Carbon and Cost Optimisation and Visualisation

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Abstract. We have developed a Grasshopper script that designs carbon-cost optimised foundation slabs to demonstrate the potency of parametric design in AEC, particularly the fact that environmentally friendlier solutions can be designed without having to cost more. The script produces 3D models of foundation slabs with minimal carbon footprint and material costs and validates each design iteration from the structural point of view with respect to project specific inputs, such as materials, cost, forces and bearing capacity of the ground. The script has been tested in a multitude of input settings and in all cases returned design solutions for foundations slabs where it was possible to identify the least climate intensive design to also be one of the cheapest solutions, if not the cheapest solution. We have developed a new service called BIM Vision to apply value driven visualisations based on carbon footprint and costs in BIM models. The result of this service is a further developed BIM model which integrates emission and cost factors with individual 3D objects. On demand, a user of the BIM model can also produce climate and cost calculations and visualise the BIM model based on the chosen sustainability aspect. Using a colour palette generator, objects are coloured with respect to carbon and cost intensity. Thus, a 3D heat map of the BIM model is created to communicate intuitively what components have the most severe impact on the project budget and carbon footprint. This kind of communication of environmental aspects simplifies consumption of sustainability related data and make it actionable.

1. Introduction
In Sweden, architecture, engineering and construction (AEC) as a branch causes 19% of the total annual production-based carbon footprint of 12.2 megatons CO$_2$e in 2017 [1]. PAS 2080 [2] discusses how the chances of having a substantial impact to minimize carbon footprint of an AEC design decrease the further down the design process a project advances. The highest potential to make strategic low-carbon decisions is thus during the early design stages before a project locks itself into certain design solutions. During later design stages, optimisation of geometry, material and product choice can still cut down the carbon footprint, however not in the same order of magnitude as strategic low-carbon decisions during the early stages, and some optimisation measures such as sustainable product choice can increase the total price of the project.

The cheapest AEC solution can be among the most carbon intensive alternatives, if carbon intensive energy is used during the life-cycle, particularly during stages A1 to A3 [3], however Sweco discovered a coupled relationship in between carbon footprint and costs of construction in projects:

- Cross Tay Link road in Scotland,
- Ostlänken (a high-speed rail Järna-Norrköping),
- E22 road in Sweden.

Initially, we found out that the most carbon intensive disciplines, components, or work moments also tend to cost the most in the given project. Later on, we discovered that carbon and cost are partially impaired and carbon optimisation would consequential optimise even costs, thus creating a win-win situation up to a threshold beyond which the project would have to choose more expensive materials or products to further minimize the carbon footprint. However, the imparity is partial as choosing the cheapest solution can on the contrary spike the embedded carbon of components.
These findings have been so substantial to spawn a new field within urban development consultancy – Carbon-Cost Management (CCM), Carbon-Cost Optimisation (CCO) and Carbon-Cost Visualisation (CCV). In this paper, we shall focus on how our newly developed tools and work methods for CCO and CCV influence an AEC design process from the designers’ perspective and how an AEC project can achieve low-carbon design alternatives at a cheaper cost.

1.1. Carbon-Cost Optimisation as a Consultancy Service

1.1.1. How biased are you? The most common consumer choices an individual can make on daily basis where more versus less ecological alternatives appear are within food, cosmetics, and amenities. The imminent purchase cost tends to be higher for the more ecological alternatives and we tend to extrapolate this relationship to many other contexts including the AEC. We expect it to be true without us questioning two crucial economic principles: 1) externalities, and 2) economics of scale.

Would the price of the more ecologically harmful product be higher, if the producers were not allowed to exclude environmental damage from its responsibility domain? Would the more ecological alternative be cheaper, if it would be the subject to economics of scale and its more environmentally harmful alternative not? Yes would probably be the answer for the both of questions in most contexts.

