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Using evolutionary optimization for low-impact solid constructions

Authors:
Hollberg, A.[1] ; Heidenreich, C.[1,2] ; Ruth, J.[1,2] ; Hartung, R.[2] ; Herzog, S.[2]
[1] Department of Structural Design, Bauhaus-Universität Weimar, Germany
[2] Department of Solid Construction II, Bauhaus-Universität Weimar, Germany

Abstract:
This paper introduces a parametrical approach for optimizing concrete slabs based on life cycle assessment (LCA). The developed method is implemented in a graphical algorithm editor. Evolutionary solvers are used to minimize the global warming potential (GWP), which serves as a representative indicator for environmental impact. Comparing a mathematical analysis of all possible solutions with the results of the evolutionary algorithms demonstrates the efficiency of these. The application of the method is demonstrated using a bike garage as an example. The great potentials for saving GWP compared to a conventional slab design are revealed. Furthermore, this paper proves that the method makes a relevant contribution towards lowering the environmental impact of the building sector.

Life cycle assessment, sustainable solid construction, optimization, evolutionary algorithm, parametric design tools

Introduction

The building sector is responsible for a great share of the world's resource and energy consumption [1]. Solid constructions made of concrete are one of the most common ways to build in almost every country. Due to the cement, the environmental impact of concrete is high, meaning there is a necessity for optimization, but also a high potential to achieve it.

Reducing the thickness of building components and the resulting reduction in the quantity of material used is an important issue in civil engineering. One possible approach is to reduce the span of a concrete slab by intelligently arranging the vertical support elements. The second possibility is to reduce the thickness by using high-strength concrete. However, the material savings achieved by doing so have to be investigated holistically within the context of environmental effects.

Environmental data

One method to systematically investigate environmental impact is life cycle assessment (LCA). The methodology is regulated in ISO 14040. In the building sector LCA is currently becoming more prevalent and environmental product declarations (EPD) are available for a range of typical building materials and products. In this study, we used the environmental data for concrete from EPD provided by the German Institute of Building and Environment [2]. They are based on data for a mix of ready-mix concrete and precast concrete parts. The mix is weighed according to the statistical share of both types in Germany. The declared unit is 1 m^3. The environmental data is given for different stages of the product. These are defined in the Product Category Rules (PCR) in DIN EN 15804.

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The different modules are shown in table 1. A1-A3 represent the cradle-to-gate phase, A4 stands for transportation to the building site and A5 for installation at the site. In the EPD it was assumed that no maintenance is needed during the use phase, resulting in zero impact in module B. C1-C3 includes the demolition, transport to the reprocessing plant and the crushing of concrete. Module C4 is not considered in the EPD. Module D represents benefits outside the system boundaries, in this case the recycling. Recycled concrete is mostly used as replacement for sand and gravel in the construction of roads.

Table 1: Global Warming Potential of different concrete classes in kg CO_2-equivilant (based on [2])

Concrete class	unit	Module						A + C	Total
		A1-A3	A4	A5	B	C1-C3	D		
C20/25	m^3	190.71	3.0	1.35	0	4.87	-23.08	199.93	**176.85**
C25/30	m^3	211.11	3.0	1.35	0	4.87	-23.08	220.33	**197.25**
C30/37	m^3	231.91	3.3	1.35	0	4.87	-23.08	241.43	**218.35**
C35/45	m^3	265.11	5.5	1.35	0	4.87	-23.08	276.83	**253.75**
C45/55	m^3	313.31	15.4	1.35	0	4.87	-23.08	334.93	**311.85**
C50/60	m^3	334.71	14.8	1.35	0	4.87	-23.08	355.73	**332.65**

When we compare the different strength classes of concrete, slight differences in module A4 are noticeable, which are caused by the transportation distances (17 km for C20/25 and C25/C30 up to 120.5 km for C50/60). The greatest differences occur in module A1-A3. This is caused by the higher amount of cement needed for higher strength. Cement production is responsible for about 90% of global warming potential (GWP) of concrete [2].

