Collaborative Planning with Digital Design Synthesis

Hrishikesh Ballal

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
of
University College London.

Centre for Advanced Spatial Analysis
Faculty of the Built Environment
University College London

September 14, 2015

I, Hrishikesh Ballal, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Abstract

The subject of this research is collaborative planning done digitally using simple diagrams to produce designs. This thesis intends to bridge the creative aspects of planning and design with a systems approach to problem solving. This topic merits research because most planning problems at the regional scale are “wicked” problems. [Rittel and Webber, 1973] Therefore, traditional methods of a solo designer that are used in architecture and landscape architecture are found lacking at this scale. There has been extensive research conducted using fully automated or agent based models on the regional scale. While some have questioned the utility of these models [Lee Jr, 1973] [Brewer, 1973], others have a more nuanced view and have explored in detail the concept of robustness in modelling techniques. [Wegener, 1994] [Box, 1979] Most problems at this scale are too complex for a single person to attempt to solve, the input and support of other experts and collaborators is key. This work is related to other work in Planning Support Systems (PSS) and Systems Approach (SA) to design in that it borrows the central concept that the key role of PSS is to increase internal consensus on designs produced. By applying a systematic approach to design, we are able conduct many experiments on the design process and evaluate results.

The systematic design process was approached through the perspective of the geodesign workflow. Carl Steinitz, Professor Emeritus of Landscape Architecture and Planning at Harvard University, developed some early and fundamental ideas about the geodesign workflow. [Steinitz, 2012] Steinitz developed a model of landscape change that enables design and assessment of alternative futures. The framework takes a multi-system approach to problems that is novel both from a design and from an analysis point of view. The “Steinitz Framework” has been put into practice for a number of years on large landscape change problems and in the form of intense two or three day workshops where participants from diverse academic and professional backgrounds and levels of experience come together and go through the process to build a design iteratively in a compressed timeframe. In that sense, this work is also a test for the framework in a digital setting. A specification for converting the workflow digitally is presented. A reference implementation of the specification was tested in a number of workshops with diverse participants. The goal was to test if "digital support" to design synthesis is indeed possible and to examine the implications of this on the creative aspect of a planning process. A new specification and a tool had to be built because most commercially available or opensource tools do not provide a good platform for this design workflow. The experiments show a planning support workflow that helps in collaboration and communication. This thesis reports on results of workshops conducted with this tool. The workflow presents a new way of collaborating with others, acting as a teaching aid in addition to acting as a platform for further research. In addition, this work contributes to the research on planning support tools by reporting on experiments that take a multi-system multi-stakeholder approach to planning problems.

A number of experiments were conducted using the tool and it was found that collaboration is indeed possible between various groups and experts over the Internet using widely available technologies and little hardware overhead. It was demonstrated that experts in different fields and varying level of experience can collaborate and understand a shared language and build plans using that language. In addition, the experiments showed the evolution of a design where the design gets progressively better over time and then after a point it gets worse. By having the ability to attach a version to a design and quickly produce more versions, participants were able to quickly iterate over design ideas and build plans using simple diagrams and diagram synthesis. This is possible very efficiently given the workflow discussed in the thesis is digital.

There are many implications for further research in planning using the software as a teaching tool. First, given that the tool is all digital, advanced analysis can be performed on the designs by widely available technologies such as GIS etc. Secondly, research can be performed in the design methods. In the experiments, seven ways of designing were tested. The tool allows free form design and collaboration as documented in the "Steinitz Framework", including the use of algorithms to build optimal goal based designs. Finally, the tool presents a great platform to teach students about planning problems at a regional scale. Given the multi-system approach taken, there are fundamental implications on the way planning is taught in universities and to professionals. With the framework and the tool, universities and professionals from different disciplines such as engineering, architecture etc. are able to collaborate in real time to produce plans and it paves a way for a more holistic planning thought in an academic or a professional setting.

Acknowledgements

I wish to express sincere appreciation and thanks to Professor Michael Batty and Dr. James Cheshire of University College London and Professor Emeritus Carl Steinitz of the Harvard Graduate School of Design. I am grateful for their constant support and patience with my work. Each of them has helped me immensely by shaping my thought process and constantly guiding me and having patience with me throughout their busy schedule. Undertaking this research under their guidance has been a life changing experience for me.

To the staff at Centre for Advanced Spatial Analysis, Sarah Sheppard, Lisa Cooper and Clare Crabb, thank you for your support and helping me, given my distance from campus. To all the friends I made here in CASA, they are too many to name, I will miss you dearly and I am hoping to collaborate with you in the future.

I want to thank all participants of the workshop for taking the time and providing valuable feedback. This work is not possible without your consideration.

This acknowledgement is incomplete without a mention of my family and the ones closest to me. This thesis is dedicated to my beloved wife Susan and our daughter Tara who was born during the course of this research and has been absolutely terrific baby and brought so much joy to us. Susan, you have always motivated and inspired me and I am thankful for your love and support through the very difficult schedule and trips to London and the 5AM start for the airport every week. I also would like to thank my Mom, Dad, my younger sister Sonali and her family for their support and encouragement.

Hrishikesh Ballal
March, 2015
Dublin, Ireland

Contents

List of Figures

List of Tables

Chapter 1

Introduction and Thesis Structure

Currently there exists a gap in the urban planning process. Geographical Information System (GIS) is now a well-established and mature technology and recently a lot of progress has been made on advanced 2D and 3D visualization technologies that work well with GIS data and analysis. Practitioners use GIS technologies to analyze problems and visualizations to share design ideas. However, both techniques a face huge amount of challenges for large scale, long term and regional level problems. This is because of the uncertainty due to time scales, multiple factors impacting the site and competitive interests and actors involved in any project. Additionally, the process of creation of design is still disjointed from that of analysis and visualization at this scale. Currently there is no way to join analysis and design procedures into a systematic, seamless experience to support both design and analysis at a regional level. This thesis describes an effective bridge between GIS analysis and the creativity of design into a seamless process. The systematic design process was approached through the perspective of the geodesign workflow with the central research question: What type of digital change management support is needed to enable the process? Using the digital workflow, this thesis documents five workshop experiments conducted to build a plan at a regional level and modern information technologies. Participants were able to collaborate and synthesize designs quickly and analyze the design performance.

The core problem between analysis and design is a problem of mis-communication and a lack of understanding and is solved by effective collaboration between various parties involved in the design process. Collaboration that enables a shared learning and shared understanding of the problem area leads to a design which can then be tested and iterated on multiple times. Communication is further facilitated by the idea of quick iteration and sharing portions of various designs. The workflow is novel and innovative in that it uses a multi-system approach and also enables free form design. Breaking down of a design into individual components enables deconstuction of a design problem into individual solutions which can be understood and compared by all. The innovation of digital synthesis of individual design components and the ability to use different design methods are also a key part of the collaboration problem. This research has significant implications for planning support tools, long term planning and also education in the context of complex regional planning problems.

Geodesign borrows from a number of different domains: architecture, engineering, landscape architecture, urban planning, the traditional sciences etc. and takes a holistic and complementary view of the design process incorporating the different stakeholders. The promise of geodesign when used in a digital environment differs from traditional design done digitally in the way it can be implemented. Traditionally, digital design involves the use of spatial optimization models of planning or allocation of land use to build a plan. Additionally, the workflow is around digitization and drawing of plan objects, which constitute a design in a serial fashion and once they are drawn, they are then evaluated for performance. However, in the context of geodesign, design deals with a collaborative design activity where the computers respond to changes in design as it is being built by various stakeholders. Thus what makes geodesign fundamentally different from traditional design process is the workflow or the process of creating a design. The ability to create a design collaboratively, measure impacts of the creation as you proceed and a platform of collaboration and communication form the basis of the geodesign workflow. Fast iteration and quick design cycles are also the way in which geodesign workflow differs significantly from a traditional one.

Prof. Carl Steinitz, an urban planner at Harvard University, is credited to have bought about some fundamental and early ideas about the geodesign workflow. Steinitz developed a model of landscape change that enables design of alternative futures. In the context of the work of Prof. Steinitz, design is both a verb and a noun; as a verb design is about asking of questions about how to solve the problem and as a noun design is the content of the solution itself. The framework has been put in practice for a number of years in the form of intense two or three day workshops, where participants from diverse academic and professional backgrounds and levels of experience come together and go through the process to build a design iteratively in a compressed timeframe. The framework takes a multi system approach to problems that is novel from an analysis point of view.

In 2015 the framework was transformed in to software that enables a digital design workflow. The digital workflow is an open system where the participants bring their data and ideas into the tool and after going through the various stages of the framework, they are able to collaborate and build plans to address the challenges the region faces. The tool is an open system and supports most commonly available geospatial file formats such as Shapefile, KML, WKT, GeoJSON etc. and data can be exported out in a Shapefile format. The system is fundamentally a designing aid that interacts with commonly available GIS data and other models and helps the users in building the design and finally the built data can be exported for use in advanced 3D visualizations etc.

The software includes a project setup step where the initial requirements are built into the project. The tool enables participants to create diagrams and select a number of them to build final designs by enabling digital synthesis. Diagrams can be built by sketching, importing existing feature data or linking to dynamic models. In addition, the tool provides a platform collaboration during design creation and also helps in analyzing the created designs. The versioning system implemented enables the users to iterate quickly on the design until they are satisfied with its performance. The tool enables multiple ways of collaboration: open mode, team mode among others and also supports multiple ways to design. The tool is novel in a way that it enables near real-time analysis of designs over multiple systems. The tool extends the existing work done in planning support systems and it can accommodate any model from any discipline as long as the model can output a map with three to five colors. The tool also mandates a specific use of colors and graphics which enforces a shared language of communication and enables broad collaboration among experts from very diverse disciplines.