Hence, the society lives in a bias today that more environmentally friendly alternatives must necessarily be more expensive than the standard industrialized alternatives. It is important for the customers, consultants, contractors and facility managers to ask themselves these questions:

- Do I also expect the more environmentally friendly design solutions for my AEC project to be more expensive from the life cycle perspective? In other words, how biased are we in our environmental-economic reasoning?
- If it were possible to include all of the negative and positive environmental, social, and economic impacts and weigh them in economic terms against each other, would the standard industrialized choice really be cheaper in the long run for the society as whole than the more environmentally friendlier alternatives?

Fortunately, within AEC we do not necessarily have to compromise between carbon footprint and the imminent direct cost of the project as win-win scenarios in between carbon and cost can be achieved with our Carbon-Cost Consulting services.

1.1.2. Parametric Design versus Human-Perceived Design. An AEC design process is always overwhelming as the number of stakeholders, legislation, customer needs, technical and legal disciplines involved, and all necessary knowledge to deliver a plausible design extends far beyond individual’s capacity to comprehend and keep up with what is going on. Hence, an individual can focus on one or a few key tasks within her domain of competence. Adiaphorization, miscommunication, and limited human and financial resources add a few more challenges on top of the information overload. However, we cannot yield before the challenge as the ongoing climate and general environmental crises demand a significant change in societies’ behavior and improvement in today’s infrastructure.

A truly more sustainable design solution would improve its performance from the economic, social and environmental perspective as opposed to its previous iteration, but how do we achieve them without jeopardising the quality at the current budgets and time frames? It would certainly be a tough task for a human, hence we decided to leave a part of the design process to the computer.

Much of human decision making is rule based and depends on working with certain variables methodologically, for example the sky is turning grey and the winds are rising – I’d better take a rain jacket with me. In such cases, human decision making regardless of its complexity can be algorithmized and automated which is even the case of engineering. In such cases where rule-based decision making dominates the work process we can delegate certain parts of the design process to a computer.

1.1.3. Parametric Design in Grasshopper. In this work, we looked at how we can generate and compare solutions for foundation slabs of reinforced concrete from the carbon and cost perspective. We developed a Grasshopper script for computer generated foundation slabs in which we algorithmized calculations regarding the global warming potential, costs, and a complete structural verification. Based on input such as material and loading, the script designs the size and optimal amount of rebars for the
foundation. The script then quantifies the weight of concrete and reinforcement steel, their respective carbon footprint within chosen life-cycle stages, material costs and socio-economic costs with a single purpose to evaluate carbon-cost performance and propose a less carbon intensive solution at a cheaper cost in the next iteration.

A part of the overwhelming complexity of our design process has thus been reduced to the matter of computational time. The time performance of our Grasshopper script has beaten our expectations as the script can generate hundreds of design iterations for several foundations in minutes, including all the consequential calculations.

Our Grasshopper-script is compatible with popular BIM-software such as Tekla via the Tekla Live Link plugin and with Revit via the Rhino.Inside.Revit plugin. Therefore, we can offer high quality low-carbon solutions for foundation slabs at a cheaper cost in most scenarios covering both civil and structural engineering.

1.2. Carbon-Cost Visualisation as a Consultancy Service

Conceived solutions for an AEC design are modelled in CAD, BIM, and GIS software in countries where Sweco operates today. The default method to visualise an AEC design in BIM and CAD software is based on either 1) component type, 2) technical system or 3) material – which means that metadata about these 3 parameters decide which colour shall be applied upon a CAD-object.

Design visualisations are crucial for us human designers to attain insights regarding various aspects of the design These insights server a base for finding improvements to design solutions, hence our BIM and CAD tools should offer us as many different types of visualisations so that we could improve the design from different perspectives. However, the common practice grounded in the three above mentioned visualization types can offer only a technocratic discipline- and system-oriented approach to design optimisation. Thus, the contemporary lack of value-driven visualisations robs the whole AEC industry of sustainability related insights, a precondition to mitigate the ongoing climate and general environmental crises which the AEC industry has a substantial role to play.

At Sweco, we saw an opportunity to bridge this gap in contemporary AEC design practices and we developed our own tools and work methods for working with value-driven visualisations in relation to crucial sustainability parameters such as costs and carbon footprint in BIM and 3D-GIS which we now offer as stand-alone consultancy services.

