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Embodied Energy Optimization Tool

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Abstract

About 40-50% of global raw materials are currently used in the building industry in the assembly/construction phase and in the use phase of the building and are responsible for 40-45% of total worldwide anthropogenic carbon dioxide emissions (Huovila [5]). These problems have led to the development of legislative policies, regulations and targets to limit material and energy use in buildings.

In order to achieve Energy Performance Building Directive's 2020 target towards energy neutral buildings, most regulations and policies focus on decreasing the operating energy, as a result of which this energy has reduced and is still reducing, thereby increasing the importance of embodied energy consumption in buildings. Most of the embodied energy and some of the operating energy of a building is related to the structure. Hence, one possibility is to minimize the energy consumption of a building by varying its structural design. Another possibility is to increase its service life. However, the relationship between adaptability and energy consumption is not always linear. Hence there exists the potential to apply computational methods to obtain a more optimal design from the point of view of energy efficiency and sustainable building design.

This paper investigates the development and application of a computational tool that optimizes the conceptual stage design of a building to have minimum embodied energy and some aspects of operating energy, depending on the adaptability required. For this purpose, a parametric computational framework for sustainable building design was developed and implemented by the tool. The working prototype of the tool focuses on low-rise rectangular grid office buildings in steel and multi-objective optimization techniques. Test cases were applied and their results were validated. Finally, conclusions were drawn on both the framework and the tool, and its limitations and possible future developments are discussed.

Keywords: embodied energy, sustainability, parametric design, computational tool, conceptual stage.

1. Introduction

Sustainable development refers to the management of various environmental resources for the sustenance of present and future generations (Lebel and Kane [6]).

1.1. Green buildings

The life of a building can be classified into several stages (Figure 1). Each of these stages consumes energy, raw materials and other natural resources, to varying extents. Non-sustainable practices may be followed in some or all of these stages resulting in wastage, pollution, and environmental degradation, leading to adverse effects on human well-being (Environmental Protection Agency [3]). According to Huovila [5], buildings account for about 30-40% of the worldwide energy consumption. In Europe, this figure is about 40-45%. Consequently, the building sector is responsible for around 40-45% of total worldwide (and European) anthropogenic CO_2 emissions. Many legislative policies are currently under development for building industry to limit this material use and related carbon emissions.

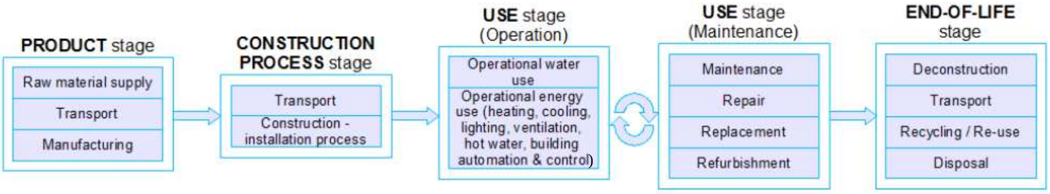

Figure 1: Building life-cycle scheme (divided into stages and modules) based on EN 15804

The concept of green buildings was developed to reduce, mitigate and prevent non-sustainable practices in the building industry. A building may be defined as green, by assessing whether it is environmentally responsible and resource-efficient throughout its life (Environmental Protection Agency [3]).

1.2. Energy consumption of a building

Energy-efficiency is one of the foremost goals of green buildings. The total energy consumed by a building can be divided into 6 phases called embodied energy (product stage of building), grey and induced energy (construction process stage of a building), operating energy (use stage of a building), demolition and recycling energy (end-of-life stage of a building). This is illustrated in (Figure 2).

Operating energy is the largest portion of energy consumed by a building during its life-cycle. Therefore, it creates the most opportunities for large amounts of energy-saving within a building. The green buildings concept has led to the development of several energy-efficiency targets for buildings, such as low energy buildings, zero energy buildings and energy-plus buildings. The Energy Performance Building Directive's 2020 target towards energy neutral buildings focus on decreasing the operating energy, as a result of which this energy has reduced and is still reducing, thereby increasing the importance of embodied energy consumption in buildings.