The central research question for this research is: What kind of a digital workflow is required for change management in the geodesign workflow? This research is important because it has significant implications for the practice of geodesign, the research around planning support systems and also how systems based design works in a fully digital context. This is important also for work in the planning support systems community since a fully digital multi system workflow has not been tested for a regional planning context in the literature. The workflow also has significant implications for education and teaching students about complex planning problems. The planning support systems literature is filled with studies that demonstrate that the primary utility of a support system is to generate consensus among the participants. However one of the main reasons why support tools lack broad acceptance is because they do not fit well with the existing workflow and operate on a black box type model where the internal working is not transparent for the participants to understand how the tools work. Thus building a completely open system where all the data generated and used is bought by the participants would prove an important test around user acceptance and understanding.

To achieve the aim of testing the digital change model workflow, a new system was created from scratch since most of the current tools do not provide a good test base for this type of work since they are single system and work serially. Additionally, most of the tools are not capable of handling the many diagrams and conduct impact analysis on the diagrams on the fly and therefore it would not have been a true test of the framework. Therefore a new tool had to be designed since it was the only way to achieve test a digital synthesis workflow. The intention of the new tool was to replicate the workflow that is used in the “Steinitz Framework”, to conduct a series of experiments.

In the experiments conducted it was found that collaboration was indeed possible with experts from different fields over the internet using ubiquitous computing devices such as laptops. Five experiments were conducted: four with the same set of data and the fifth being an independent test. I was found that by walking through the framework, participants were able to create designs and analyze them dynamically. In addition it was observed that the workflow could be used with very little training and also existing data and datasets could be used to conduct the workshops.

This work is original in the sense that it is a both a framework test as well as a tool which enables collaboration over the internet. The different workshops show that collaboration is indeed possible with various experts and non-experts even when they use markedly different design styles. The technical implementation is totally novel in that no one has attempted to implement a framework at this scale. Additionally, this research has been able to push the boundaries of design creation by enabling quick version creation and iteration over an existing design. The workshops show that the first design is rarely the best one and only through a process of iteration can better designs be achieved. The other aspect that is original is that a new system for digital design synthesis was created and it is model and system agnostic: it has been able to accommodate different disciplines, methods and professions and give them a way to collaborate.

Chapter 2: Designing in Diagrams

Chapter 2 discusses the theory behind designing in diagrams to understand and the relation of diagramming and early stage design and digital tools for diagramming support. Designing with diagrams is introduced and this chapter reviews how diagrams provide a bridge between maps, ideas and concepts. Diagrams are graphics and abstract representation of ideas or real world spatial phenomenon. This abstraction promotes understanding and comprehension of elements, relations, ideas and concepts. The chapter reviews some early contributions to digital sketching to provide a context for the work around a geodesign workflow. The focus of this review is to highlight research around cognition and diagrams and digital tools for diagrams and sketching.

Chapter 3: Systems Approach to Design

This chapter tries to put context to a systems approach to design. The nature of the design process as a problem solving process and its implications are reviewed. The review expands on the cognitive aspects of problem solving and the theories of Herbert Simon and Christopher Alexander. The focus of this chapter is on design synthesis and its role in a design problem solving context. Various synthesis strategies are reviewed. Finally the chapter concludes with a primer on digital design synthesis and how tools can play a part enabling design synthesis. The primary aim is to do a literature review and highlight the big picture around a systems theory of design by reviewing important contributions over the decades.

Chapter 4: Planning Workflow and Geodesign

This chapter covers the planning workflow in the context of planning support tools. After having reviewed designing with diagrams and a systems approach to design, this chapter introduces planning support tools and highlights the key shortcomings that prevent widespread use. The fundamental concepts of geodesign are highlighted in addition to elaborating how geodesign differs from the traditional design processs. The Steinitz framework is understood in deeper detail by documenting a workshop that was conducted with no technology support and conclude by making a case for digital workflows.

Chapter 5: Digitizing the Geodesign Workflow

This chapter deals with answering the central research question: What kind of digital workflow is needed to support change synthesis? Written in the form a specification document for a tool, this chapter takes the workshop example presented in Chapter 4 and uses it to identify opportunities for digital intervention. The key objects and data structures that are needed to convert the geodesign workflow into a digital format are identified. The chapter specifies the technical and performance characteristics of the workflow. Important user scenarios and actions are identified and then extrapolated in the form of technical specifications. These specifications contribute to the understanding of geodesign process and also building multi system planning support tools. The chapter details user interface references, performance characteristics, key operations and objects that are necessary for collaboration.

Chapter 6: Experiments in Geodesign Synthesis

This chapter discusses a series of experiments that were carried out in 2014-2015 using the newly created digital workflow. A dataset from a geodesign workshop in Japan is documented. This workshop was partially digital and using the data and the specification described in Chapter 5 a new tool was built. This chapter reports on the key development milestones of the tool and also the key results of the experiments. The final test was carried out at the University of Georgia to build a plan for Chatham County in Georgia in 2015. This chapter shares key learnings and feedback from participants in these workshops and also how the workflow progressed from its early stages to the final experiment in Georgia.

Chapter 7: Discussion and Future Work

This chapter concludes the thesis by giving a summary of the research, key findings and implications for future work. Some of the key areas for further research are discussed including: linking to Dynamic Models, Smart Diagrams, Design Methods and Scales, Crowd Sourced Design and Design in data poor environments. In addition, this chapter speculates on the implication of this work on education and practice.

Chapter 2

Introduction to Designing in Diagrams

From the earliest cave paintings humans have been skilled at constructing, understanding and communicating through diagrams. The study of diagrams has evolved into a field of its own with interest from researchers in Artificial Intelligence, Human Computer Interaction and many other domains since it has clear implications for cognition and computation. The purpose of this review is to give a broader picture of the existing literature around diagrams and understand key insights from previous research and the implications for tools that support digital diagramming.

In planning and architecture diagrams are used extensively to explore and communicate solutions particularly in the early stages of the design process. A significant aspect of drawing in diagrams, in the context of architecture and planning, is that they are flexible: in that they are iterative and accommodate reorganization and adaptation as the ideas evolve. Due to this feature, diagrams are most useful in early conceptual design phases. In that sense, a diagram represents the germ of a design idea, a graphical abstraction; it identifies only key elements and relationships in a design and omits any other information that is not necessary. In architecture and design diagrams embody a large number of graphical indicators: topology, shape, size, position and direction. Gross et al. describe diagrams as simple and powerful mental tools for managing large, complex data sets. They are abstractions resulting from the communication of information-rich concepts, key design ideas and the process of selective information loss, which has the purpose of identifying key or essential ideas. Thus a diagram is at once simpler, and more evocative than any of the more specific drawings that derive from it. [Gross et al., 1988] Diagrams have been extensively studied in literature and here the goal is to understand the nature of diagrams, how they are perceived and their importance in early stage design.

2.1 Introduction to Diagrams

Graves argues that referential sketch is a kind of a drawing that is an architect's diary or a record of discovery. [Graves, 1978] Diagrams are very common in sketchbooks of architects and designers and they are important tool used by them in solving design problems. As an example, Figure 2.1 shows a series of diagrams of the Goldberg House design. Here it is observed that the designer Kahn is exploring arrangements of different spatial objects using shapes such as square, rectangle and arrows. These limited number of symbols when combined together as below show a diverse amount of information and build help in communicating the core idea and building up to it. This is the power of diagramming: a lot of information can be communicated around spatial and other features with the use of very limited and simple symbology.

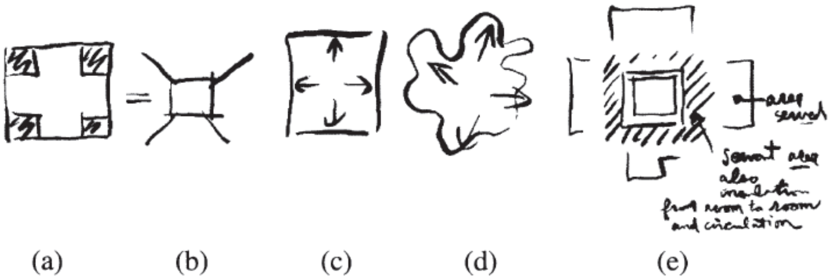


Figure 2.1: Diagrams with Simple Geometric Shapes for Goldberg House Design in Rydal, Pennsylvania [drawn by author after Louis I. Kahn, (Perspecta 1961)] [Do and Gross, 2001]

One of the salient characteristics of Kahn's diagrams is that they do not appear very “realistic”, a characteristic that is explored in detail by Tovey who describes two type of drawings: [Tovey, 1989]

1. *Schematic and diagrammatic drawings* : Schematic and diagrammatic drawings are more abstract representations of the underlying principles of an idea (as shown in Figure 2.1 above). At its most abstract a drawing can be simply a representation of, for instance, the sequences of an evolution of an idea. The value of this sort of approach is that the design ideas can be converted into more than one design for a specific object using abstract diagrams. As is shown in Figure 2.1, any of the sketches could be converted into a design idea that can be implemented in different geographies.

2. *Ideas sketches* :These are representational drawings that attempt to show what the design ideas look like as physical objects. They are useful for investigating the appearance and visual impact of such ideas.

Thus we have essentially two types of diagrams: one that provides a schematic representation of concepts and the other that communicates the appearance of such ideas. Purcell summarizes very succinctly the prior work towards the understanding of the role of drawing in design. [Purcell and Gero, 1998] This provides a comprehensive review of work relating to many types of drawing activity in the design process, including figures, diagrams and more general imagery. However we will focus our attention on sketches and the study of sketching and drawing since that is more relevant from a planning and urban design perspective.

2.2 Visual Thinking and Diagram Cognition

"A picture is worth a thousand words" is a proverb that might also be applied to diagrams. To understand whether diagrams really are better we need to understand the cognitive aspects of these representations and its implications on comprehension performance. Only then can we develop an understanding about the suitability of diagrams in design. Understanding the cognitive process associated with diagram comprehension will enable us to isolate the key requirements of effective communication to inform digital tool creation. The cognitive science literature largely explores the interaction between internal and external representation and how they are linked. That is how diagrammatic representation is processed using internal mental models.