1.2.1. What Is Value-driven Visualisations and Why Should We Care? Value-driven visualisations colour GIS, CAD, and BIM objects based on a chosen numeric parameter. Either an algorithm applies a colour to the given object, or the user creates the colour scheme of her own and assigns a different colour to a specified range of values. A typical example of value-driven visualisations applied in practice is a topographic map using the elevation data as the input for the colouring algorithm.

The modelling software influences designers within AEC who shapeshift our cities and influence their consequential environmental, social and economic impact, hence value-driven visualisations play a key role to help various stakeholders to intuitively interpret maps and design schemes regardless of their knowledge of the topic depicted on maps and schemes. However, contemporary CAD and BIM tools often lack features for value-driven visualizations. In the rare cases when BIM tools actually allow for value-driven visualisations, it has certainly not yet become a common practice among CAD and BIM users to utilize value-driven visualisations to receive insights regarding sustainability aspects in AEC projects.

Value-driven visualisation open a Pandora Box of many very bad visualisations that can cause irritation and misinterpretation on the side of the user. Assigning colours to objects in a pedagogic way used to be a subtle art until User Experience Design (UX) as a scientific field and a technical discipline within software development gathered knowledge about how to design intuitive interfaces to deliver the highest possible value to the user. We have drawn from UX knowledge to apply visualisations in BIM that natively trigger designers to improve their design from carbon and cost perspective. Any software developer or a BIM coordinator who applies value-driven visualisations without the awareness of UX design principles can cause more damage than utility. Thus, it is crucial for the AEC industry to integrate UX design practices in the software interfaces we work with as well as visualisation features.

Software developers of CAD and BIM tools have yet to catch up with their peers in GIS software developers to make it a native choice for CAD and BIM users to work with value-driven visualisations.
insightful visualisations in BIM software that intuitively motivate designers to focus on carbon and cost intensive components, systems, and materials of their design solutions already today. This service creates a precondition to an effective carbon and cost mitigation in an AEC design process.

1.2.2. Value-driven visualisations in BIM. BIM Vision offers new perspectives on construction design and automates environmental and economic analyses. BIM Vision expands the project’s BIM model with environmental and economic data in order to enable automated analyses and visualization of crucial sustainability aspects of the project. On demand, a user of the BIM model modified by BIM Vision can also produce climate and cost calculations and visualise the BIM model based on critical sustainability aspects to gain insights for improvement of solutions or the design process itself.

Using a colour palette generator, objects are coloured with respect to carbon and cost intensity. Thus, a 3D heat map of the BIM model is created to communicate what components have the most severe impact on the project budget and carbon footprint in an intuitive and a visual way. This makes it much easier for the design team to understand what actions ought to be taken to mitigate carbon footprint and costs.

1.2.3. Geokalkyl – value-driven visualisations in 3D-GIS. GIS and cartography have gathered much experience with applying value-based visualisations over the past decades. Sweco in collaboration with AFRY developed a GIS tool called Geokalkyl for Swedish Transport Administration [4].

Geokalkyl is mostly used to compare potential road and railroad travel corridors in early stages and is an indispensable tool to pick the least carbon and cost intensive travel corridor with respect to geology, topography and hydrology of the given area.

Geokalkyl expands ArcGIS capabilities to assess different types of soil and bedrock, the terrain model and water streams. Each travel corridor modelled in CAD software is dissected per 40 metres of the road/railroad and a climate and cost calculation is performed for each section of the road with respect to all geological, hydrological and topographical data. Using a 3D-GIS engine, a visualisation of the carbon footprint and production cost of each proposed line is created per section of the road/railroad. Hence, a user can understand how each design alternative is performing as a whole and at each section.

2. Method

2.1. Carbon-Cost Optimisation of Foundation Slabs in Grasshopper

The basic infrastructure of the main algorithm is created in Grasshopper. Material data, coordinates and forces acting on the foundation slab is imported from spreadsheets. Geometrical variables are defined in Grasshopper, all these are collected into a data tree of values to be used in the structural calculations. Geometrical variables are subjected to change based on the optimisation-engine, and thus updated multiple times during the calculation.

