DIGITAL TOOLS
FOR DESIGN

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Master Thesis in Architecture
and Building Technology
This thesis is the result of a dual Masters graduation project at the Faculty of Architecture at the Delft University of Technology. I participated in the multidisciplinary Exporelab studio which allowed me to combine the Masters Architecture and Building Technology in one project done over the course of 20 months. This project is a combination of an architectural design and a research using the design as an important source. The design deals with the notion of digital design as the main driver for the design of the “SCHOOL FOR DIGITAL DESIGN” and create an inspiring place for staff, researchers and, most important, students. The research focusses on the application and development of Digital Tools to support the designer in his process of designing.

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This thesis is about the use of design space exploration and the application of digital tools to make this possible. Built upon a literature study combined with the knowledge gained from the architectural design project done by the author. The aim of this thesis is to look into the relation between the design and digital tools to find out what the nature of this relationship is and, if needed, how it should be, in order to supply the necessary information needed for future development of tools. The author will answer this question according to the four experiments done within the design project. These experiments deal with the themes: Building Programme, Space, Structure and Facade.
Design space exploration in architectural design

Let us start by defining what Design Space Exploration is and what its role is in the architectural practice. The design space is defined as the space containing all possible alternatives for a certain design task. The act of exploring the design space deals with the designer moving through the design space. The goal of design space exploration methods is to support the designer in the process of exploring by defining the alternatives and moving through the design space. Although the term Design Space Exploration sounds very contemporary the idea is actually quite old. It is the development of digital technologies that renewed the interest and discussions in design space exploration as a design method.

The role that computers have in the architectural design process has grown from the first introduction of digital drawing systems in 1960\(^1\) to the current integration of digital design systems. We can recognize that architecture, and design in the broadest sense, is dependent on geometry. During the last few years we can identify a change in the way architects design; architects are starting to shift away from primarily designing the specific shape of a building to setting up the geometric relationships and principles described through parametric relations (Kolarevic 2003). These relations play an important role in exploring the so called design space. In this design space the various design alternatives for a particular design task are

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1. In 1960 Sutherland introduced the SketchPad system. This was the first Computer Aided drawing system that used direct communication through the use of a special pen, instead of written code.
collected. Developments in digital tools (computer programs) during the last 10 years made it possible for designers to capture the so important relations and use that to explore the design space. From an architectural point of view the interest in being able to explore design spaces comes from the idea to look into possible design alternatives. In a traditional process the designer usually makes a small number of alternatives in order to find one for the final design. This can be one of the alternatives, a combination of the alternatives or something completely different. The designers’ main goal for creating these alternatives is to explore the possibilities the design has. The number of possible design alternatives can vary from just a few to a theoretical infinite number. In the current architectural practice designers consider in most cases only a small part of the total number of possible alternatives. This is mainly caused by the limits of the designer; his brain can cope with only a limited number of alternatives and the limit in available time and money.

“Today functional problems are becoming less simple all the time. But designers rarely confess their inability to solve them. Instead when a designer does not understand a problem clearly enough to find the order it really calls for, he falls back on some arbitrary chosen formal order. The problem, because of its complexity, remains unsolved (Alexander 1968).”

The area Alexander describes is the one where the computational techniques can have a great advantage and be of assistance in the design practice. Design space exploration is a long standing focus in computational design research. The research done on this subject
primarily focusses on the representation of the design space and how to capture design alternatives. The three main research topics concerning the former are:

- Designer action which aims at reproducing and extending the behavior of designers

- The development of tools to amplify designers actions in design

- The development of ways of representation and development of structures to support exploration, including representing the design space itself (Stouffs 2006).

This thesis primarily focusses on the second topic where the new developed tools are additions to the existing set of tools known to the designer.

**Digital Tools**

The support of the designer in his act of exploring the design space is done by the means of tools. This thesis primarily focusses on the use of digital tools. With the introduction of digital techniques in the architectural design process an additional set of tools were developed and more important are still being developed. Among the rather wide variety of tools are the ones concerned with the act of design space exploration. The application of these tools is primarily focused on the later stages of the design process where most of the actual design is already known and is implemented in a largely “traditional” way of designing.
In this regard, the mostly uneasy relationship between novel design principles, methods and tools, on one hand and the ancient discipline of architecture, on the other, can be explained in two different ways. First the use of the new tool is misdirected or at least fits poorly in the current design processes. Second the new technology is viewed through the lens of what is common now. New techniques are applied to traditional processes, counting on the fact that these techniques follow the same rules. The inadaptability of these processes results in missing the full potential the tool can have to the task applied on (Kolarevic 2003; Kalay 2006; Rahim 2006).

When we look at the application of digital tools in the design process we can see that it mainly focusses on the design and detail phase of the design project (fig. 1). The most ready take up of computational tools has been in the detailing and construction document phase. The author claims that it is in the first stages of the design project where digital tools can be used to their full potential. Furthermore it should be acknowledged that the information stored in the later stages of production and assembly can be used in the earlier stages of design and detailing.
Research Goal

The research carried out in the field of design space exploration, and the closely linked development of new tools, mainly focusses on the technical aspect of the tools and the representation of the design space. The aim of this thesis is to look into the relation between the designer and digital tool. The results of this thesis will not directly apply to the practice of architecture as it is known but rather serve as a new starting point for future research and development. The first step into a closer relation with the architectural practice is the application within the design project performed in parallel to this thesis. The actual issue of implementing the knowledge from this thesis into practice is beyond the scope of this thesis.

Relations

One of the issues when using digital tools is the interaction between the designer and the tool. This thesis discusses this relationship and, if needed supplies the necessary steps for future development of tools. This is done from two different points of view. The first is the use of digital tools as a novel approach to a number of design tasks situated in...
the design of a building. The second is that of the development of new tools and techniques and the conditions in which they should function within the design project.

It is this area of the combination of tools, process and designer (fig. 2) that leads to the following research question: *What is the emerging relationship between the designer and the tools while exploring the design space.* The main focus is the application and use of digital tools by the designer. Information on this relation is rare and, when available, hard to validate. For the purpose of this thesis it is necessary to gain information during the process of designing; at the moment the designer is interacting with his tools.

**Research Methods**

By performing participatory research the researcher tries to study the behavior of the designer whilst using the tool. The situation of the researcher and the designer being “researched” fits the participatory design method (Wadsworth 1998). In participatory research the researcher fulfills the role of the observer studying the behavior of the designer as he works. As this research evolves around the interaction between designer and tools it is expected that this interaction primarily takes place in the head of the designer. There are various methods to externalize these interactions, all of which invoke the designer to perform a second task next to the design task itself: the externalizing of thoughts and emotions. A study done during the second Delft Workshop, ‘Research in design thinking II – Analyzing Design Activity’, held in 1994, showed that while using various recording methods (video, sketches, thinking out loud) in some cases changed the way designers worked, the fact that he was more aware of his own process even led to remarks like “I assume the camera is watching me…”
Once the gathering of data relies on the designer externalizing his thoughts after the actual event, it is hard to validate the data. This finding resulted in the decision to make the designer and the researcher the same person in this current study. By doing so the researcher has “direct” access to the designer’s thoughts and therefore can fulfill his role as observer. It is up to the researcher to make sure that he keeps his distance to the design tasks and not get involved in the design process. In this way a clear distinction between the two roles should be maintained.

The results from the design project are evaluated using the results from the theoretical study. During the design project a number of experiments are set-up, each discussing the application of design space exploration techniques as applied in the design project. The result is a description of the process carried out in the design project and an evaluation of this process.

**Introduction to the chapters**

In chapter two, an introduction to the concept of design space exploration is made. Using a number of precedents from different fields of design the work already done is described. Chapter three discusses the three main actors in the design process; the designer, the tools and the process. Chapter four introduces the design project and sets out the path to apply and test the knowledge obtained in the first part. Chapters five till eight cover the experiments and the related results which is combined in a evaluation and final word in chapter nine.


Exploring the design space

Although this thesis primarily focuses on the use of digital tools, it is worth looking at its analogue development. The term Design Space Exploration sounds very contemporary, however, the idea is actually quite old. Design Space Exploration is basically the exploration of...
alternatives in a design process and is exactly what architects and other designers have been doing for over centuries. If we look at some of their work we can see that exploring alternatives can be considered part of their way of working. A good example is the works of Durand where he, in his “Précis of the lectures on Architecture” (Bloomfield 2000), has studied a large number of alternatives in the design of buildings (fig. 1).

A second example shows a more recent approach to exploring design alternatives: rationalization. The explorations are done by D’arcy Thompson who in his book “On growth and Form” (Thompson 1961) laid the groundwork for relating forms found in nature to the diagrams of forces that shape them. His intentions were to interpret the shapes he found around him rather than exploring alternatives. Nevertheless the process of rationalizing shapes serves an usable approach to exploring alternatives (Kilian 2006). He rationalized key shapes found in
nature by using formal mapping techniques (fig. 2). This rationalization allowed him to modify these grids to transform the initial shape into other comparable shapes found in nature. By doing so he was able to rationalize a large portion of shapes found in nature (Thompson 1961). Nature can be described as one big design explorer producing endless variations and forms from the same set of building blocks and using the same generative principles. (Weinstock 2007).

Models

For over centuries the architectural practice uses a number of tools to explore design alternatives. Models can be interpreted in different ways, almost all tools model in some way. One of the most commonly used is the physical model. A physical model can be custom made to suit a certain goal; construction, spatial qualities, studies on light etc. Physical models are intensively used by designers because of their ease of use and their tactile feedback. Building and working with a physical model will give you immediate feedback of the design and is in most cases easy to adjust. Physical models can be both two dimensional (sketches) and three dimensional (scale-models). Sketching and building scale models has been, and still is, a large part of the designers’ way of working. Rob Krier did a number of studies on simple rectangular squares using simple sketches (fig. 3) (Krier 1979). The simplicity of the drawings show that a useful exploration is not totally dependent on the tool. It is the synergy between the tool and the designer that leads to certain results. The application of the tools varies between designers, they adopt the tools in their way of working.
Earlier work on design exploration using physical modeling can be found in the work of Antonio Gaudi and Frei Otto who created their formal architecture based on forces. Their approach is characterized by the use of physical models as a tool in exploring design alternatives and can be considered a vital part of their way of working.

**Gaudi’s hanging models**

The physical hanging models (used to construct the Colònia Güell) of Antonio Gaudi particularly fit the notion of design by modeling as they address both the structural and formal considerations of the design while presenting the designer with a visual and structural feedback during the entire process. In addition to this constant reflection of the designer’s intention, the hanging models allow more than one person to work on it, making the hanging model an excellent tool for collaborative
design and discussions. Most of these models were designed upside down by hanging various weights on interconnected strings, using gravity to calculate catenaries for a natural curved arch (Kilian 2006). A good example of this process can be found in the creation of Colònia Güell. Gaudí spent ten years working on studies for the design, and developing a new method of structural calculation based on a stereo static model built with cords and small sacks of pellets (fig. 4). The hanging model was created with a certain final image in mind and served primarily as a tool to explore various structural configurations that fitted the design idea. (Gaudiclub)

Frei Otto’s lightweight construction

During Frei Otto’s presence at the Institute of Lightweight Structures at the University of Stuttgart a number of physical form finding techniques based on soap bubbles, hanging chain models and foam principles
were developed. Most of these techniques were developed in the pre-computational era, and had one common characteristic; they were all based on the physical behavior of materials.

As a scientist Frei Otto spent most of his life searching for the form-finding processes of nature, which he as an architect applied on his designs. Frei Otto’s work focuses on the physical repeatable form finding rather than the biological autonomous formation process. These physical processes can be triggered in order to create their own shapes, and in Frei Otto’s work, technical constructions (Otto 2005).

Frei Otto used techniques closely related to the work of Gaudi and his hanging models. He started doing experiments following the principles of the hanging chain models, to analyze and determine the shape of domed surface structures, by testing a variety of different materials and methods, such as models made of cloth dipped in plaster, fine chain nets and textile fabrics. Models of medical plaster bandages proved to be particularly easy to construct. A second method he frequently used is the application of soap bubbles as the definition of form. When creating a soap bubble between edges it will automatically form an optimal surface (fig. 5). All of these models were interpreted using
photography, and by accurately measuring the existing physical model (Otto 2005). It was especially this last step that proved to be time-consuming. Especially the careful measurement of the physical model took a lot of time; a difference of just 1 mm in the model would be ten or even a hundred times bigger in the actual building. In 1975 while designing the Manheim Gridshell, the firm had difficulties proving the structural stability of the problem. At that moment Otto turned to Ove Arup, whose large London engineering firm dealt with structural problems and used large mainframe computers to check the balance of the forces in the structure numerically and provides information of the nodes. From this moment on the firm of Otto started using these digital tools more and more, making them capable of exploring a larger number of alternatives in a shorter period of time.