Traditionally cognitive modeling explored the interplay between these two states. [Norman, 1988] However, for this research the focus is not so much on the specific internal representations but more so on the process of cognition and how these representations help in processing. [Scaife and Rogers, 1996] This work focuses on simple two-dimensional representations and not animations or three-dimensional representations as far as architecture and urban planning are concerned.

Diagram cognition can be understood by two seminal studies: one from geometry and physics and the other on logic. Larkin and Simon included a qualification (in parentheses) in the title of their paper "Why a diagram is (sometimes) worth ten thousand words". [Larkin and Simon, 1987] Larkin and Simon compare sentential and diagrammatic representations as a way to compare computational efficiency of the reader. Which representation is more efficient? They outline an experiment where two representations are informationally equivalent and then tested for operator comprehension and efficiency. They show a diagrammatic representation of a pulley and weights and a sentential one where the arrangement is described (refer Figure 2.2 and 2.3). From a cognitive processing point of view, the diagrammatic representation was demonstrated to be superior to the sentential one. It is observed that the efficiency of information processing depends on operator comprehension and the organization of information presented. This is a simple yet profound conclusion that proves that diagrams can be used to communicate ideas and increase comprehension for a certain class of problems over traditional textual representation. Larkin and Simon characterize spatial problem solving as a search activity. Their results show that for information where location and arrangement are important, in a diagrammatic representation, the search and problem solving mechanism is more efficient. A diagrammatic display can be regarded as an arrangement of various graphic elements in space and makes it easier for the subject to process. It is one of the reasons why diagramming is more efficient than text representations particularly in the creative and planning fields. To illustrate this point, a study is shown below. The text in Figure 2.3 and the diagram in 2.2 below was presented to a group of people and were tested for comprehension; both the text and the diagram are informationally equivalent.

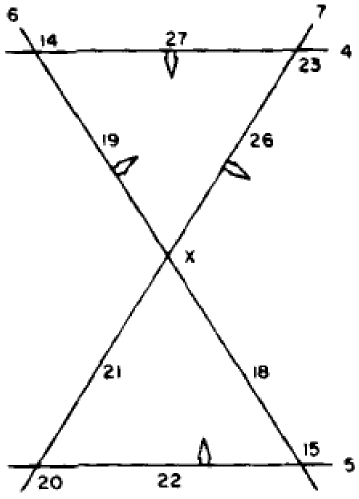
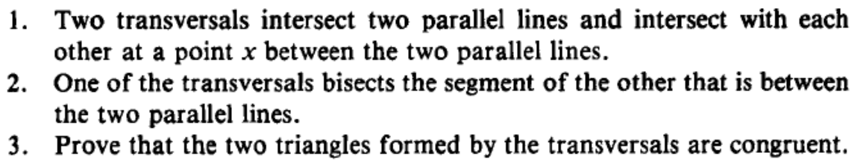


Figure 2.2: Diagrammatic Representation [Larkin and Simon, 1987]



1. Two transversals intersect two parallel lines and intersect with each other at a point x between the two parallel lines.
2. One of the transversals bisects the segment of the other that is between the two parallel lines.
3. Prove that the two triangles formed by the transversals are congruent.

Figure 2.3: Sentential Representation [Larkin and Simon, 1987]

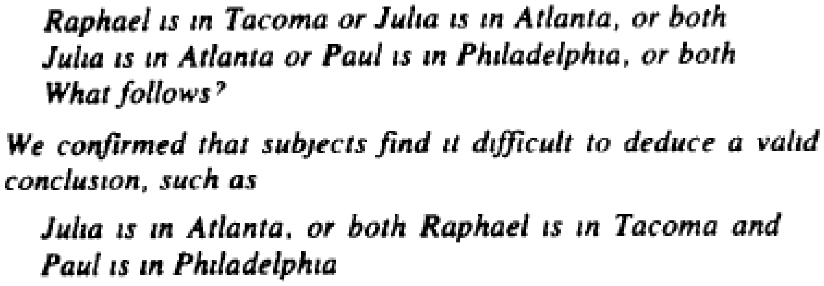
It is found that participants perform significantly better at comprehension when the representation is diagrammatic. This is because diagramming improves the search participant's search efficiency. The key search heuristic that is employed are:

1. Search operating on the node-link structures
2. Recognition that matches the condition elements to data elements located through search.
3. Inference of the associated new (inferred) elements to the data structures.

In this scheme, the recognition and inference aspects of the process are complimentary to the search process particularly when it comes to spatially explicit diagrams. This key feature speeds up cognition of such diagrams.

A analogy would be that of the chess board. While everyone can "see" a chessboard, the way search, recognition and inference functions operate between a chess expert and a novice are totally different. An expert sees moves with the vacant elements of the board and in addition recognizes the moves and processes that can be played on the chess board, while a novice may just see empty spaces and their arrangement. This recognition and inference pattern is a totally different process between the two user groups. In a sentential representation, to construct a solution for a problem, the users must do a lot of perceptual enhancement that is easily visible in a diagrammatic representation. Larkin and Simon further demonstrate that for a geometry type problem the diagrammatic representation is the most useful since all the perceptual information is added at no cost by the user's visual system. [Larkin and Simon, 1987] It is this powerful perceptual enhancement where the locations of various elements are explicit that make diagramming powerful and very relevant to the urban design field. This is one of the fundamental features of using diagrams as a communication medium between planners and designers and forms the basis of visual thinking.

Similar results are found in the context of logic building and comprehension. Bauer and Johnson-Laird studied the effect of double disjunctions and analytic reasoning with sentential and diagrammatic disjunctions. They tested sentential and diagrammatic representation of the following logic problem depicted as text and as diagrams. [Bauer and Johnson-Laird, 1993] (refer Figure 2.4 and Figure 2.5)



Raphael is in Tacoma or Julia is in Atlanta, or both
Julia is in Atlanta or Paul is in Philadelphia, or both
What follows?

We confirmed that subjects find it difficult to deduce a valid conclusion, such as

Julia is in Atlanta, or both Raphael is in Tacoma and
Paul is in Philadelphia

Figure 2.4: Sentential Representation of a Logic Problem [Bauer and Johnson-Laird, 1993]

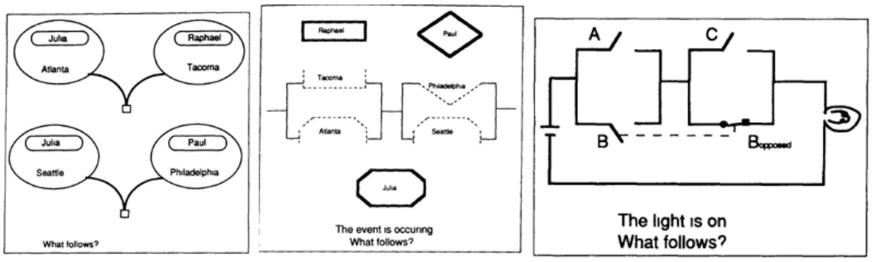


Figure 2.5: Diagrammatic Representation of a Logic Problem [Bauer and Johnson-Laird, 1993]

The participants either had to read the text or see the diagrams to build a logical conclusion to the problem. The study tried a number of diagrammatic representations for comparison shown in Figure 2.4 and 2.5 above. The second and third diagram (logic and jigsaw) in Figure 2.5 representation performed far better than the sentential and the first diagrammatic representation.

Bauer and Johnson-Laird in their study demonstrate that the graphical representation substantially helped in logical problem solving in terms of aiding, search, recognition and inference. [Bauer and Johnson-Laird, 1993] This has interesting implications on what constitutes an effective diagram particularly with respect to human cognition generally. Thus these studies demonstrate that diagrammatic representation is indeed better for certain types of problems. Scaife and Rogers share a framework to understand how effective representation reduces the amount of cognitive effort. [Scaife and Rogers, 1996] This is a useful way to think about why diagrams are more useful than text, in that they enable: [Cheng et al., 2001]

- *Computational Offloading*: The extent to which external representations reduce the amount of cognitive effort.
- *Re-representation*: How different representations that have the same abstract structure make problem solving difficult or easy. (e.g. LXVII x X is much more difficult to solve than 68 x 10)
- *Graphical constraining*: The closer the coupling between the elements in the visual display and the represented world, the easier it is to infer.
- *Temporal and Spatial Constraining*: Making the process and events more salient when distributed over space and time.

2.3 Diagrams and Design

It is hoped that the above has demonstrated why and how diagrams perform better than texts for some type of problems, particularly ones involving spatially explicit information. It therefore makes sense to explore design problems and how diagrams are useful in solving them. While the interest is in urban design and planning, the review begins with generic problems of design to get a broader perspective. The aim here is to understand the structure and the mechanics of design problems because they are fundamentally different than other logical or computational problems.

2.3.1 Well-structured and Ill-structured Problems and Solving Them

A useful way to distinguish between general problems is by classifying them around their structure as either well-structured and ill-structured. A well-structured problem is one in which the information necessary to construct a problem space is specified. [Goel, 1992] Figure 2.6 and Figure 2.7 detail a visual representation of well structured and ill structured problems. The chessboard example mentioned previously is considered again to discuss this distinction. In a chess board, start state, end state and all the possible moves within these states are specified. Rules exist that enable participants to judge whether a "move" is legal and therefore enables the problem to be transformed from one state to the other. On the other hand, most design tasks have a number of variables, a large problem space and many ways that it can be transformed. There are no "rules" as such and no way to judge whether if a step is not permitted in the design context. This is the nature of problems that need creativity to solve them and most design problems fall in to this domain.