A study conducted in Arup on an office building found that the load bearing structure contributes on an average 82% of the embodied energy, and that the embodied energy of a structure could be reduced by 20-30% based on the selection and optimization of the various structural elements (Perkins and

Tandler [7]). Similar to embodied energy, the demolition and deconstruction energy as well as recycling and re-use energy are related to the building materials. For most materials, its service-life ends with demolition, after which the waste is disposed. Metals, however, are recycled due to their inherent value, in fact, 95-99% of steel is recycled at the end-of-phase life of a building (Tata Steel [9]), which considerably lowers its embodied energy value.

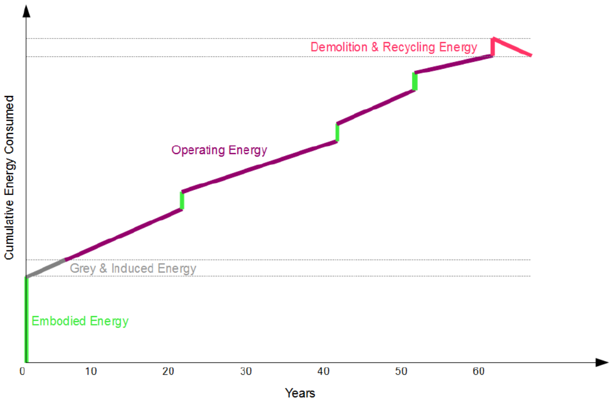

Figure 2: Energy consumed in the life of a building

1.3. Adaptability or flexibility of a building

As mentioned above, recycling and reuse of building materials can lower their embodied energy values. But this is not always possible and wastage still occurs at the end of a building’s life. Therefore, it is necessary to design buildings that are adaptable for future use (Huovila [5]). Adaptability or flexibility refers to designing a structure to accommodate future changes in services, engineering strategy, aesthetic values, architectural trends and the function of the building (Foster and Greeno [4]).

The first step to improve the flexibility or adaptability of a structure lies in identifying the various aspects that influence the life of a building. The next step is to quantify them. According to Tool [10], these aspects are the building's stability system, load bearing capacity, floor-to-floor height, structural grid size, facade, installations and lastly, the flexibility of voids in the building. Tool [10] quantifies these aspects by providing a factor range for each of them, using which an estimated service life (ESL) factor can be determined for a building as shown below:

$$ESL = Factor_1 * Factor_2 * \ldots * Factor_n \qquad (1)$$

This ESL-factor is multiplied with the lifespan of a building to obtain its estimated service life (as opposed to the estimated designed life of a building), using which the annual environmental cost of that building can be calculated.

$$Annual\ environmental\ \mathrm{cost} = Annual\ operation\ \mathrm{cost} + \frac{Construction\ \mathrm{cost} + Demolition\ \mathrm{cost}}{Lifespan\ * ESL} \qquad (2)$$

From Equation 2, it can be seen that high ESL value results in lesser annual environmental cost, i.e., construction and demolition cost. The construction cost primarily refers to embodied energy consumption. Therefore, by increasing the adaptability, it is possible to lower the embodied energy consumption of a building over its life-span.

2. Applying multi-objective optimization techniques to building design

Mathematically speaking, it can be said that a design model consists of a combination of several design variables, (often competing) objectives, fixed parameters, and constraints placed on these variables. The process of design involves alternating rounds of fine-tuning the values of these design variables and testing the resultant design models, until a suitable or optimum design is arrived at. In other words, the process of design is nothing but a multi-objective optimization procedure.

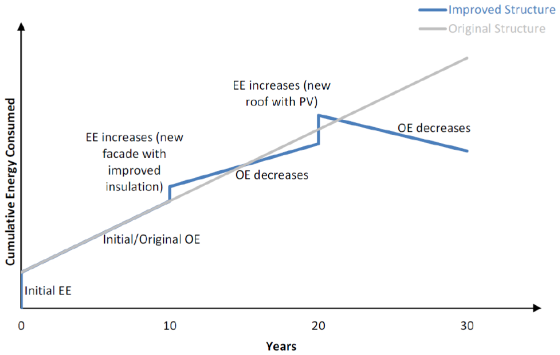

Figure 3: Example of energy consumption of an improved office building, based on Allwood and Cullen [1]

Sometimes an increase in embodied energy can result in a decrease in the operating energy, for instance, when a building is provided with a new thermally improved façade or with photovoltaics (Figure 3). Hence, there exists a trade-off between the minimum embodied and operating energy versus maximum adaptability criteria. Owing to the large amount of variables and calculations involved, it is next to impossible to manually arrive at an optimum solution. However, computational tools open up the possibility of simultaneously optimizing these objectives to arrive at the most energy efficient designs. Owing to the importance of decisions made in the early stages of design, it is especially useful to develop computational tools that aid in decision-making from the conceptual design stage (Rolvink [8]).