**Digital explorations**

As already discussed, Design Space Exploration is not necessarily linked to digital techniques, it is actually something designers are used to doing, although at a limited scale. An example of this is the models (fig. 6) created by the office of Frank O Gehry while designing the Walt Disney Concert Hall (1988). In this series of models Gehry tries to find the right shape for the main concert hall. The creation of these models is labor intensive but essential for the development of the project. The aim of this thesis is to look into new methods for exploring the possible array of alternatives and how they can support the designer in his design process, so that novel designs can emerge by discovery or by modifying existing approaches. This strategy is typically called *breadth first, depth next* (Akin 2001).
Physical study models created by Gehry during the design of the Walt Disney Concert Hall (Kolarevic 2003 p. 104)
Design Space

In this thesis the term “design space” is mentioned repeatedly but what is this design space? If we refer to the quote already posed in the introduction we can see a first indication of how this design space is identified.

“Design space exploration is the idea that computers can usefully depict design as the act of exploring alternatives. This involves representing many designs, arraying these represented designs in a network structure termed the design space, and exploring this space by traversing paths in the network to visit both previously represented designs and to find sites for new insertions in the network.” (Woodbury and Burrow 2006)

This rather technical description of design space basically defines it as the collection of all possible alternatives and the paths to come to them that are embedded in a design problem. In terms of Frei Otto designing a membrane structure, the design space would contain all possible alternative structures and the way to get to that alternative from the starting point.

The major step in starting an act in design space exploration is to define the design problem. By mapping out the design problem, the total number of design alternatives can differ between design tasks and problems at hand, ranging from just a few to a theoretical infinite number of solutions.
Moving through the Design Space

To be able to use Design Space Exploration techniques to their full potential the designer should adapt a different way of working. Usually the designer designs according to a goal, something in his head or on paper that describes what the final design should be like. Most of his design acts are aimed towards realizing that image. By focusing on that image the designer might ignore alternatives that go in another direction. In Design Space Exploration the designer should change this act. To successfully use the exploration of alternatives the designer should have an open-mind towards unexpected results and directions the design can take. One of the reasons to use Design Space Exploration is to be able to come up with new and novel designs. This needs a change in focus of the design process from a result based way of working towards a way of working where the way to get to a certain design becomes more important.

Constraints

The design space is defined as the space containing all possible alternatives for a certain design task. As mentioned before the size of the design space can differ greatly between projects. The number of possible alternatives is controlled by the boundaries of the design space. When we ask a person to pick a number between 1 and 10 the possible alternatives are 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10. The number of alternatives is limited by the constraint of being between 1 and 10. The same can be applied to a design project. Although this most likely results in a more complex set of constraints. Without these constraints
the design space cannot be defined (Kilian 2006). Therefore setting up the design space is closely related to the description of the design problem and externalizing its constraints.

**Digital tools for exploration**

Setting up and controlling the way the designer moves through the design space is a task the computer, and its digital tools can apply. At this moment there are a number of digital tools available that can help the architect perform the task of exploring. These can be divided into two categories (Kilian 2006):

- Simulation and Analytical tools
- Parametric tools

Each of the tools in these categories have their own field of expertise and application. What they all have in common is that they can be used to drive the exploration of the design space by externalizing the constraints and constructing the design space. By determining the strengths and limitations of each of the tools the designer can pick the right tool.

**Simulation and Analytical tools**

The computer simulation of building performance is aimed at the prediction and understanding of the way a design will appear and behave (Radford 1993). The use of digital tools has gone through several stages of development of changing into what it is today. In its early phases its main purpose was that of scientific and military calculations. By taking over the labour intensive calculations needed to simulate tidal changes, economic events and missile flight paths the computer proved
its use as tool too help the person to simulate and analyze the world around him. This application causes a significant growth in the use of digital tools. Simulating and analyzing structural integrity using Finite Element Modelling (FEM) was, and still is one of the main applications. Software packages like Diana, Oasys GSA and Catia are frequently used in the architectural profession. Nevertheless the architectural practice faces the dilemma that they simply cannot possess all the knowledge in all fields of expertise required to perform successful simulations. In this field specialists deal not only with the development of the tools but also their use (Degelman 1990) thereby increasing the distance between the design profession and the tools.

The advantages are easy to define; by taking over a lot of work of the designer, he is able to foresee and thereby react on the various aspects of the design before it is realized. This is also its main shortcoming; for a simulation or analysis the design must be well on its way. To be able to perform a simulation the designer must have good understanding of where his design is going and what it is he wants to simulate. The process of simulating and analyzing is largely one directional; based on the model used a set of data is generated (Kilian 2006).

**Parametric tools**

Geometry has always played a central role in architecture discourse. We can recognize that architecture, and design in the broadest sense, is dependent on geometry. Parametric modeling changes the way designers deal with the creation of geometry. Architects are starting to shift away from primarily designing the specific shape of a building to setting up the geometric relationships and principles described through parametric relations. Alexander already predicted this when discussing the increasing complexity of design problems the practice has to deal with (Alexander 1968).
Parametric design can provide for a powerful conception of architectural form by describing a range of possibilities, replacing the known with a variable and singularities with options. In parametric design, it is the parameters of a particular design that are defined, not its shape. By assigning different values to the parameters, different designs or configurations can be created. Such a parametric and editable approach to design offers a high degree of freedom of geometric control combined with the ability to rapidly generate variations. The main impact of such a design approach is best shown in the decision making process. Using conventional design tools the designer is forced to make early design decisions in order to make progress in the level of detail. In a parametric approach, the ability to make an associative model to which other components can be related, can allow us to postpone the decisions to be made until we are ready to evaluate them. (Marques 2007).

The shortcomings of parametric design approaches primarily deal with the complexity and uncertainty of the design in its early stages. Dealing with building parametric models demands for a certain amount of structure and definitions that are not always present in this early stage. This needs a lot of thinking on forehand whereas this time might better be spent on the design exploration itself instead of on the tools to make it possible (Kilian 2006).


The designer, the process and the tools

The goal of this chapter is to define the relations that exist in the design process and use this knowledge later on in the design/research process to properly evaluate the tools used and to be able to do recommendations based on the tools and how they fit into the architectural practice.

In order to address the use of design space exploration techniques in the current design process we should first look at how this design process takes place. Can digital tools be a part of design projects that heavily rely on classical methods or should new methods be developed (Liu and Lim 2005)? The first step is to determine how design methodology is situated in its historical context; most of the current design practices have been designing long before digital techniques were introduced. By determining how the process was before this introduction we can start comparing the “old” and the “new” situation.
The author claims that there are three key elements influencing a design that can be identified (besides the external conditions like the design brief) in the architectural practice (fig. 1):

- The designer
- The tools
- The process

All of these elements have effect on the design outcome in their own way. In this chapter we will explore the relation with design and the internal relation between the elements. We are especially interested in the relation the “Tools” have with the designer and with the process.

The relation between designer and process is, for the purpose of this research, of less importance. Although these relations seem well defined
it is actually the design project which is situated as the central element between the three parties. All the interaction between the designer, the process and the tools run via this design project (fig. 2).

**The designer**

In order to get a better understanding of the specific role of the designer we use Chistopher Jones’ writings (Jones 1970). In Jones’ definition we can look at a designer in three different ways; that of creativity, that of rationality, and that of control over the design process. From the creative viewpoint the designer is a black box out of which comes the “mysterious” creative process; from the rational viewpoint the designer is a glass box inside which the designer knows exactly what he is doing and why he is doing it.

A similar definition can be found in the works of Schön (Schön 1983), where he discusses the dilemma of ‘rigor or relevance’, describing the high, hard ground where practitioners can effectively make use of research-based theory and the swampy lowland where situations are confusing messes incapable of technical solutions.

In order to have a better understanding of the observations made during the design process we should be aware of the fact that from a researcher’s point of view the designer can be considered in different ways. This is especially important while observing the designer.
Black boxes vs Glass boxes

The first theory is that we interpret the designer as a black box. As externalizing the experiences the designer has while using a tool is of great importance, it is vital that the researcher has, up to a certain level, insight in the way the designer works. We as researcher can only observe his artifacts and products. The human designer is like other animals, capable of doing tasks without clearly defining how he did it. Take for instance walking, a simple task but it is hard to describe how the human body performs this action. This simple process is just as inexplicable as the creative process of designing. There are theories about how the human brain produces these results (Lawson 1997), but there is no certainty, one of the reasons for this is the extensive amount of data a designer can access during his design process. Therefore this process of design thinking is very difficult to record. When asked to describe their methods, designers often speak of experience, trial and error, intuition and even luck. In order to make these comparable with other processes we do, can define the conditions and relate the situation to previous situations. By framing the problematic situation and clarify the end product and the possible means to achieve them we can make this more valid.

“In the selfconscious process there is no possibility of misconstruing the situation: nobody makes a picture of the context, so the picture could never be wrong.” (Alexander 1968 p.77)

Where the black box refers to a situation where the researcher has no knowledge of what is going on inside the designers mind, the “glass box” is a neologism, presumably referring to the fact that the researcher
has insight in what happens in the mind of the designer. It is this situation that most designers would reject. In order to achieve such a transparency the designer must represent design problems as clear and logical structures. This increased precision in the definition of a design problem would sharpen our conception of what the design process involves. All at the cost of losing the “innocence” of design, we cannot accept intuitive methods anymore.

“... because there are many designers who are apparently not willing to accept the loss. They insist that the design must be a purely intuitive process: that it is hopeless to try and understand is sensibly because its problems are too deep.” (Alexander 1968 p.8)

In this method the designer is much alike to a computer; the designer only operates using the information directly fed to him, and follows a series of planned steps until the solution is found. But as Alexander explains; hard to imagine a designer willing to fit this profile.

A designer is only human

In contradiction to how some architects might think about themselves, a designer is only human. This brings along its strong and weak points. On the one hand a human is capable of doing complex tasks and addressing complex problems while on the other hand the cognitive limits of the brain restrain the possibilities of the designer. A good example of this is the fact that designers are only capable of considering a small number of alternatives even if the number is very large. It is especially this area that digital techniques might step in and help the designer by amplifying and extending his possibilities.
Many writers have tried to chart a route through the design process from the beginning to the end. The common idea behind this is that all these ‘maps’ of the design process is, that it consists of a sequence of distinct and identifiable activities which occur in some predictable and identifiably logical order.

Taking a closer look at these maps shows that most of them divide the process of design into a few stages, roughly categorized as stages of analysis, synthesis and evaluation (fig. 5). To explain this process we might again examine the steps a chess player takes to come to his next move. The process suggests that the first step is analyzing the current situation by studying the position of and the relation between the
different pieces. The next task would be to determine the objectives. Of course the most obvious one is to win the game, but at this stage the objectives might be to attack a certain position, defending and short and long term gain might differ from that. The synthesis stage would be to suggest a move, which might emerge as a complete idea or in pieces, such as moving a particular pieces to threaten an other piece. This idea needs evaluating against the objectives before finally the move is made.

Two academics, Tom Markus (Markus 1969) and Tom Maver (Maver 1970; Maver 1970), started with a design map (a map showing the stages of a design decision) based on this principle, including a return loop from evaluation (appraisal) to synthesis (fig. 6). This return loop might be useful; the first thought move of the chess player may on examination prove unwise or even dangerous, and so it is with design. This allows the designer to have another idea since the previous one turned out to be inadequate.
The presence of the return loop raises another question, is this the only one? We can imagine that in the stage of synthesis or evaluation we need further analysis to come to possible solutions (fig. 7). This happens more frequently in a design process when not all problems are apparent and might reveal themselves later in the process.

“In the majority of practical design situations, by the time you have produced this and found out that and made a synthesis, you realize you have forgotten to analyze something else here, and you have to go round the cycle and produce a modified synthesis and so on.” (Page 1963)

Besides the ability to go back and forth in this process, there is another problem. The way this map defines the design process assumes that the process is linear and that all steps are taken in the right order. The design starts with an overall idea and is completed throughout the smaller details, while in “real-life” design can also start from taking a junction of some kind and add to that to get a complete design. So a small alteration to the previous map can clarify this (fig. 8).
Is this the way the design process works? The answer is no. First of all there are numerous definitions of only the term design itself, and then there is the variation of designers and design projects which all can lead to totally different processes. The last map defined here already shows there is no clear path through the whole process (fig. 9).

