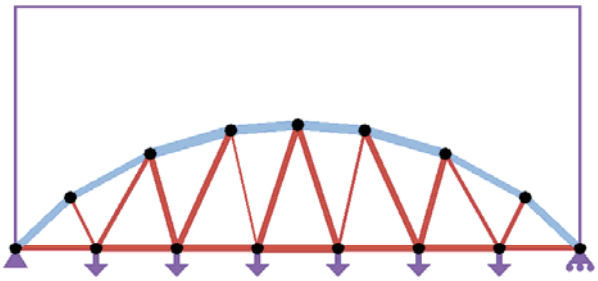
2D Trusses: a Case Study for Understanding the Engineering Design Process



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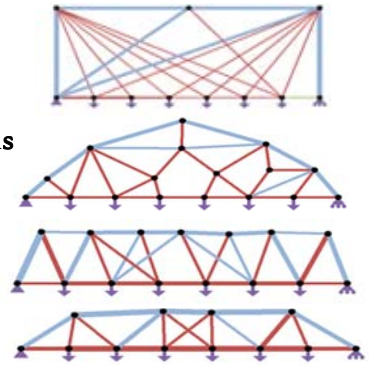
Introduction: Overview

- Performed research on a similar design problem to your class problem: Both problems require optimizing the geometry of a product to find the lowest weight solution satisfying constraints
- A Graphical User Interface recorded participants designing trusses
- Study supports notion that good design practices lead to better solutions

Why do Different Engineers Find Different Solutions to a Design Problem?

- Every engineer possesses a different set of skills and resources. For a given design problem every engineer approaches and solves it uniquely, which in turns produces variations in solutions



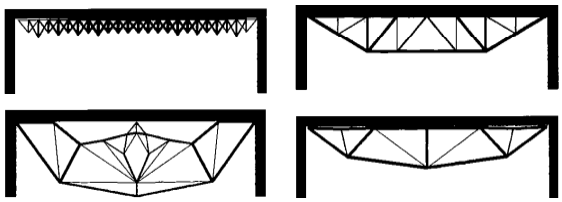
- There is often no "best" solution, but there does exist a set of "better" solutions

- Design is a process: do good strategies and practices of exploration, iteration, and optimization lead to better final products?

Background: Comparison of Trusses Designed by Experts and Simulated Annealing

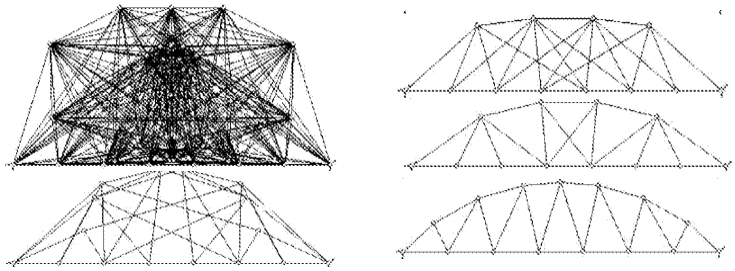
- Engineers and architects solved the same truss design problem while emphasizing different aspects of form, yet both produced functional designs (Shea and Cagan)

- Rules that captured some of the strategies of the human designers were programmed into a simulated annealing algorithm which then output similar designs (Shea and Cagan)



Evolutionary Algorithms

- Below are some steps in the process of an evolutionary algorithm solving the same truss bridge problem I give to human participants problem
- Note that it follows a different set of rules from how a human would solve the problem, it lacks intution and there are tradeoffs associated with both approaches

