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## Abstract

This paper presents a qualitative examination of the responses of architects towards the idea for including a form-ýnding structural optimization method in the architectural schematic design phase. Recently, there has been a few emerging architectural parametric Computer-Aided Design (CAD) systems that enable architects to perform an early schematic form-ýnding structural optimization such as the coupling of G o Γ h ∃ f sral ľ ľ ʿ ʿ ʆ structural performance; the interoperability and integration of architectural parametric CAD tools, engineering analysis and optimization tools as well as the usability of these tools; and the implementation of structural optimization in the architectural schematic design phase. This paper discusses the process of the investigation of these concerns qualitatively using Grounded Theory for data collection and analysis, and for the software development and testing process. Clemson University students and faculty were sampled as research participants. Form-ýnding structural optimization software that couples Grasshopper, Matlab (a scientiýc programming language) and Abaqus (ýnite element analysis software) was developed as a design method to facilitate the interviewing process. The software MAXQDA is used for the qualitative data analysis.

**Keywords**: Collaboration; Schematic design; Structural optimization; Form- nding; Grounded theory

## Inroduction

Many research studies have highlighted the problems of the current collaboration between architects and structural engineers. Although the forms of the research statements and ndings vary, many converge towards the following opinion: structural engineers and architects o en speak di erent 'languages', i.e., one as a technician who lacks innovation and another as an artist whose primary focus is merely on appearance, and the di erences o en lead to frustration on both sides during the collaboration process [1-6]. A considerable amount

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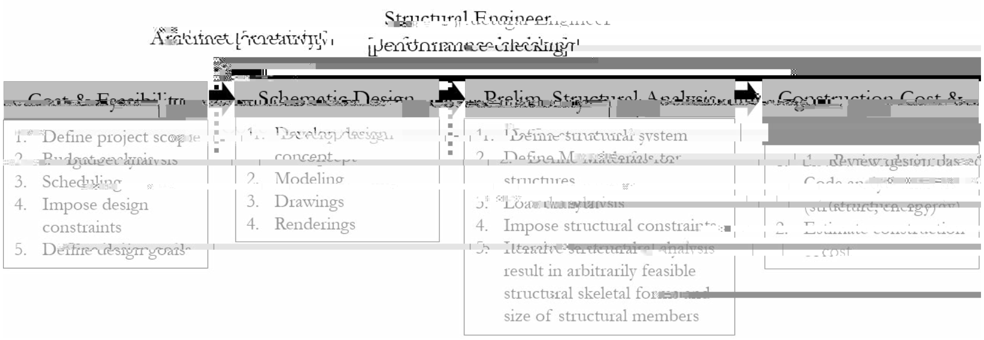


**Figure 1:** Contemporary schematic design workþow.

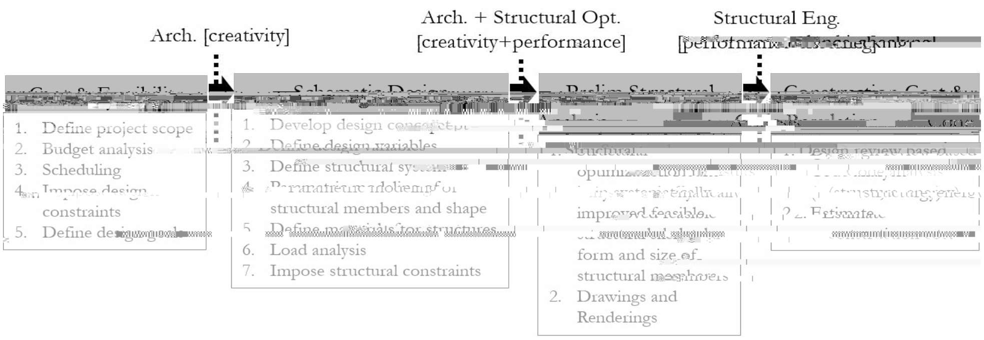


**Figure 2:** Schematic design workþow implementing form-ýnding structural optimization.

structural optimization implementation towards the architect-engineers collaboration. Based on this issue, three research concerns are developed as follows:

1. Examine difficulties in the traditional design workflow that separate the architectural form generation process from the engineering aspect of structural performance.

2. Study the interoperability and integration of architectural parametric CAD tools and engineering analysis and optimization tools as well as the usability of these tools.

