGB tool. More inconsistencies in results are visible in the Larch/Sprinkler system. The values for the DGNB Excel sheet and LCAbyg are not the same in all material instances. This is partly due to some different values entered for the larch façade and for the sprinkler head and tank. But for the aluminium in the windows and the sprinkler pipe, they did not give the same results even though the same impacts and amounts were used. The IDGB tool also gives values relatively far from the DGNB-based tools on the sprinkler system and larch façade. The big impact that the IDGB tool gives for the Larch is hard to explain, but there might be some intolerance to very large values in the program.

Interface Comparison. DGNB's Excel-based tool works by changing the marked spaces. The program is designed to describe the building in terms of building parts (such as a wall system), which are often provided in volumes from a building information model, e.g. a Revit model. Generally speaking, trying to match the unit used for measuring impacts (from the databases) with the unit available from a building information model is a very time-consuming factor in all the programs tested here. It is also a source of error when units are changed based on estimated densities, as well as opening up for calculation errors in this process.

The interface of the IDGB tool is easy to understand and you can follow the flow from process to process, but if you want to see what lies underneath each process, this is far more complicated to understand. It is possible to see the output of every life cycle stage the program calculates, which is good, because you can see which impact goes where. The graphical results the program shows are not always exact, because it cannot show impacts with a negative value. It is good that the program is bound to a geometry, because it makes it easier to understand than an Excel sheet with a long list of materials, but it also makes it hard to introduce elements of the building that are not a layer in the outer walls, roof or floor, such as a sprinkler system. Moreover, this program only calculates impacts for the GWP.

In OpenLCA, it is not possible to implement your own data, which meant that the database ELCD set the boundaries for the different materials. The ELCD database contains around 350 datasets while Ökobaudat contains more than 700 datasets. This means that using OpenLCA involves making a lot of assumptions. As easy as it can be to work with the software, the databases are indispensable for the LCA.

The DGNB's Excel-based tool, LCAbyg and the IDGB tool gave fairly similar results, but there were some inexplicable differences that might be caused by the IDGB tool's dependency on a geometry. There is a very big difference between the OpenLCA tool's results and those of the other tools. This might be because the OpenLCA only calculates for 100 years while the other programs calculate for 120 years, as required in the DGNB guide, or it

could be due to the material assumptions that were made because of the lack of cladding materials in the OpenLCA database. As for the interface and usability of the programs, there was a general issue of having to convert from one unit to another: the Revit model gave material amounts in volume, but the programs required various inputs depending on the material. It was possible to insert your own data in the database for all programs except OpenLCA, which made it necessary to make a large number of material assumptions. The programs using the same database (Ökobaudat) did not always give the same values in their results, but the tendencies of the results were similar.

CONCLUSION

Our IDGB tool proved useful in providing real-time visual feedback directly into the design process, and the case studies showed that it was flexible enough to be used both in preliminary studies of single building components and for later studies of the full building geometry. On the other hand, the tool is far from fully developed, which restricts its usability.

Comparing the tool with other LCA tools used in Scandinavian architectural studios, the results from using the IDGB tool varied from the results from the most commonly used LCA tools. However, one of the commonly used LCA tools proved to give results that varied considerably more from other commonly used LCA tools than the IDGB tool. The designers favoured the option of adjusting the geometry because it made the context more visual and clear than numbers in an Excel sheet.

PERSPECTIVES

The LCA tool proposed in this article will need to be developed and tested further and the tool needs to be peer reviewed to be used by a larger audience. The full potential of integrated dynamic modelling has not been fully investigated. Further studies will be taking place in the context of a project funded by Nordic Built. The architectural studios in the project will provide design teams in 2016-2018. One design team will use a setup of separate tools (indoor climate/energy and LCA) that together inform design decisions. Another team will use the IDGB tool. The design processes will be mapped in terms of daily reports and interviews.

REFERENCES

Hensen, J.L.M., 2004. Towards more effective use of building performance simulation in design. In *Proceedings of the 7th International Conference on Design & Decision Support Systems in Architecture and Urban Planning*. Eindhoven.

Hollberg, A. & Ruth, J., 2014. A Parametric Life Cycle Assessment Model for Façade Optimization. In *Building Simulation and Optimization*. London. Available at: http://www.bso14.org/BSO14_Papers/BSO14_Paper_048.pdf.

Laustsen, J. et al., 2011. Europe ' s buildings under the microscope, Buildings Performance Institute Europe.

Negendahl, K., 2014. Parametric design and analysis framework with integrated dynamic models. In *Proceedings of the 3rd International Workshop on Design in Civil and Environmental Engineering*.

Negendahl, K., 2015. Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction*, 54 (June), pp.39–53. Available at: http://dx.doi.org/10.1016/j.autcon.2015.03.002.

Robert McNeel & Associates, 2015. Rhinoceros. Available at: http://www.rhino3d.com/ [Accessed June 3, 2015].

Roudsari, M.S., 2015. Ladybug + Honeybee. Available at: http://www.grasshopper3d.com/group/ladybug [Accessed June 10, 2015].

Rutten, D., 2015. Grasshopper. *Robert McNeel & Associates*. Available at: http://www.grasshopper3d.com/ [Accessed June 2, 2015].

Struck, C., 2012. *Uncertainty propagation and sensitivity analysis techniques in building performance simulation to support conceptual building and system design*. Technische Universiteit Eindhoven.

U.S. Department of Energy, 2015. EnergyPlus Energy Simulation Software. Available at: http://apps1.eere.energy.gov/buildings/energyplus/ [Accessed June 10, 2015].

Ipsen K., Zimmermann R., Pedersen L., Comparison between different lca methods in regard to fireprotection, DTU Report Department of Civil Engineering , 2015