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A Holistic and Parametric Approach for Life Cycle Assessment in the Early Design Stages

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ABSTRACT
This paper presents an approach for implementing life-cycle assessment (LCA) in the early design stages of a building project based on the new plugins for Rhino and Grasshopper of One Click LCA, which aims to contribute to fight climate change from within the construction industry. These new tools developed by Bollinger + Grohmann in collaboration with Bionova Ltd. combine the extensive environmental database of One Click LCA with a user-friendly interface and an object-oriented structure to provide parametric and holistic LCA within the environment Rhino + Grasshopper. A case-study of the implementation of this tool in the design phase of an office building complex in Berlin is also included to illustrate new possible workflows in the early design stages regarding comparison of embodied energy of design alternatives, automatic LCA from architectural and calculation models, optimization processes based on global warming potential (GWP) and environmental benchmarking.

Author Keywords
Life-cycle assessment; sustainability; parametric design; optimization; object-oriented programming.

1 INTRODUCTION

1.1 Climate emergency and shortage of resources
With more than 30 % of global carbon dioxide emissions, the construction and building materials sector is the biggest driver of global climate change [1]. The current world climate report of the International Panel on Climate Change (IPCC) underlines the absolute necessity for an immediate rethink and the readiness to implement existing solutions in the short term. The goal of this radical change is a drastic reduction of the grey energy contained in new buildings and the associated reduction of CO2 emissions. At the same time, the enormous resource consumption of current construction, especially in the area of mineral materials [2], requires a rediscovery of material-saving construction that is oriented towards the basic concepts of material effectiveness, robustness, structural diversity and the use of local resources. The use of materials based on renewable raw materials should be a priority.

1.2 Life-cycle assessment in the early design stages
In order to effectively fight climate change from within the construction industry, an adequate metric must be implemented from the very beginning of the design stage to positively affect the environmental outcome of a construction project. Life-cycle assessment (LCA) is arguably the most extended objective methodology for evaluating the environmental impact of products, processes and services which can also be applied to evaluate the environmental impact of a certain building [3].

However, the LCA of such a complex product as an actual building presents some major challenges [4]. Firstly, environmental information of all materials and processes involved must be gathered. This data is quantified in the so-called environmental product declarations (EPD). Secondly, all material quantities must be measured and processes must be covered to properly assess the environmental impact of the whole building over its lifetime.

The current approach to the LCA of buildings usually involves gathering the relevant data of the EPDs of the different materials in an Excel file or similar database to combine these values with also manually introduced material quantities, but unsurprisingly this analogic and time-consuming workflow tends to discourage designers from applying LCA. The use of Building Information Modelling (BIM) can help automating the generation of the bill of quantities of the building, including at times also mapping the EPD values to the corresponding building materials [5], but a complete and ready to use BIM model is usually not available until the late design stages, when there is unfortunately no much potential for further design changes.

Alternatively, LCA can also be implemented and automated in a certain design software tool. There are various software packages designers use in the architectural practice, but the most preferred option when parametric design is involved is clearly Rhinoceros + Grasshopper3d [6].

1.3 Review of existing tools

According to food4rhino.com, "Tortuga" is the most downloaded tool for LCA in the environment Rhino + Grasshopper. Although this Grasshopper plugin offers an intuitive interface and output of results, its EPD database is constrained to the German ÖKOBAUDAT and the last update of the tool took place four years ago [7].

Another available plugin in food4rhino.com is "Bombyx" [8]. This is an exhaustive tool for LCA which also calculates operational energy. However, the EPD database is strongly focused on Swiss materials and also the not object-oriented structure of the plugin leads to a not very user-friendly experience when dealing with all input and output parameters of the different components.

Finally, the last widely used LCA tool in Rhino + Grasshopper might be the implementation of the commercial software CAALA [9]. Although the web platform provides the designer with an exhaustive and yet flexible LCA tool, the EPD database is also constrained to ÖKOBAUDAT and, furthermore, the Grasshopper plugin consists currently of a single component for merely exporting material quantities from a Rhino model to their web application, without importing LCA results back into Grasshopper, which provides no option for analysis or visualization of results in Grasshopper, let alone for parametric optimizations.

