Abstract

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1. Introduction and overview of the work

# Introduction

The structural design process is never a straightforward procedure. Rather, solutions are reached through an iterative, and often chaotic process. The process can be divided in to the four following steps [1]:

1. **Conceiving**: The most important design step where the overall design concept and significant details are developed.
2. **Modeling**: Idealization and simplification of the structural design concept, building of models for structural analysis and calculation of forces.
3. **Dimensioning**: Deciding sectional dimensions of structural members depending on the choice of materials.
4. **Detailing**: Final details of nodes and connections including the creation of construction documents.

In reality there is not necessarily a clear distinction between the different design steps, the process can repeatedly move forward and backwards until a solution is reached. In this thesis the word *conceptual design* is used, that refers to the first design step *conceiving* and the initial phase of the *modeling* step. In the initial design phase the design freedom and impact of decisions are very high and then declines as the design matures, controversially the design knowledge and availability of tools increases as the design matures [2,3], see Figure 1 and Figure 2. The lack of tools for the initial design phase combined with the high impact of decisions creates an opportunity to develop such tools – tools that can support the designer to make well informed decisions in the conceptual design phase.



Figure Structural design process [2]

## Problem statement

Many different geometric modeling tools are today available for architects. These geometric modeling tools have since the introduction in the 1980s grown increasingly sophisticated, and has together with the widespread perception of the benefits of technological innovation created a more intimate relationship between technology and design. This relationship has resulted in parametric design and scripting methods that can generate complex shapes and forms [4]. The distinct separation that architects use geometric modeling tools and engineers use analysis tools further reinforces the architects role as *form-giver* and the engineer as *form-verifier* [5]. To move away from this separation, when the term *designer* is used in this thesis it represents either an engineer or an architect.

The architect often conceives a design without involvement of the structural engineer. Hence, the importance of the conceptual design phase is often overlooked and structural aspects are often only considered in a late design stage [6]. A contributing factor to this is that very few computational tools are available for conceptual design.



Figure 2 Impact of decisions and availability of tools in the design process [3]

The challenge with developing such computational tools is the fuzzy nature of the problem, knowledge and constraints of the problem are imprecise and incomplete [3].

Conventional advanced structural analysis software requires precise knowledge of the problem and are insufficiently agile to follow a designer’s iterative workflow. Conventional structural analysis software is developed for use in the late design stage, when the major design decisions have been made, as a tool for the engineer to verify the form.

A subsequent problem with the current workflow, where the architect is the form-giver and the engineer is the form-verifier, is that the engineer is often provided a detailed geometric model – and it can be tempting for the engineer to directly do a full structural analysis on the detailed geometry which today’s structural analysis software can do. If instead the engineer starts with a simple mathematical model and then gradually increase the complexity - known as hierarchical modeling [7], see Figure 3 – the risk of fatal mistakes is decreased.

By starting with a simple mathematical model the engineer can focus on the overall structural behavior and get an understanding of how the stresses follow through the structure and also get an understanding of the magnitude of the stresses in the different structural members. This information can be valuable when the more advanced mathematical model is used to confirm the feasibility of the results. It has been shown that premature use of advanced structural analysis software negatively affects the conceptual understanding and the quality of the conceptual design [8].

“In practice a great many problems are solved by what is called judgment. The better a man understands how the stresses follow through a member or structure, the better his judgment will be.”   
– Wolfe [9]

In the present work two similar computational conceptual design tools have been developed that make use of simple mathematical models, that enables modeling earlier in the structural design process. The motivation for this is two-fold - it can give the designer valuable feedback on structural performance in the conceiving phase, when the impact of decision still is high; it can also give the engineer valuable feedback on structural behavior before a more advanced model is used.

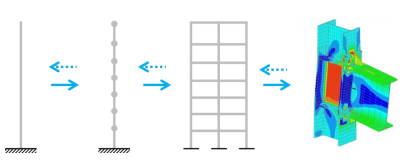


Figure Hierarchical modeling

The type of design tool that is used to generate and represent ideas also affects the quality and quantity of early prototypes. It was shown in [10] that physical prototyping generated a higher quantity of prototypes under a limited amount of time, the developed prototypes were also perceived as more novel compared to the prototypes that where developed using CAD or conventional sketches. The prototypes that were perceived as more novel also tended to fare poorly on all other measureable qualities [10]. As conceptual design is important and few conceptual design tools are available, an opportunity exists to improve the design process by developing such tools, see Figure 2.

