# An Interactive Evolutionary Framework for Structural Design


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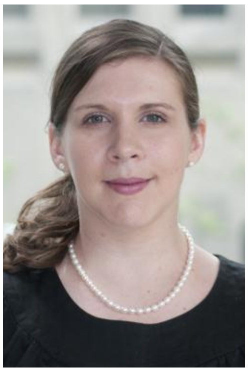


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## Summary

This paper presents a novel interactive evolutionary framework for conceptual structural design. In contrast with tools for structural analysis, tools for structural design should guide the design process by suggesting structurally efficient options, while allowing for a diversity of design choice. The framework proposed here implements an interactive evolutionary algorithm to achieve this behaviour. Additionally, a cohesive and intuitive graphical user interface is introduced. Finally, a novel approach to approximate the design space, and thereby improve the speed of the algorithm, using non-parametric regression is discussed.



**Keywords:** *structural design; conceptual design; evolutionary algorithm; interactive optimization; structural optimization; multidisciplinary optimization.*


## 1. Introduction

A prevalent current standard for the structural design process is a segmented, linear approach: an architect synthesizes a conceptual form without structural considerations, and then an engineer analyses and tweaks the form to make it meet structural requirements. This process is time-consuming and produces designs that are often inefficient and sometimes unsafe. Additionally, the historically celebrated elegance of structurally expressive forms has become difficult to achieve.

The research area of structural design tools enables an alternative approach that integrates structural considerations into the conceptual phase of design. While conventional practice requires an architect to decide on a form prior to structural analysis by an engineer, these computational tools allow designers to make structurally informed decisions from the start. They bridge the gap between qualitative structural intuition, which can be helpful but has a limited scope, and sophisticated computational analysis, which is too time-consuming to be performed multiples times in an explorative, iterative process. At their best, these tools can also serve a didactic role, improving the user's structural understanding.

While there are several important features of structural design tools, this paper focuses on a key issue, performance-based guidance, which is critical for conceptual design because it directly relates to design synthesis. In contrast with structural analysis, structural guidance has been difficult to implement. Structural optimization methods are one seemingly attractive approach, but they have yet to become widely used in practice.

This limited success of classical optimization in the architectural design process stems from the natural incompatibility of the two fields. Optimization is a mathematical procedure for finding the best solution according to formulated criteria within a specified domain. In design, it is very difficult to describe qualitative criteria and domain constraints mathematically. Also, in many cases,

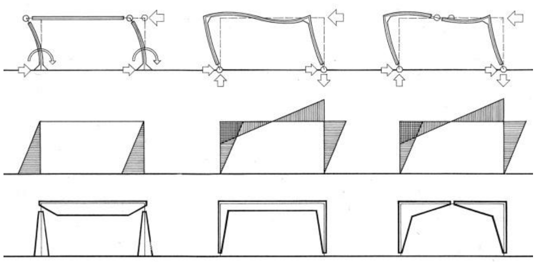

*Fig. 1: Three design solutions found by varying fixities in a statically indeterminate frame [1].*

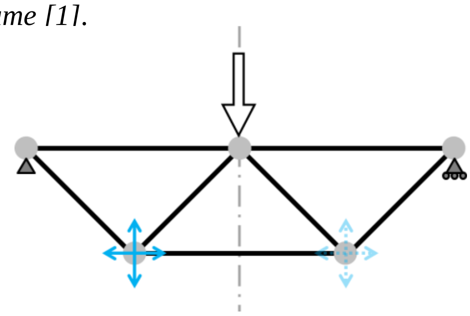

*Fig. 2: Simple truss design problem with two variables: horizontal and vertical position of lower left node. Lower right node remains symmetrical.*

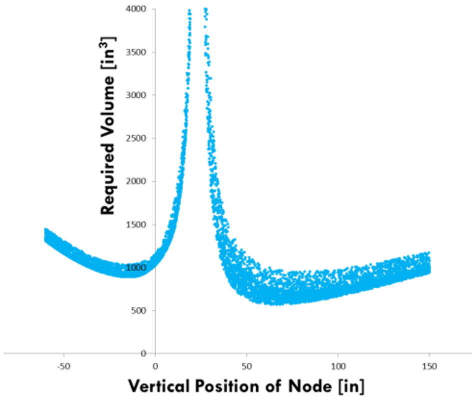


*Fig. 3: Projected plot of design space for vertical position variable. Asymptotic behaviour toward infinite volume occurs when the truss approaches zero depth. The asymmetry arises due to local buckling in compression.*