2 METHODOLOGY

On the basis of this review, the authors found the necessity to develop a new plugin for Rhino and Grasshopper that overcomes the previously commented shortcomings at implementing LCA in the early design stages of a building project. This new development would need to:

- Include an extensive materials EPD database, covering a significant range of countries.
- Support both structural and non-structural materials so that the tool can be holistically used to assess the environmental impact of a whole building.
- Allow both simplified and complete LCA.
- Return results of LCA in Rhino + Grasshopper for their analysis and visualization and also for allowing building optimizations regarding embodied carbon.
- Provide an user-friendly experience for both basic and advanced Rhino and Grasshopper users to encourage LCA in the design phase.

Due to its compliance with the above-mentioned criteria and a demonstrated interoperability with other software such as Autodesk Revit, One Click LCA was the preferred LCA software to implement in the environment Rhino + Grasshopper.

2.1 One Click LCA

One Click LCA is a commercial automated life-cycle assessment software focused on calculating embodied carbon or life-cycle assessment of building and infrastructure projects. It includes the world's largest materials EPD database in this field and it is offered as a cloud service [10].

Furthermore, it is complemented by an API which includes many of its functionalities, so third-party applications can set up and run a LCA from their own user interface (UI). The API of One Click LCA has been already implemented in plugins for applications such as Autodesk Revit and it will be used for this implementation in Rhino and Grasshopper as well.

Although not all the functionalities of One Click LCA are included in the API, it includes a method for exporting material data into their web platform to run the LCA there and access all functionalities such as input materials verifications, advanced LCA, graphic analysis of results or embodied energy comparison with benchmark projects [11].

2.2 Plugin for Rhino

The plugin for Rhino is particularly intended for designers who might not be advanced users of the parametric environment, but can anyway benefit from a geometrical 3D model to automate estimation of material quantities for a LCA. This tool does not only accomplish this, but it also provides functionalities for mapping material environmental profiles, including EPDs, to the geometric objects of the Rhino model by grouping them according to their corresponding model layer and also by implementing certain filter options related to the material properties of the EPD database. The final step is to export the list of materials to the cloud service of One Click LCA through the API.

All the plugin functionalities are packed inside of the tabs of a dockable Graphical User Interface (GUI) which lead the users through different steps to run a LCA:

- Materials: An overview of all geometry objects of the considered layers is provided so that the user can choose to manually map these objects to certain resources by using the filter options, by picking a material from the database, by manually specifying a material description or just to leave the material field empty to assign it later in the web platform.
- Layers: Selection of the layers whose objects must be considered in the LCA with the possibility of later mapping all the layer objects to different materials or to the same one. Layer names are used to define the groupings used for the LCA, and each material is assigned to one of the groups.
- Settings: Choice of master materials database (Europe, US, ÖKOBAUDAT, INIES, etc.) and specification of building area for later calculation of relative embodied carbon and benchmarking. In order to retrieve the environmental impact results

from the server into the Rhino model, it is necessary to log in into One Click LCA from this tab.

- Results: An overview of the mapped materials and the environmental results retrieved from the One Click LCA server is provided.

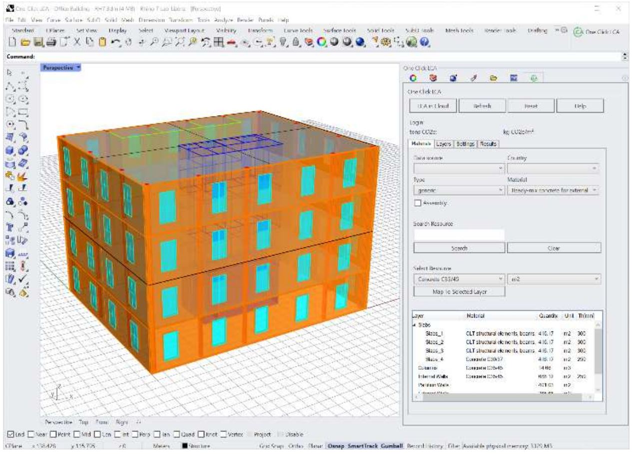

Figure 1. UI of the Plugin for Rhino of One Click LCA.

Besides the tab functionalities, the GUI also contains a toolbar with the following commands:

- LCA in Cloud: Materials can be exported at any time from the Rhino Model to run the LCA in the web application of One Click LCA.
- Refresh: Environmental data of the Results tab are updated.
- Reset: All fields are reset to the default values.
- Help: Link to the help documentation site.