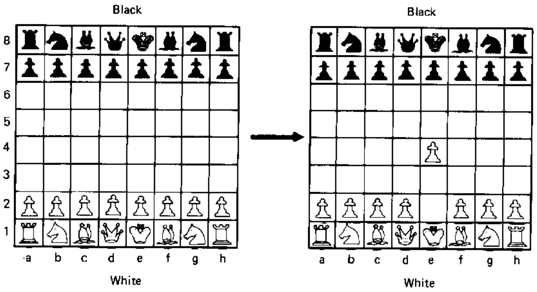


Figure 2.6: Diagram of a Well—structured Problem [Goel, 1992]

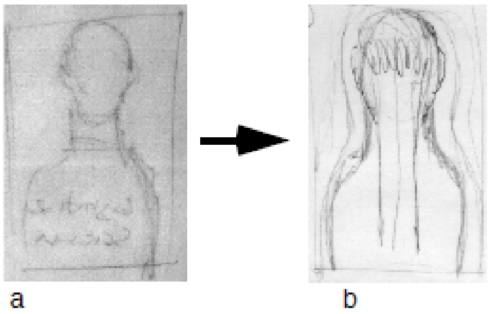


Figure 2.7: Diagram of a Ill—Structured problem [Goel, 1992]

Goel identifies seven properties that distinguish well-structured and ill structured representations with the first five adopted from Goodman [Goel, 1992] [Goodman, 1976]:

1. Syntactic Dis-jointness: Each token belongs to at most one symbol type.
2. Syntactic Differentiation: It is possible to tell which symbol type a token belongs to.
3. Un-ambiguity: Every symbol type has the same referent in each and every context in which it appears.
4. Semantic Dis-jointness: The classes of referents are disjoint; i.e., each object referred to belongs to at most one reference-class.

5. Semantic Differentiation: It is possible to tell which class a particular object belongs to.
6. The rules of transformation of the system are well specified.
7. The legal transformations of the system are such that these properties are preserved at each and every state.

To elaborate, the diagram on the right in Figure 2.7 is an ill-structured representations because it does not fit the seven rules mentioned above. Specifically, it does not have any rules of transformation; it does have syntactic dis-jointness or differentiation. Indeed many people would have a number of interpretations on the figure on the right. Is it a light-bulb or a caricature of a person? There is no correct answer. Goel argues that ill-structured problems cannot have well-structured representations because of the lack of clarity in the rules of transformation, symbology and descriptions. Thus ill-structured problems need abstract representations to trigger certain cognitive processes to come to a solution. This is because of the ambiguous nature of diagrams that leave them open to interpretation thus most useful in solving ill-structured problems.

Simon asserts that most of the real world problems faced by designers, planners, professionals and architects are best regarded as ill structured problems. [Simon, 1977] They become well-structured problems only in the process of being prepared for the problem solvers. It is not exaggerating much to say that there are no well-structured problems. To put it in a different way, there are only ill structured problems that have been formalized for problem solvers. This is a useful approach to have towards problem solving since adding structure bounds the problem space and enables designers to focus on the solution. Figure 2.8 shows a system that is used to solving ill-structured problems.

Simon argues that there is no real boundary between well-structured and ill-structured problems and therefore algorithms, Artificial Intelligence (AI) etc can be well equipped to solve these problems. Instead he states that all problems are ill-structured problems and all we have are a set of requirements, that are a list of criteria and that these collectively can change the nature of the problem from an ill structured problem to a well structured one. These criteria are not final and he concludes that a problem can be a well structured problem if it has the following characteristics:

1. There is a criteria for testing a proposed solution and a mechanizable process for applying the criteria.
2. There is at least one problem space in which can be represented the initial problem state, the goal state and all other states.
3. Legal moves can be represented in the problem space
4. Any knowledge that the problem solver can acquire about the problem can be represented in one or more problem spaces.
5. If the actual problem involves acting upon the external world then the definition of states changes and the effects reflect the laws that govern the external world
6. Finally, the solutions can be reached with practicable amount search.

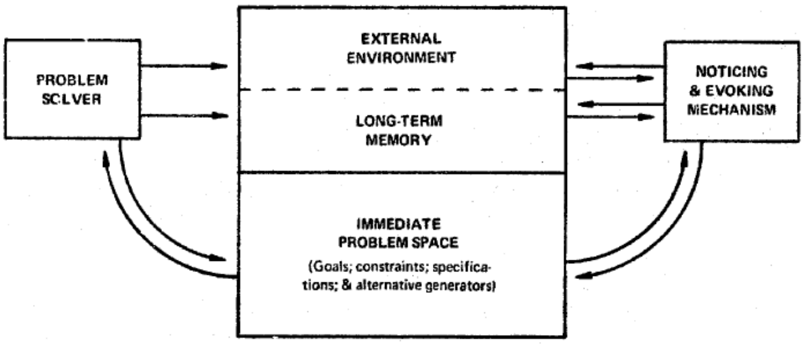


Figure 2.8: System for Ill-structured Problem Solving [Simon, 1977]

Goel demonstrated that design solutions have four distinct phases: problem structuring, preliminary design, refinement and detailing. [Goel, 1995] The nature of the problems

Figure 2.9: Phases of Design Solutions [Goel, 1995]

changes from ill structured to well-structured as the designer advances in the solution. Goel sets about a framework of describing how a designer navigates this framework (schematic shown in Figure 2.9) by doing lateral moves (in the first two phases) and what he calls vertical moves in the latter two phases. [Goel, 1995] The lateral moves are around different possible solutions that may or may not be similar and then once a satisfactory idea is found, the designer then moves in a vertical fashion.

According to Goel, this generation and exploration of alternatives is facilitated by the abstract nature of information being considered, a low degree of commitment to generated ideas, the coarseness of detail, and a large number of lateral transformations. He further defines a lateral transformation as one where movement is from one idea to a slightly different idea, rather than a more detailed version of the same idea. Lateral transformations are necessary for the widening of the problem space and the exploration and development of kernel ideas. [Goel, 1995]

The refinement and detailing phases are more constrained and structured since it is an iterative phase and in some ways the “search” phase has been completed. There are phases where commitments are made to a particular solution and propagated through the problem space. They are characterized by the concrete nature of information being considered, a high degree of commitment to generated ideas, attention to detail, and a large number of vertical transformations. A vertical transformation is one where movement is from one idea to a more detailed version of the same idea. It results in a deepening of the problem space. [Goel, 1995]

One way to think about these lateral and vertical moves is by characterizing them as a search for the problem space and as the designer progresses in their work, they start to move “vertically” or “zoom-in” to a solution by progressively refining and the solution. This framework is a useful way to think about how designers solve design problems. To illustrated this, Goel documents an experiment where freehand drawing is compared to drawing / painting in MacDraw with the following three hypothesis:

- Free-hand sketching is syntactically denser than MacDraw.
- Free-hand sketching is semantically denser than MacDraw.
- Free-hand sketching is more ambiguous and/or non-disjoint than MacDraw.

The experiments demonstrate that for the development of lateral solutions and search, ambiguous drawings and representations are necessary. Additionally, programs like

MacDraw hamper exploration and development of possible solutions since the subjects are constrained by the drawing tools. This has significant implications for digital tools for sketching particularly in the early / conceptual stages of designs. The experiments tell us that sketching and ambiguous design is an important component of preliminary design and any conceptual design tools should support free-form sketching. Thus the designer starts with ill-structured problems, puts constraints on them and then advances to the solution phase with the help of diagrams.

To understand this phenomenon better, the mechanics of sketching and how it enables design formulation should be illustrated. As is shown above, this notion of lateral search is very relevant to the problems of early stage design where the solution is not yet decided. Designers use sketching at the earliest phases of design to help them with problem structuring and organization. This kind of free-hand sketching is usually employed at the front end of design. As discussed earlier, design problems are generally very loosely framed and conceptual sketching is a technique designers use to better define and frame a problem. In early design stages, when the designer does not have an availability of displays or visuals so sketching is a way to quickly build these visuals to understand the problem and explore the solution space.

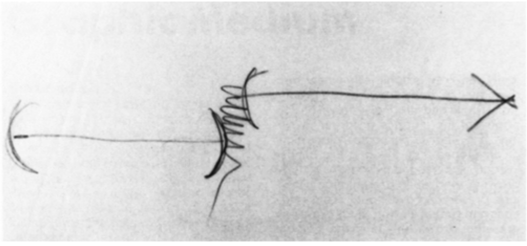


Figure 2.10: Example of an Architectural Study Drawing [Herbert, 1988]

In his research on Architectural study drawings, Herbert proposes a theoretical framework for extending our understanding of sketching and study drawings. [Herbert, 1988] A example of a study drawing is shown in Figure 2.10. He identifies five properties of study drawings that affect the origin, nature and methods of obtaining knowledge in a design. The five properties as identified by Herbert are:

1. *Hidden Structure*: Study drawings always represent a set of hidden structural relations that entail irreversible losses of information about the design problem which they are intended to solve.

2. *Gaining Information*: Study drawings provide the graphic means to add information from our cognitive experience to the solution of design problems.
3. *Graphic Conventions*: Study drawings use rudimentary graphic conventions as a basis for changing from a private to a public audience and for recalling remembered images.
4. *Continuity and change*: Study drawings provide both continuity and change in a dynamic working process for studying design problems.
5. *Drawings as a metaphor*: Study drawings act as graphic metaphors for extending from the known to the unknown in design problems.

These properties provide an insight on the nature of study drawings since they are more than mere sketches of thoughts or ideas, but play crucial part in the design process itself.

2.4 Sketches and the Design Process

Sketching is a technique that almost all designers use to communicate, refine and analyze their initial ideas. It is a creative exercise that embeds design intent and consideration at the earliest stages. Sketching and diagramming are an essential practice that every designer uses, not just to document an idea but help to refine, regenerate, and focus it. Study drawings are usually private drawings by designers as they start to tackle the design problem and help in problem framing and exploration, thus putting structure to ill-structured problems. In the process of sketching the designer walks through different concepts to come up with a design solution. The relevance of study drawing as a part of the drawing process has been studied widely in literature. Before sketching comes concepts.