One such possibility is to organize the design process in the form of a Genetic Algorithm, as illustrated in the following example. On the left-hand side of Figure 4, there are 4 design variables. For the optimization algorithm to work with these variables, each of them is provided with identification (binary) codes, which acts as genes. The population contains the different possible combinations of these variables (genes) to make chromosomes. Some of these combinations may result in weak or bad designs; some of them will be the best. From this list, the optimizer randomly selects chromosomes to create the initial population. These combinations of design variables go through the structural calculations. Based on the building code checks, only those combinations are passed after calculations which result in a feasible structure. At the bottom-right of the figure, the feasible chromosomes go into the energy calculator, which determines the energy consumption of the building for these chromosomes. Based on their energy values, each chromosome is provided with a fitness value, such that higher the energy consumption, lower the fitness (or vice-versa).

Then the optimizer selects a new generation of chromosomes. This new population is obtained by selecting the combinations that are most fit, eliminating the weakest combinations and obtaining new combinations via reproduction of the members of previous generation. With this new population, the design calculations are performed and the energy consumption of the feasible combinations is obtained. Once again, they are provided with fitness values. This process continues and with each generation, the fitness of the population increase until only the fittest combinations remain, or in other words, convergence is achieved.

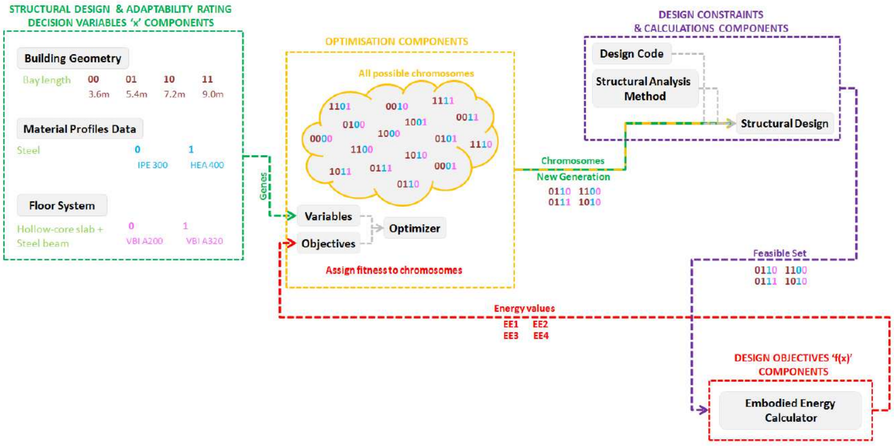

Figure 4: Multi-objective optimization in Building Design with a genetic algorithm

2.1. A computation framework for sustainable building design

By generalizing this idea, a computational framework for sustainable building design was developed, as shown in Figure 5.

This framework consists of the design variables (including but not limited to structural design variables, building services design variables and adaptability rating variables), design methods for structural analysis and design, objectives functions (such as embodied energy, operating energy, adaptability) and any suitable genetic algorithm for optimization. Each of these parameters is provided with its own interface, and has certain associations with each other. Each parametric interface is to have its own primary attributes which is inherited by all of its children. This ensures that the framework can easily incorporate new or improved features when necessary, without breaking the functionality of the rest of the framework. It is to be noted that since the objectives functions here are related to sustainability, the framework has been termed as a parametric sustainability framework. However, it is also possible to add sustainability-independent objectives such as cost-optimization into the framework, if desired.