The definition of the three main stages itself is already something that is not clear in most situations, mostly because of the natural process of design that a designer uses. But besides that it is good to be aware of the fact that there are stages that can be defined, which in the case of this thesis, can help us in defining how the different digital tools work, so for the purpose of this research we will assume these three stages are present.
Now we have agreed upon this definition, let us refer back to the example of the chess player. We already showed that for each move he “runs through” a series of actions which results in his next move. But this in not a one-time only occurrence, during the game of chess he has to make numerous moves, each move influencing the next ones. Each time the player has to make a move he is subjected to run trough the process again.

There are certain kinds of problems, like some of those in the field of economics, or a game of chess which can be clarified and solved with a well defined solution. In design we mostly deal with less well defined problems, therefor the outcome or the expected result differs from the well defined solution. A design problem is not an optimized problem. In other words the designer does not have the intention to meet all requirements in the best possibly way but rather to find a solution which satisfies the most (Alexander 1968).

**Design as a rational problem solving process**

The chess player’s clearly defined way of working is what Simon (1996) describes as a rational problem solving process (fig. 10). In this process there is much stress on the rigor of the analysis of the design processes, objective observations and direct ability to generalize the findings. Logical analysis and contemplation of the design are the main ways of producing knowledge about the design and the process.

Going back to designing we can identify a similar kind of structure, the designer is presented with a design problem, the project, handed by a client. This can for instance be: how to design a library? The answer in this case would be the design of the library in which the solution of the question is embedded. But this is not the only question in this process, the main question can be divided into several design questions
which all need answering and which can be of different magnitude and importance. Each design problem having its own constraints and area to work in. Because most of the design problems are well defined it is a small step towards defining the constraints of the design space.

**Design as a process of reflection-in-action**

In real world practice most design questions do not appear as clear givens. They need to be constructed by the designer. Somehow he must construct a clear defined problem from a, most of the time, unclear situation. Schön calls this ‘the artistry’ of design practice. In *The reflective practitioner* (Schön 1983) he uses an example which illustrates the complexity of this situation: When professionals consider what road to build, for example, they deal usually with a complex and not well defined situation in which geographical, topological, financial, economic and political issues are all mixed up together. Once they have somehow decided what road to build and go on to consider, what the best way of building is, they may have a problem they can solve by the application of available tools; but when the road they have built...
leads unexpectedly to the destruction of a neighborhood, they may find themselves again in a situation of uncertainty. Schön sees design as a ‘reflective conversation with the situation’. Problems are actively defined or set by the designers, who take action to improve the current situation. This allows for a more loose structure in comparison to the more rigid definition of Simon. Describing design as a process of reflection-in-action works particularly well in the conceptual stage of the design process, where the designer has no standard strategies to follow and is proposing and trying out through trial-and-error. Seeing design as a reflection-in-action manages to describe the design activity without the need for complete rigidity, which gets us much closer to the activity of design as experienced by the designer (Dorst and Dijkhuis 1996).

Similar for both approaches is that a design can, and in most cases will, contain several smaller design questions which all are closely related to each other, and which all can have their own approach (Schön 1983). For example the question of the load-bearing structure of a building is not only related to the ability to be realized but is also influences the internal organization, shape, look of the internal spaces etc. The solution to a design problem is an integrated response to a complex multi-dimensional question, where the answer to one question is most likely to answer multiple questions and at the same time raise new ones. Therefore making it very hard to identify all design questions on forehand. Nevertheless each of these individual design questions play an important role in this thesis. The absence of these questions troubles the definition of constraints.
The tools

Since the start of designing of buildings various tools are used to visualize designs, find solutions to design problems and explain ideas. In the area of the master builder, (small scale) models were used to prove that a design could be built. Besides models, drawings introduced themselves as valuable means to define a design, especially with the introduction of perspective manipulations drawings proved their value. Nowadays it is necessary to define the whole building using 2D drawings. With the introduction of digital tools the designer has another addition to his set of tools.

“You probably think of a tool as something to hold in your hand. It is something to extend your powers: a piece of technology, or applied intelligence for overcoming the limitations of the body.” (McCullough 1996 p. 59)

A tool can be defined using two terms, the first describing the technology used, the second defining the technique to use it. Ali Rahim defined in his book Catalytic Formations what the relation is between these two terms.
“A technology can be defined as the application of a purely technical or scientific advance into a cultural context. Whereas technical refinement is directed towards the efficiency of a mechanical, electrical or digital operation, the effectiveness of a technology depends on his ability to produce in users new patterns of behavior and levels of performance.

....

Technology makes the technical useful within wider context. For example the difference between a slower and a faster car is a matter of technical refinement. The car itself, on the other hand, is a technological advance, since it qualitatively changes the relationship between the user and the machine”

(Rahim 2006)

This shows that in order to use the available technology the architectural practice should develop new techniques to put them to use. Techniques are basically behaviors that are systematic, repeatable and communicable. To put technology to use the techniques to use them should be developed (fig. 11). This is not solely related to digital
technology, also simple technology like a pencil cannot be put to use if the knowledge (technique) to draw is not present; tools take practice. You must learn how each tool works and work with another and above all what tools are for. Besides the development of techniques, technologies are subjected to constant improvements. This makes that techniques can become inadequate and insufficient over time. It is the users’ task to keep improving these techniques which can lead to the invention of new, or the adaptation of existing technology. This two-way feedback mechanism is vital to the integration of technology and techniques. The way this feedback loop works is very common in other industries like shipbuilding, automotive and aerospace design, therefore being an excellent starting point for innovation in the architectural practice.

A tool usually belongs to a set; the toolkit. The toolkit provides every function needed to perform a certain task. The different tools may each work in specific combinations, like a knife and a fork, to complete this task. As described above, the user should learn to use each tool, and more importantly the complete toolkit in order to pick the right tool or tools for the task up hand. (McCullough 1996)

Creating Possibilities

The tools used can have an impact on the design. In the era of the master builder the architect had to consider both designing and constructing his design. When an “innovative” design was made, it was the architect who had to think about how to construct it. Most of this was done based on experience and making models (ranging from scale models to life size mock-ups). If the technology or technique to construct it was not available the design was considered not buildable. Nowadays the range of tools is much larger compared to earlier era’s.
This is where the earlier described feedback loop fits in, a seemingly not buildable design might be possible with the introduction of new tools. This counts for the so called freeform and double curved shapes, which are hard to draw using simple 2D drawing techniques. The introduction of the 3D digital model made it possible for the designer to create and construct shapes which seemed impossible before (fig. 12). A good example is the Disney Concert Hall designed by Gehry, when it was designed in 1989 it seemed impossible to construct the design within budget, mainly because of the complex geometry which proved very difficult and expensive to create. The project came to a halt, and was not continued until almost 10 years later. In these years Gehry’s architectural practice invested a lot of time in the research in digital technology. In that time they did 13 projects in which each they took a step forward in using this tools until in the end Gehry’s office had the knowledge to complete the design for the Disney Concert Hall (Lindsey 2001).
Working or not?

In the case of Gehry the use of new tools enabled them to produce a certain shape. But a tool can also have a negative influence on the design. An extensive study done by Goel (Goel 1995; Stones 2007) revealed that when the designer is forced to use only symbolic systems, such as the ready-made shapes generated by digital design programs, in some cases resulted in a reduction of the creative qualities. This also makes that tools cannot be used to find a solution to every possible design problem or in any design process. The collection of tools the designer has available to him can be seen as the toolbox of a carpenter. For certain tasks he has a specialized/optimized tool which makes fulfilling that task possible. The same counts for a designer, at certain moments he needs tools that allow him to continue his design. A tool may not only perform a certain action, but may also come to represent that action; the tools become part of the process and vice-versa. As we have seen in this chapter the tool is, as are the designer and the process, entangled in the design project.

Purpose

We have already seen that there is a close relationship between technology and technique, which means that there is a close relation between the tool and the user (the designer). The success of the utilization of a tool is therefore dependent on the tool itself and how it is put to use. The most obvious conclusion from this is that when a tool is designed properly and is used in the way it is meant to be used, the result should be, solely looking at the tool, satisfying. This automatically means that we must acknowledge that the user of the tools must have sufficient knowledge of the tool to put it to good use. Nevertheless
there are situations where, using the tool for a purpose that was not initially intended can also lead to satisfying results. One of the most common uses of the flathead screwdriver, besides its intended purpose, is to open paint cans. Previous attempts to launch a special tool designed for this purpose failed and we are still using the screwdriver. This shows that a tool can be used for some other purpose than initially intended, as long as it meets the two criteria mentioned above. That using tools for other purposes can deliver good results is shown by a design made for the Yokohama Port Terminal by Foreign Office Architects (FOA): It is their habitual use of CAD and computers to design their structures, rather than physical models (perhaps more usual now than at the time of the competition in 1995) that means FOA can take this adaptive, procedural approach. To cope with the complex shapes and forms, the architects used techniques from rollercoaster design to engineer the complex curves and intersecting surfaces of the design. During development the transformation of one part of the continuous surface inflected the whole design as it would in a rollercoaster design. (Kleinman 2006) The main reason for this positive result is the fact that this tool fits well within the practice of FOA.

**General vs. Useful**

In general tools are designed for use in multiple situations and by more than one designer. As mentioned before the usefulness of a tool for a particular designer depends on the ease of use and the ability to fit their specific way of working. From that we can conclude that designing a custom tool that matches both the designers way of working and the task he needs to perform will most likely be considered as very useful. But the use of this tool for another task or by another designer is less likely to give the same result; the tool is too specific. The exact opposite
of this happens in most current tool developments. Larger firms (not always related to the architectural practice) design tools that must be used by several designers, all with their own way of working, and be used for various tasks (fig. 13). The tools designed by this development are designed to be useful in a large number of cases but have trouble performing well in specific situations. The optimum is a tool which can be considered useful in most situations. An example of this is Autodesk Maya. This program, originally designed for use in the movie industry, houses a powerful modeling engine which allows the user to model almost every kind of shape, simple or complex. Once the shape is created it is more difficult to transform the shape into information suitable for production. This would need another tool.

### Designing tools

Architecture has a long standing history of borrowing tools from other professions and putting them to use in their design projects. Programs like Autodesk Autocad, Autodesk Maya and Catia are used in multiple architectural practices. None of these three are designed specifically for the architectural practice nonetheless they are used. Because these
tools are not developed from a designers point of view it can conflict
with the way a designer works. The development of new tools, fit for
the architectural practice, becomes of greater need with the expanding
use of digital tools. To be able to determine when a new tool needs
to be developed the designer, first of all, needs to be familiar with the
limitations of the tools the designer already has. Second the designer
needs to have an idea of what the tool must be able to do; what is the
task to perform and what is the desired result. As defined in this chapter,
a design problem is not always well defined. The question of what the
tool should do is not always one which can be answered, even though
there is a clear idea of the desired result. This is especially apparent
in the early stages of a design project. A close relation between the
designer and the toolbuilder is necessary to close this gap. This is
where the speciality of a toolbuilder has its strength; the tool builder
that has knowledge of how architectural design works and that can
communicate with the designer on a conceptual level.

This new profession of specialist tool builders is something we can see
emerge within a number of large architecture firms. The increasing
complexity of designs leads to an increasing demand for specialists.
For the larger firms setting up a special group of people capable of
supporting the designers proved to be worthy (i.e. Specialist Modelling
Group, Foster and Partners). In this case a tool builder works closely with
the designer to create the tool. Most important is that both the designer
and the tool builder have some knowledge of the other profession.
Designer satisfaction

When developing a new tool designer satisfaction plays an important role. In any case the tool to be developed serves a purpose and is created because the existing tools do not coincide with the designers wishes. The level of satisfaction the designer gets from the tool is based on the results het gets and depends on two factors:

- Time to develop a tool in relation to the complexity of a problem
- Re-usability of a tool

First is the time it takes to develop the tool in comparison to the task it need to fulfill and the complexity of the task. When it takes a long time to develop a tool that performs a rather simple task the satisfaction of the designer is expected to be low (fig. 14). Even more so when in the time it took to develop the tool, that task could have been done manually by the designer; the tool is considered not efficient.
Taking a long time to develop a tool for a more complex problem is more acceptable. For design tasks that cannot be done manually the time it takes to develop the tool can be considered of less importance. The third factor is the ability to repeat a task. For developing a tool that takes over an action so that it can be applied to a number of design problems it is accepted to take a longer development time. There is a limit to where this is accepted. The moment this occurs will differ between projects and between architecture firms. When a tool is developed for a kind of project that the firm is sure of re-using it is more easy to accept (fig.15). For a project that most likely will occur only once or at best a few times this limit is reached sooner.