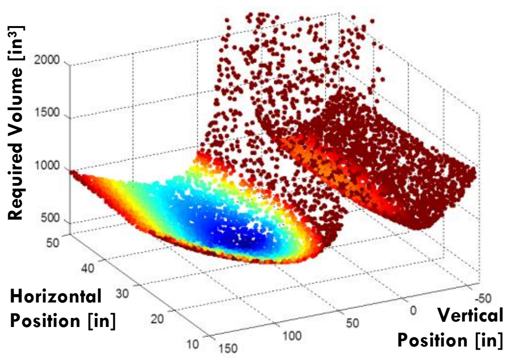


*Fig. 4: Plot of two-dimensional design space, showing two local minima.*

even the quantitative objectives and constraints have some flexibility, or fuzziness, inherent in them. Moreover, important criteria and constraints are often discovered during the course of the design process, and therefore cannot be stated at the start.

Another important contrast between optimization and architectural design is the concept of the optimum. While there may be an ideal design for an airplane wing, architecture is subjective in its quest to accommodate form and functionality. Therefore, there is no single best solution to an architectural problem, but rather a plurality of solutions that can vary widely. A simple example of this is shown in Figure 1, in which three valid, structurally efficient solutions are shown for a single design problem. It is important that the designer be able to consider many solutions in order to make choices based on unformulated criteria. A second example is illustrated in Figures 2, 3, and 4, where it is seen that even a simple two-dimensional design problem has a complex design space with multiple local optima. Again, many of the possible solutions may be structurally acceptable.

## 2. Background

Interactive evolutionary algorithms are an alternative to classical optimization and have proven effective in addressing the issue of qualitative and fuzzy design goals. In general, these algorithms involve simulated populations of solutions from which high-performing candidates are chosen to be recombined and mutated to form subsequent generations. Over the last twenty years, there have been many examples of their success at tackling difficult problems with partially qualitative criteria [2][3].

Within the field of structural engineering, a number of researchers have shown that these and related algorithms are promising for conceptual structural design. Noted work includes that of Von Buelow [4], Shea et al. [5], Martini [6], and Byrne et al. [7].

While these examples prove that interactive optimization methods are a viable way to provide guidance in structural design tools, they also suggest several challenges. First, most work addresses the design of truss structures; extensions to a variety of structure types would make these algorithms more useful in practice. Relatedly, most work focuses more on computation and algorithms, with structural analysis methods, usually the finite element method, taken as a given. As more complicated structure types are considered, approximation and abstraction of structural models will become very important. Third, little attention has been paid to the user interface and visualization of results in these tools, which is crucial to their usability and success.

# 3. Methodology

## 3.1 General approach

This research aims to extend existing work by developing a generalized framework for applying interactive evolutionary algorithms to structural design problems of many types. There are three main components of this proposal: the algorithm itself, the implementation and user interface, and a novel regression-based approach to increase speed.

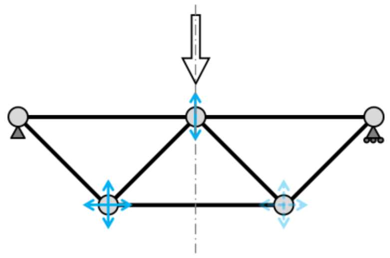

*Fig. 5: Truss design problem with three design variables.*

Two sample problems are used for demonstration, illustrated in Figures 5 and 6. The first is a seven-bar truss, with a single point load and simple supports. The second is a more complicated rigid frame structure, subject to distributed vertical loading and a lateral point load, with fixed supports. Both structures are modelled in the vocabulary of nodes and members. The design variables for each of the problems are the horizontal and vertical positions of a subset of the nodes, chosen because of their strong impact on overall structural form. These variables are constrained within an allowable range specified by the user.