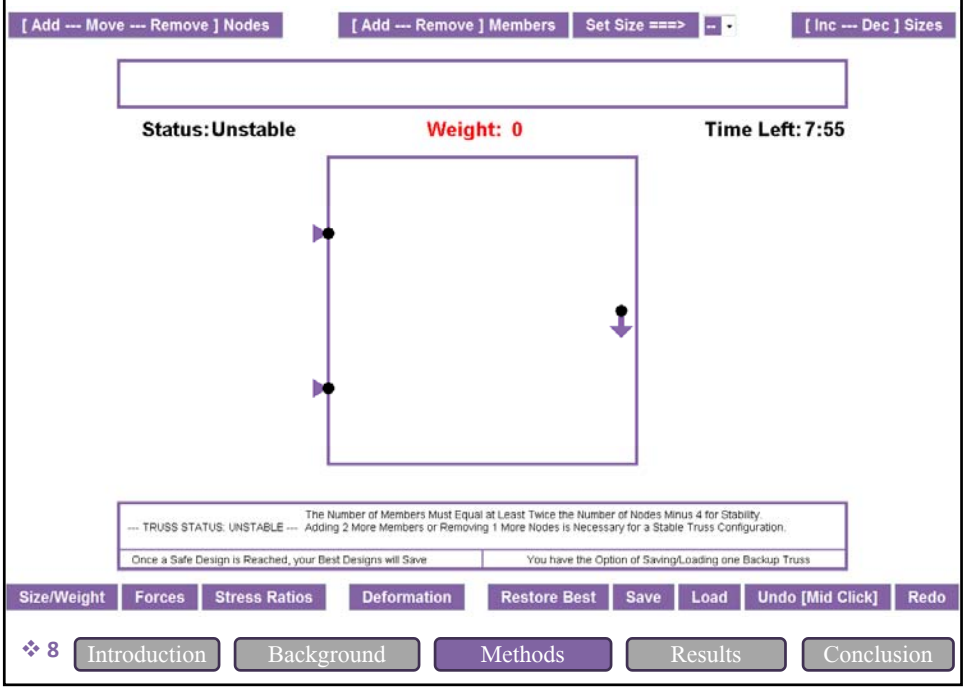


Methods: Hypothesis

- Problem solving consists of an understanding process and search process. Properly applying these processes becomes impeded as problem becomes more complex (Jonassen)
- Increasing the range and resolutions of available truss members will improve problem solving performance in simple search spaces (tower problem), but impede the design process as searches become more complex (bridge problem)

Graphical User Interface (GUI)

- Programmed in JAVA, Real-time FEA Calculations
- Given a network of nodes and members, solves for displacements, reactions, forces
- Stats are written to file every second, all design actions recorded for later viewing
- Tutorial, practice problem, and minimum weight objective



Methods:
Experimental Design Conditions

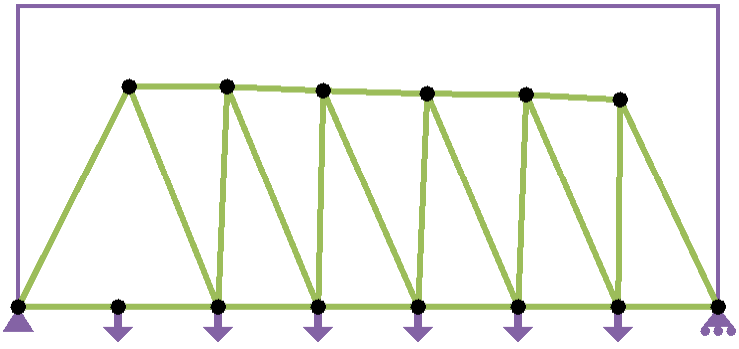
Provide participants a sequence of four different problems

Participants build the truss by configuring members geometrically

Divide participants into different design conditions with access to different combinations of truss members for construction

Rules of Truss Configuration

- Topology: Spatial distribution of nodes relative to each other
- Shape: How nodes and members are connected
- Size: Variance in cross-sectional area of members

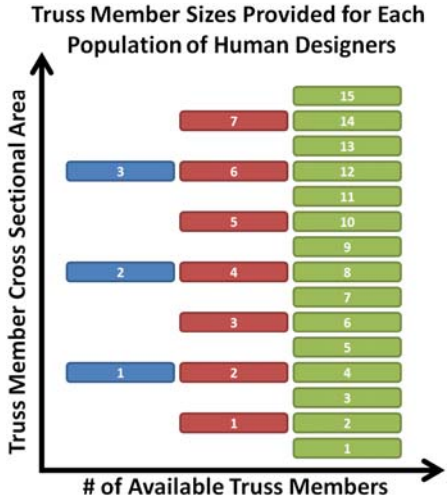


Varying Complexity of Design Problems

- The different problems simulate different top-down constraints imposed from the implementation level
- Problem choice contrasts a complex and simple search space
- Ten minutes allotted for Bridge, eight for tower

Varying Complexity of Available Truss Members

- Participants were divided into three different populations
- Each population had access to a different range and resolution of wide flange steel sections