3. Examine the implementation of structural optimization in the architectural schematic design phase.

These research concerns are qualitatively examined using Grounded Theory for data collection and analysis process. The term Grounded Theory was originated by Glaser and Strauss [12] as "the discovery of theory from data that is systematically obtained and analyzed." Due to the lack of publications and studies on these concerns, the only viable research method for examining these issues is the qualitative approach. It is important to note that a qualitative research method such as Grounded Theory does not assume that the researcher knows enough to formulate specific hypotheses [13]. Thus, unlike in traditional quantitative research methods, research questions are not formulated. Instead, research concerns are used to drive the research process. The reason for using a qualitative research method as opposed to a quantitative research method is the fact that architects generally do not have sufficient knowledge of statics and structural mechanics to be able to sufficiently understand the process involved in structural optimization. Thus, it is assumed in this research that it is necessary to have back and forth communication between participants (architects) and the researcher during the data collection process. The communication is necessary to educate the participants about architectural, structural optimization such that the responses from the participants are the mix of the newly acquired education and their academic and design practice experiences.

The target population for the qualitative study is the Clemson University architectural students and faculty. The second section of this paper briefly discussed form-finding structural optimization software that was developed during the study to facilitate the interviewing process and as an example method that can be used for implementing form-finding structural optimization in the design process. The third section discusses the Grounded Theory procedure and how it is applied in this study for data collection and analysis to gain in-depth understanding towards the issues being raised above and for the software development purpose. The fourth section discusses the findings that are written as theoretical narrative reflecting the research participants' responses toward the issues being raised and the developed tools. The fifth section presents how the outcomes of the research help develop the tool. Finally, the sixth section of this paper discusses the proposed design flowchart for implementing form-finding structural optimization method in the design process.

## Form finding architectural, structural optimization tool

The developed optimization tool integrates Grasshopper (a visual programming language in Rhino), Abaqus (a finite element software) and Matlab (a scientific programming language). This tool is initially used for the interview. The responses from the interviews are then used to modify the software further. Premade components in Grasshopper were made to allow parametric control over the structural analysis setup (loading conditions, element type, and section properties) and to manage the interoperability between Grasshopper and Abaqus. Matlab

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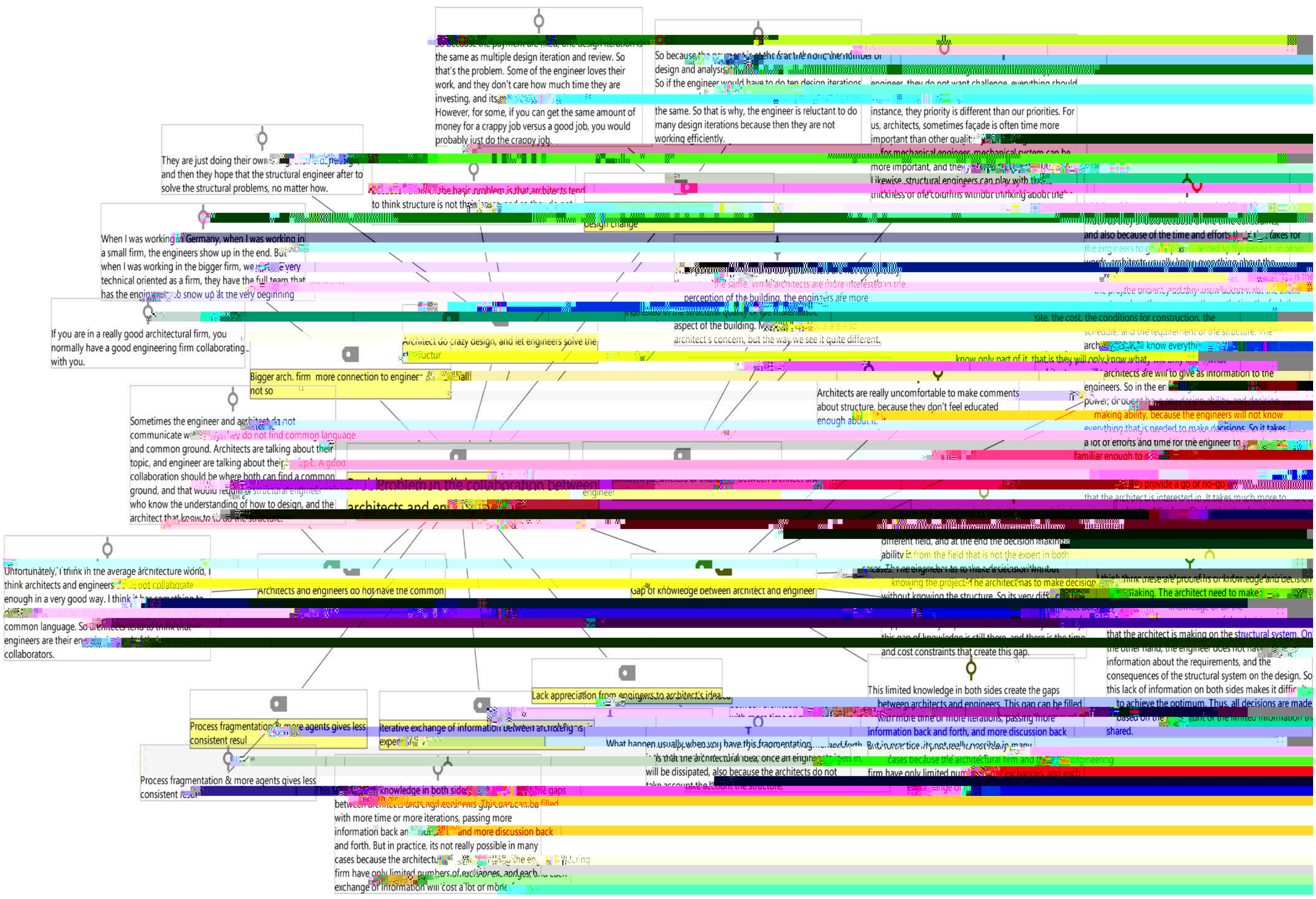
manages the interaction between Grasshopper and Abaqus to initially