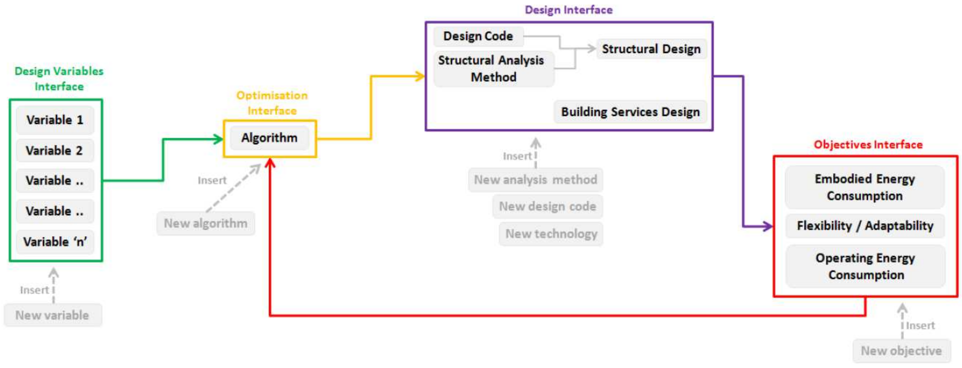

Figure 5: A computational framework for sustainability

3. Development of Embodied Energy Optimization Tool

The Embodied Energy Optimization Tool is a software tool built by implementing the parametric sustainability framework. Below is a description of its design specifications and development process.

3.1. Main features

The tool is expected to design a building, calculate its life-cycle embodied energy consumption, its life-cycle operating energy consumption and optimize the design to achieve (one or more) sustainability objectives (minimum energy consumption, maximum adaptability, etc). In addition, it is also useful to be able to export the design to operate with third-party tools. Certain use-case situations were created to further elaborate these features for each user class, as shown in the use case diagrams (Figure 6 to Figure 10).

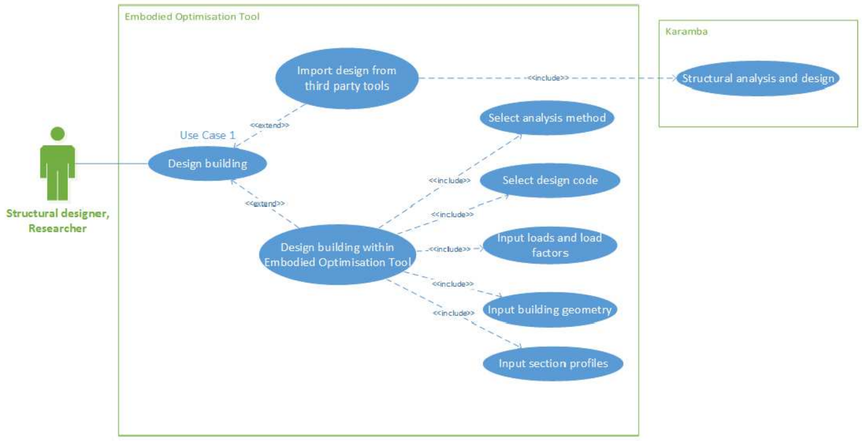

Figure 6: Use Case 1 – Design a building

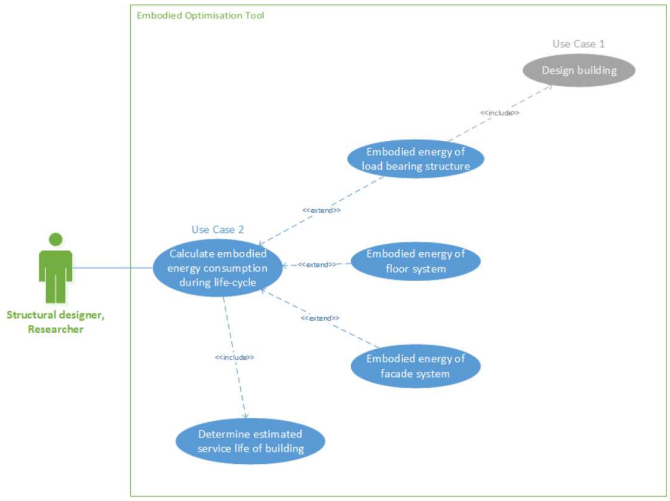

Figure 7: Use Case 2 - Calculate embodied energy consumption

The scope of these features is large; it therefore becomes necessary to apply certain restrictions and assumptions to make each feature into realizable portions. Based on the availability of data for tool development, the region was restricted to Western-Europe (accordingly, Eurocodes for design), the building material is Steel, building function is office-use and lastly, life-cycle analysis aspects considered are energy efficiency and carbon emissions of a building.

