Heuristic Methods in Architectural Design Optimization

Monte Rosa Shelter: Digital Optimization and Construction System Design

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This paper focuses on optimization methods and their role in the “digital chain” in architectural design and production. These methods were developed in the research phase of the project ‘New Monte Rosa Shelter’ to improve cost efficiency and to adapt the design for the specific environmental and constructive constraints of the site.

The New Monte Rosa Shelter is a project designed by students for a mountain shelter at high altitude. For transportation and construction reasons, optimization was required to minimize costs, material, and weight of the structure. For this project a series of programs using genetic algorithms were written to optimize the geometry of the wooden framework. These programs were combined to create a digital toolset, giving the architects direct output of surface information from the framing data, and allowing for output as a three-dimensional model. This optimization toolset gives creative control back to the architects themselves, who can now transform and manipulate the architecture.

This paper describes the overall process, and outlines one specific optimization tool, a program that enables architects to “fill” the wooden framework automatically with different material and construction systems and understand the cost and efficiency implications based upon the structural analysis software and the programmed heuristic methods.

Keywords: Heuristics; algorithm; evolutionary strategy; digital chain; generative design; computer aided optimization.
Introduction and overview on the Monte Rosa project

The “Monte Rosa Shelter” project was initially a student design course assignment and architectural competition in 2004 at the Federal Institute of Technology in Zürich (ETHZ). The task was to design a mountain shelter for 120 people on the highest mountain of Switzerland, Monte Rosa.

To aid in the realization of this project a research group was formed in 2006 to research materials, fabrication methods, and construction strategies, to adapt the design for the specific environmental and physical constraints of the site, and to determine the best strategies for optimizing the cost. The concept of a ‘digital chain’ was introduced to implement a continuous set of data and processes within the project, and ensure that all of the project participants are working collaboratively. The individual steps of this digital chain were developed by the Chair of Computer Aided Architectural Design (CAAD). The research group consisted of Prof. Andrea Deplazes, Chair of Architecture and Technology, Prof. Dr. Ludger Hovestadt, Chair of Computer-Aided Architectural Design (CAAD) and Prof. Sacha Menz, Chair of Architecture and Building Management.

Digital design translation - the “rubber band” model

The initial step to prepare the project for optimization was to transfer the project geometry and parameters into usable data structures. The project geometry and data was “digitized” and the subsequent data set imported into a software program (written by Markus Braach) which represents the design as a series of parametric relations. This program enabled the architect to manipulate and visualize the basic design, both exterior and interior, and have simultaneous feedback on the important parametrically
associated features. Exterior modifications affected issues such as structure, surface, wall section and thickness, while interior modifications of affected usability issues such as total number of beds. The program thusly balanced the substantial building parameters against the overall site and program requirements, acting like a tension system – equalizing the parameters of the design (like a rubber band). This program gave to the designers, an overview of the impact of each change and allowed real time evaluation of appropriateness, efficiency, and also a rough cost estimate.

The defined geometry of surfaces (walls) were then exported as an “edge-node” model to the next step of the digital chain. At this stage the surfaces are defined and evaluated with different material assemblies, and the wooden framework can then be optimized using heuristic methods.

**Heuristic algorithms –the genetic algorithm**

Heuristic algorithms are mathematical representations of simple, strategy based, rule systems. A heuristic algorithm will try to follow a simple set of rules to return a specific solution, but it cannot guarantee that the “best” solution will be found. As a result a heuristic algorithm based program may only be considered as an “approximate solution finder”. Heuristic algorithms are used to find an acceptable solution and find it with minimal computing time. The benefit of the Heuristic algorithm is that it is efficient and can be used for “real time” representations; the disadvantage is that it does not guarantee the “best” solution in all cases.

For certain multi-parametric tasks there are no clear analytic solutions. For such tasks one can try to determine a solution using an optimization algorithm. But there are differently algorithmic strategies. Genetic algorithms (GA) are optimization procedures which take the biological evolution as model. In nature organisms adapt to their environmental context through evolution of their genetic constitution. This adjustment process is directed by three basic principles: natural selection, recombination of the hereditary characteristics, and mutation.