Hertz defines a concept as an idea that has been prepared for use by an act of will. [Hertz, 1992] This means that all concepts are ideas, and the idea is the fundamental unit of the mind. When an idea becomes a concept, it is related to other concepts of the conscious part of the mind at least as an unidentified object or phenomenon. Lawson elaborates on this: "*Design involves a highly organized mental process capable of manipulating many kinds of information, blending them all into a coherent set of ideas and finally generating some realization of those ideas*". [Lawson, 2006]

Thus there is a distinct way that designers solve problems that comes from concepts and sketching. Cross distinguishes the “designer-ly” ways of problem solving as a distinct activity from scientific and scholarly activities. [Cross, 2006] Fundamentally, this implies that scientists and designers operate differently in that scientists problem solve by analysis and designers by synthesis. The ability to generate a satisfactory solution quickly is the key to synthesis. This is because most of the design problems are ill-defined and the designer will never have access to exhaustive and complete analysis of all the aspects of the design problem. This is the fundamental difference between science and design: Science is analytic while design is constructive. [Cross, 1990] The designer knows tacit information from experience and prior knowledge and practice in the same way that a martial artist knows his art. Cross identifies five aspects of designer-ly ways of knowing that are the key characteristics of designers and the design problem:

- Designers tackle “ill-defined” problems
- Their mode of problem solving is “solution-focused”
- Their mode of thinking is “constructive”
- They use codes that translate abstract requirements into concrete objects
- They use these codes to both “read” and “write” in object languages.

Having demonstrated the nature of sketching, how does sketching help designers? Fish states that sketches help designers attend to thought and help trigger short-term memory. [Fish, 1996] Goel argues that drawings are used as “external symbol systems” to represent real world artifacts which can be manipulated and reasoned with [Goel, 1995]. Mezughi argues that sketching is the principal means of visualizing design solutions and crystallizing the thinking process. [Mezughi, 1996] In architecture, these sketches and drawings are called as Conceptual Diagrams and they represent core ideas of a design. Dogan and Nersessian in their study of conceptual diagrams define some characteristics of a conceptual diagram [Dogan and Nersessian, 2002]:

- they embed the core of a design solution encapsulating its generic characteristics and constraints and conveying the form of possible specific solutions

- they are not detailed thus preventing early commitment to a specific design solution and, thus, they facilitate exploratory reasoning
- they are not ambiguous in the way sketches are in that they fix meaning and define a set of related solutions

Dogan and Nersessian also identify two properties of a diagram that make them especially useful for collaborative designing and communication [Dogan and Nersessian, 2002]:

- Conceptual diagrams provide idealizations that represent complex ideas in a simple and easily communicable and retainable form.
- They can represent spatial, functional, or formal relationships. These two characteristics make them important in collaborative design problem solving and communication with the client.

Dorst demonstrates that the “problem-solving” aspect of design can be described usefully in terms of Maher's model of the co-evolution of problem and solution spaces, and that the “creative” aspect of design can be described by introducing the notions of “default” and “surprise” problem/solution spaces by their study of the design for a dust bin for the Dutch railways. [Dorst and Cross, 2001]

2.5 Sketching Deep Dive

The process of creating a sketch in the context solving design issues with a focus on mental and cognitive aspects of sketching is of interest here. In a series of papers Goldschmidt studied the protocols of both novice and experienced designers. She identifies sketching as interactive imagery. [Goldschmidt, 1991] One can only retrieve an image of something that was previously perceived. Therefore, the difference between ’ordinary’ imagery and interactive imagery is that in the case of the latter, in the process of creation of the sketches, images are not retrieved from memory at all. In the early phase of design the entity that is being designed does not yet exist and therefore could have never been perceived. This is why sketching is so helpful in that it helps the mind perceive the object to be designed. Consequently the process takes on a new dimension when it is seen as an interactive process of symbolic representation. The aim of this next section is to understand literature on design studies and protocol analysis to build a comprehensive understanding of the role of sketching in design activity. It will then explore how this is used in the context of planning support tools. Design sketches are different from "drawing an object". It is an exercise where the designer is involved in a process of creating and defining an imagined idea. Sketching is not used in planning and architecture exclusively.

Goldschmidt asserts that the purpose of this early sketching activity is primarily to avail oneself of potentially meaningful clues to the solution of the design problem. Hence, early sketching is sketching done by the designer before the problem space is crystallized. The early sketches provide clues that can be used to form and to inform emerging design concepts. Goldschimdt found that the designer uses imagery in a peculiar way: they read off the sketch more information than was invested in its making. This becomes possible because when the designer puts down on paper dots, lines and other marks, new combinations and relationships among these elements are created that could not have anticipated or planned for. The designer discovers them in the sketch as it is being made, and some of these new configurations can potentially provide useful clues. Seeing something as something else (which is not there physically) is the essence of imagery, and since in this case imaging is brought about through sketching, Goldschimdt calls this process interactive imagery. This is the nature of sketch design where it is necessarily iterative and subsequent sketches more refined and communicate more information than previous ones.

Goldschmidt divides the design process into a series of moves and arguments. A move in the design process divides the activity in to the smallest units of design reasoning. Arguments are statements or questions about the design entity or the design itself that are posed by the designer in their mind. Goldschmidt relates the sketching activity as active sketching within a move or whether the sketcher is reading off a sketch, i.e. deriving information from a sketch. She classifies the arguments as "seeing as" and "seeing that" where the designer sees the actual sketch and then infers from the sketch emergent properties and reinterprets the sketches.

Goldschmidt further argues that the process of sketching is particularly effective in solving the ill-structured design problem in that the designer has to construct an artefact and the process of sketching is an effective way to test and arrive at a single design relatively quickly. She presents sketching as a process of a series of activities and often designers make a number of sketches: each sketch generates images in the mind, and these images inform a continued search for greater coherence that leads the designer to transform the previous image by adding, deleting, modifying or replacing certain parts. [Goldschmidt, 1994]

Goldschmidt's work presents insights into the mind of the designer and how they work and process information as they sketch. Goldschmidt contrasts the process of sketching to use of the most prevalent computer tools in early stage design:

- *Brevity and Vagueness*: Sketching can be extremely brief and vague and use some sort of a personal 'shorthand' notation in the imagistic process of reasoning about the forms he or she elicits through sketching.
- *Algorithmic*: To date, computers operate well on an algorithmic basis. They are still rule-based and incapable of making the leaps that a person using imagery can make to create a match between a totally new pictorial configuration and some previously stored information that may be encoded in an altogether different way.
- *Economical*: Free-hand sketching is economical because it can be carried out very fast, but also because transformations are particularly easy to achieve if layers of transparent (or translucent) paper are superimposed one on top of the other, as is usually the case in contemporary architectural practice.

Suwa introduces the term "figural concept" to describe the prevalent building block of the process of making a design. [Suwa et al., 2000] The way these building blocks are built is a process of search that exchanges imagery in the mind to that of sketches on a paper. This is visual thinking. Thus it can be concluded that the free-form nature of sketching and how they encourage solutions at early stage design. The ambiguity and the lack of detail are in fact key aspects of early stage design that make diagrams and sketching particularly powerful.

Schon and Wiggins broadly corroborate the findings for Goldschimdt. They describe the sketching activity as a "reflective conversation with the materials of a design situation". [Schon and Wiggins, 1992] The designer, by the process of drawing, discovers features and relations that give them a better understanding of the problem space. This reinterpretation also leads to discoveries and evolution of the design and thought. Designing serves as a base for further designs, that the discoveries and interpretations from past and current designs are carried over by designers to other projects. In agreement with the findings of Goldschimdt, they conclude that the seeing function is nuanced and is beyond visual comprehension or literal seeing of objects. It provides a method for reinterpretation and creative capacity that feeds to the next iteration of the design. Having reviewed the design process and some of the characteristics of sketching, a few protocol studies of the design process will be reviewed.

Protocol studies will help us analyze the design process from a designer's perspective and also help understand the implications for design tools particularly in early stage design problems. Studies in the other design professions also corroborate the findings. In his work for the automotive design world, Tovey details the roles that designers ascribe to such representations in design. [Tovey et al., 2003] Sketching in the automotive design world is useful in:

- Generating concepts
- Externalizing and visualizing problems
- Facilitating problem solving and creative effort
- Facilitating perception and translation of ideas
- Representing real world artefacts that can be manipulated and reasoned with
- Revising and refining ideas.

Similarly, Suwa, Purcell and Gero summarize the conceptual diagrams and their properties in the following way [Suwa et al., 1998]:

- Sketches serve as an external memory in which to leave ideas for later inspection.
- Sketches serve as a provider of visual cues for the association of functional issues.
- Most importantly, sketches serve as a physical setting in which functional thoughts are constructed on the fly in a situated way.

2.6 Methods to Study Sketching

It has been shown that the fundamental utility of sketches is same for architecture, planning and other domains, in that they are design aids that help in the creative process and facilitate communication and collaboration at a stage of the problem where there is a lot of ambiguity. Conceptual sketching provides a very fast and easy way to iterate over a design problem and come to a solution. Thus sketching or doodling is an effective way to work thorough a complex architectural problem.

In the literature, the process of sketching is primarily studied by three different techniques:

1. by analysis of think-aloud protocols,
2. retrospective analysis of the process,
3. introspection.

The "think-aloud" protocol involves the designer verbalizing his/her thoughts as they are designing. There is an analysis of the verbal recordings and the graphical sketches for co-relations, causation and relationships. A key drawback of this method is that sometimes there are side effects which account for incomplete activities. [Schooler and Engstler-Schooler, 1990] In addition the verbalization interferes with the design process and also participants mis-state what they are thinking. [Wilson, 1994] A way to avoid this is by conducting a retrospective analysis. [Suwa and Tversky, 1996] In this technique the design session is recorded and after the session, the participants are asked to verbalize their thoughts as they watch the recorded video. Finally, the third method of studying sketching is introspective. [Galle and Kovács, 1992] In the introspective method, the designer conducts the design process and then produces a written account of his train of thoughts after having ample time for reflection.

Experience (or lack of it) plays a very important role in designing. It has implications on design performance, efficiency and quality. This is important from a tool development point of view. Are there any differences between how novice and experienced designers sketch? Do they use sketching differently?