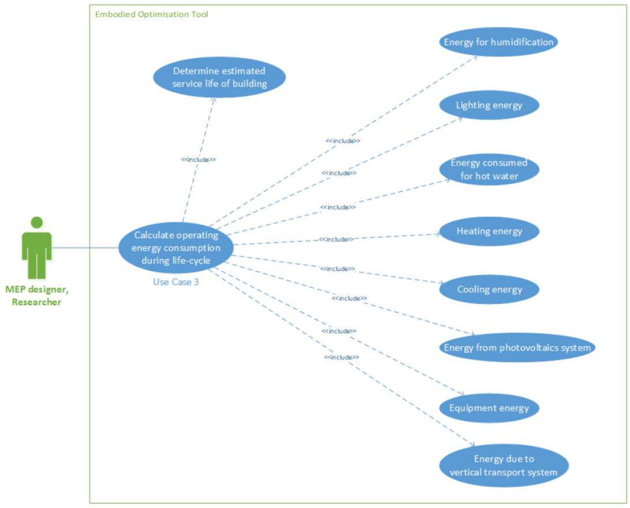

Figure 8: Use Case 3 - Calculate operating energy consumption

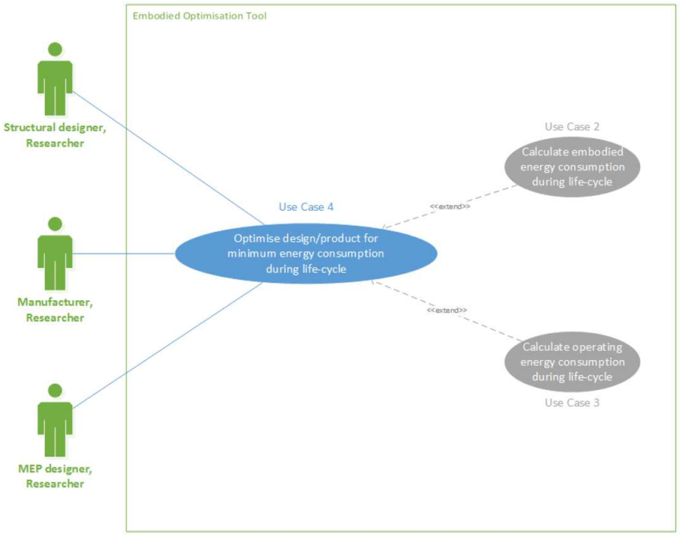

Figure 9: Use Case 4 - Optimize design or product to achieve (one or more) sustainability objectives

Further assumptions were made on the design of the office building so that the structure is a low to medium rise braced frame in steel, with horizontal stability provided via diagonal wind bracings. All beam column connections are pinned or hinged, so the connections have no moment capacity which would otherwise facilitate additional calculations. Furthermore, it is also assumed that the façade (including roof) is replaced during the life of the building, so as to determine the life-cycle embodied energy consumption.

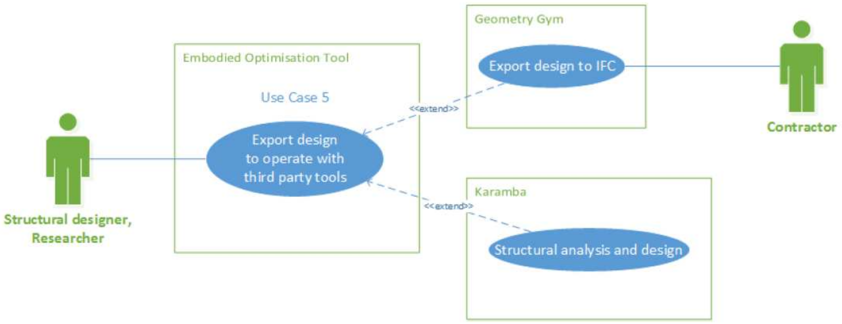

Figure 10: Use Case 5 - Export design to operate with third-party tools

3.2. Development and operating environment

The embodied energy optimization tool is developed in C# (C-sharp) programming language. Using Microsoft Visual Studio integrated development platform (IDE), the tool is integrated with the 3D-modeling tool, Rhinoceros and its plug-in Grasshopper. It is available as a tab within the Grasshopper user interface, which contains the different components of the tool. A screenshot of the final graphical user interface (GUI) is provided in figure below (Figure 11).