In the present work the prototypes are structural models, and as computational models are used a measurable performance can be computed and presented to the user in real-time, which potentially can improve the quality of the structural models. The measureable performance and guidance in the present work put emphasis on the geometrical form of the structure as this has the greatest potential to improve the structural performance.

### Benefits of integrated conceptual structural design

## Human-computer interaction

With new technology such as novel input devices and increased computational power comes new possibilities. The present work make use of novel user input devices for structural modelling, and increased computational power for real-time feedback on structural performance.

### Direct manipulation

Direct manipulation is a human-computer interaction style with continuous representation of objects of interest with rapid, reversible and incremental feedback [11]. Users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to further explorations [12]. This is achieved through reducing the perceptual and cognitive resources required to understand and use the user interface [13].

### Technology

The introduction of different input devices such as the mouse and joystick significantly improved the human-computer interaction of user interfaces that adapted accordingly [13]. Later, when the touch screen was introduced, it had an advantage over all these devices with a very direct method of inputting information [13], it closed the gap between the human and computer, and the user could literally touch objects on the screen to manipulate them.

There is a wide repertoire of interaction techniques to create direct manipulation user interfaces for 3D applications using 2D input devices such as the mouse [14]. However, since this type of input devices has one degree of freedom less then the 3D user interface there will always exist a need of gestures or similar methods.

Computer games has seen an increase in the amount of novel input devices along with a new style of games to address some limitations of conventional systems [15], e.g. the Wii remote [16], Microsoft’s Kinect for Xbox [17] and PlayStation Move [18]. These novel input devices move away from the conventional human-computer interaction to invoke an intuitive interaction that supports the natural human way of working. Games have for long been perceived as fun and engaging, and it has been investigated in many different disciplines if gaming methods can improve the human-computer interaction to create more effective, immersive and engaging learning or training [15]. In computer aided design tools the user experience has been compromised by the engineering design system’s step-by-step evolution, which the present work moves away from to create an interactive gaming like experience by using a novel 3D input device.

This is beyond the scope of this thesis, but interest and development of virtual reality glasses, such as the Oculus Rift [19] and PlayStation’s Project Morpheus [20], has recently increased. This type of virtual reality glasses have primarily been developed for games but other fields has also shown interest, e.g. in [21] a virtual reality is used to help students understand complex structural behaviour.

## Methods

### Form Finding

Antoni Gaudi was the first to use the mechanical element in common architecture in the 1890s. He used physical models with ropes and weights to form his structural forms [23]. Since then many designers have experimented with physical methods to find efficient structural forms. Theoretical

The computational methods for form finding such as dynamic relaxation [24] and force density [25] has now been used for decades and can be useful for finding structural forms for large roof systems and grid shells. Heinz Isler has for over 40 years promoted the use of physical models to find three dimensional forms [26,27]. Under the same time period the German architect and researcher Otto Frei have performed similar work [28] as Heinz Isler.

#### Dynamic relaxation

Dynamic relaxation is a method to solve a set of non-linear equations. The method computes the movement of a structure over time to find equilibrium between the internal and external forces.

In each time step, , the internal forces for all elements are computed from the nodal displacements *u*. A residual, *R*, can be computed by using

By using Newton’s second law the acceleration (time derivative of the velocity) can be computed as follows (at the node *i*, in the x-direction,at the time *t*)

Where is a lumped, fictitious mass at node *i*. To enforce boundary conditions, the residual is set to zero for the corresponding degrees of freedom. With the time step known the velocity of node *i* in the x-direction can be computed using finite difference method

With the velocity known the updated geometry can now be updated by using

As the geometry is updated, an iteration is complete and the computations start over, by again, computing the residual. The geometry is modified each iteration until equilibrium between external and internal forces has been reached.