2.7 Novice and Experienced Designers

Section 2.6 reviewed the key contributions to the general trend of design methodology, which is a synthesis of science in the process of design. A good way to conclude this review of science and design is to review the concept of design ability and expertise in design. It is important to understand this in the context of design performance and differentiating between expert and novice designers and outstanding designers. Such an understanding has a number of implications for design tools and knowledge systems. The ability to "teach" design as a science and as a way of thinking has powerful implications on the curriculum of various courses in architecture and urban planning.

Kavakli and Gero in a series of studies identify why there are performance differences between a novice and advanced designer when it comes to perceiving objects from conceptual sketches.[Kavakli and Gero, 2002] [Kavakli and Gero, 2003] [Kavakli et al., 1999] In two case experiments, they find out that there exist some cognitive actions that are common in both novice and experts. They found that experts have structural organization and systematic expansion in the cognitive activity, while the novice's function are primarily an exhaustive search. In addition the experts' productivity were as high as three times that of the novice. They speculate that the expert has highly focused attention as opposed to the novices' distributed and defocused attention which has a major role to play in this difference. A key insight is that while the expert's focus is useful for performance, the novice's cognitive processes support remote association and discoveries that the expert might not be able to make. Therefore novices can create "novelty".

In another study Menezes describes how novices and experts perceive different things from conceptual sketches. [Menezes and Lawson, 2006] Participants were given tasks to describe concept sketches, remember the sketches and also a review task. The study showed that advanced participants used more verbal cognitive actions per minute than novices to describe the images and their performance was even better with sketches in their own domain. This suggests that experts are more efficient than non-experts in the way they describe and use formal verbal references.

Kavakli and Gero describe a similar conclusion: that experts demonstrate more cognitive activity than novices in processing conceptual drawings. [Kavakli and Gero, 2001]

The rate of remembered information is almost twice as high for experts and the ability to use the remembered information to generate sketches is the source of the major difference between the two. Thus it can be concluded that experts think very differently about diagrams and sketches than novices.

Suwa et. al. detail a study with two practising architects and seven advanced students working through a task of designing an art museum. [Suwa and Tversky, 1996] The participants design the museum individually and are recorded and then the recording is played back to them and they explain the design process to them. They categorize the responses to classes and subclasses to build a taxonomy of the design problem. In their research they describe a chunk as a subjective grouping of unrelated items and conclude that experts are able to organize elements that seem unrelated to a novice into cohesive, meaningful units. In their study they suggest using this insight on the web-like nature of design has implications for building the design tools.

Experts attend to shapes / angles and sizes, the visual attributes of depicted elements, just after they have shifted their focus to new thoughts. The key implication from a tool point of view is that after the sketches are drawn on the digital tool, there will be options to organize or specify functional relations arising from perception of visual features (by the computer) in the sketches. Novices and experienced designers are also different in the way they are able to analyze design problems and “see” patterns. The cognitive model of the visual thinking process impacts the performance of the designers. Sutherland proposes a simple model of visual pattern recognition [Sutherland, 1968]:

1. a processor that extracts local features from the input picture, preserving information about spatial relationships between the features;
2. a mechanism that produces an abstract description of the output from the processor;
3. a store in which such descriptions are held.

Understanding how designers interpret shapes and how this knowledge is used in acquisition and transformation of design processes will give an insight as to why the designers act differently. This is tackled in detail in a number of studies of how designers perceive shapes as they advance through the design process. Gottschaldt [Ellis, 1999] shows that recognizing sub-shapes is a natural human ability but when looking for sophisticated sub-shapes, humans must search for the shape and it maybe extremely difficult to decipher.

Liu explored behavior exhibited by experienced and novice designers when it comes to seeing shapes, transforming them, recognizing emergent shapes. [Liu, 1995] When looking at drawings at any stage, the designer normally restructures the shape to pursue his own design intent, this seeing sub shapes in a shape is a unique facet of human designers that cannot be easily mimicked by computers. In the experiment, novice and experienced designers were asked to draw as many shapes that emerged from two primary shapes in three minutes. The experienced designers were able to outperform novices in the number of emergent shapes that they produced primarily because of past experience. The second finding of the experiment was that given enough time, even novice designers were able to perform at the same level of experienced ones in that they were able to identify more shapes. Another key finding is that subshapes can only be found after a certain time and the time is proportional to the complexity of the shape. Finally Liu suggests that experienced designers have lowered their threshold of recognizing activation for seeing shapes so that they are able to discover implicit emergent subshapes. The study of emergent shapes has implications for tool design since while it is almost trivial for a human subject, emergent shapes are very difficult for a computer to process and analyze. How can this pattern recognition be accelerated? Reed showed that subshapes can be interpreted better with verbal descriptions and subshapes emerge only after their corresponding higher level shapes have been correctly interpreted. [Reed, 1974] These aspects have various implications on teaching, while a thorough review of this is beyond the scope of this chapter.

Cross summarizes the core features of design ability in a individual as the following [Cross, 1990]:

- resolve ill-defined problems
- adopt solution-focusing strategies
- employ abductive/productive/appositional thinking
- use non-verbal, graphic/spatial modelling media

The underlying premise of this list is that design ability is possessed by everyone. While in industrial societies design is "professionalized" meaning that it is in the domain of experts, in non-industrial societies design is democratized and practiced as a craft.

Cross also presents a good review of design abilities and expertise in design. [Cross, 2004] It is useful to review them here to understand the ways that this can be taught and practiced more broadly in education and by tools that will be built in the future. Expertise is not just about innate talent but it is dedicated application to a field by rigorous practice. Therefore teaching design must involve this transfer of implicit knowledge to explicit tools about the art of design. In design, novice designers are characterized with a depth-first or sequential approach to problem solving i.e. linearly identifying and solving sub-problems while experts have a tendency to use a breath-first or a holistic approach to problem solving. A good summary of how successful designers behave is captured by the following:

- in terms of the creativity quality of their solutions, the designer asks for less information, processes it instantly, and gives the impression of consciously building up an image of the problem. They look for and make priorities early on in the process. [Christiaans and Dorst, 1992]

- in comparison to the freshmen, senior students gathered more information, considered more alternative solutions, and transitioned more frequently between types of design activities. [Atman et al., 1999]

- in contrast to the novices trial-and-error approach, the experienced designers employed integrated design strategies. [Ahmed et al., 2003]

- the expert seems to have control of his cognitive activity and governs his performance in a more efficient way than the novice, because his cognitive actions are well organized and clearly structured. [Kavakli and Gero, 2002]

The common theme in these examples is that an expert seems to want to understand the problem fully in all its possible dimensions and requirements before attempting to form a solution. They rapidly build conjectures and work their way and understand the design problem. This solution focused method is a theme that is practiced by expert designers; in fact Cross presents several examples where the fixation on the solution or an initial idea is a characteristic that is prevalent among many expert designers and designers are reluctant to abandon early concepts and generate a range of alternatives.

Indeed Fricke identifies a balanced approach to either too many constraints to the alternatives or too few which can lead to early fixation or a paralysis with too much choice. [Fricke, 1996] Thus the framing of the design problem appears to have a large impact on the performance of designers.

The field of participatory design in planning and architecture is beyond the scope of this chapter but there is an increasing focus on getting more and more people and non-professionals involved in the activity of design. Given that design ability is innate in everyone, it is also a skill that can be damaged or lost without practice. Therefore, to nurture the design skill, it is important for teachers to understand these different abilities and nurture them. In his review of outstanding designers, Lawson notes that such designers seem to have the ability to maintain ambiguity about features and aspects at different levels of detail and this is what separates them from novice designers. In addition, it is clear that the way the problem is structured has a large impact on the performance of the solution, expert designers pro-actively frame problems and guide the solution generation. Expert designers therefore differ from novice designers in that solution focused not problem focused. However, expert designers switch their cognitive processing from the solution and problem while they design, where their thinking evolves along with the evolution of the design.

2.8 Implications for Tools

Thus the ability to “understand” the spatial relationships is critical from a sketching tool point of view. It is this understanding that will enable the tool to help novices to become more “expert-like”. It has been demonstrated above that novice and experienced designers perform in the context of perception, pattern recognition and ways that can be accelerated in the planning support tool context. Novice and expert designers behave differently but can they collaborate? Can the best aspects of novice designers work in conjunction with experts. Can the correct tools help skill up novices?

Skills can be thought of in two domains: Problem solving and creative skills. Skill acquisition in problem solving is discussed by Anderson. [Anderson, 1982] Anderson proposes a model: the Adaptive Character of Thought (ACT) production system that makes a distinction between procedural and declarative knowledge. The ACT theory provides a framework for structured cognition that can be used to learn new domains using standard trial and error, analogy and search skills. Thus given the right context and declarative knowledge in the system, the participants can be made experts given enough time.

Newell, Shaw and Simon present a set of features that a computer tool should possess which would help mimic human problem solving behavior [Newell et al., 1958]:

- Set
- Insight
- Concept formation
- Problem structure hierarchy.

Anzai and Simon present a theory of process of learning by engaging in the activity of problem solving that has been verified by simulations. [Anzai and Simon, 1979] Knowledge of results obtained through search of the problem space provided the foundation for all of the learning. If the search led to bad results (e.g., repetition), new productions were formed that detected the circumstances in which repetition had occurred and avoided the offending moves. When good results were attained, new productions were formed that could make the appropriate preparatory moves when it was noticed that the sub goal was nearly within reach. Thus by doing the process of design, there is a strong evidence that skills can be attained.

The other skill is that of creativity. For creativity to occur many aspects need to converge and in this case, this work is focused on the systems theories about creativity. Amabile describes creativity as a mixture of task motivation, relevant knowledge and abilities, and creativity-relevant skills. [Amabile, 1983] While Gruber has proposed a developmental and systemic approach to creative work based on stages of development. [Gruber and Barrett, 1974] Csikszentmihalyi took a different "systems" approach and highlighted the interaction of the individual, domain, and field. [Csikszentmihalyi, 1988] An individual draws on information in a domain and transforms or extends it through cognitive processes, personality traits, and motivation. The underlying theme between skill and creativity from a systems point of view is that creativity and skill can be facilitated by using the correct tools that encourage exploration, have the right balance of novice and experts and final can be used to facilitate novel solutions.