questions were prompted based on it. e background module contextualized the scope of the research by informing the participants that the study was interested in the process of designing organic and free-from structures as opposed to more conventional structural systems. Buildings with organic and free-from structures are typically designed using a performance-based approach, which is well suited for optimization, rather than a prescriptive approach, which generally relies on prescriptive codes. e education module introduced the participants to the basic concept of structural optimization and how to model a structural optimization problem. Finally, the demonstration module introduced the participant to the developed optimization tool [20,21].

but, in practice, multitude exchanges of information can cost a lot of money and thus is not really possible.

**Figure 8:** Theoretical coding using MAXQDA.



structure in design process
As practitioners, we only deals with conventional structure
Only need the low tolerance optimum with less precision
Looking for the design improvement rather than the optimum
Prefer a single optimum for simplicity

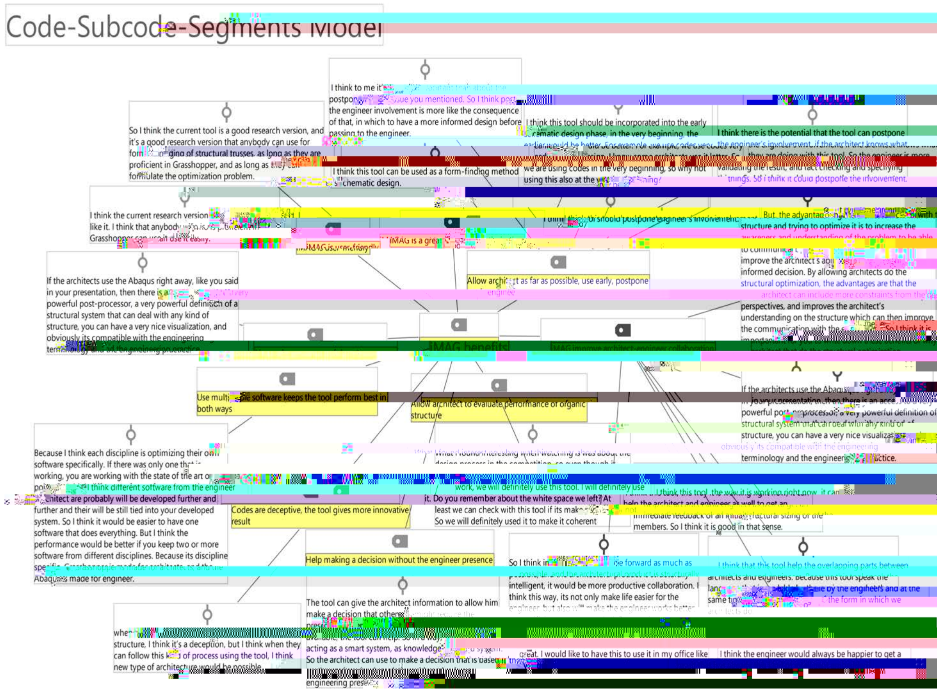


**Figure 9:** Code-subcode-segments model of the generated themes using MAXQDA.

far as possible to create a structurally intelligent design before the collaboration took place.