### Optimization methods

Many different optimization methods exist for structural optimization. For continuum optimization different types of topology optimizations exists, these methods compute the strain energy of each individual finite element and iteratively remove the elements with the lowest strain energy until user criterions are met . The critique for using this type of optimization for design is that the result is often predictable and rarely

### Eigenvalue analysis

Eigenvalue analysis can be used to find the dynamic or static modal shapes for a structural model. From the stiffness matrix **K** of a structure, a set of scalar stiffness values can be determined [29]. Assume that a set of displacements **a** exists, that are proportional to a corresponding set of forces **f**, i.e.

This can be combined with a linear elastic finite element formulation, i.e.

|  |  |
| --- | --- |
| Which can be rewritten as |  |

This is a standard eigenproblem. The eigenvalues has the unit force/length, also called canonical stiffness values [30]. Every eigenvalue has a corresponding eigenvector , which describes a modal shape.Eigenvalues equal to zero means zero energy is required to form the corresponding modal shape, i.e. a rigid body motion. The eigenvectors are only defined within a scalar multiple. The eigenvector is normalized and multiplied with a positive and negative scalar, the result is two different shapes. An animation of the rigid body motion can be achieved by interpolating between the two different shapes.

### Graphic statics

## Analysis-based tools for engineers

The development of finite element analysis (FEA) has resulted in many different, but very similar, software analysis tools. However, these software tools are developed for the engineer to verify or dimension a form. These tools are often to advanced and not agile enough to be used for conceptual design, its use often requires a high level of skill both in connection with the software and in engineering terms. The analysis procedure for this type of software is often a step-by-step workflow, where all the steps need to be completed in order before the analysis is carried out, see Figure 4.



Figure Conventional simulation cycle

However, the commercial finite element (FE) software SAP2000 [31]made some improvements in this regard when they 2012 launched a *model alive* feature, this feature enables real-time feedback with deformations and forces for truss-structures [32].

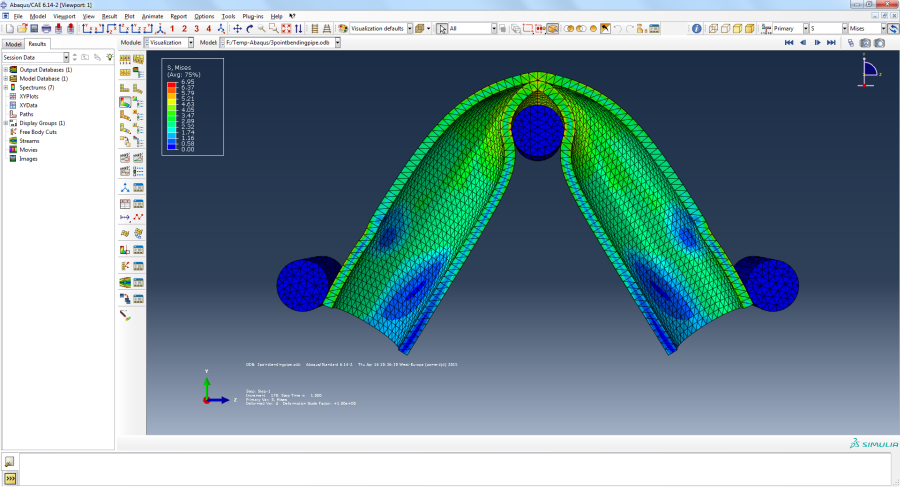


Figure User interface of conventional analysis software (ABAQUS)

## Geometry-based tools for architects

### History

The first computer-aided design (CAD) tool was developed by Ivan Sutherland at MIT in 1963, named Sketchpad [33]. The revolutionary feature of Sketchpad was real-time representation of the geometry on the display, which could be modified with the use of a new input device, a light pen. The light pen enabled a complete interaction loop between the computer and the designer. The software had support for complex relationships between graphical elements, for example, a line could be defined by relationship to other graphical objects, perpendicular to, parallel to, same length etc. Sutherland had an idea that the designer first could create a rough sketch of the design and then, as the design matured, apply constraints to the graphical objects to get a more detailed and precise design. It took 20 more years until this technology was affordable and accessible to a wider audience [33].



