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Prerequisites for Using Genetic Algorithm Optimization of Structural Systems in the Conceptual Design Phase

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Abstract

The construction industry is undergoing a transformative shift towards environmental sustainability. This shift demands that building projects not only adapt to traditional benchmarks of time and cost but also integrate considerations for minimizing CO_2 equivalent emissions. In this context, the critical decision of choosing an optimal structural system during the concept exploration phase becomes crucial to lowering the environmental footprint in the industry. Understanding a building's carbon emission in the conceptual design phase will become even more essential. Therefore, this study explores the possibilities of using genetic algorithms (GA), a multicriteria optimization method inspired by the evolution process, as a work support for structural engineers in early design phases. This study is performed to design a database and investigate the prerequisites for software using genetic algorithms to optimize structural systems based on cost and environmental impact.

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Keywords: Conceptual design; genetic algorithms; artificial; structural system; optimization; database; construction; buildability; sustainability

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1. Introduction

Since the construction sector accounts for approximately 20% of Sweden's CO_2 equivalent emissions, an adaption is crucial to reach the climate targets of "Net Zero Emissions" by 2045 [1]. In addition, the number of buildings being built today has not been this high since 1970 [2]. In "The Roadmap for Fossil competitiveness for the Swedish Construction and Civil Engineering Sector" released by Fossilfritt Sverige, 2018, the construction industry collectively has agreed on a plan to reach the targets [3]. The plan describes a gradual reduction in emissions, with one of the goals being to reduce greenhouse gases by half by 2030. In 2022, a requirement for reporting climate declarations was introduced in the construction of new buildings, with the purpose of making developers more aware [4]. Today, there are no limitations regarding emissions, but maximum values are planned to be added in the year 2027 [5].

This paper discusses genetic algorithms combined with buildability, including sound classes and fireproofing. The long-term goal is to develop a genetic algorithm which can generate as complete a structure as possible to give a more precise cost and CO_2 equivalent emissions. The project goal is to define and build a database that provides a population for the training for the algorithm, in which each individual is a structural system consisting of slabs, walls, columns, and beams. Firstly, a literature study is performed, which introduces climate declarations and genetic algorithms. Secondly, the two methods are presented, followed by the results and a discussion. Lastly, the conclusions of the study are presented.

Nomenclature

AI	Artificial intelligence
CO_2	Carbon dioxide
GA	Genetic Algorithm
LCA	Life Cycle Assessment
SBD	Set-based design

2. Theory

A structural system is a load-bearing unit that transfers static, dynamic, and live loads to the ground. These structural systems can be designed in several ways, but the system's main structural elements are columns, beams, slabs and load-bearing walls [6]. The system can also be built using concrete, steel, timber, or mortar materials. Selecting an optimal structural system is crucial to minimize environmental impact and costs. When designing a system in the tendering process, a short deadline, together with a lot of manual work, often limits the number of systems being evaluated. Embracing advanced methodologies, such as genetic algorithms, offers a powerful solution. GA uses a technique inspired by natural evolution, and by using artificial intelligence, these algorithms navigate the complexity of sustaining construction. When such a tool is implemented in the early process, more possible structural solutions can be analyzed, and the possibility of achieving a cost and environmentally effective solution increases.

In the design process, factors other than load-carrying and stabilization capacity need consideration. For example, the construction cost is one of the most important; the more material used, the higher cost. Also, the environmental impact must be considered, as some materials are more climate-friendly than others. To satisfy all necessities the structural system requires optimization. Therefore, software that can combine different materials with aspects such as sound classes, fire classes, and buildability to create a complete solution would be considered useful.

2.1. Climate declaration

Since 2022, the Swedish National Board of Housing, Building, and Planning, *Boverket,* has requested a climate declaration for every building built in Sweden. Today, the climate declaration considers the construction phase, however, *Boverket* has suggested including other stages of the building process in the future. Also, a limit for maximum CO2 equivalent emissions will be instituted and brought down gradually with the aim of reaching the goal of "Net Zero Emissions" by 2045. The *Swedish institutes for standards* have divided different stages of the life cycle into different modules to easily identify different processes and enable comparison between products. The life cycle is first divided into four different stages: A1-3 – *Product stage,* A4-5 – *Construction stage,* B – *Use stage,* C – *End of life stage,* and D – *Benefits and loads* [7].

The construction phase consists of modules A1-5. The modules A1-A3 constitute the construction stage of the material and elements. A1 contains the raw material supply, meaning the felling of timber or limestone quarrying. A2 includes the transportation of the raw materials to the factories and A3 the manufacturing of the materials [8]. After the construction stage, the construction process stage starts, including A4 and A5, which represent the transportation from the factory to the construction site and the construction-installation process, respectively. A5 includes all work accomplished at the construction site, during building, fuels from machines, and in sheds and waste material. Since choices apart from the material options also need to be considered, the whole process should be planned [9].