In this paper we based our analysis on GWP. Other environmental indicators show the same behaviour when the strength class – and therefore the amount of cement – is increased (see table 2, figure 1). Furthermore, it can be seen that the GWP curve lies in between the other indicators. We took GWP as a representative indicator for environmental impact. Furthermore, we only compared the different concrete strength classes, assuming the amount of reinforcing steel stays the same. According to Zilch et. al, the reinforcing has less influence on the environmental impact than the concrete [3].

Table 2: Environmental indicators of different strength classes in comparison

Indicator	Unit / equivilant	C20/25		C25/30		C30/37		C35/45		C50/60	
		absolute	%	absolute	%	absolute	%	absolute	%	absolute	%
PET	**MJ**	654.75	100	717.75	110	797.75	122	960.75	147	1389.75	212
PENRT	**MJ**	654.75	100	717.75	110	797.75	122	960.75	147	1389.75	212
GWP	**kg CO_2**	176.85	100	197.25	112	218.35	123	253.75	143	332.65	188
ODP	**kg CFC11**	5.79 E-07	100	6.02 E-07	104	6.43 E-07	111	7.06 E-07	122	8.64 E-07	149
AP	**kg SO_2**	0.29712	100	0.32112	108	0.34832	117	0.39662	133	0.51422	173
EP	**kg PO_4**	0.0515	100	0.0552	107	0.0596	116	0.0672	130	0.086	167
POCP	**kg C_2H_4**	0.036941	100	0.040041	108	0.043341	117	0.049141	133	0.062541	169
ADPel	**kg Sb**	0.000338	100	0.000377	112	0.000417	123	0.000467	138	0.000546	162
ADPfoss	**MJ**	608.64	100	663.54	109	734.14	121	877.44	144	1276.14	210
Cement	**M.-%**	11.1	100	12.4	112	13.7	123	14.5	131	16.8	151

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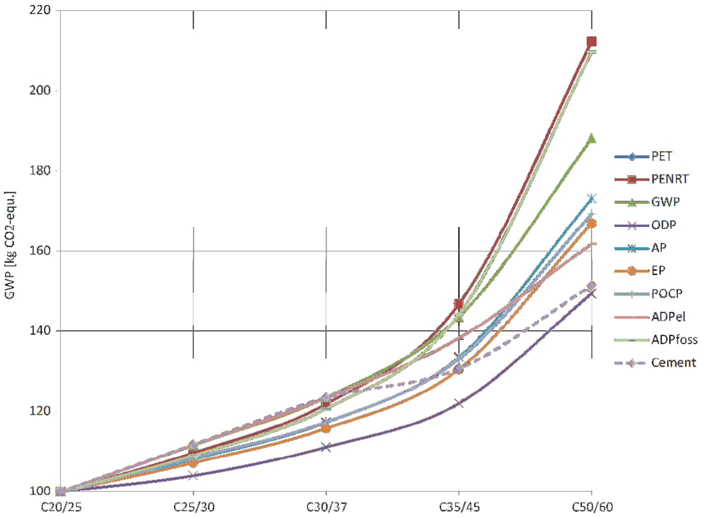

Figure 1: Normalised environmental indicators compared to C20/25 in %

Early design stage

Decisions made in the early phases of the design process have significant consequences as they lay down general conditions for the subsequent planning process [4]. As such, they also have the biggest effect on energy demand and environmental impact [5]. Optimization based on LCA should therefore be carried out as early as possible [6]. Especially in the early design phases, when a lot of changes occur, the models for the geometry, structural analysis and LCA should ideally be adjusted easily and this requires a parametric approach. That is why we are seeing the more widespread use of graphical algorithm editors (e.g. Grasshopper3D by Robert McNeel & Associates). The finite element tool Karamba3D is fully integrated into Grasshopper3D and offers the possibility to investigate the statical behaviour, deformations and stresses for beams and shell structures in the preliminary design. Based on a parametric geometry model, a plurality of different variants can be investigated.