Figure 6 Sketchpad - the first CAD tool

Succeeding Sutherland’s Sketchpad was an era of 2D drafting, that continued the trend of 2D representation of designs. The 2D drafting software unfortunately failed to capture Sutherland’s original intensions of using the computer as a creative design tool, by not including the constraint model.

### Present day

As mentioned earlier, many different modeling tools are today available for designers. There has been an emergence of parametric modeler tools for designers. These parametric modelers have successfully captured some of Sutherland’s ideas of constraint models. These parametric modelers have support for scripting methods that can generate complex shapes and forms [4].

The software Rhinoceros 3D [34], which is a NURBS modeler, can be combined with the plug-in Grasshopper [35], that enables a visual programming environment, see Figure 7. The software developer company Autodesk has also released a parametric modeling tool named Dynamo [36] that has similar features.

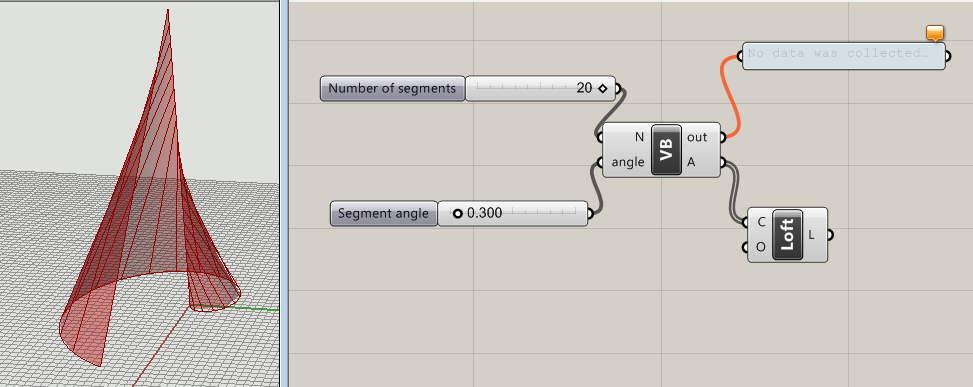


Figure The parametric modeling tool Grasshopper

In Grasshopper the designer can connect a slider to a parameter - for example the width, curvature, number of bricks and so on – then the geometry updates in real-time as sliders are manipulated. This enables complex shapes and forms to be generated and manipulated, allowing the designer to explore the parametric design space.

Many plug-ins also exists for Grasshopper that can be combined with each other, one example is Karamba [37], which enables structural performance feedback within the design environment.

## Existing conceptual design tools

“Geometry and algorithms can exist in the abstract, but to be of any practical significance, to become a design tool which can be used by designers, then these have to be encapsulated in an executable form, as working software…” - Robert Aish [38]

Existing conceptual design tools can be divided into two categories depending on their key features, feedback or guidance [2]. Tools with feedback key features rapidly respond, preferably in real time, to user input. Tools with guidance key features instead of giving feedback on the existing form suggest new forms based on structural criteria, this can be accomplished with different optimization techniques.

### Feedback feature tools

Multiple software tools for conceptual structural design that deploy truss models have previously been developed. The first two such tools was developed in parallel and released in 2006, named PointSketch [30] (see Figure 8) and Arcade [39]. In the two different software tools, the user can create a computational model using mouse and keyboard input. Forces can then be applied to the model and the result from the computations are visualized. The two software tools were both developed in academia but industry has shown interest in the concept.