2.2. Genetic algorithms

Genetic algorithm is a data management sorter inspired by natural evolution where the most adapted individual reproduces [10]. Charles Darwin's natural evolution theory, proposed in the 19th century, contains the selection process through which the most adapted genetics will be propagated to improve development. The process is based on different stages, which in this project are presented as identified solutions, fitness functions, selection-, crossing- and mutation phases. In this project, genetic algorithms produce a population of different solutions for structural systems. The population consists of individuals, which represents a total structural system. The systems are sorted and evaluated based on qualities in different areas. Those areas are weighed against each other based on the client's demand. Artificial intelligence (AI) can decide between suggestions to find the most optimal.

Genetic algorithms have recently begun to be implemented in the construction industry for structural optimization purposes. Previous studies focus on the visualization of the structure and the geometry of grids to find the most optimized one regarding span length and sizing. In A genetic algorithm tool for conceptual structural design with cost and embodied carbon optimization, Kanyilmaz A. et al. (2023) designed a tool that uses genetic algorithms (GA) to analyze structural systems using different steel, concrete, and timber members [11]. The tool was used to find the most optimized system based on cost and CO2 equivalent emissions by letting GA create different systems in terms of geometry for each material. The result was that both cost and the carbon footprint could be reduced significantly by choosing well-fitted materials and structural systems.

The population is randomly created, and the performance determines the fitness level of each solution. This level of adaptation can be presented and assessed in different ways depending on which parameters each solution is evaluated. A selection process identifies the most adapted individuals, and different methods are used to generate a new population through different crossing and mutation methods. This procedure continues till the convergence criteria are matched.

Each structural system is given a fitness level that represents how well performed the solution is considered to be. The mutation phase is a function of variations, which means that the new solutions can have elements that differ from the previous solutions. This is important due to the invention of new properties that otherwise would not have been combined. Each individual to be evaluated is according to something called a fitness function, shown in equation (1), which evaluates new solutions based on at least two different aspects. These two aspects must be weighed against each other to receive a fair assessment.

$$F(x) = af_1 + bf_2 \quad (1)$$

3. Methods

The study contains two different methods, shown in Figure 1, that support the research work and the software. The first method, which is the workshop, is mainly used to receive opinions about how the model shall be designed and which parameters a structural engineer values. This is crucial to make the software user-friendly and with the correct conditions. The other method, which is the database, is a base where all the data will be collected to be used in future software. The database presents all the information necessary for the creation of different structural systems.

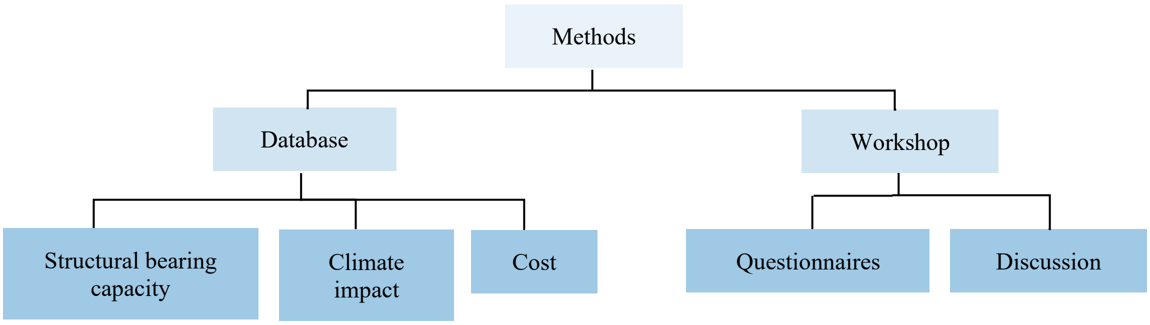

Fig. 1. The structure of the method

3.1. The workshop

The first method is two physical workshops, which include two parts: a quantitative study where the participants got to answer two questionnaires and a qualitative study including a discussion. The two workshops included the same approach and material, where only the participants differed. The workshops were carried out in the following order: *Questionnaire 1, a presentation of the research and genetic algorithms, a semi-structured discussion*, and lastly, *Questionnaire 2.* The participants consisted of structural engineers with at least ten years of experience in structural engineering. Because the questionnaires were carried out during the workshop, all the participants completed the questionnaires, and thus, the response rate was high.