2.3 Plugin for Grasshopper

Unlike the One Click LCA plugin for Rhino, in which similarly to CAALA [9] not all the geometric objects that make up the LCA need to be mapped inside of Rhino, the Grasshopper plugin requires the user to parametrically map all building components to LCA profiles. This is a similar approach to the Tortuga [7] and Bombyx [8] plugins and it is required for optimization processes in which the result of the LCA in terms of global warming potential (GWP) must be calculated inside of the Grasshopper script.

Therefore, the plugin for Grasshopper of One Click LCA is intended for rather intermediate and advanced users of this visual programming environment who are willing to take more time setting up the LCA inside of Grasshopper to parametrically explore the environmental outcome of different design alternatives, optimize a design proposal in terms of GWP or embodied carbon or just make use of the visualization options that this plugin offers. Because of this, in terms of simple calculations of LCA or embodied carbon, the Rhino plugin achieves the first set of results faster.

In order to populate the plugin with user-friendly Grasshopper components, an object-oriented structure must be defined so that the user just needs to manage individual LCA objects instead of the properties of all of them which would result in an unnecessarily complex Grasshopper definition. The following classes were defined for this purpose:

- LCA Profile: To be selected from the database of One Click LCA. It has properties regarding material type, EPD database, corresponding country or region, etc. to make it possible to filter these objects within the database and select the desired one.
- Material: It is constructed by assigning an LCA Profile to a certain building element so it also has properties regarding quantity and units.
- Construction: These are the objects that are actually fed into the LCA. They can consist of several Materials, they have a class assigned to them so they can be grouped during the LCA and they include environmental results once the LCA is completed.

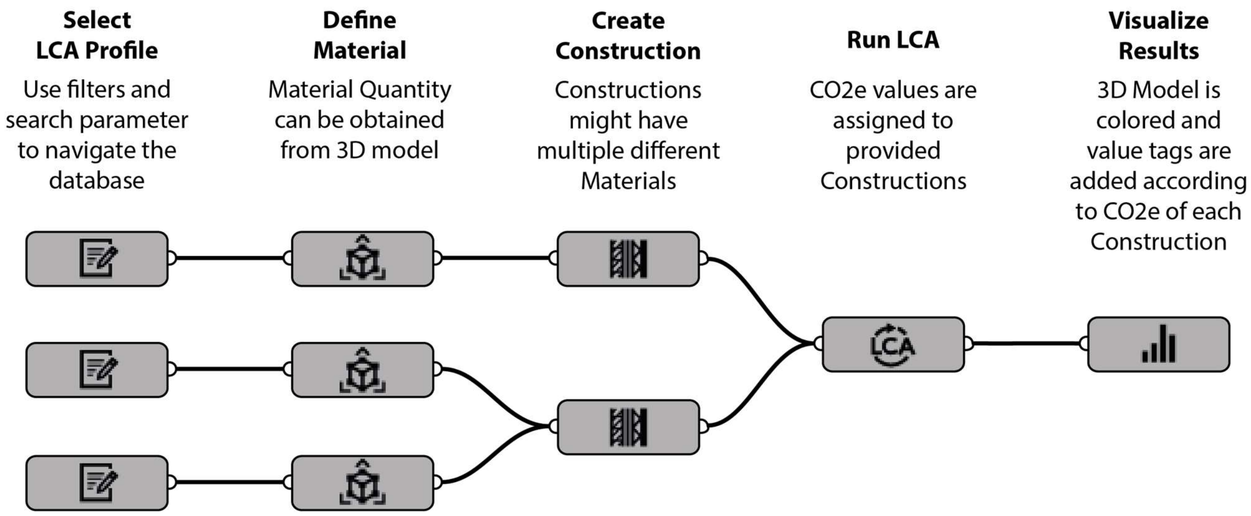

Figure 2. Workflow diagram of a LCA with the Grasshopper plugin of One Click LCA.

The plugin components were compiled using the same GUI widgets as the Karamba plugin [12] (see Figures 3 and 5). They provide Grasshopper components with additional functionalities such as extendable menus, dropdown lists, checkboxes, etc. and are ideal to manage objects with multiple properties in the Grasshopper environment. Also, tooltips were implemented to select LCA Profiles with particularly long names from the dropdown menus of the "Select LCA Profile" component.