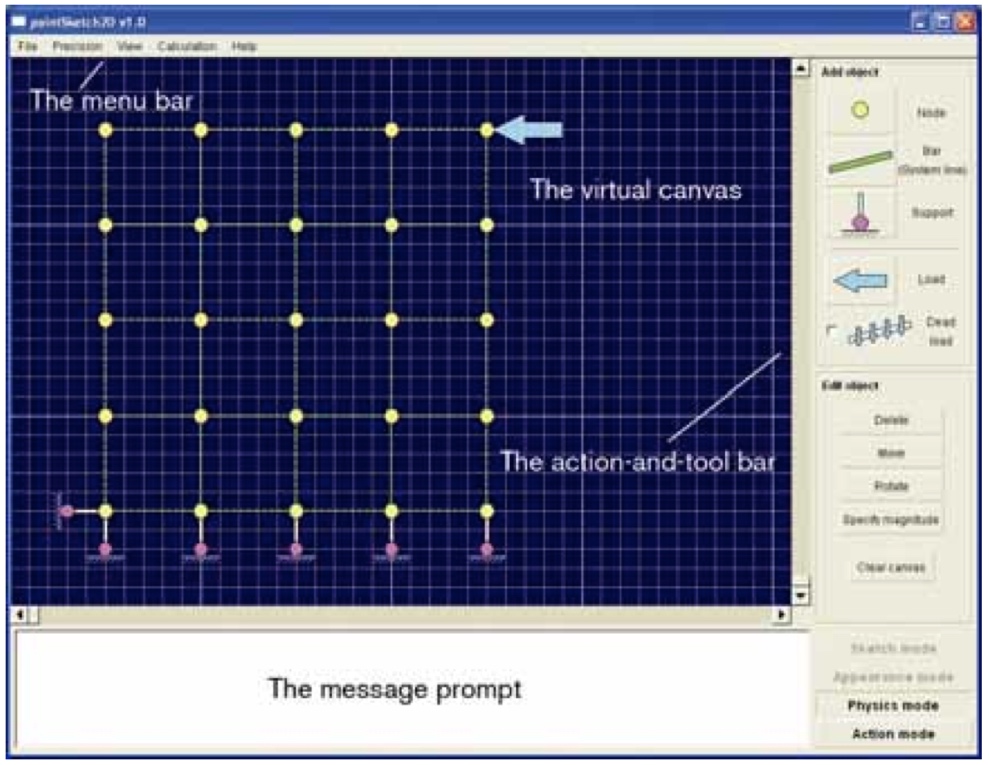


Figure The software tool PointSketch

Autodesk launched a new application in 2011 named ForceEffect [40], which is available both as an tablet application and as a web application. The application is developed for designers to analyze and visualize two-dimensional truss structures. The tablet application utilizes a direct manipulation user interface style where the user can make changes to the model by directly touching the objects.

Recently an interactive physics engine was developed to create a user experience inspired by games for design and education [41]. The developed physics engine has been used to create an interactive game called Catastrophe, which aims to teach users which elements are critical to system stability through play.