The purpose of Questionnaire 1, which included 30 questions, was to gather information about how the construction industry works today and to collect information regarding design choices from a structural engineer. Following a short presentation about the research and an introduction about genetic algorithms and the implementation of these in the software. The discussion had a semi-structured approach to keep the discussion to certain predetermined topics but also allowed follow-up questions and further information not covered by the direct question. The discussion was recorded, and notes were taken to provide information for the later analysis. The workshop ended with Questionnaire 2, which included 16 questions about the discussion to gather concrete thoughts and opinions about the different topics.

3.2 Database of structural systems

To evaluate the structural systems against each other in the model, a database with information concerning prices and CO_2 equivalent emissions is needed. Therefore, climate data from *Boverket* is used to supply information regarding CO_2 equivalent emissions. The price for each structural member includes the material cost and the cost of the construction work and it is provided by one of Sweden's biggest construction companies. Furthermore, interviews with LCA- and calculation-experts to gather an understanding of how calculations are carried out. Both cost and the CO_2 equivalent emissions are provided for each material separately and later assembled, creating elements.

The cost and CO_2 equivalent emissions depend on the amount of material used, which depends on several factors. To ensure certain sound class materials can either be added to an element or the thickness can be increased, depending on the element. Moreover, a higher structural bearing capacity and longer span widths also increase the amount of material. The database is, therefore, provided with information to guarantee these inputs will be met. Further, standard dimensions for structural elements are used to ensure buildability.

4. Results

In this section, the results from workshop discussions and the two questionnaires are presented in parallel. The results will be presented in the six main themes elements, fitness function, inputs, flexibility, outputs, and usability.

The first theme discussed was **elements.** In the first questionnaire, the respondents were asked to rate the extent of usage of different structural elements and the probable cause of their choice. The factors that mainly govern their choice of structural element are aspects such as the architect's floor plan, the entrepreneur's preferences, and the client's desire. The top three highest-rated slab elements in Figure 2a show how concrete stands out as the most common material in today's construction industry. Among the walls, shown in Figure 2b, the result is more scattered among different materials; a lightweight wall with steel columns is the most common, followed by some concrete walls, and lastly, two alternatives of wood walls. Based on the results of the columns shown in Figure 2c, most participants prefer to use the HSS steel column. Lastly, the beam results are presented in Figure 2d, where most elements share the same score.

When the structural system is assembled in the software, the structural elements will be combined in numerous ways. A discussion was held on whether combinations could be controlled or combined randomly. Most argued was that combinations should be randomly generated to introduce new structural systems. If some element combinations were to be avoided, it would be due to environmental reasons, for example, timber should not be exposed to moisture-prone environments. However, apart from exposure classes, all element combinations should be permitted.