For calculation of socio-economic costs, Trafikverket’s rate of 7 SEK per 1 kg CO2e was used in the script.

2.1.1. Calculations in SMath. To establish a software infrastructure that is reliable and easy to use for a wide range of users, the structural calculation and verification is performed in SMath [5], a math software created to solve, review and document mathematical problems. This provides the possibility to output traditional structural calculation reports for every foundation, to be reviewed by the structural engineer.

The script is written in such a way that all variables of interest in the calculation sheet is imported to the main-algorithm in Grasshopper where they are replaced by updated values, according to input and trends in the optimisation, and the calculation is updated based on these values. In this step, calculations for ultimate limit state, serviceability limit state and static equilibrium are checked, and a required reinforcement amount and foundation size is designed.

At this point, key values, such as emissions and cost as well as structural utilizations ratios are imported back into the script to be used by the optimisation engine.
2.1.2. Optimisation procedure. We applied the multi-objective optimisation tool Octopus which “allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal. It is used and works similarly to David Rutten's Galapagos, but introduces the Pareto-Principle for Multiple Goals” [6].

At each design iteration, Octopus is allowed to manipulate geometries of the slabs and select from several types of concrete qualities/mixes with their respective structural properties, material costs, and carbon footprint. The process analyses trends in the result in order to find a solution with the best carbon-cost performance for the slabs. Since Pareto-Principle is applied to meet multiple goals, carbon-cost optimisation is achieved by finding the best trade-off between carbon emission and investment cost, if these goals are not coinciding.

Any solution that does not meet the necessary structural criteria gets excluded from the list of viable solutions therefore the user can safely choose any solution that has been found and focus on choosing the most fit solution from the carbon and cost perspective.

As Octopus keeps on manipulating the design of the slabs in Grasshopper, Tekla Live Link or Rhino.Inside.Revit manipulates the original model in Tekla or Revit respectively.

2.2. Carbon-Cost Visualisation

The goal was to achieve value-driven visualisations in Solibri, a BIM validation tool we use for 3D coordination and metadata control during our design process. Solibri offers a great value to the design team and we simply wanted to extend the value offered with sustainability related analysis in one file which is used by the whole design team.

Solibri as such does not offer features for value drive visualisations, however the Classifications view has an option to colour-code object classes manually or by importing a colour scheme from Excel (.xls, .xlsx). Hence, we developed an Excel-based tool for generating colour palettes using numeric values as input.

2.2.1. BIM Vision for Solibri.

2.2.1.1. Colour Palette Generator. The colour palette generator we wrote to support BIM Vision in Solibri was written in Visual Basic in Excel. The colour palette generator contains three logarithmic equations that convert numeric input to RGB (red, green, blue) values which are combined together by a macro to colour the background of a cell.

There are 4 input parameters that together manipulate the behaviour of the three logarithmic equations, hence the generator can return a great many colour palettes, such as using one colour in different saturations and creating transitions of two to six different colours.

We usually apply a colour palette based on a transition from blue for low values to red for high values in the context of carbon footprint in order to calm down the user when seeing low-carbon
solutions and alarm the user when high emissions occur. However, any numeric input can be translated to a colour palette using our colour palette generator.

2.2.1.2. **BIM Vision and Klimatkalkyl.** BIM Vision for Solibri consist of a series of Classifications that manage what components get included and excluded from calculation, material and product names, material densities, emission factors and material costs of materials and products, aggregated results net weight emissions and net costs. Further on, the tool contains information take-off templates for producing bills of quantities including costs and carbon footprint. These features are packaged in a Solibri extension and distributed to Solibri users within Sweco Sverige’s Solibri license pool.

The Classification for management of emission factors is using Swedish Transportation Administration’s generic data which can be found in their tool Klimatkalkyl (Climate Calculator). The user herself must do the mapping of materials with CAD-objects as BIM practices differ from project to project, however an excellent BIM practice can result in automated mapping of objects with any data.

2.2.2. **Geokalkyl for ArcGIS.** Geokalkyl 3.0 as a tool for ArcMap is published on Trafikverket’s official web including the user manual which we refer to for the method description [4].