In graphic statics, robot risa kangaroo

### Guidance feature tools

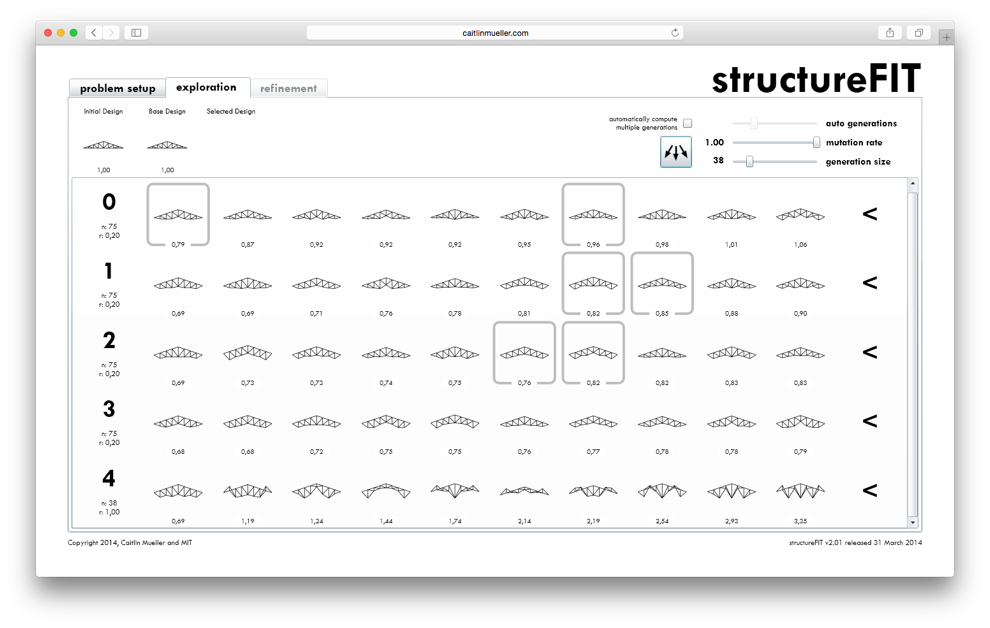


Figure Screenshot of StructureFIT

A conceptual design tool that can generate structures through interactive optimization, using genetic algorithm, is called StructureFIT [42,43], see Figure 9. The software tool also has a direct manipulation mode where the user can further explore a generated

structure by moving nodes and in real-time see how a relative performance index is updated. Another version of this tool has been developed for Grasshopper [44], named Stormcloud [45], which enables for interactive optimization using genetic algorithm in Grasshopper.

Two other applications that are developed for design exploration using topology optimization are Forcepad (see Figure 10) [46] and TopOpt [47], in the two applications a 2D geometry is modelled on which a topology optimization is performed and the resulting optimized shape is visualized.

Another conceptual design tool [48], makes use of graphic static to provide feedback in force diagrams