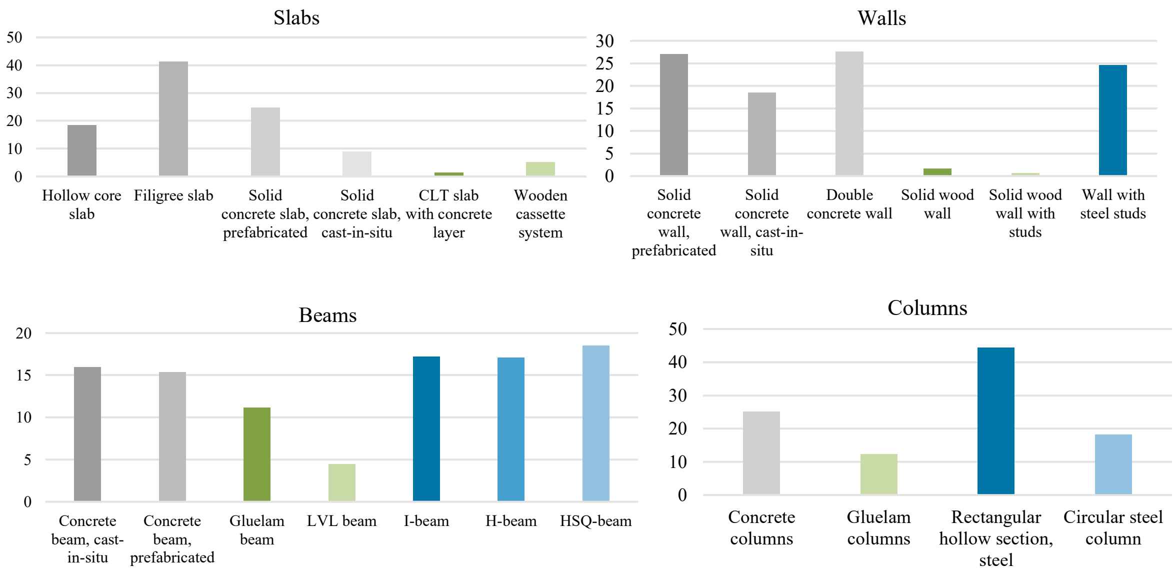

Fig. 2 a-d. The estimated usage frequency of different structural members

The **fitness function** reflects how the cost and CO_2 equivalent emissions aspects are valued against each other. The use of fitness function was brought up during the discussion to understand how these factors are handled in different stages of the planning process. During the workshops, the participants were asked how they would estimate how the industry value cost against environmental impact today. The average result was 76% cost and 24% environmental impact. It was mentioned that during tender calculations, winning the contract is prioritized; hence the environmental impact becomes secondary. If the tender is won, the environmental impact would be valued higher, and the goal is to lower the CO_2 equivalent emissions as much as possible within the budget. Because of the shift of prioritization from the tendering process to the planning process, a representative shift of the fitness function would be beneficial. Further, it has been seen through experience that clients have not been willing to reduce the CO_2 equivalent emissions because of the increased cost it entails. The participants were asked about the usefulness of controlling the fitness function in the model, and the overall response was that it would be considered useful.

To understand which factors influence the choice of a structural system, a discussion was conducted considering possible inputs. The **inputs** entered into the software, and the solutions performed should fulfill these requirements to be considered useful. During Questionnaire 2, the participants were asked which inputs they would consider relevant and how they should be implemented in the software. Regarding inputs such as number of floors, the total height of the building, span lengths, and total ground area, the general opinion was that the user should be able to enter a maximum and minimum value. Further, a discussion was conducted regarding whether the model should be able to freely generate structural systems with different materials. Since some materials are not suitable for some environments, the overall opinion was that it would be desirable to either prevent some materials from being used or assign some materials to a certain environment class.

Flexibility considers to which extent the inputs need to be fulfilled. Some inputs might be assigned a set value early in the process and cannot be modified, whereas other parameters may retain more flexibility. The participants were given a short introduction to the use of penalty functions, where a penalty would be used to reduce the fitness of a solution due to how well the solution fulfills the requirements from the inputs. The approach was positive, and, in the discussion, the overall viewpoint was that solutions should not be excluded. If inputs were too strict, innovative solutions would be eliminated, and the possibility of lowering the climate impact and cost would be limited.

How the output is presented is consequential in ensuring the trustworthiness of the software. Further, the **output** should describe the differences both between elements and between the result in the form of cost and CO_2 equivalent emissions. The participants got to rank different outputs based on the expected trustworthiness the result would entail. The two highest-ranked outputs were a solution space and a 3D model of the structural system. During the discussion, it was mentioned that the design of the output is important to ensure others of a certain solution. Further, to ensure the user of the software's credibility, the participants would want to be able to track the solution. To see what parameters the solution is based on and what outputs represent the elements individually.

Usability is a theme raised to inform whom and at what stage the program can be helpful. The idea is that a structural engineer should be able to use the program to analyze and have a fundamental basis to select a certain structural system. To make the most use of this program, it was discussed that it should be introduced very early in the tender process to be able to discuss the design with the architect. The discussion concluded that the program should preferably not become too complicated to avoid the software being burdensome and slow. Facilitated parts of their work were discussed in the questionnaire, which was described as making quick decisions, generating more options, and demonstrating motivational documents. One of the questions raised during the workshops was possible challenges and barriers for implementing such a program. The participants believed that one factor that could prevent success was that the software becomes too difficult to handle. Another aspect was the difficulty of managing the surrounding environment. A slightly more recurring problem will be updating the material prices. The prices depend on many factors that are controlled by, among many things, the market, demand, inflation, and project.

4.1. Database

The database will contain information regarding structural bearing capacities, climate impact, and cost of the materials and elements used in the software. The **climate impact** will be represented by CO_2 equivalent emissions, which in Boverkets climate database are presented by the unit [kgCO2e/kg] and are provided for modules A1-3, A4, and A5 separately. The unit later used in the software to compare elements will be [$kgCO_2e/m^2$]. In Table 1, an example of a slab is shown, here for a hollow core concrete slab.

Table 1. The calculations of CO2 equivalent emissions from the database for a cast-in-situ concrete wall.