Evaluating tools

Evaluating tools, whether they are digital or analogue, plays an important role in the development and future use. This thesis aims at evaluating the tools used in the experiments. In order to perform this evaluation
a number of criteria is defined. We can divide these criteria into two

groups: tool specific criteria and user-tool criteria. The tool specific
criteria deal with the tool in a technical sense:

- Reliability
- Robustness

The evaluation according to these criteria is important to the toolbuilder
as it tells little about the interaction between designer and tool. The
user-tool criteria deal with the relation and interaction between the
user (the designer) and the tool in relation to the design task:

- Validity
- Efficiency
- Effectiveness
- Support
- Acceptability

Validity is the key in the successful application of design space
exploration. To create design alternatives which meet the design criteria
the output of the tool needs to be valid. In the previous section the
efficiency of a tool is already mentioned. One of the main reasons for
the introduction of digital tools is to improve designing. Once use a
tool causes more work compared to the result it gives the tool can be
considered not efficient. Related to the efficiency is the effectiveness.
Whereas the efficiency primarily relates to issues of time and use,
effectiveness focusses on the outcome of the tool. Does the result
satisfy the designer? Related to the issue of satisfaction is the criteria
of support. How does the tool support the design process (Does it
supports creativity, is it to perform repetitive tasks?). The last criteria
of acceptability defines wether the tool is accepted by the designer.
This will play an important role when looking at implementation in the
architectural practice. It are these five criteria that provide the most
useful information for this thesis.


Introduction to the experiments

Besides being the architectural component in this graduation, the design project is also an important source of information for this thesis. As mentioned in the introduction, the introduction of design space exploration needs a different approach from the designer; Looking at relations at different levels rather than designing an image. During this project the designer will focus on the application of digital tools to explore design alternatives.

The design project

Digital design and manufacturing is becoming more and more important in the design process. The integration of digital design tools is not bound to one specific practice; it can be found in various design fields amongst which automotive, aerospace, product and building design. An improvement in one field can influence the other fields.
There is a need for more research and better education in this field, current educational facilities at the TU Delft are not fit for this purpose. Therefore a new facility, SCHOOL FOR DIGITAL DESIGN, which can be used by all faculties (and design fields) can lead to the much needed improvements. The building will create an environment where the different disciplines can interact and learn from each other. Furthermore the building should give the possibility to exhibit what digital techniques can do, so the building should be able to house and display the work produced both digital and physical product. At this moment the understanding of digital tools can do is very limit partly due to the abstract level of the computer models, showing physical in combination with digital models can increase this understanding.

Another important step in digital design is the translation of the digital model into a physical product regardless of the scale. At this moment the TU Delft has a number of CAM-tools (Computer Aided Manufacturing tools) scattered around the campus, therefore not easily
accessible for both students and researchers. By bundling these tools in one building they can be used more efficiently and more important increase the awareness of the tools.

The building will house educational, research and supporting facilities summing up to approximately 3500 m$^2$ and a large atrium in which all the function should be visible. The main idea behind the atrium is the concept of seeing and being seen (fig. 1).

For a complete overview of the design brief and the location see appendix A

The experiments

In the second part of this thesis the experiments conducted are explained and evaluated. All experiments are done during the design project which was done in parallel to this research and is part of the Master of Architecture graduation project. The main goal of the experiments is to test and evaluate the results from the first part of this thesis. Furthermore these experiments are used to get a better understanding of the relation between the architect and the tools used. The design project focusses on trying out “new” techniques (“new” meaning; new to the author, not necessarily new to the architectural practice) and thereby pointing the design into possible other directions. This will not only affect the concept of design, but also the role of the architect and the process of designing (McCullough 1996).

We have already determined that it is difficult to envision all possible design problems that the designer will encounter in a design project. Therefore it is difficult to determine in advance which experiments will be done. In the real world practice most design questions do not appear as clear givens, they need to be constructed by the designer. Somehow
he must construct a clearly defined problem from a most of the time unclear situation. The experiments are defined during the design process by the designer and can be considered part of the total design.

**Designer and toolbuilder**

For this project the designer will also take the role as toolbuilder. As discussed in the previous chapter the toolbuilder should work together with the designer. By doing so the communication between designer and toolbuilder can be excluded as an influence in the use of the digital tools. Second we can exclude one of the evaluation criteria: Acceptability. As the designer and the toolbuilder are the same person, so it can be assumed that the tool designed is accepted by the designer. The tools developed, for this design project, are primarily designed with this project in mind and can therefore be considered specific, or not general (fig. 2).
How to continue during design?

This research consists of a theoretical research and an architectural design project. The design is, besides an architectural project, also the source for information needed for this thesis. The research will be adapted to fit the design project. Schon defined the process of designing as:

“From the perspective of Technical Rationality, professional practice is a process of problem solving.” (Schön 1983)

A more strict definition of a design project is, that it can be subdivided into several smaller and bigger sub-problems. It is impossible to define all these problem on forehand (fig. 3). There might be a number of design problems which might appear later on in the design process.
“Problems of choice or decision are solved through the selection, from available means, of the one best suited to established ends. But with this emphasis on problem solving, we ignore problem setting, the process by which we define the decision to be made, the ends to be achieved, the means by which may be chosen.” (Schön 1983)

To react to this uncertainty the experiments are not defined beforehand but emerge during and form the design project. The author will define a number of experiment which are limited to a certain design problem. Nevertheless there is a structure in the choice of experiments; the main focus will be on the same part of the design process as discussed in the introduction of this thesis: the early stage of the design process (fig. 4). This stage is divided into four themes: Building Programme, Space, Structure and Facade. An experiment will be done within each of the themes. What the exact setup of the experiment is, is determined when the experiment starts.
Protocol

A protocol is setup to structure the experiments. In this protocol the problem is described and the expected results are laid out. The protocol also defines the criteria used for the evaluation of the experiment. Four criteria are already defined in the previous chapter: validity, efficiency, effectiveness and support. These criteria apply to all four experiments. As each experiment differs from the others there might be an additional set of evaluation criteria. During the process of designing and working with the various tools the experience of the designer while using the tools should be recorded.

Recording designer experiences

By keeping a record of the designer’s experience while working on the problem posed and all tools used/considered we can define the relationship between the designer and the tools. This could also give insight in whether the chosen design methods are suited for the implementation of digital tools and where improvements are needed.

The process of recording the designers experiences, during the design phase will be done by keeping a logbook. What is important here is that these reports should not solely discuss the experiences but also describe the choices that were made, the outcome and the options considered. The difficulty of this method is that the description of the process is done afterwards, which could lead to the loss of information that was there during the process. There are methods of externalizing these experiences during the design process but, as discussed in the
introduction, these can have influence on the design process. Therefore the design will rely on the notes taken and, immediately after the experiment, writing down what is in his memory.

**Evaluation**

Once each experiment is done it will be evaluated using the information gained. In the previous chapter four criteria are defined for this evaluation:

- Validity
- Efficiency
- Effectiveness
- Support

Each of these criteria will be discussed together with the additional criteria defined in the protocol. The results from this evaluation will be combined in a final chapter. In this final chapter the whole design project will also be evaluated. The research question, as posted in the introduction, will be answered by defining areas of interest within the field of digital tools and design space exploration. These themes can serve as a starting point for future studies.


“The diagram is no longer an auditory or visual archive but a map, a cartography that is coextensive with the whole social field. It is an abstract machine. It is defined by its informal functions and matter and in terms of form makes no distinction between content and expression. It is a machine that is almost blind and mute, even though it makes others see and speak. […] It never functions in order to represent a persisting world but produces a new kind of reality, a new model of truth.”

Gilles Deleuze
**Protocol**

This experiments rises from the interest to use spatial relations between the various functions as the start for the creative process. The ability to visualize spatial relations and the beauty of Voronoi diagrams caught the designer’s attention and becomes a big influence in this design project. The first stage is to be able to generate three dimensional Voronoi Graphs. The second stage is determining the potential of the Voronoi Graph in architectural design and determining the direction for the explorations of the third stage. From a researchers point of view it is the way these tools are put to use in a situation where the architectural design is in an early, more conceptual stage. From the developers point of view the possibility to create a tool to visualize and create Voronoi shapes is interesting. From a designers point of view it is the search for intriguing shapes and configurations that drives this experiment. The final result of this experiment should be an architectural diagram which can act as the starting point for the design project.

**Voronoi**

Designers use nature on a regular basis as a source of inspiration for their designs. The study of natural systems and patterns and how to “mimic” their behavior using the computer is applied in various stages in the design process. For this particular project the designer is interested in the use of Voronoi diagrams as a starting point for further explorations and as a stimulant for creativity.
Voronoi diagrams are named after Russian mathematician Georgy Fedoseevich Voronoi (or Voronoy) who defined and studied the general n-dimensional case in 1908. A Voronoi graph for a given set of sites shows the region around each site in which each point is closer to that site than any other, each cell has a maximal size (fig. 1). By doing so for a complete set of sites it not only describes the inner cell relations but also the relations between the cells. This is inherent to the Voronoi logic, as it calculates the graph by drawing a perpendicular line at the center of a connecting line between two sites. The Voronoi graph is a common natural pattern. It is the most effective sub-division of three dimensional space, the fundamental arrangement of organic cells and the natural formation of soap bubbles. It bears fundamental similarities to the way structures as bones tile space (fig. 2).

2 - Examples of voronoi-like structures in nature.
Using a computational algorithm we can create our own Voronoi Graphs in both 2D and 3D. The script will be developed as the experiment goes on, starting by making a script able to generate Three-Dimensional Voronoi Graphs. During the design process (experiment) the script can alter functions and might be added. This all in response to the outcome of that or previous iterations. Because a Voronoi is based on a fixed logic the results will be identical as long as the input remains unchanged.

Creating Voronoi Diagrams

As discussed in the previous section, it is possible to generate Voronoi diagrams using computation. The first step is to create the possibility to do so. The two programs that initially have been selected for this design project (Bentley Generative Components and Autodesk Maya) both lack the ability to generate three-dimensional Voronoi diagrams (fig. 3). This led to the creation of a tool that is able to create Voronoi Diagrams in Maya. In Appendix B of this thesis the complete creation of the script can be found.
The script accepts a number of points as input and generates a Voronoi graph from it (fig. 4). The position of the points is determined by the designer. The results from this stage of the experiment have no direct relation with the design but are primarily meant to start the creative process in the designer’s head.

Creating Physical models

To get a better understanding of how the Voronoi graph works internally a physical model is created (fig. 5). The first model is created using a Voronoi graph from one of the earlier examples. This first unfold was done using in Rhino and unfolded it using a script which places the surfaces from one Voronoi volume on the base plane next to each other. These were manually “stitched” together and printed on paper, and assembled. The methods works, but there is too much unnecessary labor involved: the script should create a layout automatically instead of doing it by hand.
Potential

According to the designer the Voronoi can be interpreted in two ways; defining the maximum volume for each point or defining the bisecting lines between two point. The last interpretation is the most interesting aspect derived from the results of the Voronoi script. It is the way the inherited relations become visible in the Voronoi shapes. Each surface represents the link between two points generating a spatial model of the relations.
Spatial Relations

The main purpose of the design project is to house academic functions; teaching, doing research and working in one building. To improve the relation between the different disciplines and between students and researchers, it is important to provide a proper network of spaces which encourages this.

When we look at some precedents we can identify two types of networks; The cathedral of Chartes located in Chartes, about 80 km from Paris, is considered one of the finest examples of all France of the “Gothic” style of architecture, which was also the oldest form of a place for education. The linear layout of the plan shows a large space in the center, and forms several smaller rooms on either side of the cathedral. The circulation system represents a centralized network, where the activities occur in the larger center area (fig. 6).

A more typical contemporary educational building, on the contrary has a different circulation structure. The rooms are usually connected by corridors that are rather long and narrow, resulting in a decentralized network. Classrooms act as clusters of programs which are connected by paths. A good example of this is the former faculty of Architecture of the TU Delft (fig. 7). Each department is housed on one or more floor
which forms a “cluster”, all of which are connected through the elevators and stairs. It is hard to see the relation between these clusters and it results in a decentralized network.