2.9 Diagrammatic Elements of Sketches

Given that sketching can be ambiguous and abstract, a relevant question is about the content of these sketches. What is being drawn in these sketches? Is there a consistency in representation? How are these shapes arranged spatially? What insights can be gained from the shapes themselves that can be used in building planning support tools? To understand the shapes, the drawings created by designers should be analyzed. Ellen Yi-Luen Do in her study of drawings identifies two very important characteristics of architectural designs [Do, 2005]:

1. Designers share drawing conventions: symbols and their configurations.
2. Designers draw furniture in space and to put themselves in context.

The context of this study was in architecture, never the less, it is has implications for interpreting sketching in general. Do found that designers use drawing symbols in their design in a consistent fashion and in addition she found that designers draw simple shapes representing furniture in order to put themselves in the right context to think about design.

Do also conducted a series of studies to understand the different activities and drawings that consistently appear in the conceptual stages of design. [Do, 2002] It is of interest how these symbols associate with different design activities since it is relevant research in the context of tool building and using computational tools for design using diagrams. She analyzed concept drawings of 62 architecture students doing concept drawing. She performed protocol analysis of four architects conducting design of an architect's office to test her hypothesis that designers represent architectural concepts in a consistent way, using limited diagrammatic elements. In the first study, 62 students were given the four tasks:

1. Making diagrams from stories
2. Writing stories from given diagrams
3. Pairing diagrams and stories

Finding	Description	Implication for design tools
Graphic symbols represent design concepts.	Do discovered that designers use graphic symbols to represent physical objects, design tasks and concerns. The participants chose primitives from a limited universe of geometric shapes and symbols to draw their diagrams, and composed these in highly conventional ways. They predominantly used lines, ovals and blobs, and rectangles, lines and arrows.	Digital sketching implementation should provide the ability for the designer to draw simple shapes and lines. In the conceptual design world, the requirement for complex drawings and visual clarity is not needed.
Design concepts suggest sectional or plan preferences.	Designers seem to share a preference for using plan or section to illustrate concepts. Most participants chose a plan view to illustrate relations between different functional spaces and acoustics.	2D plan view is sufficient to communicate spatial arrangement in the case of conceptual drawings. Digitals need not have complicated 3D or sectional authoring support to show spatial relations and concept.
Keywords as text labels in plan diagrams.	Participants frequently included key words from the design concepts as labels in their drawings. Designers occasionally put beside the shape with an arrow or line from the label pointing to the shape it identified.	A text annotation is useful to label conceptual drawings, sometimes overlaid or put beside the drawings. The combination of text and diagrams communicate the concept sufficiently well to designers.
Consistent diagram interpretation among designers.	Participants shared similar and consistent interpretations of the diagrams. This suggests that designers agree with each other's diagrams.	Tools need to be “specialized” for a certain design style or develop a special language for communication between design domains.

Table 2.1: Tool Design Implications

4. Commenting on existing diagramstory pairs.

The study revealed four significant features of diagram making: The participants used a limited set of symbols to represent concepts. In the architecture domain, concepts suggest sectional or plan preferences. Keywords and text were used to label the diagrams and that led to consistent interpretation and understanding. These findings have significant implications on the design of digital tools for conceptual drawing using sketching and need elaboration with respect to their implication for design tools and they are summarized in table 2.1. Consistent with the recommendations mentioned above, Do and Gross recommend the following as desirable components of an architectural system

Finding	Tool Feature
Freehand drawing input, as opposed to structured diagram entry and editing.	This is one of the critical features of a tool since most designers have a preference for free hand drawing instead of the structured drawing elements present in most tools.
Maintaining spatial relations among elements as the diagram is transformed.	The ability for the tool to understand spatial relations as the diagram is transformed.
Recognizing 'emergent' patterns and configurations in a diagram.	The tool should 'emergent' patterns based on history.
Performing transformations that carry one diagram to another.	A computer system to support diagram reasoning ought to be able to acquire and store graphical transformations of diagrams, which it can then apply on command.
Identifying similarities and differences among diagrams.	Thinking with diagrams requires, on occasion, comparing two diagrams and identifying the similarities and differences.
Representing designs at varying levels of abstraction and detail.	Finally, a computer system that supports diagram reasoning for design should allow the representation of diagrams at various levels of abstraction.

Table 2.2: Tool Features

[Do and Gross, 2001] and is summarized in table 2.2.

In conclusion, the following are some key features for digital sketching tools:

1. Sketching must be a freehand tool.
2. There should be a back-end logic that understands spatial relationships.
3. A tool should have an understanding of user intent and should analyze the diagrams for them
4. Transformations of shape and size should be in built into the system.

2.10 Digital Sketching Tools

Bridging the gap between the way designers work and how sketching tools work has been an area of intense study. Having reviewed some key features of digital sketching tools earlier, the focus of the next section is to feature a handful of sketching programs and their characteristics to understand the foundational elements of any such digital tool. The goal here is to study the literature on existing sketching tools and understand their pros and cons.

2.10.1 Key Characteristics of Tools

It is useful to build a framework of what the key characteristics and features should be. Forbus presents a computational model of sketching from a tool point of view. [Forbus et al., 2001] He identifies the key characteristics that a sketching tool should be able to provide to the user.

1. *Visual understanding*: This dimension characterizes how deeply the spatial properties of the ink are understood.

2. *Language understanding*: Language can ease the load on vision by labelling entities and specifying what type of thing is being drawn. It is used for stating what spatial relationships are essential versus accidental, and describing entities and relationships not depicted in the drawing.

3. *Conceptual understanding*: the depth of representation i.e. how simple or complex a shape should be to communicate the concept. The tools should provide qualitative representations of space and shape, and use standard uncomplicated graphics conventions and visual symbols.

4. *Drawing Capabilities*: The software should provide tools that enable users to sketch and provide assistance in so far as neatening the drawing or enhancing them.

From a user interface viewpoint, Gross and Do say an interface for design should *capture users'intended ambiguity, vagueness, and imprecision and convey these qualities visually and through interactive behaviour.* [Gross and Do, 1996] They also identify three properties that are critical to effective sketching tools from this point of view:

1. Abstraction permits postponing detailed specification and allows detailed configurations to be replaced by higher-level elements.

2. Ambiguity permits entertaining several alternatives for the selection or identity of an element.

3. Imprecision permits postponing decisions about exact dimensions and positions.

Therefore an interface for early stage, conceptual design should provide:

1. the means for users to express abstractions, ambiguity, and imprecision;

2. the means for the machine to represent these qualities internally; and

3. the means for the machine to express them in its output and interactive behaviour.

2.10.2 Tool Review

Having reviewed the key features that are required for sketching tools, a review of some tools is presented below. The review is important to understand the features that make a tool more suited for conceptual design and also gives an insight in to the authoring environment that is needed.

In their work on the "Electronic Cocktail Napkin" (ECN), Gross identify two properties of early conceptual sketching tools that are important [Gross, 1996]:

1. Adopt a paper-like or pen-based interface that allows designers to draw directly what they have in mind, with varying degrees of precision, ambiguity, and abstraction.

2. Provide internal representations that can tolerate ambiguity and incompleteness, yet which can be made more formal and structured as designing proceeds.

3. The ECN provides a function for electronic recognition and parsing of hand drawn or sketched layers. It does it in a three step process: the program recognizes the symbols or glyphs drawn, it analyzes the spatial relations between all the symbols and diagram elements and finally it matches these symbols and relations against a previously defined configuration to parse and interpret the diagram.

ECN software has a set of stored binary predicates such as: containment, above, below, right and left-of, line intersections, crossings, and tees. Since most diagrams are imprecise a small set suffices, thus the ability to understand spatial relationships that are sketched out implies a computer system that can understand designer "intent".

Landay and Myers discuss SILK (Sketching Interfaces Like Krazy), an informal sketching tool that combines many of the benefits of paper-based sketching with the merits of current electronic tools. [Landay and Myers, 2001] SILK however is more focused on sketching computer user interfaces such as windows, scroll bars etc. that then become interactive once the system recognized the drawn elements. SILK recognizes four primitive components —rectangle, squiggly line (to represent text), straight line, and ellipse. Figure 2.11 below shows how SILK converts a sketch drawn with these primitives into a full featured interactive interface.

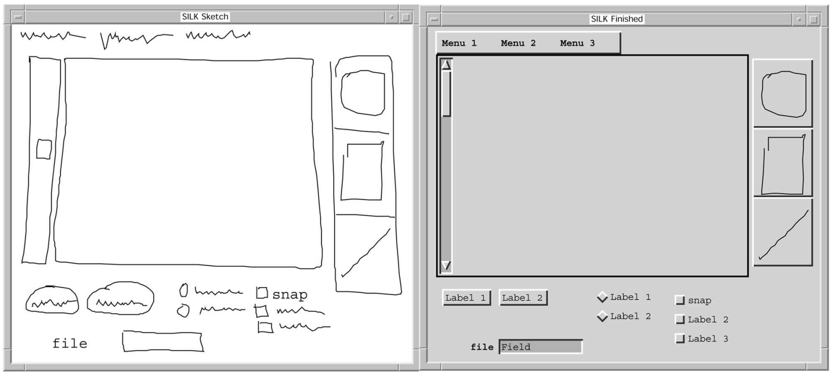


Figure 2.11: SILK Sketch (left) and Final Interface (right). [Landay and Myers, 2001]

In the same way as the ECN, SILK also has a spatial inference engine that detects:

1. Does the new component contain, or is it contained by, another component?
2. Is the new component near (left, right, above, below) another component?
3. Is the new component in a vertical or horizontal sequence of any combination of components that are the same type or are sequences of that type?

In addition there is one key result of the user experience studies conducted by the authors: an electronic sketching tool leads designers to focus on the overall interaction and structure rather than on the detailed look and feel.