Materials:	Climate improvement:	Sound class:	Thickness [m]:	Mass [kg/m^2]:	Generic factor [$kgCO_2/kg$]: A1-A3:	A4:	A5:	Total:	Generic [$kgCO_2/m^2$]:
Concrete C35/45	40%	B	0.7	164.5	0.10	0.004	0.005	0.11	17.6
Hollow core floor			0.265	357.75	0.13	0.032	0	0.16	57.4
									74.9

The option of adding climate-improved concrete is available by reducing the environmental impact in A1-3, the production stage. For concrete and solid timber walls, a higher sound class is received by increasing the structural concrete or structural wood or adding additional material, such as step-sound carpets. The fire resistance class can be increased by adding gypsum fireboards, insulation or by painting. The thickness and, in turn, the amount of material used will, therefore, change depending on the sound class.

The **cost** includes the material cost and production cost. Information regarding **structural bearing capacity** for each element will need to be implemented in the software to allow the model to present systems that withhold the load assigned. Further, bearing capacity depends on the amount of material, which in turn determines the cost and environmental impact. In table 2 an example of how the bearing capacity in the database will be structured.

Table 2. The calculations of the bearing capacity and cost from the database for an HSS steel column.

Dimensions [mm]:	Thickness [mm]:	CS area [mm^2]:	Mass [kg/m^2]:	Bearing capacity [kN]:	Cost [SEK/m]:
80 x 80	6.3	1810	14.2	263.2	881

5. Discussion

An overall analysis indicates that concrete is generally the most used material in structural systems. This could be due to many factors, but some might be the capacity to handle long spans, construction workers being used to the material, and the fact that it meets most requirements at a low quantity. Another factor that must be considered is the optimization of the amount of material to prevent the building from being over-dimensioned. This is often related to timber buildings since a larger amount of material, compared to concrete and steel, is needed to fulfill the same load-bearing capacity.

The fitness function reflects how cost versus environmental impact is valued and is not constant during the project process. Furthermore, stricter values in the form of maximum CO_2 equivalent emissions will be implemented in the industry, demanding a change in approach. The results from this study show that structural engineers would like to change the fitness function depending on where in the process the software is used. It would also be beneficial to evaluate how small changes in the fitness function impact the algorithm's choice of an optimal structural system.

The role of a structural engineer includes discovering innovative solutions reflecting the opinion regarding not wanting to weed out any solutions at an early stage. However, preventing materials from certain locations would be beneficial due to material properties. Preferably, the software would allow the flexibility to be determined by the user. The software must be easy enough to use but still provide enough design choices and flexibility for the structural engineer to trust the software's reliability. However, as the result of this study shows, the structural engineers prefer to have many solutions to choose from, and the actual decision of which final solution to proceed with shall not be automated but left to them to make. The approach is to create software that is simple to use and present solutions quickly in order to speed up the decision-making process since the intended use is as a decision-support in the early stages and not a complete design software.

During the planning process, previous projects are often used as reference. This approach would be useful for implementing a function in future software that forwards experiences of a specific system. However, pre-requisites vary from project to project, and accordingly, no restrictions should be implemented. The experience should rather be applied as feedback in the form of a comment. In the future, the software could expand by integrating further aspects apart from cost and environmental impact. Since a project often comes with a time limit, the inclusion of time would be of interest. Time is affected by factors such as logistics and suppliers' delivery time, making the time factor difficult to integrate in each element in the software.

Further, the environmental impact is based on the production stage, which might give a misleading comparison; thus, the whole life cycle is not presented. The choice of only including module A1-5 is based on the current requirements from *Boverket.* Implementation of the remaining modules during further development of the software would give a more representative picture of the actual environmental impact. Furthermore, the price is not consistent; consequently, the database will need to be updated to stay relevant. As for the environmental impact, the cost implemented in the database includes material and production costs, and costs like potential maintenance are not taken into account. In addition, the lifespan is not considered.

6. Conclusion

Overall, the future software is considered to become a useful tool for structural engineers during the creation of conceptual design, with the approach of creating ideas. Instead of selecting one solution that is considered to be the optimal one, it would be preferable to present a range of solutions from which the user can choose the most fitting system for the specific project. For the software to be considered useful, it must be simple and easy to use but also provide sufficient reliability. The evaluation criteria (the fitness function) must be flexible since it may vary between projects and project phases.

To improve future software, several aspects must be considered. The process for updating material prices from different suppliers must be investigated. Further, the interaction between structural systems must be considered during the crossing phase. How element adaptation proceeds during the generation of new structural systems to create complete and functional systems needs to be investigated further. Adding a feature that the user can implement and receive feedback on regarding a specific system is considered beneficial. In the future, it would also be valuable to consider additional factors, such as construction time and production methods. Further continued studies are needed to determine how information regarding these factors should be gathered and integrated into the software. To validate the correctness of the future software comparisons with traditional set-based design (SBD) or conducting case studies can be done. In such case studies, structural engineers should compare results from the future software with results from their own produced results.

Acknowledgments

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