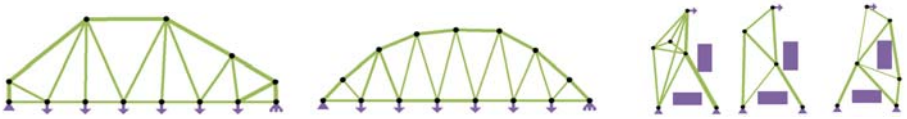


Experimental Hypothesis

- Populations with access to fewer members will perform better in larger searches spaces (bridge problem)
- Populations with access to more members will perform better in smaller search spaces (tower problem)

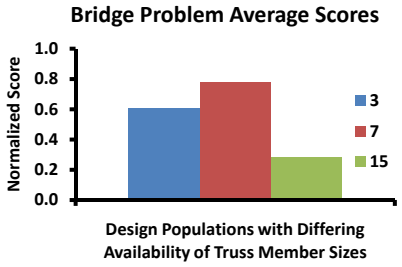
Results: Piloted Experiment

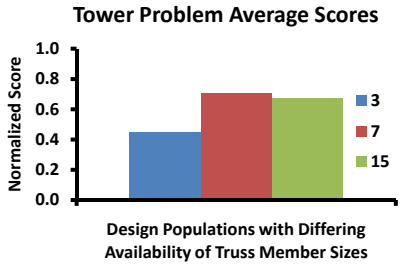
- Seventeen total participants, CMU graduate and undergraduates students all with ME backgrounds
- Large variance in design performance, both across problems and within populations of participants
- Partial designs were not included in statistical results



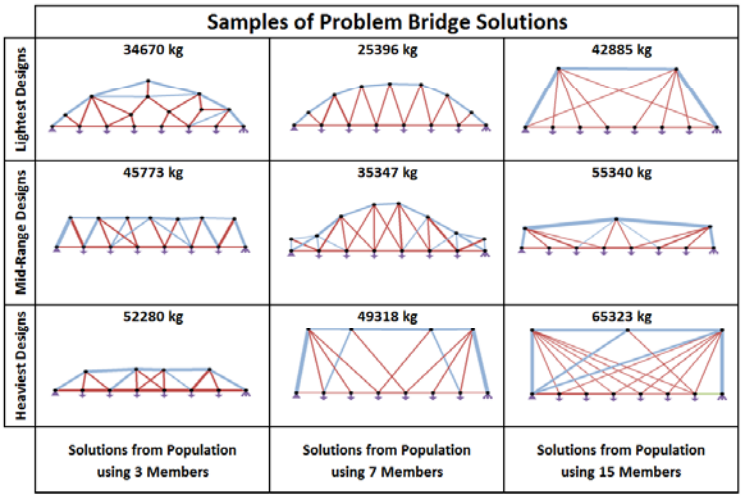
Comparison of Normalized Scores

- Seven member population scored best on both problems
- Fifteen member population scored worse on bridge problem relative to other groups, and better on the tower problem
- Trends in data support hypothesis that humans design "optimally" under certain conditions of complexity