Participant G described that in Europe, architectural education is closer to engineering education with a degree that is equivalent to an engineering degree and architects are legally allowed to evaluate the structure. In this case, he mentioned that architectural firms are allowed to work all the way from the design to analysis without having to worry about the difficulties of the collaborative process. Participant G was educated in Europe and has eight years of design practice experience in Europe. Regarding the education issue, the education in Europe is different from the typical architectural education in the U.S., which puts less focus on the structural aspect. For instance, some participants mentioned that in the U.S., graduate students are required to do some type of structural evaluation only once in their studio carrier, i.e., in the comprehensive studio, which is generally during the last semester of their graduate studies.

Some participants mentioned that structural optimization tools such as the one developed in this study should be incorporated at the very beginning of the schematic design phase to have a more informed design before the collaboration takes place. Participants mentioned that the advantages of allowing architects to do the form-finding structural optimization are that the architect can include more constraints from the design perspectives, and improve the architect's understanding and awareness of the structure which can then ease the communication with the engineer once the collaboration begins. Another mentioned how the tool, if used properly, can potentially help architects make a decision without the engineer's presence. Despite the foreseen advantages and the fact that the tool can be used without requiring the users to have in-depth technical engineering knowledge, some participants emphasized the need of architects to be able to at least formulate meaningful design constraints, goals and variables along with the structural constraints before or during the parametric modeling phase. They mentioned that architects should typically be able to formulate related geometrical constraints. However, the understanding of structural constraints and how they are related to the geometrical configuration and sectional properties are often beyond architects' comprehension. As a result of this technicality that is involved during the architectural schematic design phase, some participants foresee that the engineers' involvement in the collaboration would be postponed if the tool was implemented. Participants expressed their concurrence with the notion that the proper implementation of the developed structural optimization in the schematic design phase can potentially build a common ground between architects and engineers once the collaboration takes place.

There was some interest of participants for using the tool. Some interviewed students were particularly interested in using the developed tool for their semesters' studios. Some faculty also mentioned that they would have used the tool if it had been available years ago when they were working in their architectural design practice.

Regarding the functionality of the tool, participants mentioned that combining architectural design with engineering analysis provides a powerful post-processor and more compatibility with engineering terminology. Regarding the results of the structural optimization process, in particular the type of results provided by the optimization, most participants preferred multiple optimal design options rather than a single optimum. Particularly, they mentioned that various feasible and improved design options are considered sufficient and that the variations can be used for further design tweaking. Participants also mentioned that they prefer a faster computational time with a low tolerance optimization process for the purpose of form-finding during the architectural schematic design phase rather than an optimum design that necessitates excessive computational power to be identified. This is due to the fact that it is impossible to include all the constraints from all aspects into a design problem and there is always room for changes when relating to the aesthetic criterion. Thus, having high precision results is not necessary during the schematic phase.

## Responding to the eoretical Narrative

A er the second cycles of the Grounded eory several research questions and corresponding hypotheses could be formulated from the theoretical narrative. Examples of hypotheses include:

1.