The "Calculate LCA" component has two outputs. The first one includes all the Constructions with environmental results so that they can be analyzed either graphically with the "Visualize Results" component or numerically with the "Disassemble" components. The second output provides the numerical result of the embodied carbon of the building (kg CO2-equivalent emissions). These results make reference to the stages A1-A3 (manufacture stage) of a life cycle analysis [13]. If a more thorough LCA was, the user should choose the option "LCA in Cloud" to import the Constructions to the web platform of One Click LCA similarly to the Rhino plugin and calculate the LCA there.

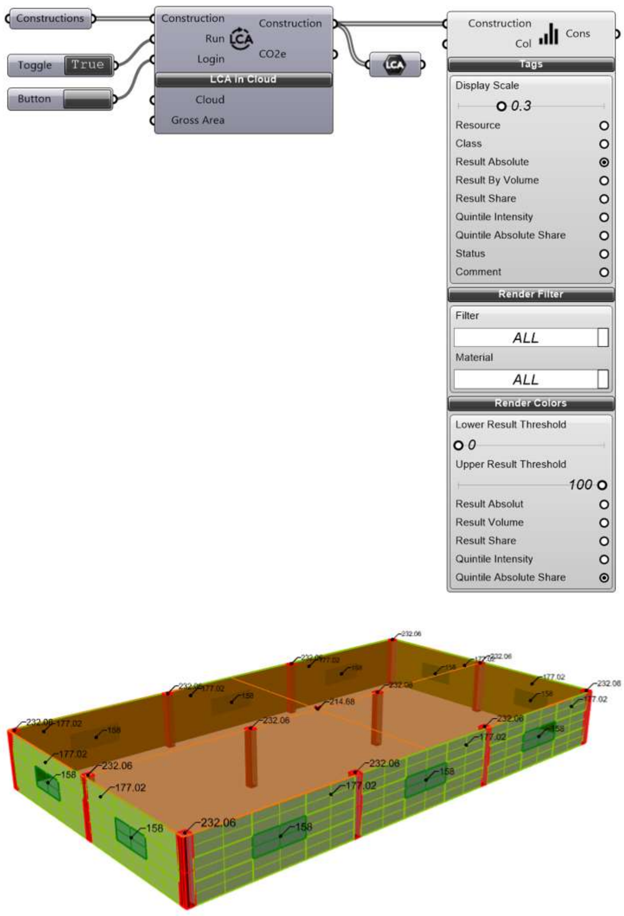

Figure 3. Results visualization of LCA with the "Visualize Results" component of the Grasshopper plugin of One Click LCA.

The numeric output of the "Run LCA" component can be perfectly used for building optimizations targeting the minimization of the environmental impact. The return of first environmental results from the server takes usually a few seconds, however, the plugin implements a cache so results of previous calculations are saved and the connection with the server is just necessary when constructions with new LCA profiles are provided. If the results are obtained from the cache, this usually takes no more than some milliseconds, which makes this plugin optimal for such optimization processes (see Figure 8).

2.4 Case Study Description

In order to further test the plugins and to evaluate to what extent they can enhance the design process, they were used in the design phase of an office project (Berlin, Germany) designed by the architectural team of Thomas Hillig Architekten GmbH and Bollinger + Grohmann as structural engineers.

Figure 4. Aerial render of the office complex in Berlin, Germany © Thomas Hillig Architekten GmbH.

The case study will focus on House B which is planned as a flexible office building with adaptive service units. The building consists of a multi-level structure with a maximum of eleven floors. Thus, the entire building is subject to the building code requirements of a low-rise building. The dimensions on the lower floors (ground floor to 2nd floor) are approx. 41m x 60m and are reduced to approx. 32m x 34m on the top floors (8th to 10th floor). Since there was no major constraint from the architectural or engineering point of view regarding the usability of concrete, steel or timber, this project was the perfect case-study to test the potential of these tools to positively influence the environmental impact from the early design stages.

3 RESULTS

The One Click LCA plugins were used throughout the design phase of the project by the structural design team of Bollinger + Grohmann. This section shows one of many possible design approaches and they can also be applied by other specialist teams involved in building design.