THE SCHOOL FOR DIGITAL DESIGN requires a different type of networked structure; the interaction between the different disciplines and functions needs a distributed network to allow allogamy and exchange of information and experience. When the distributed network is transformed into a three-dimensional network the number of relations allow for an even higher number of relations which should be enough to meet the designers demands (fig. 8). The distributed network system can also be found in nature. Objects created by nature are formed in ways to achieve maximum strength possible under their conditions, in order to survive. The co-existence of cells in such a formation is key in their strength. One way of generating these formations is to use an algorithm to create Voronoi Graph. The Voronoi graph is used to design cells as a three dimensional grid of interconnected cell midpoints (input sites) that form a interdependent network with their neighbors (distributed network). The generated cell
is no longer seen as a single entity but it considered part of a whole in which singular entities are not interchangeable but where modification has its affects on the overall system.

What became clear during the creation of the first set of Voronoi graphs is that the Voronoi graph itself has a lot of potential in providing a base to the architectural ordering of spaces. The results trigger the designer to rethink the relations embedded in the design project and the shapes stimulate the creative process in this early stage. However the use of the results is very limited as they are merely studies of form and order based on a random set of points from which a formation of shapes emerges.

It is all about the points...

One of the preconditions to get a “useful” and tangible result from the Voronoi script is to create a meaningful point set. Most of the studies/models I have made so far are based on more-or-less random sets of point. The goal is to give each point an association to give the results of the studies meaning and to be able to use it in the design process.

Associate according to Merriam-Webster:

*To bring together or into relationship in any of various intangible ways*

An association can take place at many different levels:

**First level**

Associations within and “about” the object.

For this design project each point will represent a place/function; atrium, entrance, instruction rooms etc. When defining these places we can also assign dimensions (fig. 9).
Second level

Points (or places in this case) can have relations which “bind” them together. These relations can be of any form, tangible and intangible; the architectural brief describes that the visibility of the whole digital process is key, therefore we can identify visual relations between spaces. Some of the spaces also need to be close together, like the entrance and the atrium. These are all very conventional ways of working with the program, but applied in a different situation. Relations can be of different strengths, some more than others (fig. 10).

Third level

The position of the points can be related, besides each other, to exterior influences as found in the location. The choice of site has its influence on the placement of the points. In this case we can identify the boundaries and direction of the site (fig. 11).

Based on these associations the first set of “real” point was created, dealing with the exterior boundaries and the visual relations between the various sites.
Explorations

This experiment comes from the need to create “meaningful” point sets to use as input for the Voronoi script. When we look at the diagram containing all the relations it is easy to conclude that capturing this complex network will be a hard task. This part of the experiment tries to help the designer to explore the various alternative ordering of sites that comply with the relations found in the design project.

In the search for a method to define the positions of the various sites the designer started by looking into methods to capture the relations as defined in the program. As discussed previously, one of the bigger tasks is to capture the more intangible relations found in the external conditions of the location. Some are very strict like the boundaries of the location (the area to build on) but above a certain height the building can go across these boundaries, dealing with totally different influences; the intangible ones.
The final relational scheme incorporates many relations between many functions/sites. The challenge is to be able to capture these relations and create a feasible model from it. The initial idea is to use dynamic models to provide the designer with alternative solutions to the model. Based on the outcome of the experiment the designer can take appropriate actions to create new alternatives or decide to stop the experiment.

**Dynamic Models**

In physics, dynamics is the branch of classical mechanics that is concerned with the motion of bodies. It is divided into two branches called kinematics and kinetics. Kinematics is concerned with the space-time relationship of a given motion without considering the effects of forces. In other words, it only deals with the geometric aspect of
motion. Kinetics is concerned with the motion of bodies produced under the action of forces. The foundation for this tool is the Dynamics Engine of Autodesk Maya. This engine is equipped with a solver which is capable of solving complex networks of both forces acting on objects and objects interacting. It tries to find a state of equilibrium in which it satisfies as much of the “rules” as possible. The forces can either attract or repel and the magnitude can be set thereby defining the properties of a relation. The designer uses this to define and apply the various relations. An example would be the Atrium as the central object and the CAM-lab which has a strong visual relation with this atrium. In this case the Atrium would get an attractor field which influences the CAM-lab with a relatively high strength. An attractor can either reside at a static place (for instance the center of the location) or be attached to another site. For instance the storage area needs to be close to the CAM-lab but not necessarily close to the atrium (fig. 13).
Because of the number of relations, the differentiation in forces and the influences the sites have on each other the results are expected to be unpredictable. The designer has to verify the results and judge if the result is useful. He can do this by comparing the outcome to the relational scheme and verify if all the relations are present in the model. Second he must judge the potential of the result using his experience as designer.

**Tool**

Although Autodesk Maya is very capable of solving the complex network of relations (and thus forces acting on each other), it is not so good in visualizing them. This makes it hard for the designer to set-up and control the forces in the model. Therefore a tool is created. The tool is the interface between the dynamics engine and the user (fig. 14). Its main purpose is to create a good overview of what is happening in the model.
In the interface of the tool the forces, sizes of the sites and the connections are easy to view and modify. This is especially important when using this tool to create variations. To support this it is also possible to save a state the model is in. This is saved as a copy in the current model and all the used values for the forces are stored with it. This makes it easy to track the changes and the influence a certain change has.

It works by defining a place or space (the site) with a certain size (the radius) and a name. Each site represents one of the places in the relational diagram. Once the sites are created, forces can be added. Each force has a name and a magnitude, either positive (repelling) or negative (attracting). Each force can be assigned to:

1. Act on one or more sites from a position in space.
2. Act on one or more sites from the position of another site. The force will be attached to its “parent”.

External relations can be found in the first category whereas relations between sites are found in the second category. It is important to remember that a force always works from one point (either fixed in space or fixed to another object) but can influence more sites. The numerical values assigned to the magnitude should be considered relative. There is no direct physical link between that number and any “real” world definition of forces. When force A has a magnitude of 10 and force B has a magnitude of 20, B is considered twice as strong as A.

The dynamical model also uses collision detection, so that sites cannot penetrate each other. This can also be used to define hard boundaries.
What to model?

The starting point of this exploration is based on the program needed in the building. The program consists of entities on different levels. The force model asks for a modeled representation of this program. The designer chose to start with a fine grained model; each individual room is modeled as a separate volume in the force model. In the first part of the total experiment the outcome shows how this fine grained model works in combination with the forces applied. In most cases the resulting formation of the volumes was surprising and triggered reactions from the designer. While the experiment continued the need to change the grain of the model became more apparent. The initial choice to represent all the individual rooms had a negative influence on the outcome of the experiment; the large number of smaller spheres made it hard to get consistent and usable results (fig. 15).

15 - Result of the tool with a fine grid of spheres
Creating alternatives

The goal of this experiment is to create alternatives to help the designer explore the possible “solutions” that work with the relational diagram. For a complete list of recorded actions during the experiment see appendix B. Besides the first two models, which are there to setup the forces, all models until 28 are created in a linear way. This means that the existing model is adapted to create a new version. The earlier described change in grain of the model made a new series of models producing more useful (considered by the designer) results. The configuration of sites is transformed to a Voronoi Graph by taking the center points of each sphere and using that as the input for the Voronoi script (fig. 16 & 17).

16 - The center points of the spheres used as input for the voronoi tool

17 - Result of the voronoi tool with the spheres as input.
Evaluating Experiment_01

This evaluation evaluates the two tools developed and used for the purpose of this design problem. The application of both tools focuses on the conceptual stages of the design project. This experiment has three stages; experimenting with Voronoi Diagrams, finding the potential within the Voronoi and putting the Voronoi to use in a series of explorations.

18 - Overview of the complete process.
In green the steps recorded in the design tools.
Voronoi Creator

The purpose of the first tool applies to three stages of this experiment: experimenting with Voronoi Diagrams, finding the potential within the Voronoi and putting the Voronoi to use in a series of explorations.

The main purpose of this tool is to **support** the designer with the construction of complex three-dimensional Voronoi shapes. The designer is able to create a two dimensional Voronoi diagram manually, although the initial number of points has a great influence on the time it takes to compose the diagram. The complexity of a three dimensional diagram, especially with 5 points or more as input, makes it extremely difficult for the designer to compose and very time consuming. By taking over the task of manually creating the Voronoi shapes the designer can focus on the design project and explore the design space more **efficiently**. The ability to experiment with the Voronoi shapes...
gave the designer the understanding of how it worked. The fact that the
designer and the tool-builder are the same person was an enormous
advantage; to be able to create a tool that builds Voronoi diagrams you
need to have full understanding of how the script worked. Therefore this
information was directly available to the designer. Most of the script was
created during the experiment and some features were added because
the designer demanded them. Although the creation of Voronoi is
automated by the tool the designer is responsible for the input and
has thereby a great influence on the outcome. Because the process of
creating Voronoi shapes is based on a fixed set of rules it is possible
to validate the output, as long as the input remains unchanged. The
alternatives can be compared and validated because of this property.
During the firs stage of the experiment the input of the Voronoi Tool
is random. This makes the Voronoi Tool ineffective for the exploration
of alternatives, but effective in helping the designer understanding
Voronoi. In this stage of the experiment the results and knowledge
gained from the first to determine the potential of Voronoi and to set
out the direction for the explorations for the last stage. In this stage the
designer took some shortcuts by directly relating the potential of the
Voronoi to the internal relations of the design project. Further study on
the use of Voronoi and the potential the script has might have led to a
better integration of the Voronoi diagram. In the latter stage the input
for the Voronoi tool is based on the building program, and thereby
gained meaning. This makes the output of the Voronoi tool useful as
design alternatives and the tool effective.
Relation modeller

The second tool used the results and knowledge gained from the first to determine the potential of Voronoi and sets out the direction for the explorations for the last stage. The goal of this script is to relate the internal relations within the building to the input of the Voronoi tool. The relations are defined based on the functions as described in the design brief. The number and complexity of the relations make it difficult for the designer to envision a model that would omit to them. The designer decided to use the internal dynamics solver of Autodesk Maya to solve the network of relations. This resulted in the need to make a separate tool to drive the numerous spheres and forces within the model. The tool acts as a mediator between the designer and the dynamics solver. What the tool basically does is building an index of all the forces and sites and support the designer in keeping overview of the relations. This made making the tool fairly easy, as compared to the Voronoi tool where a logic needed to be programmed. Although it was possible to do the explorations without this tool, it proved to be a valuable time saver for the designer. The whole series of experiments were done over a period of two days, making it efficient. The addition of the possibility so save a state and later compare them was of great importance for the explorations. By modifying an existing state based on the evaluation done by the designer, it is either abandoned
or modified into a new alternative. Defining the grain of the model proved to be the biggest challenge for the designer. The quality and **effectiveness** of the tool and the output that comes from the exploration is affected by the grain of the input. In this experiment the designer started with a very fine grained model, which led to results that were to correlated to be used for further explorations. Changing the model to a finer grain improved this. If this was known before the experiment started it would have saved time and may have improved the overall result. The second issue which became apparent in the later stages of this design project is the decision of what to model. In the initial list of functions or places that were meant to be modeled some were missing which later proved to be essential. The same applies for the definition of relations. This was most apparent while the designer was working with the access of the individual spaces after experiment 02. The abundance of proper definitions for stairs, lifts and shafts as well as for fire escapes made it difficult to integrate them. Including this in the original model, including the proper forces (i.e. to make them vertical) would have made this a lot easier and would probably have led to a more elegant solution. Changing this by re-doing the first experiment is considered but the designer manually applied changes to the model which were time-consuming to redo and therefore not an option.

**Overall**

Overall experiment 01 worked out well for the designer. It **supports** the designer in his search for an architectural diagram in the early stages of the design process. In this stage the amount of knowledge about the design is limited and the ideas of the design need to form themselves. The success of the two tools developed primarily relies on the fact that
the designer and the toolbuilder are the same. This success is achieved because the designer/toolbuilder developed the tool along with the development of the architectural idea. By constantly modifying the tools the designer could explore the possibilities. It can be questioned whether the same results can be achieved when the designer and toolbuilder are not the same person. The ability to communicate vague ideas becomes an important factor in this success.

Although the experiment relies on two rather unpredictable processes, the creation of Voronoi and the use of dynamic solvers to provide in solutions for the complex relations between the individual programmatic elements, the designer still feels in control of the process. By critically evaluating the results from the “automated” tools instead of accepting them right away the designer stayed in control, and more important, gained extra knowledge about the design and the concepts he choose (ie. The way Voronoi works). This might prove useful later in the process. There are two areas that need further research to improve further applications; The potential that Voronoi can have and the information that is needed before the internal relations of a design project can be defined. The first is an issue of concept and design whereas the second is of vital importance for the success of the exploration in the later stages of the design.