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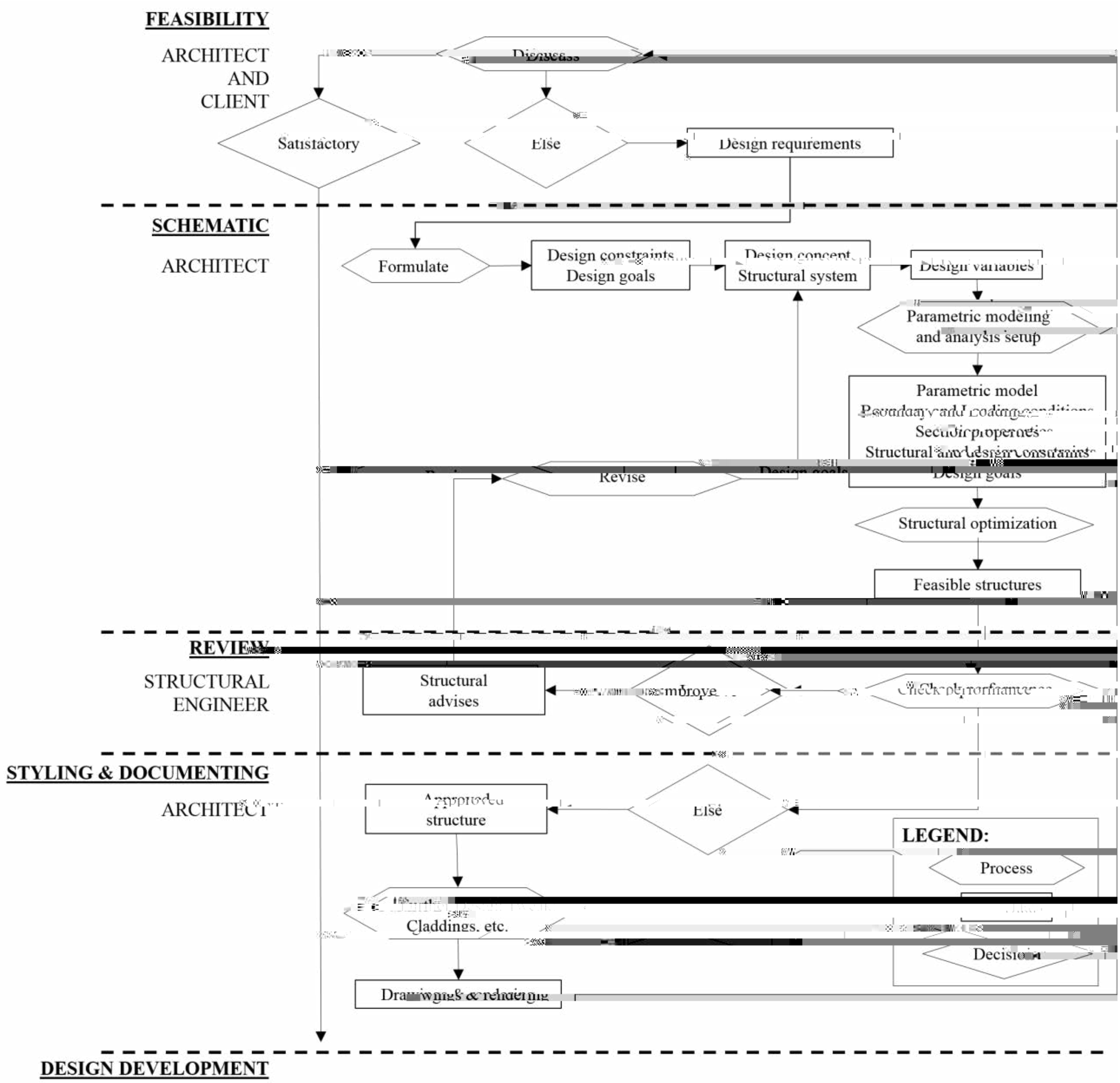


Figure 11:

by the architect. is information is used to generate the form via the structural optimization procedure. It must be noted that the form- nding structural optimization here does not only consider the structural aspect, but it may include variables and constraints that are relevant to the design such as manufacturability, sustainability, and so on. e right-hand side of the related geometrical constraints such as total area can be easily evaluated by the geometric modeling system such as Grasshopper. e incorporation of the sustainability aspect into the optimization model may require the inclusion of customized or commercial codes that are able to evaluate the necessary parameters (e.g., calculating daylight factor, thermal loads, etc.).

As shown in Figure 11, once the structural engineer is involved in the design process, the collaboration starts with the model that has already the performative aspect incorporated. e owchart re ects participants' opinion to push the architect's role as far as possible in the design process before the collaboration takes place. us, parts of the engineers' tasks in the traditional design work ow are shi ed into the architects' responsibilities by allowing the architect to incorporate the consideration of materiality, structural system, structural sizing and structural feasibility into the schematic design phase as factors that drive the form- nding process. When using the proposed design process as shown in Figure 11, some of the suggestions from the structural engineer to the architect may include modifying or

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