A similar model can be represented in software programming. GA programs optimize an initialized set of individuals using similar symbolic steps: evaluation and selection, recombination, mutation. During initialization, quantities of dissimilar individual solutions are produced; similarly to nature it is important for a successful evolution that the population is sufficiently large. The solutions are then evaluated based on a series of “fitness criteria” and selections are made by the programmed fitness function. The more “fit” a solution is, the higher the probability that the solution will be selected to “survive”. The next step serves to propagate the population through recombination of the hereditary characteristics. Recombination composes new individuals from the genomes of the “good” solutions. Mutation functions also exist to allow for diversification of the population and the formation of variants. Mutations prevent the emergence of local optima and ensure diversification for the next cycle. This three step process is then repeated, with each cycle representing one step of the evolution. The process is cyclical and continuous until an either an abort criteria is reached or the system achieves an equilibrium where every “new” variant is less fit than the existing population.

**The “Monte Rosa” problem**

The chosen architectural design for the shelter consists of a wooden frame structure and exterior panelization. The entire construction must be optimized to reduce the weight, as the only realizable method of transportation for large materials to the site, is to be lifted by helicopter. A significant cost optimized can therefore be achieved using lightweight, prefabricated wooden framework and a prefabricated wall panel system, thereby saving costs of material, waste, transport, and reducing assembly time in a “difficult to access” location.
Initialization

After the first “rubber band” design manipulation, the resulting geometry is processed by a program (written by Kai Rüdenauer) to determine the structural geometry of the timber framework. The architect can use the program to specify different subdivision “fill styles” on the different vertical faces (interior and external walls, ceilings and floors, walls of the internal core).
The architect can choose a timber framing which integrates a window (a), a framework over the entire field (b), a framework over the entire field with king post truss (c), a timber framing with two diagonal studs (d), triangulation studs (c) and a timber framing with randomly placed studs (f).

The best initialization type for the framework is to fill each face with a random number of beams, resulting in a larger variety between individual of the first generation. This generates a larger ‘genome pool’, reinforcing the probability of finding optimal solutions.

**Evaluation of each generation**

The initial generated framework was exported into the structural analysis software RSTAB, which simulates the framework under static load testing. The structure is exposed to different load cases, such as wind, snow, working load, and self-weight. During the simulation the behavior of each single beam and joint is determined and recorded. After the determination of the whole structure, all axial forces and all bending moments of each beam are stored in a data structure (comma separated value file) which can be read back in to the software. The results from the analysis are reintroduced to the optimization cycle, and are used to evaluate the fitness criteria.

**Fitness criteria**

The fitness criteria of each structural component are based on the load and type of force carried by each beam in the wooden framework. Every structural part should bear its maximum (safe) load. This avoids any over-sizing of the structural elements, and results in economies of weight, cost, and transport. With this primary constraint all unnecessary beams are eventually deleted, and the overall structure is reduced to an optimized minimum over the evolution of the process.

For example: A beam which carries its maximum load it is validated with an excellent fitness rating. If a beam is bearing a load over or under its maximum load it is validated with a lesser fitness. The fitness criteria of a beam is also influenced by the amount
of material required compared to the specific planar face. A face where all beams take their maximum load, will be more valued if it uses less material. After the validation, each face of the structure has its own fitness rating and the combination of the structure and the face values creates an overall fitness evaluation. The actual calculation of fitness is based on engineering simulation data and the heuristic rule set developed for the project.

**Selection and recombination**

To prepare the individuals for the next generation the different models are ranked. The higher a fitness of an individual is, the higher is the degree of a probability for a recombination with another individual of the same generation. This rule ensures that even poorly ranked framework have the possibility for recombination.

Individuals are “recombined” by merging the structural detailing from the face of each model (parent) to a new face (child). There are two strategies to merge two faces. One is to translate fifty percent of each filling style and combine the geometries into a single face. The second method is to analyze the two fillings styles and to “mediate” the positions of the beams as an average of the two styles combined.

**Mutation**

A face is mutated by randomly inserting or removing a beam from the filling. The number of beams can only be reduced to a minimum of one, but can be augmented to a local maximum depending on the geometry and dimensions of the face.