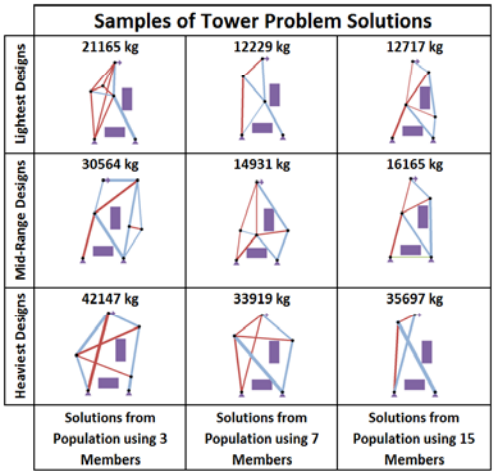




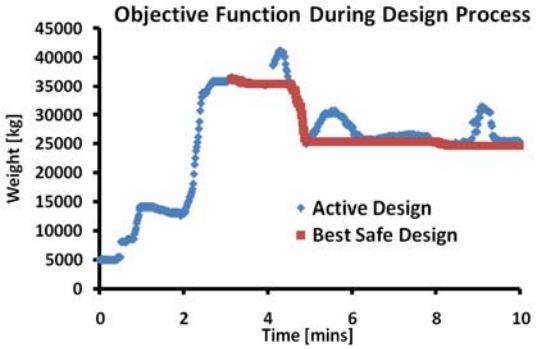
Bridge Designs



Tower Designs

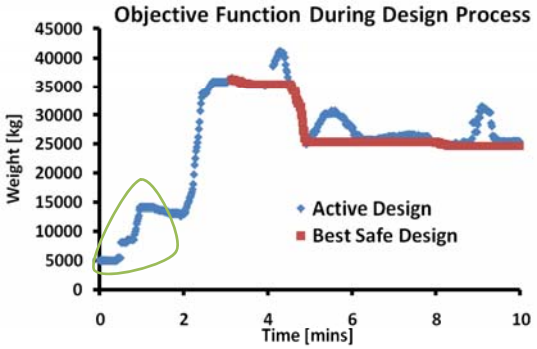


Tracking the Design Process

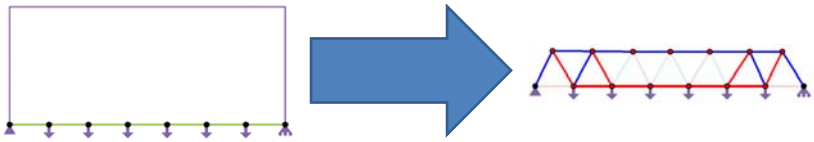


- Design iterations are tracked by following the objective function (weight of design)
- Graph represents the design process of the best bridge solution from entire study

Tracking the Design Process



- Initial Design
- Conceptual Design: Utilizing intuition or previous domain experience to propose an initial design



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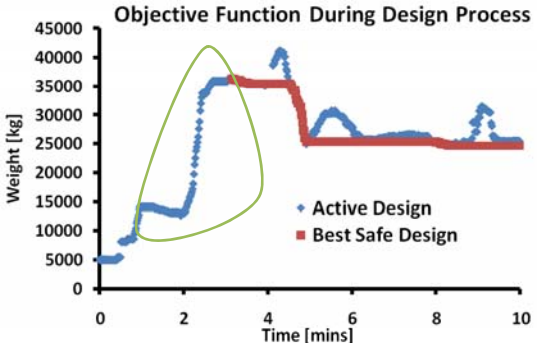
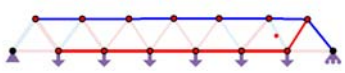


- Re-sizing members and moving nodes
- Preliminary Design: Tweaking the conceptual design in order to fulfill design constraints



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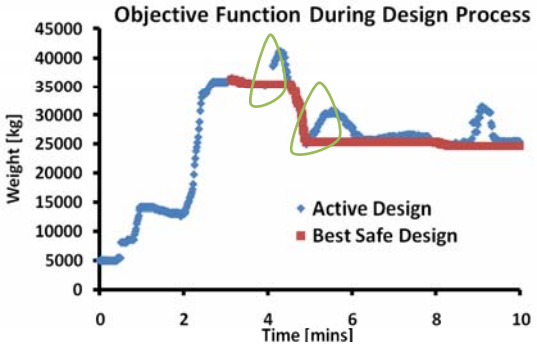
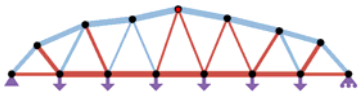
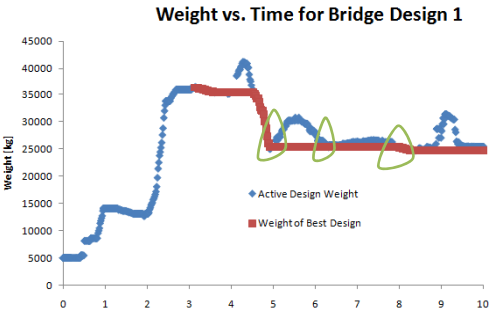


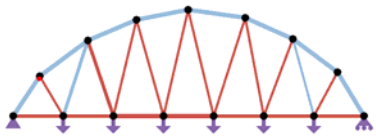
- Topology Exploration
- Moves away from objective function, which opens up new design possibilities for sizing optimization



Best Bridge Design Process



- Topology Optimization
- Detail Design:
  A Strategy to sequentially move each node to optimal location