The concrete slab as a functional unit

Many studies have compared different classes of concrete using LCA. The results depend a great deal on the functional unit, usually defined as 1 m^3, compressive strength in N/mm^2, or sometimes permeability [7]. For a 1m-wide strip of slab spanning 10 m we analysed five different strength classes of concrete. All of them were uniformly loaded with 5 kN/m² and their specific deadweight. We defined the functional unit as ‘span 10 m and carry 5 kN/m² and deadweight’.

For each concrete slab the height was varied from 10 to 30 cm in incremental steps of 1 cm. The utilization and the amount of GWP were analysed and plotted (see figure 2). In order to withstand the load, a utilization of 1.0 (which equals 100%) or lower is needed. The minimum possible slab height can be found at the point where the curve of utilization intersects with the line of utilization being equal to 1. A slab of C50/60 can be achieved with a height of only 15 cm, while 27 cm are needed for C20/25. Although almost twice the material is needed, the overall GWP is lower. The optimum could be found using C30/37 with a corresponding height of 20 cm (see table 3, figure 3).

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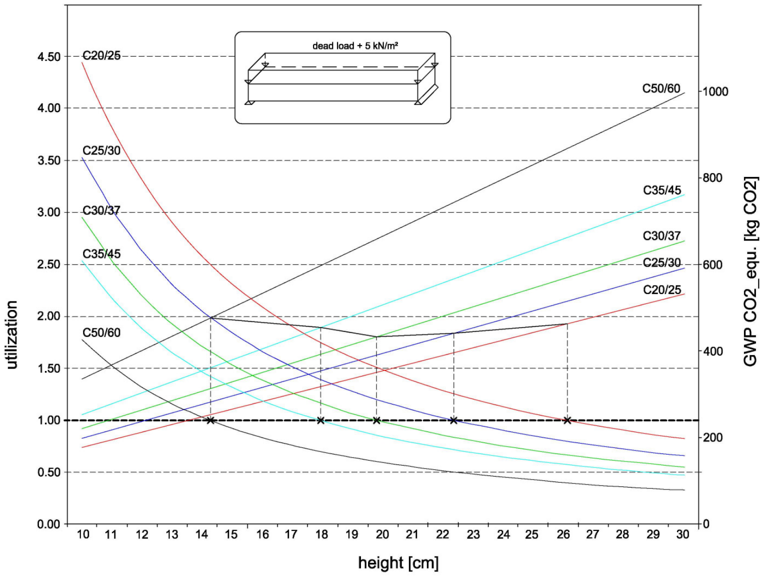

Figure 2: Utilization and GWP for different concrete classes depending on the slab height

Table 3: Minimal GWP for the slab using different concrete classes

Concrete class	Slab height	Utili-zation	GWP [kg]
C20/25	27 cm	95 %	477.47
C25/30	23 cm	96 %	453.68
C30/37	20 cm	98 %	436.70
C35/45	18 cm	99 %	456.73
C50/60	15 cm	92 %	498.98

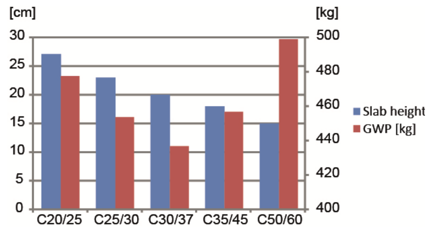

Figure 3: Slab height and GWP for a utilization of one

Simulation and Optimization

Optimizing concrete slabs is of great interest in construction design. The complexity of the optimization problem can increase dramatically depending on the amount of variable parameters. The selection and application of appropriate optimization tools defines the required time of computation. Furthermore, the applied algorithm defines whether every possible solution will be investigated or whether there are restrictions in the search field. The slab shown in figure 4 can be optimized by two different approaches: a mathematical method and an evolutionary algorithm.