3.1 Comparison and evaluation of design alternatives

Firstly, the Grasshopper plugin was used to compare and optimize different design alternatives. A representative and manageable local model of the building was used for this purpose (see Figures 8 and 10), so different design possibilities could be effortlessly explored without modelling and analyzing the whole building. The use of a Grasshopper definition for the calculation of the LCA has the advantage that the designer needs to set up the Grasshopper definition for the first design alternative and it can be easily adapted for the other ones [14] without the necessity of defining the LCA from scratch several times.

During the design exploration process, it was noticed that the selection of a certain material for a particular building element affects the building embodied carbon in different ways. Obviously, different building materials possess different GWP values (kg CO2e / kg), e.g. steel materials usually present higher values than cross laminated timber (CLT) ones [15]. However, there are some additional considerations to take into account:

- Building elements such as beams, slabs, etc. must be dimensioned accordingly to the chosen building materials in order to accurately calculate the absolute impact of the system [15]. If the steel members turn out to be relatively much smaller than the timber ones for a certain design situation, the timber solution might not be the one that results in the lowest environmental impact. Furthermore, changes regarding building materials of certain building elements like structural beams can influence the sizing of neighbor elements such as columns or foundation elements due to the new design loads, connection requirements, etc.
- Structural elements of different building materials imply the use of different types and quantities of non-structural materials. For instance, a concrete slab has different requirements in terms of noise insulation and fire protection than a timber one. Since data regarding non-structural elements might not be available from the very beginning of the design phase, assumptions are necessary in order to properly evaluate the environmental impact of a particular solution [16]. The database of One Click LCA includes assemblies (see Figure 5) consisting of different single structural and non-structural materials that simplify this holistic design comparison process. Otherwise, it is encouraged to set up a library of standard Constructions in the Grasshopper plugin consisting of the structural and the corresponding non-structural materials in order to efficiently compare different design alternatives.

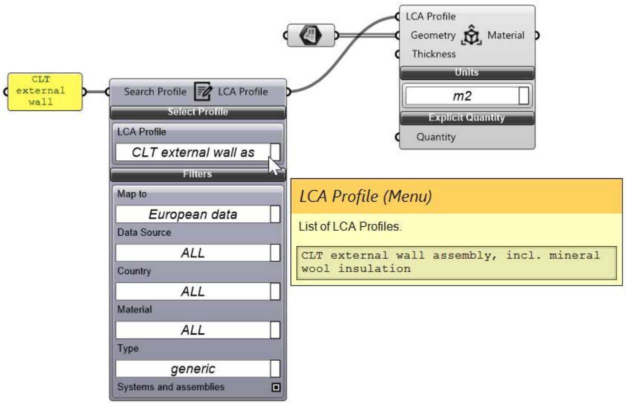

Figure 5. Systems and assemblies of the database combine different structural and non-structural materials.

Three different slab systems were compared in the design phase. It will be shown that the horizontal elements concentrate most part of the embodied carbon (see Figure 7, also [17]). Furthermore, the also relevant interior walls were designed as reinforced concrete elements due to fire protection and lateral stability requirements. Therefore, the comparative study focused on the slab and beam elements:

- System 1: Closely spaced 50x110 CLT primary beams and 20x110 CLT secondary beams and slender 10 cm thick CLT panels.
- System 2: Widely spaced 12x60 laminated veneer lumber (LVL) beams and 22 cm thick CLT panels.
- System 3: Traditional steel construction with IPE profiles and sandwich slab panels. Used to quantify the expected impact reduction of the timber systems [18].

Once all building elements were dimensioned, the models were exported to the web platform of One Click LCA with the "LCA in Cloud" option for further analysis and comparison. Some of the available graphical results are displayed in Figures 6 and 7.

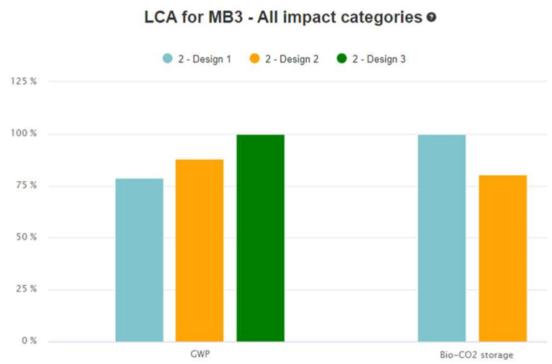

Figure 6. Comparison of impact results of the different design alternatives with the web platform of One Click LCA.