On the next page the diagram (fig. 20) shows the internal logic of the two tools and one script that connects them. The Driver shows what determines and generates the Input, which is Processed to generate the Output. The dotted lined show the connections between each of the four stages. The importance of the User (designer) as driver and generator of the input is clearly visible.
20 - Overview of the structure of the tools used.
Experiment_02
A place to work

Protocol
This second experiment deals with transforming the clusters of rooms that are defined by the Voronoi volumes from the previous experiment into the actual rooms, thereby taking the relations defined earlier in the relational diagram into account. The goal is to come up with a configuration of individual rooms which respects the Voronoi shapes and the relations of the design project.

Introduction
For this experiment the designer starts defining the individual rooms as they are defined in the design brief. During experiment 01 the decision was made that a number of smaller rooms will be clustered in larger volumes. This experiment reverses this process by indentifying the individual spaces again.
For this step in the design process the designer re-used the Voronoi script from the previous experiment. In Experiment_01 the use of the Voronoi primarily focuses on creating a visual representation of the relations in the model. Because the program consists of a lot of individual elements, and thus points for the Voronoi script to calculate, it is hard for the designer predict what the result will look like. In this experiment the use of the Voronoi Script is brought to the next level. Instead of getting totally unexpected results the script is used to consciously sculpt the rooms.

**From unpredictable to predictable**

The reason for the results of the first experiment being unpredictable can be related to two properties of the model. First there is the difficulty to imagine the separating surfaces before the Voronoi volumes are created. This makes controlling the direction of the resulting surfaces difficult. By looking at the logic behind Voronoi a simple but, for this experiment, vital rule can be defined; when two points are placed exactly above each other the surface separating the two volumes is horizontal. Having a horizontal floor is a prerequisite for defining the
individual rooms (fig. 2). The second property is the number of input points. As we already saw in the first part of the first experiment large amount of initial points makes it hard to foresee any how the resulting Voronoi graph will look like. In the second part of the experiment the number of points was reduced and the results got more manageable, although not yet predictable. So there is a relation between the number of points used as input for the Voronoi script and being able to predict the outcome. For this second experiment the number of points is reduced to a minimum, controlled by the number of rooms and transition spaces needed. This makes the outcome of the Voronoi script more predictable. Therefore we can say that the knowledge gained from the previous experiment changed the result from being unpredictable to predictable (fig. 1).

Criteria

After a configuration of rooms is created the result needs to be evaluated. In this experiment the evaluation is done by the designer. He evaluates the outcome using the following criteria:

- Layout
- Easy to access
- Horizontal floors
- Usable space
• Possibility for daylight and view

The designer applies each of the criteria on the design and uses his experience and common knowledge to determine if the criteria are met (fig. 3). If the criteria are not met the designer can decide to change the original input (the points) according to the knowledge he gained from the evaluation. The final result is a cluster of rooms and transition spaces.

Multiple Runs

This experiment, as the first experiment, for a large part relies on the designer having knowledge of the building program and configuration of places and individual spaces. In the previous experiment we already concluded that this knowledge is not always present at the moment it is needed. This was also the case during this experiment. Later during the design project the designer found the initial configuration of the rooms...
not suitable and too chaotic. Based on the knowledge he gained after doing this experiment he redid the experiment to come to a different result (fig. 4).

**Evaluating Experiment 02**

For this experiment the designer chose to keep the process as simple as possible. Furthermore he decided to re-use the Voronoi tool that was created for experiment 01. This was not only a time-saver but it fitted well within the design-strategy followed by the designer. Compared to the use of the Voronoi Tool in the previous experiment the evaluation is almost identical. It differs on the criteria of **effectiveness** and **support**. The effectiveness has increased because of the knowledge and experience the designer has after working with it in the previous
experiment. The ability to predict results based on the input makes it easier to use the tool. By evaluating the output and relating that to the logic of Voronoi the designer is able to do quick adjustments making this an **effective** process.

In this experiment the evaluation of the results was done by the designer using the criteria defined and thereby relying on his knowledge. The decision to do this evaluation himself was based on saving the time of programming the criteria in a tool. It can be interesting to see if and how the different criteria can be programmed in a tool so that the tool can judge the outcome itself and thereby **support** the designer in the decision making process. This process is shown in the diagram on the next page.
6 - Overview of the tool used and the evaluation done by the user.
Experiment_03

Structural Optimization

Protocol
The main purpose of this experiment is to determine the visual implications the construction has on the overall design. The alternatives come from a series of structural optimizations, each using different criteria. The suggested alternatives can be considered structurally stable. During the conceptual phase of the design project it was assumed that relating the structural system of the building to the shape of the Voronoi diagram would give a stable solution. The structural optimization is considered secondary to the architectural image and is primarily used to support the decision making instead of pure verification.

Introduction

After the first experiment the designer claimed that a construction based on Voronoi shapes will be stable. This claim was based on the relation with structures as found in nature (like bones, beehives etc.) which have a great resemblance with the Voronoi structures. After
building a physical model of the Voronoi structures, the visual strength of the edges of the Voronoi volumes became clear (fig. 1). Until this moment the dimensions of the structural elements are unknown. This experiment will determine these dimensions; by simulating the forces acting on the structure and analyzing the data generated alternatives are created. By defining which dimensions to affect and the constraints that apply, the shape of the structural elements can go through a process of optimization. The outcome of these optimization will serve as the alternatives between which the designer will choose. The visual aspects of the construction in the overall design are the main criteria.

**Initial Data**

This experiment starts with the Voronoi volumes from the first experiment. The designer decided to use the edges of the Voronoi volumes as construction lines; the beams. Changing the direction, length or angle of any of the beams would inevitably lead to creating a new model, as all beams are connected. This limits the possible optimization to the section of the beam instead of the overall shape.
of the structure. The initial shape of the individual beams and the resulting connections is also pre-defined. The beams are constructed from steel L-shaped elements, with a differentiation in the angle of the “L” (fig. 2). These elements will be filled with concrete to meet up with fire regulations. The design of the profiles comes from a combination of esthetics and buildability. The profiles are placed within each Voronoi volume. This means that when two Voronoi volumes meet, the two adjacent beams are combined, and thereby doubling the total section of the beams.

**Simulation**

Because of the complexity of the model and the demand to do a section optimization for the profiles creating a physical model is not an option. It is this area that digital tools already prove their use. Simulations based on Finite Element Methods (FEM) are commonly used for the calculation of structures in buildings. There are various programs available on
the market that are able to perform the needed calculations. The two criteria for selecting the program to use are the ability to use the existing three dimensional data and the availability of the software during this project. This leaves two options: Diana and Oasys GSA, the latter being the final choice, primarily because of its ease of use. The missing feature for GSA is the absence of optimization strategies. The designer took this opportunity to develop a tool that would add this functionality to Maya. The goal is to use Maya as the driver and GSA as the calculator. Connecting both these programs results in an tool that communicates between the programs and drives the optimization (fig. 3).

**Transporting information**

The first and most important issue of communicating between two different programs is the language they use; the difference in how geometry is defined. While working with a large number of individual elements it is important to keep track of where each element is located and how it can be identified. Using the existing communication protocols this cannot be guaranteed. For that purpose the tool developed includes its own translator which is able to perform this task.
of communicating. With this tool set-up the designer is able to transport structural information into Oasys GSA, perform the needed structural analysis and transport the results back into Maya for processing (fig. 4).

Optimization

Optimization literally means an act, process, or methodology of making something as fully perfect, functional, or effective as possible. So the first question would be: What to optimize? As discussed before, the profiles have a fixed common shape and allow for a change in dimensions. These dimensions are:

- The height of the profile
- The depth of the profile
- The thickness of the material used

Taking each of these dimensions individually presumably will result in a number of alternatives with a difference in visual appearance. In addition all three dimensions were used in a fourth optimization process.

Description of the optimization process

The process of the optimization of the profile dimensions follows a series of clearly defined steps:
1. **Define the initial data**
   The initial dimensions of the profile act as the starting point for the total process. The designer bases these initial dimensions on previous experiences and rules of thumb. This initial choice has great impact on the results coming out of the experiment. Because the tool is designed to perform the optimization by increasing the profile dimensions rather than decreasing them it is crucial not to start with a too high or too low dimension. A low value would result in an unnecessary long process of optimization whereas a too high value is unlikely to be optimized at all.
   At this moment the designer also defines the forces that will be used in the simulation. This is done using a high level of abstraction. Each of the forces is re-calculated to act on the nodes only (fig. 5.). The secondary construction needed to create the floors is ignored to simplify the model.

2. **Create the output file**
   The initial dimensions and the shape of the overall construction are written to a text file which can be read by GSA (fig. 6). By writing this file in GSA its own language the identification of each individual element can be guaranteed.
3. **Perform structural simulation**

With the data imported in GSA the structural simulation can be done. The results include the stresses and displacements acting on the structural elements.

4. **Import the results**

The results are imported into Maya (fig. 7).

5. **Evaluating the results**

This is one of the most important steps in the process of optimization. The results from the simulation are evaluated according to a number of constraints; The stresses in the profile cannot exceed the maximum allowed stresses for steel and the displacement of the individual element cannot exceed the maximum allowed displacements.
6. **Perform action based on the results**

   The result of the evaluation in the previous step triggers a reaction in the model. If all the criteria are met the structural element is ignored. If one of the criteria is not met the current dimension is increased.

7. **Repeat the process from step 2**

   If structural elements are ignored the optimization is considered complete and the process is ended. If not the process is done again from step 2 until all criteria for all elements are satisfied.

**Visual Results**

The alternatives resulting form the optimization process each meet the criteria set for the structure, each of the results can be considered structurally feasible. It is the designer who has to decide which of the alternatives fits best within the overall design. The criteria used for this decision is far less well defined as the criteria used in the optimization process. The latter are predominantly numerical and therefore relatively easy to verify whereas the first are the “softer” criteria that deal with
emotions, visions and ideas of the designer. These criteria are difficult, if not, impossible to externalize and rationalize in order to be evaluated by the tool and therefore must be evaluated by the designer himself. To visualize the results from the optimization process the designer developed a tool that constructs the structural elements based on the dimensions found in the optimization (fig. 8). The development of this tool took a lot of time because of the complexity of the knots. Finally the designer resorted to a method which chooses visualization over accuracy for the model.

**Evaluating Experiment 03**

In comparison to the first two experiments, which deal with the earlier stages of the design process, this third deals with a later stage in where more information is available to the architects and the design question is more clearly defined (fig. 9). Compared to the former two experiments
this made performing the experiment easier in a sense that it could be performed by following a strict protocol, the four optimization strategies, instead of relying on the instincts of the designer.

**Structural Optimization Tool**

The first tool developed for this experiment is the structural optimization tool. The purpose of this tool is to facilitate and perform the communication between the model-data and the structural analysis software. The tool supports the designer by automating a large part of the structural optimizations. The tool takes over a number of decisions needed for the optimization: it checks the maximum stresses and deformations allowed in the elements and evaluates the results from the structural analysis in a fraction of the time it would take the designer. This makes the tool highly efficient and easy to validate. The outcome of the tool is a structural model optimized for one of the four criteria and can be considered structurally stable. The effectiveness of this tool depends on the ability to visualize the results so that the designer can make the needed decisions.

**Structure Visualization Tool**

To visualize the results from the first tool this second tool is developed. The output of the first tool consists of a table of numerical definitions of the dimensions of each individual structural element. As it is hard to envision the spatial implications by looking at these tables, this tool must support the designer by visualizing the construction. The development of this tool has been problematic because of the complexity of the knots where the structural elements meet. In this case the designer being also the toolbuilder did not work out as the
designer spend more time on developing the tool than anticipated. It can be questioned whether it would have been quicker to model the construction manually, making its efficiency questionable. Once the tool worked it produced the results needed for the evaluation of the four alternatives which helped the designer in the decision making.

**Feedback loop**

This experiment is a good example of the possibilities a feedback loop can offer to the designer. As discussed in the introduction this experiment started with the Voronoi shapes as the input for the structural analysis. During the analysis the designer found the need for the possibility to change not only the dimensions of the profile but also change the order of the Voronoi shapes. For instance to move the large rooms to the lower regions of the building where larger structural elements fit better. The preceding actions taken, by the designer, on the design before this experiment prevented the designer to perform such a step back; The designer would have to manually redo his previous actions. This is what makes it difficult to take this step backwards.
Experiment_04

Looking for a random pattern

Protocol

The setup of the fourth and last experiment is different compared to the previous experiment. Instead of focussing on the use of a specific tool designed for this design project we focus on a more general principle: randomness and how the designer deals with it. In the previous experiments the designer already dealt with a certain level of unpredictability in the experiments, this experiment will show what the designer accepts and what he considers not useful. The experiment evolves around the design of the outer facade for the building.