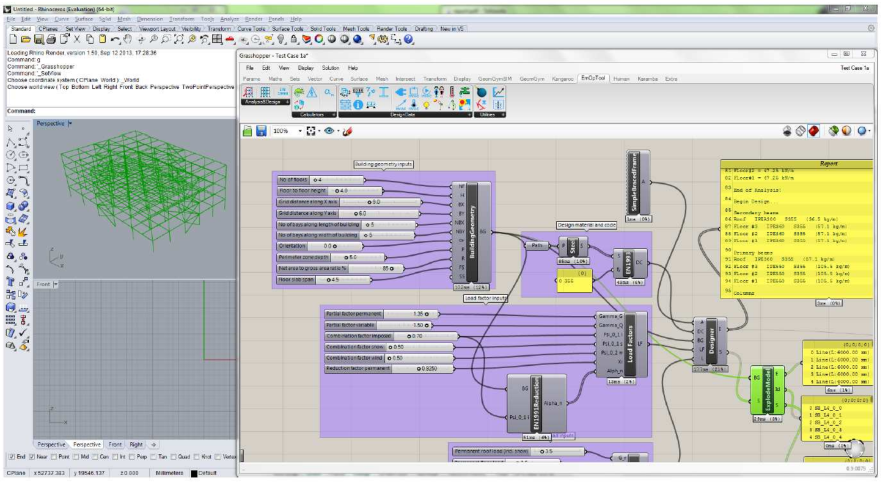

Figure 11: GUI of Embodied Energy Optimization Tool

3.3. Other non-functional requirements

The additional qualities desired in the tool are adaptability (so that the tool can be adapted for any kind of structure, building material, building code, analysis method, etc.), availability (such that the tool is made available as an open source sustainability platform, based on which others can contribute to further development of the tool) and reliability (through visualizations and reports, so that the operations and calculations made are available to the user).

Making the tool adaptable for any kind of structure, building material, code, analysis method, etc. is also one of the main features of the parametric framework for sustainability. Accordingly, a sequence diagram was developed (Figure 12) such that each step of the design of a building is handled by a separate module, which can be easily replaced with suitable alternatives.

3.4. Testing, validation and results

The Embodied Energy Optimization Tool has 5 main features, each of which requires testing in order to render the tool as functional and a validation of these test results to ensure that the tool can be trusted. Test cases were prepared for each feature, in the form of an ensemble of components connected to each other, called a Grasshopper script.

The design calculations were tested with the example from The Steel Construction Institute (Brown *et* al. [2]), as well as with Karamba, a Finite Element Analysis plugin for Grasshopper. The results proved to be very satisfactory. The calculations methods in the current tool prototype are approximate, based on simple mechanics and hand calculations, and therefore, useful for early stages of design. For later stages, a well-developed structural analysis and design software is recommended, until the design methods in the tool are improved to be at par with such software.

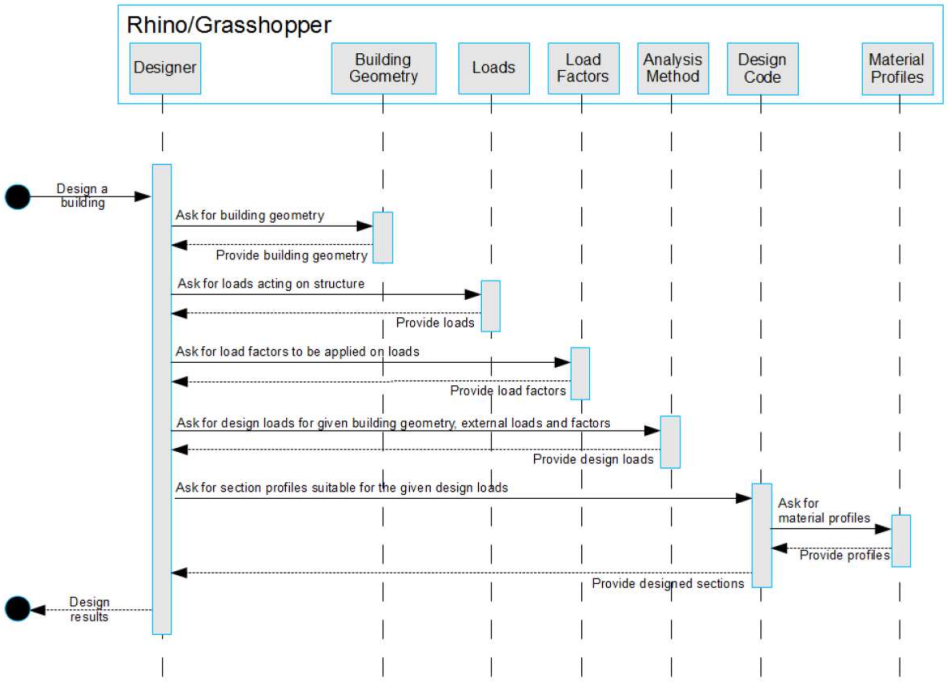

Figure 12: Sequence diagram illustrating the interactions during design of a building