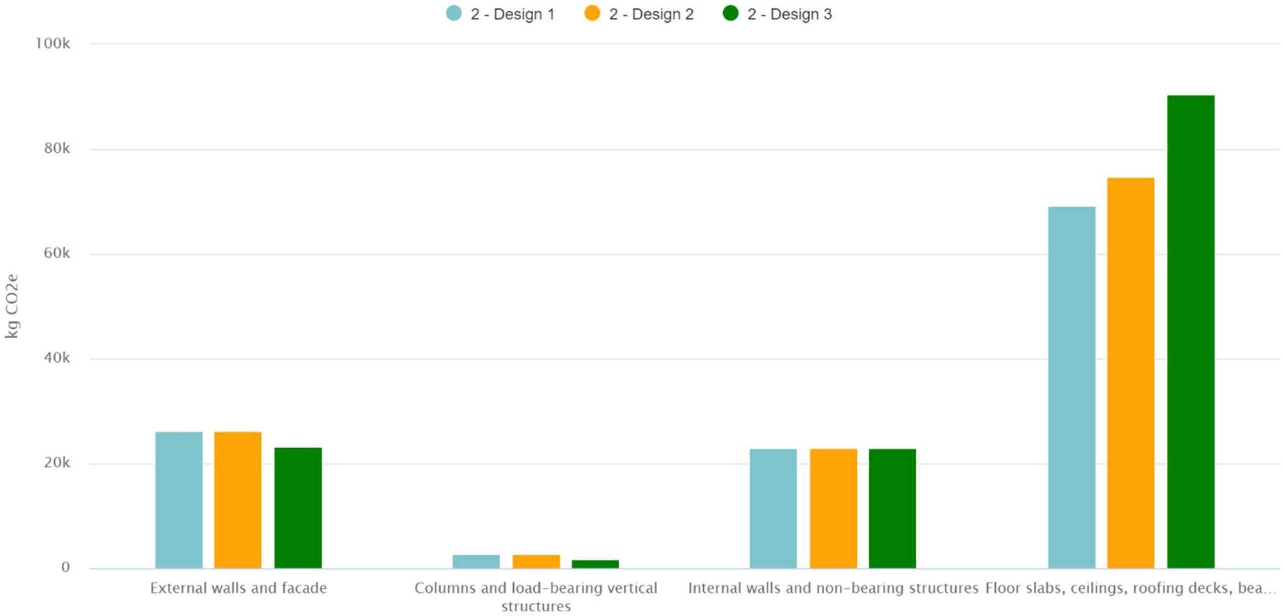

Figure 7. Distribution of embodied carbon among the different building elements.

The results summary of Figure 6 shows that the timber-based solutions present lower embodied carbon than the conventional steel floor system. Moreover, Figure 6 shows the Bio-CO2 storage regarding the CO2 sequestrated by the timber solutions, which can arguably be subtracted from the overall CO2 result [19].

However, it must be noticed that the results also include the impact values of walls and columns, which are identical in all systems (see Figure 7), in order to make it possible to compare the absolute impact values with other benchmark projects. Among the two first timber systems, the "System 1" with the close spaced CLT beams results in the lower embodied carbon. This might not only be related to the different embodied carbon values of CLT and LVL, but also to the fact that the thickness of the relatively structurally inefficient slab element was minimized to 10 cm by providing secondary CLT beam elements [20].

On the basis of the results of this representative local model, the "System 1" was chosen to design the rest of the building accordingly.

3.2 Integration with other Grasshopper Plugins for multi-criteria optimization

The plugin for One Click LCA can be integrated in the same Grasshopper script as other plugins, which might not be directly related to LCA, in order to couple the analysis of CO2 emissions with other criteria. In this section, the focus will be on the optimization of the discussed office building in terms of both embodied carbon and structural performance.

Karamba

Regarding the optimization of structural systems with one single building material, the solution resulting in lower embodied carbon will be the one with the minimum amount of material and these optimization processes have already been extensively reviewed and improved [21]. However, regarding structural systems with different materials, the solution with lowest embodied carbon might differ from the most economical one. Such optimization processes have already been formulated, but they usually involve importing environmental data into Grasshopper either manually or through Excel sheets [22]. The Grasshopper plugin of One Click LCA enhances this process by integrating the material selection in a single component in Grasshopper. The dimensions of the CLT and LVL element of the "System 2" of this study of design alternatives were determined by setting up an optimization process with Karamba [12] and Galapagos [23] that would lead to the lowest embodied carbon also under consideration of the code regulations in terms of allowable deformation values.