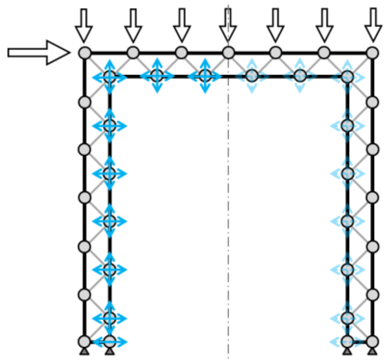

*Fig. 6: Rigid frame structure design problem with 17 design variables.*

The structural evaluation metric is the required volume, computed using the direct stiffness method. Member sizes are determined by the computed member forces and given allowable stress values. The frame structure is analysed as a truss, using the well-established truss analogy for beams [8]. In statically indeterminate cases, such as the truss-approximated frame, a determinate approximation is used, with all member areas set to the same value for the analysis.

## 3.2 Interactive evolutionary algorithm

A schematic diagram of the algorithm used for this study is shown in Figure 7. The intended behaviour is somewhat like that of a standard genetic or other evolutionary algorithm: the randomness allows for robust design space exploration, while the ranking and subset selection simulates a "natural selection" of the best designs. The addition of the interactive step allows the user to express preferences that have not been encoded in the problem. Depending on the needs of the user, the algorithm may or may not find a global optimum. However, in either case, it should find good, optimally directed solutions that capture the user's intentions.

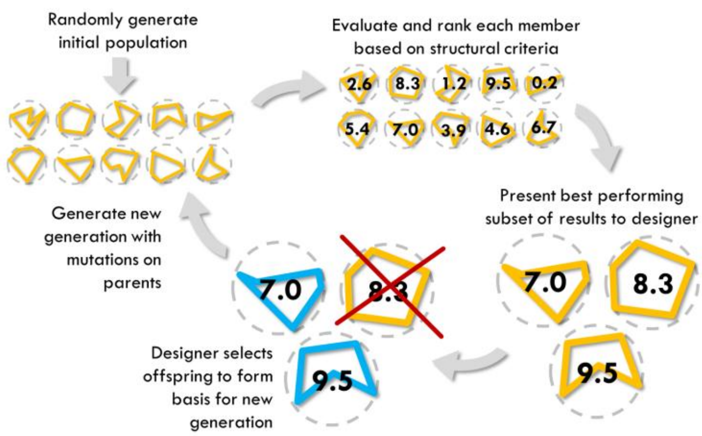


*Fig. 7: Diagram of interactive evolutionary algorithm.*

## 3.3 Implementation and user interface

In order for a tool using this algorithm to be effective, it must enable a fluid, efficient user experience. Key features for this are broad accessibility, ease of problem input, and near-instant interaction speeds. This implementation addresses the first two requirements through an interactive web application using Microsoft Silverlight technology, written in the C# programming language. The program will be available from any internet-connected computer independent of operating system or internet browser.

The user input mode of the program involves an interactive CAD-like environment in which geometry and other structural information can be specified through drawing and spreadsheet manipulation. This mode also allows the user to designate design variables, constraint ranges, and parametric relationships such as symmetry lines.

The interactive evolutionary mode also involves a graphical user interface: the top ten candidate designs of each generation are presented as rendered images. A normalized score appears beneath each design, so that the user can consider the relative performance of the options. Previous generations are displayed in addition to the current generation, so that a visual record of the evolutionary process is clear. This also allows the user to step backwards in the process, returning to a previous generation and changing her selections to redirect the design space exploration. Finally, the user can further control the process by varying the mutation rate and generation size.

### 3.4 Non-parametric regression model

Because each design in a generation must be evaluated using the direct stiffness method, larger generation sizes require more computational time. Depending on the complexity of the design problem, the wait time between each generation can exceed tolerable limits, even for small generation sizes. This limitation is overcome through the use of non-parametric regression modelling. Prior to the interactive evolutionary mode of the program, the program simulates two populations of candidate designs, and uses the first to train non-parametric regression models such as random forests and neural networks. The second population is used as a validation set to help choose between potential models.

The program then uses a novel modification of the standard interactive evolutionary algorithm: instead of actually evaluating each candidate design, the program predicts the performance using the regression model. The top ten to twenty design according to the regression predictions are then actually evaluated in order to present accurate scores to the user. While the values of the predicted scores tend to be incorrect, the relative ranks of the candidate designs are generally well predicted. Because predicting the performance through the regression model is very fast compared to using the structural analysis method, this modification essentially decouples computation time from generation size. This greatly improves the opportunities for rapid design space exploration.