The calculations for embodied energy is directly related to the quantity of each material used and can therefore be easily validated by hand calculations. For this purpose, the tool also generates a calculation report for the user. The operating energy calculations are based on the Building Energy Tool for low to medium rise office buildings developed and validated by Arup.

The Embodied Energy Optimization Tool currently do not possess its own optimization component, instead this was performed with the native Grasshopper component Galapagos and with Grasshopper plugin – Octopus. It was found that Galapagos only provide a single optimum solution which is not always the case. The user needs to therefore apply caution and be aware of possible pitfalls so as to have a back-up method or idea for verifying the results obtained. Octopus on the other hand provided a Pareto-Optimal front, matching the expected results.

The design was exported to an IFC file using Geometry Gym components successfully. The design was also exported successfully into inputs for analysis by Karamba components. Since the current prototype depends on the interoperability of Rhino & Grasshopper, with the aid of plug-ins like Geometry Gym, Karamba, etc.; users that are new to these tools will need some time to get used to the layout and working style of visual programming before they are able to work independently with the tool.

It should be noted that the tool was tested successfully with limited number of test cases. In depth testing is required with the assistance of end-users to identify and eliminate possible issues.

4. Discussion

Several assumptions were made in the tool to determine the flexibility of the building and in calculating the life cycle embodied energy consumption. In particular, the information on grey and induced energy consumptions of a building can be improved. Additional research is required to shed more light on these topics, so as to identify the stochastic factors involved in determining more accurate values for flexibility of the building and for complete life-cycle analysis.

The tool requires further development to eliminate these short-comings. In order to implement these suggestions, further study is necessary to identify and understand the different types of structures and better optimization algorithms, analysis and design methods, user interface and visualizations, energy calculations, database management systems, and so on.

In the current user interface of the tool (inside Grasshopper), each independent component provides detailed information about itself, however, the overall association of the different components is not visible to a new user, who is therefore unaware which combination of components are required to perform a particular task. Since there are a fixed set of components used in each task, it is recommended that a wizard or at the very least, an example file should be provided to guide new users on working with the tool.

The tool operates in the Rhino & Grasshopper environment and can interoperate with third-party developed plug-ins of Rhino. Modifications will be required to the different interfaces of the framework that are implemented in the tool, when it is desired that the tool is to function independently as stand-alone software.

5. Conclusions

Most present day tools calculate (and sometimes, optimize) either embodied energy or operating energy of a building. And most of them do not consider adaptability at all. The Embodied Energy Optimization Tool, however, is able to aid in studying the influence of these three aspects on the design of a building, from within a single tool. Thus, the tool is able to provide answers relating to sustainability, as early as in the conceptual design stage of a building.

Both the framework and the tool are in accordance with the goals of Building Information Modeling (BIM), by aiding in decision making from the conceptual stage of the building until its entire life-cycle. In the area of energy efficient building design, the tool is able to cater to the demands of the key players in the building industry - architects, engineers, building material and products manufacturers, as well as researchers. It aids the user in quickly designing a building, or importing/exporting a building design from/to an external software, for further actions. It assists in determining the life-cycle embodied energy consumption and operating energy consumption of the particular building design; and allows for comparing and studying different building designs, materials or products to identify the most suitable (optimum) option for a given set of requirements or targets.

Both the framework and the tool follows a very modular approach to building design, such that new features can be easily added or old features can be modified or replaced without affecting the functionality of the rest of the tool. This results in a flexible tool, which the user can adapt to satisfy his/her requirements. This implies that the tool has a lot of development potential to easily move from crude to finer calculation methods with the progress of the design of the building. It can easily include other optimization aspects such as cost assessment, or other design aspects such as fire engineering, to the list of tool features. The Embodied Energy Optimization Tool is not limited by a particular building material or calculation method or optimization algorithm, etc. owing to the framework structure. Aside from buildings, it can also design and optimize all types of structures, from offshore to bridges.

Acknowledgements

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