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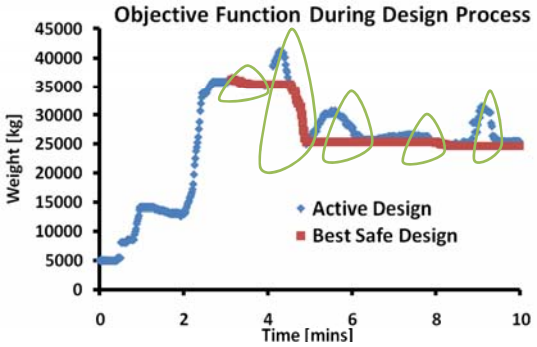
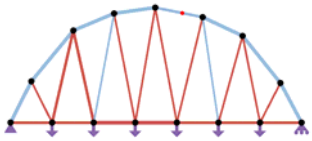
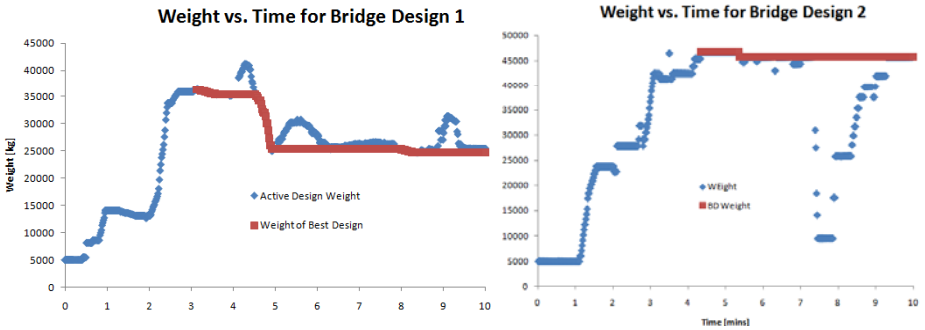
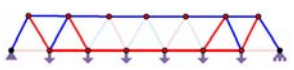


- Sizing Optimization
- Detail Design:
  A Strategy to sequentially set each member to optimal size

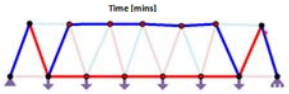


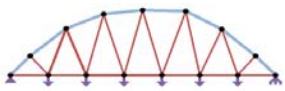
Contrasting two Design Processes



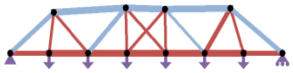


Similar Initial Designs



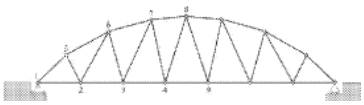


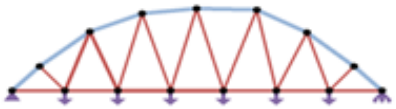
Different Final Designs



Humans compared with Evolutionary Algorithm

- One human designer produced, within ten minutes, a solution very close to that found by evolutionary algorithms which required 488 minutes of computational time
- Total human effort put forth on the study was 170 minutes
- Very different design processes and approaches, but both produced similar end results





Conclusions

- Experiment shows that human designers perform optimally below a certain threshold of complexity
- The most successful designers used iterations and shuttled between strategies of initiating a design, exploring the design and optimizing the design
- Those with general design experience often did better than those with no design experience, even though no one in the study had experience with designing trusses (Supports the idea that Intuition is **LEARNED** not innate)

Lessons relating to your Project

- Everyone in class has different resources of knowledge, time, and experience which leads them to different solutions. A good engineer produces His/Her best solution by utilizing all of their personally available resources
- Intuition is developed with time and hard work
- Try Different strategies! Design is a creative process, there is no single best method to design a product…also, if you're not having fun, you're not designing!
- It's counter-intuitive, but sometimes moving away from the solution brings you forward to an even better solution
- Iterate, iterate, iterate….
- Keep it Simple!

Acknowledgements

- Advisor: Dr. Jonathan Cagan
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  - Dr. Christian Schunn
  - Dr. Phillip LeDuc
- Integrated Design Innovation Group (my labmates)
- *Discussion of The Method* by Billy Vaughn Koen
  - Popular Science format detailing the engineering design process from an Engineering and Philosophy perspective
  - Get this book! Integrated Design Innovation Group (my labmates)
- And, Professor Collins, of course