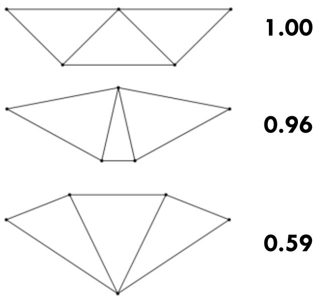


*Fig. 8: Sample designs with normalized required volume scores for seven-bar truss problem.*

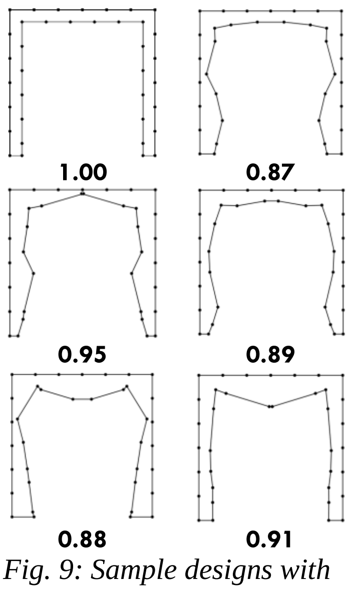


*Fig. 9: Sample designs with normalized required volume scores for shaped rigid frame problem.*

## 4. Results

### 4.1 Seven-bar truss

A sample of the designs for the seven-bar truss is shown in Figure 8, including the original and two final designs. Despite the simplicity of the problem, there is still an interesting range of solutions. The first design shows the central node moving up and the bottom two nodes moving inward. The second involves the top node moving down, and the bottom two nodes moving up, so that the tension and compression elements switch. Because of local buckling, the problem is not symmetric, and the second design with fewer elements in compression is much more efficient.

### 4.2 Shaped rigid frame

There are two important features of this design problem: a large number of variables and static indeterminacy. This means that there are many local minima, and the interactive evolutionary approach can help the user find a broad variety of optimally oriented designs. Figure 9 illustrates the interesting variety of design solutions found for this problem. It is of note that while each design evokes a possible moment diagram of the structure, none is a direct moment diagram translation. This shows the flexibility of the interactive evolutionary approach to balance structural efficiency goals with qualitative concerns such as aesthetics and constructability.

## 5. Conclusions

### 5.1 Discussion

The interactive evolutionary framework presented here is a flexible method that enables structural designers to explore a variety of conceptual design problems. Two examples, planar trusses and shaped rigid frames, have been illustrated in this study. Both show that a broad range of structurally efficient solutions are possible for a single design problem. While no solution is guaranteed to be optimal, the algorithm finds very good solutions that are guided by a user's qualitative preferences. This is a key step towards developing computational tools for structural design.

In addition to the general framework, this study introduces several specific novel contributions to the field of structural design. First, an extension of the interactive evolutionary algorithm to shaped rigid frames and beams has been presented, using the truss analogy for beams. This is important because flexural elements are common in structural design, and expressive shaping can both save material and enhance aesthetics. Second, an integrated web-based user interface has been developed to foster an efficient and highly visual user experience. Finally, a non-parametric regression method has been devised to approximate the design space and significantly reduce computation time for large generation sizes.

### 5.2 Future Work

As an emerging research area, interactive evolutionary structural design offers many challenges and opportunities for further investigation. This study suggests two directions as particularly important. First, the framework presented here should be expanded to support more structural types. In theory, any structure that can be represented by a reasonably small number of parameters and analysed in a fairly quick manner can be designed using this framework. However, parameterization and fast analysis are not trivial for many types of more complicated structures. This is therefore a worthwhile area of study that will help make interactive evolutionary methods more useful for structural design in practice.

A second key direction is algorithmic improvement. While this study has shown that the regression approximation is a promising way to increase the speed of evaluating large generations, there are still opportunities to further develop this technique. For example, the regression model could be enhanced at each generation by including the new design candidates that have been analysed. This would help focus the regression model on the areas of the design space of most interest to the user, improving accuracy where it matters.

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