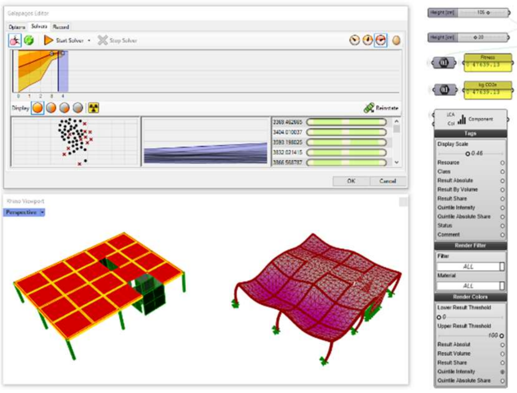

Figure 8. Minimization of building embodied energy with Karamba, Galapagos and the Grasshopper plugin of One Click LCA.

The evolutionary solver of Galapagos takes as genes the height values of the slab and beam elements and the CO2 emissions serve as fitness function to be minimized. A penalization value is added to this function if the slab deformations overcome a certain limit value.

Octopus

The above-mentioned optimization of the structural system of the office building in terms of embodied energy led to a solution based on a thin slab supported by relatively strong end efficient beam elements. However, it was necessary to evaluate the actual economic cost of these design options in parallel with the embodied energy.

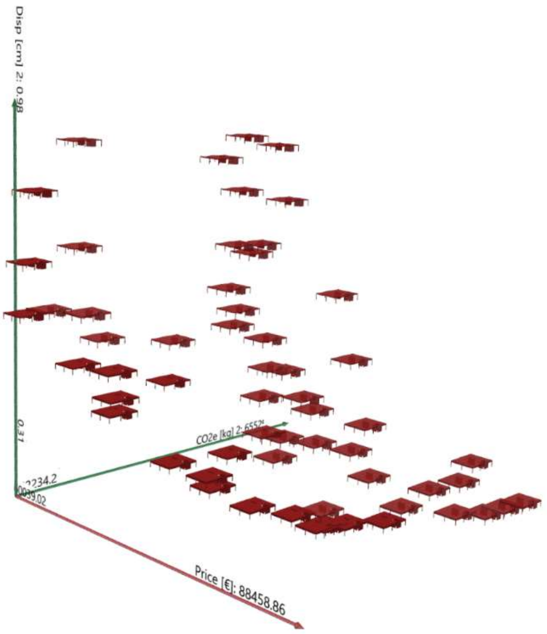

Figure 9. Multi-objective optimization with Octopus and One Click LCA.

The plugin octopus was used for this purpose [24]. It provides a multi-objective optimization solver, which was used to simultaneously optimize the dimensions of the structural system in terms of carbon emissions, economic cost and structural performance.

The result is a Pareto front or set of optimal solutions (see Figure 9), from which the user can choose the most convenient one. It can be noticed how many different solutions are contained in the plane "price-displacement" which present a very low value of embodied energy but vary enormously in terms of the other two parameters.

Parametric FEM Toolbox

As the deign process progresses, the final dimensioning of the different building components usually takes place within a structural design software package, where the designer explores different configuration options for the different building elements, until an economical solution that also fulfills the code regulations is reached. In this context, the Grasshopper plugin of One Click LCA and the Parametric FEM Toolbox [25] were used to set up a connection between the FEM program Dlubal RFEM and Grasshopper in order to estimate in real time the environmental impact of different design alternatives.

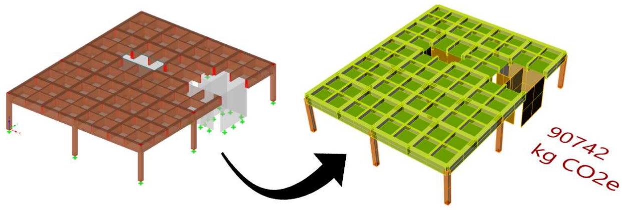

Figure 10. Real time environmental impact analysis from a structural calculation model with the Parametric FEM Toolbox and the Grasshopper plugin of One Click LCA.