Introduction

The design of the facade is a continuation of an earlier action the designer performed on the total building mass. The idea of taking out some of the volumes and dividing some others in order to make the
total volume of the building respond to the surroundings is taken to the next level. The designer decided to make the difference between a volume that is taken out (clean cut) and a volume that is divided (fracture) visible in the facade (fig. 1). This is done by a difference in surface roughness. To create the idea of a fracture the designer is looking for a random configuration of facade elements that matches the overall style of the design; using Voronoi.

In search for a pattern

By reusing the Voronoi script as the main ingredient the designer starts his exploration in search of a satisfying result. Because the designer is not able to describe how the result should look like, he decides to start generating simple configurations (fig. 2). Although these do not give the desired result, they do help the designer in finding out what it is that the he is looking for. Because of the experiences with the Voronoi tool the designer had he is able to generate alternatives in a predictable manner.
2 - Simple facade division

3 - Minor variations.
The configurations generated do not satisfy the designer’s initial idea; it is easy to see a pattern and the configurations do not look random at all (fig. 3). He tries a second approach: using a logical approach to generate the feel of “randomness”.

By transforming an initially rigid grid of points into an irregular grid the configurations gets less predictable and looks more “random”. Using attractors the designer tries to link the inside to the facade. Because of the internal structure this also results in predictable patterns that are easy to spot (fig. 4).

Randomness

In an attempt to get rid of the clear patterns that appear and mimic the idea of a fracture the designer started to experiment with the concept of randomness. Randomness is an objective property, or it seems like it. Humans are really good at pattern recognition, and visualization allows
us to use our eyes and brain directly for this purpose. Nevertheless, what appears random to one observer may not appear random to another observer. One of the intriguing aspects of random processes is that it is hard to know whether the process is truly random. The observer can always suspect that there is some “key” that unlocks the message. So, why is it hard to test whether a given sequence of numbers is random? The reason is that if your random number generator (or your die) is good, each possible sequence of values (or die rolls) is equally likely to appear. This means that a good random number generator will also produce sequences that look nonrandom to the human eye (e.g., a series of ten rolls of six on our die) and which also fail any statistical tests that we might expose it to. If you flip enough coins, you will get sequences of coin flips that seen in isolation from the rest of the sequence don’t look random at all. What the designer is looking for is actually the opposite; it should look random disregarding whether it actually is random.

Some mathematically defined sequences, such as the decimals of pi, exhibit some of the same characteristics as random sequences, but because they are generated by a describable mechanism they are called pseudorandom. To an observer who does not know the mechanism,
a pseudorandom sequence is unpredictable. The random number generator of Maya, used in this experiment, works as a pseudorandom and should therefore be fit for this experiment.

The inevitable result of using the random number generator as a driver in any process is the fact that each time the procedure is performed the result will most likely be different (theoretically the result could be exactly the same but it is very unlikely). When we take a square as boundary and place 36 points randomly within that square the result looks totally different in all three cases (fig. 6). Although this unpredictability and randomness is something the designer desires, he feels out of control. This feeling, that is discussed earlier in this thesis, goes against the nature of the designer and is therefore not accepted by the designer. The urge to control the process of designer turned out bigger that anticipated. The question arises whether the designer would accept the results if they would meet up to his expectations and satisfy his ideas; would the designer accept a design, generated by a computer if it completely satisfies his ideas.

Nevertheless the results from the experiment are compelling and give the designer a direction to continue. As the designer did in the first experiment, he tries to find a way to keep the random looking style in such a way that it is controllable. As the first try led to a completely uncontrollable distribution of points, the designer tried the exact
opposite for the second try. He started the next experiment with a regular grid and performed a series of random moves by splitting the transforms into three different alternatives, each of the two directions and the combined version. By limiting the maximum distance the amount of “randomness” visible can be controlled. This satisfied the designers ideas and proved to be the best way to generate the desired facade (fig. 8).

Evaluating Experiment_04

In this evaluation it is not a specific tool that is discussed but rather a more common phenomenon of using the computer’s internal random number generator as design input. This immediately brings up the issue of who is designing; the computer or the designer? This is closely related to the acceptance of the tool by designers. In this experiment the author witnessed the designer using the random function available. The acceptance of the tool changed with the amount of control the designer had over the random number generator. It must be noted that this is in close relation to the outcome of the process. In this experiment the complete randomness caused a feeling of losing control. But, as already written before, we cannot envision what would happen when the results from the process meet all the criteria of the designer. A
second property of the random number generator makes it difficult to test such a situation. After-all it is not known when such a situation occurs if you do not know what the output of the random number generator will be. We know that the random-number generator used is a pseudo-random type, so the new result will always be different from, and unrelated to the last result. This is also an issue when we discuss the efficiency of the tool. Compared to the previous three experiments, this experiment will produce different results without changing the input. When looking at the idea of design space exploration and generating alternatives one can say that the random number generator is great because it can produce a large number of alternatives without changing the input. Nevertheless it is impossible to validate and redo a certain alternative simply because the tool “changes” itself. Second it is hard to determine, for the designer, when to stop because it is unknown what the next iteration will generate. Time and money available will play an important role in this process as the designer his decision to continue or stop is limited by both factors. In the previous experiments the designer followed a path in the exploration of the design space. In this experiment it is easy to gain a large number of alternatives but difficult to continue on one alternative and try to improve that. It can be doubted whether a truly random process can help the designer in his design process.

In this experiment the designer regained some control over the process by defining limits which bound the randomness. By applying randomness to some elements of the design he was able to produce results which satisfied him. Nevertheless the designer is not entirely satisfied because it is unknown to him whether he got the best possible solution.
In the following sections, the author summarizes the key result of the experiments conducted in the framework of this thesis concerning the design process and the application of the tools developed. The results from this evaluation are generalized when possible and reflected on the practical application in future design project. The author also defines a number of criteria for this future application and discusses the use of design space exploration techniques.

The early stages of the design process

In the introduction the early stages of the design process are defined as the primary focus of this thesis. In these stages the amount of information available is limited whereas Design Space Exploration methods call for a more structured setup. If we refer to the diagram...
showing the actual design process and compare that to the design project as it has proceeded it becomes clear that this chaotic representation is not far from what actually happens (fig. 1). It is this area that digital tools can help the designer to start his explorations. The first experiment is a good example of this situation and how a digital tool supported the designer in his design process.

Feedback and knowledge

In each of the experiments it becomes clear what the importance is of information and the ability to feed information back into the design process, especially knowledge gained after the experiment which makes it worth redoing the experiment, a feedback loop. A good example is the first experiment where the knowledge at the beginning was limited and increased drastically during the design project. This shows best in the integration of the vertical transport elements such as the elevators and emergency staircases, which proved to be a hard
task. This could be simplified a lot by adding these elements as well as their constraints into the first experiment and redoing it, and by this constructing a feedback-loop.

Practical application of the feedback-loop

Although the possibility of a feedback moment (or the possibility to redo a previous step) sounds like a simple step, reality proves otherwise. In the image above the situation is illustrated as a simple scheme (fig. 2). Consider Experiment 1 the experiment which we did with a limited amount of knowledge and the travel to Experiment 2 the moment that we gained more knowledge. As one of the key tasks within Design Space Exploration is the recording of design action we could say that redoing Experiment 1 with new data should be a breeze; just change the input and the output should change accordingly and generate a new alternative (fig. 3).

A practical example is the second experiment in the design project which was redone later during the design process when more information on the actual positioning of each of the individual rooms was present.
The success of performing these feedback-loops rely on the ability to successfully record the design process. This results in two criteria that should be met:

- The ability to record every single step and action within the total design process.
- The ability to redo a step or action with a different input.

It is the first criteria that proved to be the hardest to meet. This results in the question whether the designer should be forced to record all his actions and perform them in such a way that they can be repeated with a different input. When we look at the actions the designer performed between the experiments we can say that they are hard to record (fig. 4). Even if they are recorded it is unlikely that they can be redone with a different input as the choice of action is based on the output the previous step produced. An example is the first experiment of which we already concluded that redoing the experiment using the knowledge gained during the design process would possibly improve the overall design; the abundance of various elements in the initial model caused problems during the implementation later in the design process simply
because there was not a proper place to put them. Although there are enough reasons to perform the feedback-loop this was simply not possible without disregarding a large part of the design which was done between the experiments and therefore not recorded.

This somewhat changes the focus for the successful implementation of the feedback-loop from the recording during the experiment towards what actually happens between the experiments. The designer expected this and therefore decided not to pursue the development of one experiment capable of capturing the whole design project. The ability of manual actions and decision making, are an important criteria in the acceptance of design space exploration techniques and the use of digital tools.

Furthermore the designer should ask himself whether it is the right moment to implement the feedback loop. Generally speaking a designer will have more information available by the end of the project compared to the beginning, but this not necessarily means that he

4 - Designers action between the experiments.
should redo the whole design process. He needs to make the decision whether it is useful to explore alternatives and take a number of steps back or to continue design using the current outcome.

**Designer control**

The last experiment shows an example of a tool developed to generate design alternatives in such a way the designer has very little control over the process. In the first two experiment the designer is the one taking decisions. The optimization tool of the third experiment is capable of making a number of decisions without user intervention. These decisions were programmed by the designer during the development of the tool. The decision to perform a certain action (ie. increase beam width) when a certain value is reached (ie. maximum stress level reached) is rational and easy to justify. Decisions the designer makes during the design process are usually rather irrational and the choices are sometimes hard to justify because there is not one right answer. In a typical situation the designer has to deal with multiple criteria, each with its own optimal solution. This needs for a decision to be made satisfying multiple criteria which might be conflicting. The goal of optimization is satisfying a given condition, usually defined by a set of variables and constraints. In a design process we refer to satisfying as something that does not necessarily has to be mathematically exact, but “good enough”. This will depend on the judgement of the designer for the given conditions. These decisions are primarily made in the head of the designer and are, what can be considered, part of the design process. Therefore giving these decisions out of hand is hard to accept. Second, and maybe even more important, is the question whether the tool is able to make those decisions. A designer has his knowledge of designing and his experience from previous projects he can use help
him make the decisions. A digital tool can only make these decisions once programmed in advance and therefore its decisions are a result of what is programmed in the tool.

**Flexibility**

After evaluating the tools used during the design project the author defined an extra criteria: Flexibility. During the design project the designer re-used the Voronoi tool from experiment 01 in experiment 02 and 04. The flexibility of this tool allowed the designer to use it in ways it was originally not intended, while satisfying his needs. The flexibility matches the desire of the designer, not to be bound by his tools. Therefore it is desirable to have some degree of flexibility in all tools developed without making the tool general. Whether it is possible to achieve this flexibility is questionable. It will need extra effort and time while programming the tool; the developer needs to envision all possible scenarios of future use and adjust the tool accordingly. Second it is difficult to foresee future use of the tool. Therefore the author claims for a **modular approach** where tools are broken into smaller tools which are able to communicate but also function in a different setup. In the design project done, the designer/toolbuilder made the tool to create Voronoi volumes a separate tool which enables him to integrate it in other tools (like the facade builder tool in the fourth experiment.
Final words

Support

The main focus of the digital tools for this thesis is supporting the designer while exploring the design space. The way digital tools supported the designer during this design project can be divided into these categories:

- support with complexity
- support in creativity

Support with complexity

In the introduction the author referred to a quote of Alexander introducing the relation between the complexity of a design problem and the designer’s ability to find an appropriate solution. This uneasy relation is related to the cognitive limitations of humans to deal with this increasing level of complexity. In the design project done parallel to this thesis the designer experienced this during the first experiment. It is this area that digital tools can be of great advantage for the designer. The ability to structure and visualize large amounts of data and control relations enable the designer to deal with more complex problems. Nevertheless the designer should remain cautious. Although the computer can handle complex models, the designer should not resolve in building complex models instead of designing. The ability to deal with this complexity might seduce the designer in making more and more complex models, taking all possible influences into account. This might result in an unsolvable model and a designer focussing on complexity and not the design itself.
It is in the field of representing complexity using tools, that already a lot of development is taking place. The use of parametric and simulation tools enable the designer to deal with increasingly complex models and break them down into simpler models. Nevertheless the application in the early phase of the design project is difficult because of the many unknown variables. Future developments should focus on the generalization of the initial ideas of the designer and not on representing even more complexity.