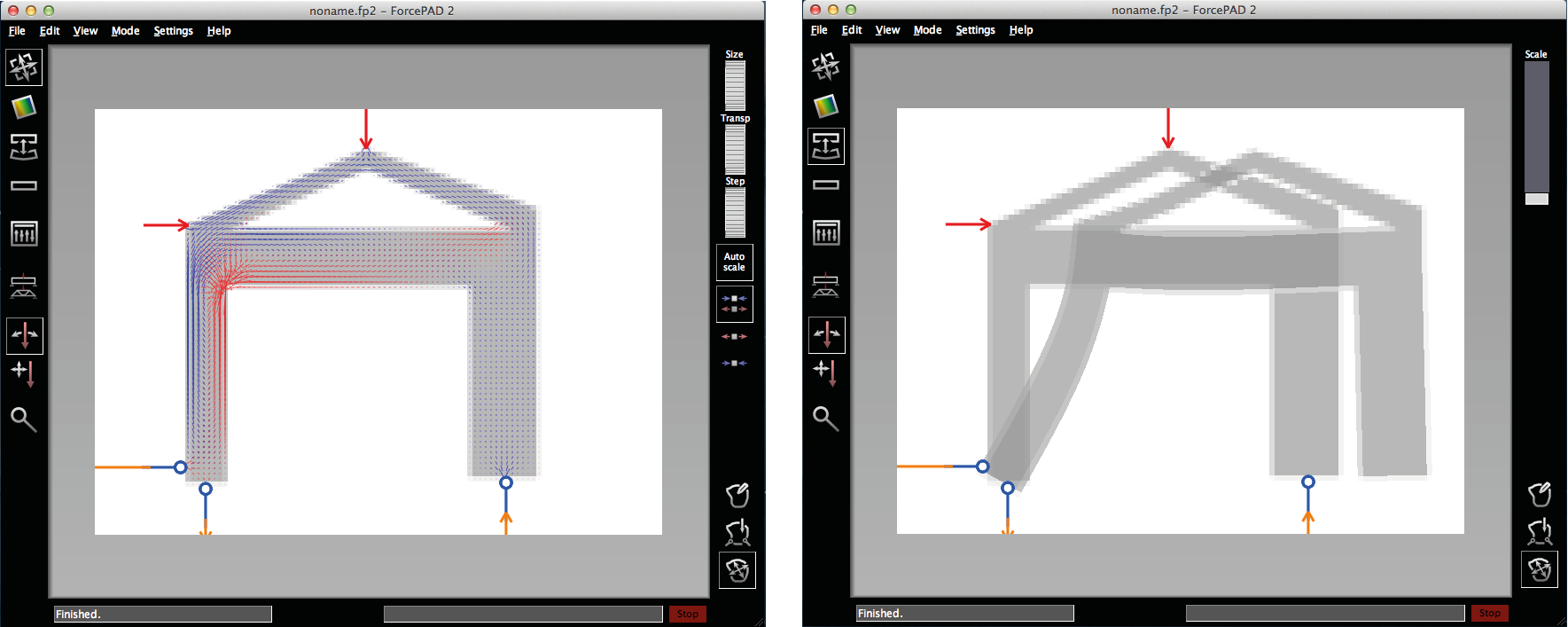


Figure Software tool ForcePad

# Summary of appended papers

## Paper A

*A tablet computer application for conceptual design*

D. Åkesson, Lund University

J. Lindemann, Lund University

Published in Engineering and Computational Mechanics, 2015

Summary

A tablet computer application for conceptual design was developed, named *Sketch a Frame*. The application uses a direct manipulation cycle where the result is computed and updated in real-time, which can be described as a feedback application. The result is automatically presented when the structural model is stable – moving away from the conventional structural analysis software step-by-step workflow. If the model is not stable and a force is applied, the first modal shape is visualized by use of animation.

The different result that are presented in the application are normal force, moment envelope, stress and normalized redundancy. No numbers are presented for the user from the result, to encourage the user to focus on the general structural behavior and not the exact numerical results.

The application has a very direct manipulation not before achieved for this type of application.

Genetic algo…!?

## Paper B

*Using 3D direct manipulation for real-time structural design exploration*

D. Åkesson, Lund University

C. Mueller, Massachusetts Institute of Technology

Submitted for publication

Summary

A proof of concept conceptual design application with an unprecedented very direct manipulation user interface for 3D. The existing application ObjectiveFrame is combined with the 3D input device the Leap Motion controller, allowing the user to interact with a structural model by using hand gestures.

Three different cases were implemented:

* *Structural* *feedback* – The user can apply, and manipulate, a force to a structure by interacting with the hands. Creating a metaphor that the user can get a feeling for how the structure feels.
* *Performance feedback* – The user can move nodes by interacting with the hands. A performance index is presented to the user giving feedback for how geometric manipulations changes the structural performance.
* *Dynamic relaxation* – The dynamic relaxation method is used together with gravity load to create an interactive case where the structure constantly converges to static equilibrium using an animation.

## 

# Discussion



Figure : Previous and work summarized in present work in bold

A summary of the evaluated conceptual design tools can be seen in Figure 11, the tools are grouped according to number of dimensions and how direct the manipulation is experienced. The two developed applications have a higher degree of direct manipulation for 2D and for 3D then any other existing software for conceptual design. This is achieved by using novel technology, the multi-touch user interface and the Leap Motion Controller.

By improving the human-computer interaction, the ability for the user to explore the design space is also improved, which results in a more intuitive environment where the user is encouraged to explore different design options.

## Summary of intellectual contributions

* Thesis includes critical review of existing tools and techniques for design manipulation in conceptual computer-aided design.
* Paper A proposes a new direct manipulation cycle that automatically computes and presents the result when a structure is stable.
* Paper A introduces new multi-touch interaction models for conceptual structural design on tablets.
* Paper A
* Paper B is the first paper to propose very direct manipulation as human-computer interaction mode for 3D structures, thanks to new 3D input device such as Leap Motion controller
* Paper B, introduces implemented design tool that allows users to interact with 3D structures through very direct manipulation.
* Paper B demonstrates potential applications of 3D input devices through three case studies.

## Future work

## Concluding remarks

* Paper responds to need for new, more intuitive and natural interaction modes in computational design and analysis
* Very direct manipulation improves significantly beyond existing direct manipulation paradigms prevalent in computer-aided design.
* New technologies like the Leap Motion controller and the multi-touch interface open up unprecedented possibilities for engaging users in the exploration and design of 3D structures, leading to improved understanding of design options and performance in the built environment.

# Conclusion

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1. Appended Publications

## Appended paper I: A tablet computer application for conceptual design

## Appended paper II: Using 3D direct manipulation for real-time structural design exploration