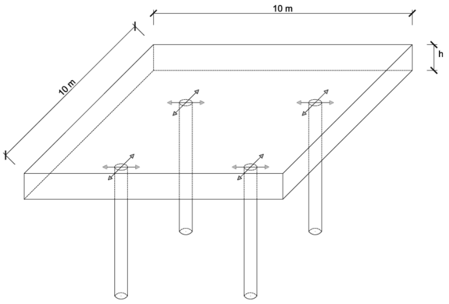

Figure 4: Point-supported slab

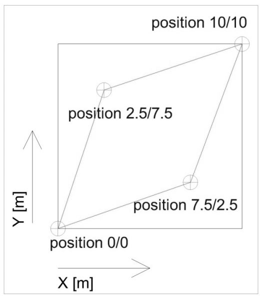

Figure 5: Mathematically evaluated support position

Mathematical Programming

The applied method of mathematical programming is based on a parametric definition of the geometry. The positioning of the supports and the slab thickness are defined as variable parameters. In addition, the material strength can vary according to the considered types of concrete. By applying mathematical programming, all possible combinations of support positions are investigated. The combinations are generated by a self-developed tool. Afterwards, every single variant is investigated for the resulting utilization and deformation considering the different types of concrete. This is made possible by employing a loop-component. The results of the investigation are transmitted to a spreadsheet program for further evaluation and unsuitable variants, e.g. impermissible deformations, are identified and rejected. The acceptable variants are analysed with regard to the GWP. For this purpose, the CO_2-equivalent of the slab is calculated on basis of the EPDs. Finally, it is possible to determine favorable support combinations depending on the plate thickness and the concrete quality. The application of mathematical programming allows for the complete examination of the solution space. Therefore, a problem-specific description of the optimization model is required. In addition, long computation times have to be accepted.

The mathematical approach was exercised for a 10x10 m slab with four supports. With a grid size of 2.5×2.5 m there are 12,650 possible combinations of column positions. Four variants of concrete quality and four different slab thicknesses (15, 20, 25, 30 cm) were investigated resulting in a total of 202,400 variants. The solution with the lowest GWP (3.9 t) was found with the columns positioned as shown in figure 5 and with a thickness of 20 cm using C25/30. The whole analysis took 20 hours on a standard PC.

Evolutionary Optimization

Evolutionary algorithms offer a further possibility for optimization. In civil engineering and architecture in particular, evolutionary algorithms are used when conventional algorithms cannot achieve satisfactory solutions [8]. Furthermore, they can be applied even if only little background information about the optimization problem is known [9]. These algorithms generally emulate the natural evolution with key parameters like selection, recombination and mutation.

Due to the variety of interdependent parameters, the previously considered slab (see figure 4) is evolutionarily optimized. This allows for the simultaneous consideration of the three variables: position of the columns, slab thickness and concrete quality. The evaluation of the static parameters such as deformation or utilization of the components is done in Karamba3D. Based on the defined fitness criteria (see equation 1), the evolutionary algorithm evaluates each individual solution. Optimization with the overall objective of minimizing the GWP is accompanied by secondary conditions: the limitation of deformation and utilization and the definition of a minimal distance between columns. These secondary conditions can be defined by adding special penalty criteria. The objective function itself can be defined directly in the optimizer's settings.

$$
\begin{aligned}
&min.GWP(x) \in R \\
&with\ \ secondary\ \ condition\ \begin{Bmatrix} f(x) & \in [0,1/300] \\ u(x) & \in [0,1] \\ min.span & \in [distance>4m] \end{Bmatrix}
\end{aligned} \tag{1}
$$

We employed an evolutionary solver called Galapagos which is integrated into Grasshopper3D. The process of optimization is displayed in figure 6. The best solution found by the solver requires a GWP of 3 t with C20/25 and a thickness of 17 cm. It also becomes apparent that normal-strength concrete (C20/25 or C25/30) is sufficient and performs better than the higher strength concrete in this investigated case.