3.3 Global LCA and comparison with benchmarks

Once all the structural and non-structural elements had been defined at the end of the concept design phase, a global architectural 3D model including non-structural elements, such as partition walls and facade elements, was used to run the LCA of the whole building and compare it to benchmark values. If a coherent layer structure is used for the architectural 3D model, the pre-processing time for the LCA can be significantly reduced due to the automatic grouping and mapping functionality of the Rhino plugin.

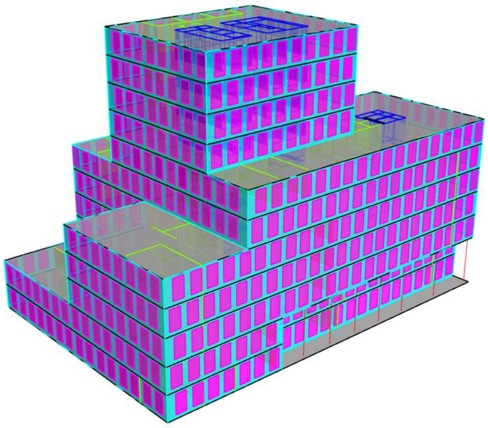

Figure 11. Rhino 3d model of the office building for LCA.

The LCA and the comparison with similar benchmark projects showed good results in terms of embodied carbon, therefore the design phase was considered satisfactory and little further optimization of building elements regarding sustainability concepts was done. Furthermore, the required time for setting up and running the LCA from the already available Rhino model for a user already familiar with the tools took less than 30 minutes, which is significantly lower than what similar experiments have shown [9].

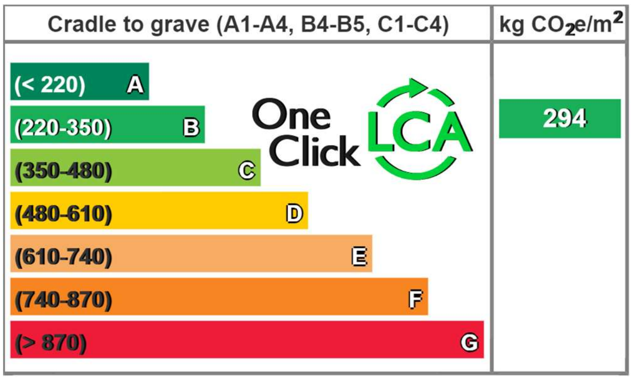

Figure 12. Embodied carbon benchmark of the office building.

The focus of this case-study was the applicability of LCA in early design stages. In case that a more thorough LCA was to be done in the later detailed design phase using a BIM Model as the source for material quantities, the already available environmental data could be calculated using tools such as Rhino.Inside®.Revit, or other means.

4 CONCLUSION

The new plugins for Rhino and Grasshopper of One Click LCA have proven to have the potential to enhance the early stages of the design phase by providing the design team with a workflow for efficiently and accurately implementing LCA in the design phase. They improve current parametric strategies to reduce building embodied carbon in early design stages [8, 9] by implementing a more extensive construction materials EPD database in the Rhino + Grasshopper environment, by providing an user-friendly interface and an object-oriented structure, by adding automatic result visualization options and by enabling an export process to the web platform for additional verifications and comparison with benchmark projects.

These tools aim at encouraging designers, who might not even be advanced Rhino and Grasshopper users, to implement LCA in their designs also for projects that are not explicitly asked to obtain a green certification and thus fight climate change from within the building industry. Furthermore, their ease of use and pedagogic graphic results (see Figure 3) make them appropriate for introducing them into the education system to raise environmental awareness among the next generation of architects and engineers.

Finally, it must be pointed out that the proposed design strategy relies on chosen environmental profiles. Generic LCA profiles are provided at country level precision, and users can use manufacturer specific EPDs. However, manufacturing markets also vary locally. All users may not be able to evaluate the material market for their location, and this introduces uncertainty to the results. Addressing this would require a solution to identify the most representative baseline product for each project location, also considering the high variance in commercially feasible transport distances between concrete, steel and CLT materials for example.

Other topics for further research include implementing and connecting the impact of retained design to the operational carbon footprint [4], incorporating Design for Disassembly and Design for Adaptability into the optimization strategy and how to implement decision-tree algorithms for architectural optimization in terms of embodied carbon [9], and tracking the progression of project carbon footprint and LCA over the different design phases of project and the as-built results.

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