**Abort criteria and “tuning”**

The optimization process is programmed to stop either after a predefined number of generations, or if a solution is found via the algorithm that satisfies a predetermined criteria. Too many parameters or parametric variance require many more iterations to optimize a problem. As such, it is worth “tuning” the influencing parameters (such as the mutation probability, recombination probability and population size), so as to find reasonable settings for the scope of the problem. A very small mutation rate may lead or premature convergence of the genetic algorithm into a local optimum. A high mutation rate may lead to a loss of good solutions due to genetic drift. There are theoretical but not yet practical upper and lower bounds for parameters that can help to guide through the selection. To find the right settings is perhaps one of the most difficult tasks after the implementation of the algorithm. For this project the abort criteria were to stop the program once the “structural weight to load capacity” ratio hit equilibrium, and became adequate based on cost estimations.

**Optimization and export of the evaluated solution**

The final phase of the process is to run the GA on the geometry model and produce the structural design. To do this the program is required to interface with existing engineering software. The data was provided as a geometry file and translated to XML, VectorScript, and as an import file for RSTAB. The RSTAB data enabled the continuation of the digital chain and export of the 3D model and to all static load environments of the structure into Cadwork; an industry standard software for timber construction engineering. The structural analysis software allows for objective and traceable evaluation of each individual model and component.

**Result**

Each model cycle of the GA (recombination, mutation, selection and validation) could be calculated in an acceptable time of 40 to 60 seconds. The optimization began with a minimum number of forty individual components and each full evolution of the structure required approximately one hour to calculate.
Compared with the original timber framework (as designed in the students design), the resulting optimized structure is approximately 30% lighter.

**Conclusion and discussion**

The Monte Rosa Project provided our research team with an ideal basis under which to develop these optimization programs. The combination of clear goal parameters and a minimal architectural design upon which to apply them, allowed us to develop an equally clear and consistent methodology.

The opportunities for geometry optimization in architecture are clear, in the reduction of material, waste, and cost, but the use of such programming can also have an effect on the production of architecture; allowing for more expressive and interesting structures to be built.

Using the “digital chain” concept for such a project provides additional advantages. The use of programmed software to describe geometry allows for automated generation of the component drawings. To draw or even to transfer such an illustration of a design in a conventional way into a CAD program opens up the possibility of error, and is time consuming. Any “down wind” change in the geometry of the building would consume a lot of time in reworking all of the associated CAD representations. With the described automated filling of the faces, new models or iterations can be updated in minimal time. As such it is easy to provide variations of the wooden structure by simply changing the fill style.

The software developed provides unique opportunities to both the architect and the structural engineer; to review many solutions in a very efficient manner. The processes outlined in this paper allow for a close inspection of the structure, and allow the components to be dimensioned based on loading rather than standardized on the individually most loaded element. The combination of a GA with structural engineering software has created a positive feedback loop, providing for refinement of the design, but also allowing for advantages of measurability. Additional research and work is still required to develop a strategy for “tuning” the GA and parameters, but overall the process of optimization through GA is a success. By giving the structural engineer access to this information the structure can be dimensioned rationally, instead of using a highly reduced and abstracted model.

The application of such optimization programs is reasonable in projects where the structure and
geometry can be described with a minimum of parameters, however algorithmic optimization is not limited to only the structure of a project. GA programming has been used in the architectural design of forms, architectural layout, landscape, and urban design.

The manufacturing data of the timber framework is simplified by choosing a fabricator who is also responsible for the engineering of the connection details. This minimizes requirements for multiple “shop drawings“ and used the digital chain to directly move into the fabrication process allowing for additional savings.

The specification of the static loads for each piece is one of the basic data elements passed along the digital chain. By providing the overall geometry, and the load information it is possible for the fabricator to engineer the fixing and assembly patterns for each piece. The results is that the fabricator is responsible for the assembly detailing, not specified by the architect or engineer, but described heuristically only by the load data and the style guide. This process allows for the detailed production data to be generated based on the results of the overall process. This process is also an economic decision.

The intersection of CAD/CAM software with construction allows for high control over geometry and its physical production. The building industry, for the moment need not completely retool their production methods for buildings using these technologies, like the Monte Rosa shelter. This project is a “one-off” occurrence, due mostly to the interesting parameters of its site. However, there is much from this project that can migrate to real-world commercial construction.

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**References**