3. **Results**

When working with Geokalkyl, BIM Vision and parametric design for carbon-cost optimisation, carbon and cost tend to be impaired. Disciplines, components or work moments with high carbon footprint tend to also drive purchase and production costs the most.

3.1. **Carbon-Cost Optimisation**

Octopus generates dozens of carbon-cost optimised solutions that are validated from the structural point of view in a matter of 5 minutes using a standard CAD laptop.

We tested the script using different kind of input settings for initial geometry, material, emission factors, bearing capacity of the ground and socio-economic costs. Octopus managed to significantly reduce both carbon and cost over 14 different runs, reducing from a few dozen to a few hundred percent depending on the initial settings.

The socio-economic cost of the most carbon-cost optimised solution was 146% of the material cost.

3.2. **Carbon-Cost Visualisation**

3.2.1. **Carbon-Cost Visualisation with BIM Vision.** A showcase of quantitative and visual results of BIM Vision in Solibri can be found below on Figure 2 and Figure 3. On Figure 2, reinforced concrete is shown red, an alarming colour as it is the most carbon intensive material in the project at this project stage. On Figure 3, the same reinforced concrete is shown in blue, a calming colour as it has a relatively low emission factor per kg compared to structural steel which is visualised in purple.

Using the same input data and geometries, one BIM model can offer many insights to the design team.
3.2.2. Geokalkyl. Quantified carbon footprint and costs were exported to Excel and visualized using the Excel built-in feature 3D-maps, see Figure 4 and Figure 5 which show one of six potential travel corridors that were analysed using Geokalkyl. Interestingly, the longest route of six proposed alternatives turned out to be the cheapest and least carbon intensive as the topography, geology and hydrology worked out to be least demanding on drilling, shafting and moving masses.

4. Discussion

4.1. Carbon-Cost Optimisation

If Trafikverket would apply the socio-economic cost of the project as a penalty for the entrepreneurs, the consultants and itself as the customer, mitigation of carbon footprint would become the effective activity to cut down the costs of the AEC project. This shows how much we currently develop our societies at the expense of future generations.

Since Octopus has always found a way how to optimise the solution, the results have as far shown that we have an effective tool to cut down carbon and cost that could be potentially used in any project.
4.2. Carbon-Cost Visualisation
A design team intuitively understands the environmentally problematic components and materials in its design when UX-aware and value-driven visualizations are applied. Designers get then natively motivated to improve their solutions from carbon-cost perspective or to choose more sustainable alternatives. Hence, AEC industry should focus on embedding User Experience-thinking to its design practices.

4.3. Carbon-Cost Visualisation with BIM Vision. BIM Vision has been applied to visualize and semi-automate climate and cost calculations in a few projects so far, however the same method can visualize any parameter – such as loads, flows, energy consumption and water use or recycling and reuse potential of the components. We are convinced to see many more applications and use cases where value-driven visualizations will be applied in contexts we cannot imagine today as the idea of demanding value-driven insights AEC projects has just emerged.

4.4 Automation of Calculations over Time. A snapshot of carbon footprint of an AEC project does not tell much to a design team. We noticed that a design team gets a better support when presented climate and cost calculations of their solution over time and can see, it improves or gets worse from iteration to iteration.

Hence, climate and cost calculations should be produced upon each model exchange and delivery automatically to offer tracking of carbon and costs over time. Automation of climate and cost calculations can be achieved with FME, Solibri Autorun or UiPath. An analysis of calculated results over time effectively achieved and communicated with Power BI.

5. Conclusions
Carbon-Cost Optimisation using Grasshopper is a working proof of concept. Octopus has managed to cut down carbon and cost in all the test cases, however corrections in structural calculations must be done in our Grasshopper script to offer 100% correct validation decisions.

Carbon-cost visualisations natively motivate designers to opt for more sustainable solutions and to make changes to their design in order to minimize carbon footprint and costs, if applied in an AEC design process. The key to the success is in presenting critical parameters and their values in a pedagogic and consumable way.

6. References

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