**Support in creativity**

Together with the support in complexity is the support in creativity the field that the author claims as most potential for future development. Digital tools lack a sense of creativity, its actions are based purely on logic decisions whereas a human can rely on emotion, experience and so on. Nevertheless a digital tool can support the designer by presenting alternatives the designer. Future developments in computational intelligence and the ability to have tools that can learn and thus have experience to help in the judgement might change this situation. Whether this will work and, most important, is accepted by designers will need more research.

According to the author, the application of digital tools, in the early phases of the design process, can help the designer in the process of designing. By being involved in the development of custom tools, the designer approaches the design problem from a different direction. This can give him new insights and ideas. By working closely with the toolbuilder or even developing (parts of) the tool himself he can use this as a new way to visualize his ideas. Therefore it is highly recommended for future research to proceed in involving the designer and toolbuilder in the process of building design specific tools.
Practical Application

As discussed before the practical application of this thesis, on the design practice, is not a clear given. A number of decisions are based on the actions of the designer, this makes the results unique for this situation. As opposed to the actions of the designer, the actions of the designer as toolbuilder can be considered generalizable and useful in practice.

Sketching using code
The designer as toolbuilder led to a phenomenon introduced by Hugh Whitehead (2007) which he refers to as Sketching Using Code. The creation of the Voronoi tool is a good example of this; the script is created out of a vague idea in the mind of the designer and constructed along with the further development of the idea. The interaction between this development and the idea of using Voronoi led to improvements in both fields. In chapter three the author already referred to the link between technology and practice and the importance of feedback for the development of tools (fig. 5).

That this can also work as a disadvantage as is visible in the third experiment, where the development of the Construction Visualization tool did not go as anticipated and held the designer back in his process of designing. This is primarily because of the limited knowledge to solve that particular problem. In a multidisciplinary design team this is
not an issue but, as discussed before, the designer needs to be able to communicate his initial ideas and the toolbuilders needs to be able to react to this.

The possible advantages of a designer being a toolbuilder is a subject for further research. A successful implementation of this way of working relies on the knowledge the designer has in building tools and vice-versa. As the designer found out during this project, the amount of knowledge, of tool building, needed to successful apply this concept is of great importance. Further research on toolbuilding by designers, with a limited amount of knowledge about tool building, can help in this. This research should include the following topics: determine the amount of knowledge needed by the designer, implications on the design education and implications on the design process.

**When to use or build a tool?**

In this design project the goal is to research the relation between the designer and the digital tool he is using. To be able to do this, the designer is motivated to use digital tools whenever he found possible; the importance of using tools is chosen above the usefulness of the tool. This made the decision whether to use a digital tool for a certain design problem straightforward. In practice the decision to use or develop a tool can be more difficult. The questions of when, why and how to apply the tool is for the designer to make. It is the designers experience, during this project, that there are no distinctive criteria that he can use beforehand. The main objective is that the application of the tool is useful to the designer and/or the design project. Whether this is the case can be assessed once the tool is in use. This means that the designer should start using the tool before he can determine its effect. Nevertheless the designer can rely on his experiences and instincts to help him make this decision. Second the designer must keep
in mind that the tool is there to support him or the design following the criteria as used in this research. Once the tool does not fulfill these criteria the designer must decide whether to continue using the tool. In contradiction to the project done by the author, the use of the tool should be secondary to the progress of the design project. Further research in the architectural practice might reveal criteria that can help a designer make the decision to use a tool.

**Implications on the design practice**

In the introduction the author posed the research question: *What is the emerging relationship between the designer and the tools while exploring the design space?* During this thesis the author determined that the relation between the designer and the tools has another influence; the toolbuilder. It is the role of this toolbuilder that has its effects on the current architectural practice.

**Toolbuilders**

In this project the designer and toolbuilder are the same. This is a rather unique situation compared to the current architectural practice. One of the benefits of this situation is that the issue of communication is not a limiting factor; in this project the toolbuilder knows exactly what the designer is thinking and vise versa. In practice it is expected that designer and toolbuilder are not the same person. Especially in the early stages of the design project when the problems are not as clear defined and the amount of information is limited it is the designer who needs to communicate his ideas. In the introduction the author referred to possible problems with externalizing the designers ideas and the effects that it can have on the design process. The communication between designer and toolbuilder is one of the most
important issues when working together. A way of closing the gap between the designer and the toolbuilder is, as mentioned in chapter three, to introduce the toolbuilder to the process of designing. The author claims that the knowledge of the design process is essential for successful communication and understanding the tool to be developed. The architecture firm of Foster applies this quite literally by combining toolbuilders with the design team so that they can learn from each other and gain better understanding of each others profession (Whitehead 2007).

**Effects on the designer**

Besides the designer affecting the tool he uses, the use of tools also affects the designers way of working. Especially when the designer, as suggested in this thesis, is closely involved in the development of the tool these effects are apparent. As discussed previously, the act of **sketching using code** can help the designer in his process of designing. During the development of the tool the designer needs to formalize certain aspects of the design problem to be able to deal with them in a computational manner. This formalization needs a more structured way of thinking and can therefore help the designer to convert his thoughts and ideas into a design. The designer must be able to deal with this different approach. The more systematical way of thinking might not always fit the designer’s way of working. In this situation the designer should decide whether to continue by this manner or follow another way of working.
Importance of decisions

Besides the effect the need for formalization has on the designer’s way of working, it also has its implications on the design process. As defined in the third chapter the design process can be considered a process of decision making. As also defined in this chapter, the designer relies, during the act of designing, for a large part on his experience and intuition. This compared to the systematic way of decision making that comes with the act of exploring the design space. This difference is of great influence on the way the designer can move through the design space. The first limitation is discussed before: the possibility to take a step back, the feedback-loop. The systematic decision, of the designer, to formalize an aspect of the design project limits the amount of alternatives by the output the formalization generates. At first this might seem obvious and not necessarily negative, but the ability of the designer to decide to go in an other direction and ignore the formalization is of great importance to the outcome of the design project. The process of formalizing an idea usually requires time and effort which makes it difficult for a designer to ignore. This compared to more intuitive decisions which are generally easier to change. Therefore the author states that performing design space exploration techniques changes the importance of the decisions made by the designer. The process of formalization, common in design space exploration, makes it possible to study alternatives but also limits the ability to change the course of the design. Small changes are possible whereas large changes are more difficult to do. The designer should be aware of this.


Appendix A: Design

Brief and location
## Program

### Education

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**Total**                  |        |      | 3843     |
Location

TU Delft Campus - Delft, The Netherlands
The location is surrounded by the faculty of Civil Engineering in the north and the (former) faculty of Architecture in the south. On the left is the Mekelpark.
Appendix B: The Voronoi Script

The first version

The goal of this first version of the program is to be able to generate simple Voronoi diagrams. The program was written in the Maya MEL language. Instead of calculating every single point, I choose the simpler, but heavier in terms of processing power, way of doing it. The nice (and totally unexpected) addition is that I can watch how my volumes are built up during the script, like some kind of animation.

A single point, not directly related to the others...

...but we can identify a visual relationship...

...and generate a spatial relationship.
So how does the script work?

The script works by computing the Voronoi volumes one at a time (so point-by-point). It does this by creating the maximum possible volume and subtracting everything not part of the Voronoi. So the first step is to create the maximum possible volume, by taking all the points and creating a bounding Box around it which it scaled 1.1x to make sure all the points are inside the volume (and not in one of the surfaces).

From now on the script works by iterating through the complete set of points. Lines are drawn from the sampled point to all other points to connect them. On each line a plane is created at the middle point (T=0.5) and perpendicular to the line. This plane is extruded (away from the sampled point) with a distance bigger than the maximum distance found in the Bounding Box.

And this process is repeated using all points, and for every point. This is a very “brute force” way of creating the volumes, there is no
optimization concerning which points to take into consideration:
when the script is working with point A it not only uses the connection
between A-B, A-C, A-D etc. but also between B-C, B-D and C-D, and even
vice versa (C-B, D-B, D-C). All sets not directly related to the sampled
point (so in this case not connected with A) can be ignored. An idea for
future updates might be to optimize this and only use the direct related
points.

The results
The first results of the script were satisfying; it was capable of creating
three-dimensional Voronoi graphs based on a given set of points. These
first models gave good insight on how the Voronoi logic is “working”.

The second version
While running tests with the script I found that having a bounding box
as the outer limit of the Voronoi diagram to limiting. All the models
looked the same from the outside…. I wanted to have more control
over the boundaries of the object. Therefore two new functions were added: the ability to define your own polygonal boundary volume and the option to use a “Voronoi” boundary. Besides that a Graphical User Interface is created to make the script easier to setup.

**Polygonal boundary**

Instead of being limited to the default bounding box, it is now possible to define your own bounding box shape. The general rule being that all the point used for the Voronoi should be inside the shape.

**Voronoi Boundary**

A second option added is to create a Voronoi shaped boundary. The
idea behind this script is to create extra points at the borders of the bounding box. These points will be included in the creation of the Voronoi graph. These extra Voronoi volumes can later be deleted, thereby revealing the Voronoi structure to the outside. This can be set for any of the six sides individually.

The extra points are created by copying the initial set to the outsides. Because these copies are directional (a point will only be copied in the x, y or z direction) the edges will be parallel (black arrow) to one of the baseplanes (XY, YZ, XZ). To prevent this random number between 0 and a specified limit can be chosen, the point is moved in that direction too.
**Graphical User Interface (GUI)**

To make working with the script easier a GUI is created to access all the options. The various new options as described above are added.

**The third version**

As described before, the script works using a rather un-intelligent method, with a lot of overhead in the computation. When working with larger sets of points (20 or more) the computer ran out of available memory resulting in a crash of the program. Until this moment optimizing the script seemed useful but not necessary. The predicted set of points based on the program of the design was more then the 20 it could handle. Therefore optimizing the method of computation became a priority.

The most straightforward optimization that could be done was limiting the total set of points needed to calculate one Voronoi volume. The new version of the script uses the following method and makes it possible to use large sets (60 points with ease) of points as input:

[1] The distances from the sampled point to all the other points are measured and ordered ascending. The closest point is taken to calculate
the first Voronoi section.

[2] Before a point is used to create the intersection with the Voronoi, the script will determine if it intersects.

[3] In this case the green point will not intersect with the volume and therefore excluded from the calculations. This saves time and resources.
Appendix C: Voronoi Patterns
grid structures

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Points:

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<td>2.15</td>
<td>4.00</td>
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<td>4.00</td>
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</tr>
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<td>4.00</td>
<td>4.00</td>
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</tbody>
</table>

Points:

<table>
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<tr>
<th></th>
<th>max. Area</th>
<th>min. Area</th>
<th>avg. Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>5.09</td>
<td>1.41</td>
<td>4.00</td>
</tr>
<tr>
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<td>4.00</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>4.00</td>
<td>4.00</td>
<td></td>
</tr>
</tbody>
</table>
Attract with shifted grid
<table>
<thead>
<tr>
<th>Points</th>
<th>max. Area</th>
<th>min. Area</th>
<th>avg. Area</th>
</tr>
</thead>
<tbody>
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<td>3.20</td>
<td>4.00</td>
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<td>5.14</td>
<td>2.66</td>
<td>4.00</td>
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<td>4.72</td>
<td>3.15</td>
<td>4.00</td>
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<tr>
<td>36</td>
<td>4.79</td>
<td>3.35</td>
<td>4.00</td>
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</tbody>
</table>
random move in Z, 1.0 [top] 0.5[bottom]
regular grid
Random move (0.5) in x, z with regular grid bottom with removed if closer than 2
random move [1.0] in x, z with regular grid
bottom with removed if closer than 2
<table>
<thead>
<tr>
<th>Points</th>
<th>max. Area</th>
<th>min. Area</th>
<th>avg. Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>11.14</td>
<td>1.02</td>
<td>4.00</td>
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<tr>
<td>22</td>
<td>11.45</td>
<td>4.31</td>
<td>8.47</td>
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<tr>
<td>31</td>
<td>10.92</td>
<td>5.41</td>
<td>7.92</td>
</tr>
<tr>
<td>36</td>
<td>11.05</td>
<td>4.31</td>
<td>8.47</td>
</tr>
</tbody>
</table>
horizontal shifted grid with random move
vertically shifted grid with random move

Points:
max. Area
min. Area
avg. Area
vertical shift max 0.5

Points:
max. Area
min. Area
avg. Area
vertical shift max 1.0

Points:
max. Area
min. Area
avg. Area
horizontal shift max 0.5

Points:
max. Area
min. Area
avg. Area
horizontal shift max 1.0

Points:
max. Area
min. Area
avg. Area
shifted in both directions max 0.5

Points:
max. Area
min. Area
avg. Area
shifted in both directions max 1.0