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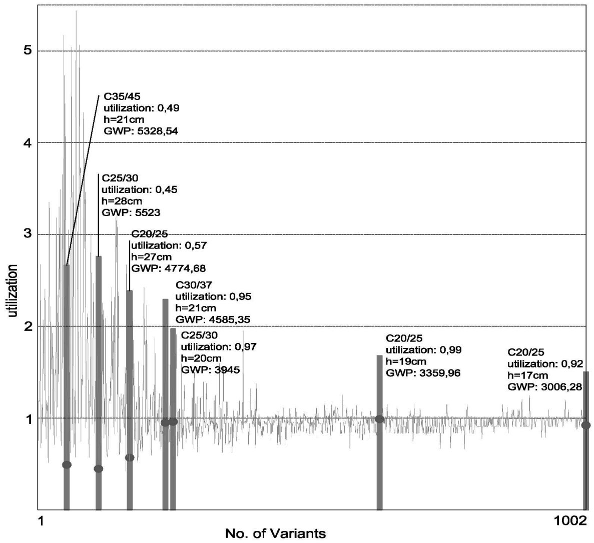

Figure 6: Evolutionary optimization of a 4-point-supported slab

Case Study

The case study of a bike garage illustrates one of the many possible applications of the optimization method developed. The parametric geometry is based on a user-defined length and width of the slab. Here, a size of 15×30 m was chosen. The arrangement of the supports is parametrically adjusted according to the computed statical deformation behaviour. If during the repositioning process the columns are positioned closer to one another than a given limit, the algorithm automatically merges them. In this way, the amount of supports and the material needed for the columns can be kept low.

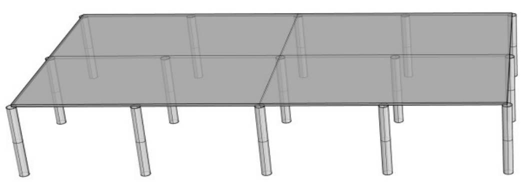

Figure 7: Standard ceiling for a bike garage

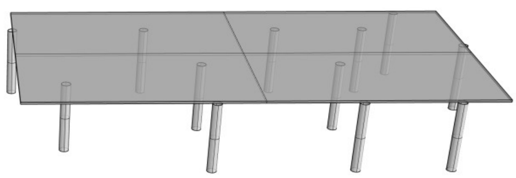

Figure 8: Optimized solution

The optimum was found using C20/25 and a slab thickness of 16 cm, with 12 supporting columns (see figure 8). This results in a GWP of 12.7 t for the whole slab. If C50/60 is used, the slab height can be reduced to 15 cm, while the emitted GWP amounts to 22.5 t. The standard solution (see figure 7) has a regular grid of 15 columns with a spacing of 7.5 m. If C20/25 is used, a thickness of 20 cm is needed, which results in a GWP of 15.9 t. Comparing the optimized and the standard solution shows that 3.2 t of CO_2-equivalent can be saved. This corresponds to an improvement of 20.1%. The optimization process took 17 minutes on a standard PC.

Conclusion

The first basic conclusion which can be drawn is the fact that solely reducing the amount of material by using high-performance material is not effective. In the presented studies here, from an ecological point of view, it was always better to choose a higher slab thickness and thus use more material of lower strength and environmental impact than to reduce the

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thickness slightly by employing a high-performance concrete. It should be mentioned that the results could show a different trend when analysing other construction elements, e.g. columns. Additionally, it could be shown that the result depended to a great extent on the chosen boundary conditions and the defined functional unit. A transfer to other types of concrete or building materials requires further investigation.

The second main conclusion concerns the applied evolutionary algorithms. The algorithms proved to be efficient for the optimization especially with regard to the short computation time. On the one hand, their performance could possibly be enhanced by specific settings of the controlling parameters, such as mutation and recombination. On the other hand, their quick detection of adequate solutions without any detailed background knowledge shows their universal application. Due to this wide field of application, they are highly suited for problems in the building sector.

Optimizing concrete structures will become increasingly important in order to meet climate and environmental protection aims in the building sector. The examples given prove that the presented method makes a relevant contribution towards lowering environmental impact. The method presented here will be examined in more detail in future studies. For example, the minimum thickness of the floor slab according to the standard and the exact influence of the reinforcement could be considered. Furthermore, the impact of the columns could be integrated into the analysis.

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