In his work on Translucent Windows —Dissolving Patches, Kramer works on sketching as a part of a translucent medium and observes that translucency preserves context, allowing us to relate multiple bodies of information at the same time. [Kramer, 1994] In the Architects Electronic sketch board, Kramer describes the use of patches as a way that patches essentially act like selections and sub views, in that they are used to create structures, spatial subsets of marks, in that operations are provided that act on the selected subset as a whole. (Refer Figure 2.12 and 2.13)

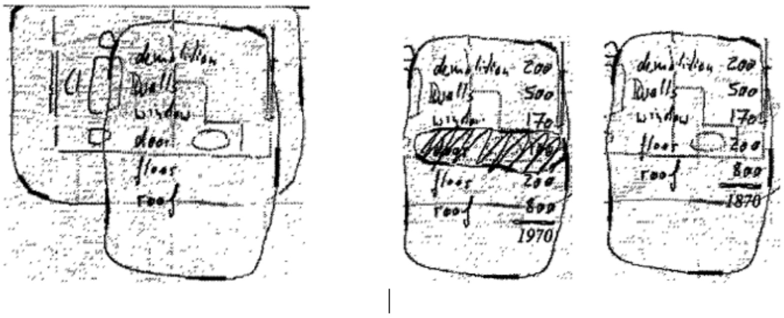


Figure 2.12: Architects Scribbles: A Patch and Experiments with Calculator Impression. [Kramer, 1994]

In this case, the architect is sketching (and erasing) items from the patch and the computer recalculates the total cost of the plan based on the changes to the patch. What is more interesting is that they created a set of gestures that help the system interact with the patch and they are below. Do and Gross approach the problem of early stage

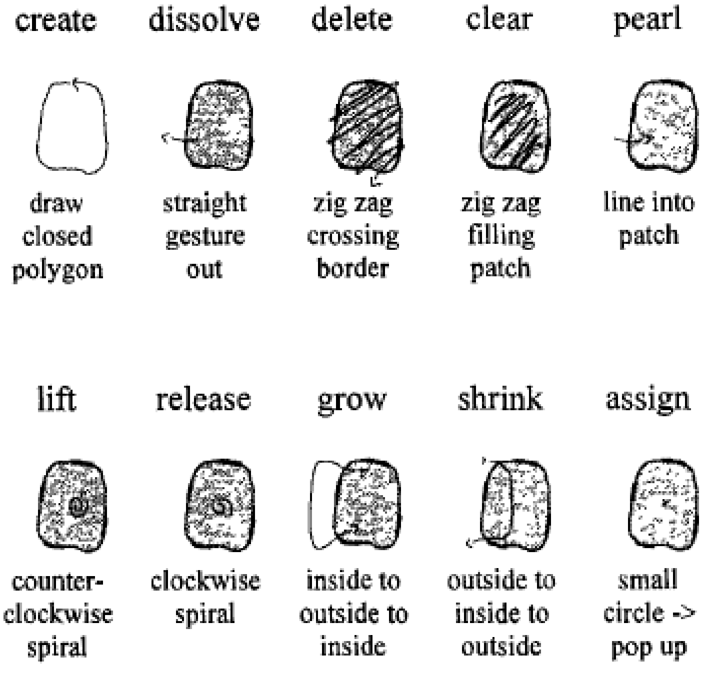


Figure 2.13: Gestures Related to Patches. [Kramer, 1994]

sketching tools with a different strategy. [Do and Gross, 1995] They start with the observation that designers use inspiration from outside to start. By providing access to different collections through the act of sketching, the tool aids designers in finding interesting and sometimes useful references for creative design. They describe a tool that provides images based on their visual similarity to the designer's sketch. They use the term visual metaphor to the work by Goldschimidt (described earlier) and use them to expand the search space for a designer. In their research they have visual references that use objects from the natural and artificial world that inform their designs. They identified that designers classify their activities broadly as organization, conception and fabrication, Figure 2.14, Figure 2.15, Figure 2.16 and 2.17 show these in action.

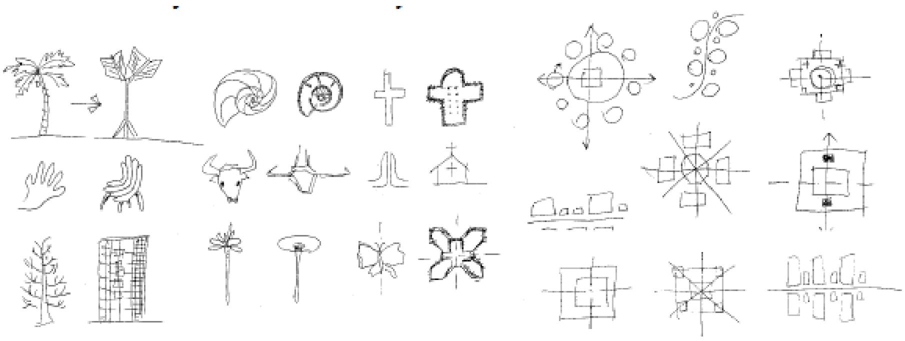


Figure 4. Conception drawings explore shapes and forms.

Figure 2.14: Conceptual Sketches. [Do and Gross, 1995]

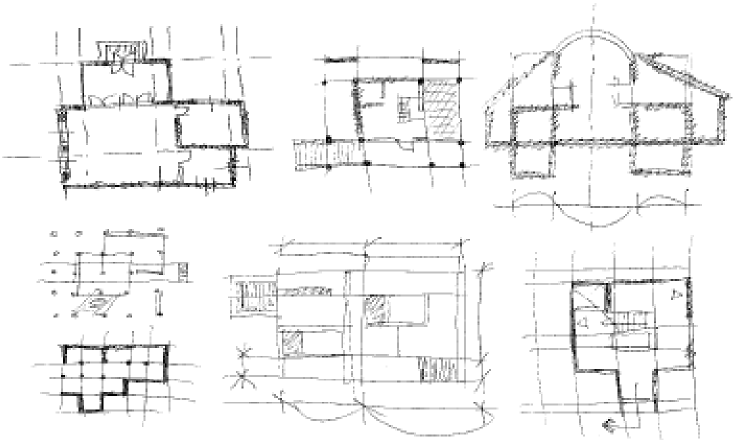


Figure 5. Fabrication drawings tend to be more definite and precise.

Figure 2.15: Fabrication [Do and Gross, 1995]

They assert that there are many tools that support fabrication and organization but there are relatively few tools that support conception. They then use the Electronic Cocktail Napkin and its infrastructure to classify and relate sketches by various diagram similarity as shown below in Figure 2.17 Once they have a general structure of diagram similarity, they then query different databases for a conceptual equivalent of

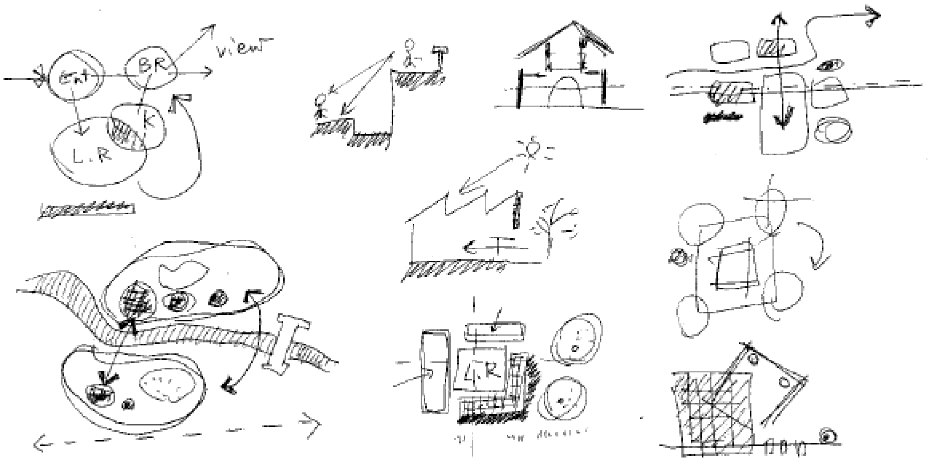
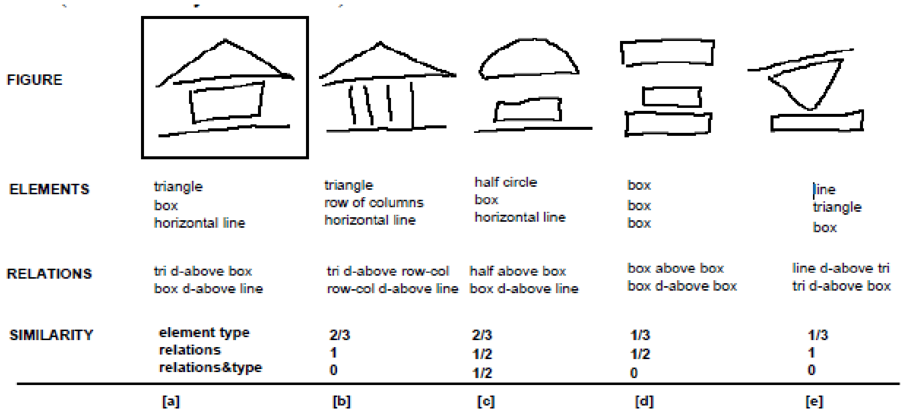


Figure 3. Organization drawings explore programmatic concerns.

Figure 2.16: Organization [Do and Gross, 1995]



	[a]	[b]	[c]	[d]	[e]
FIGURE					
ELEMENTS	triangle box horizontal line	triangle row of columns horizontal line	half circle box horizontal line	box box box	line triangle box
RELATIONS	tri d-above box box d-above line	tri d-above row-col row-col d-above line	half above box box d-above line	box above box box d-above box	line d-above tri tri d-above box
SIMILARITY	element type relations relations&type	2/3 1 0	2/3 1/2 1/2	1/3 1/2 0	1/3 1 0

Figure 8. Some dimensions of diagram similarity: [a] compared with [b, c, d, e].

Figure 2.17: Similarity of Diagrams [Do and Gross, 1995]

the diagram as shown in 2.18 This sort of system attempts to enhance the design pro-

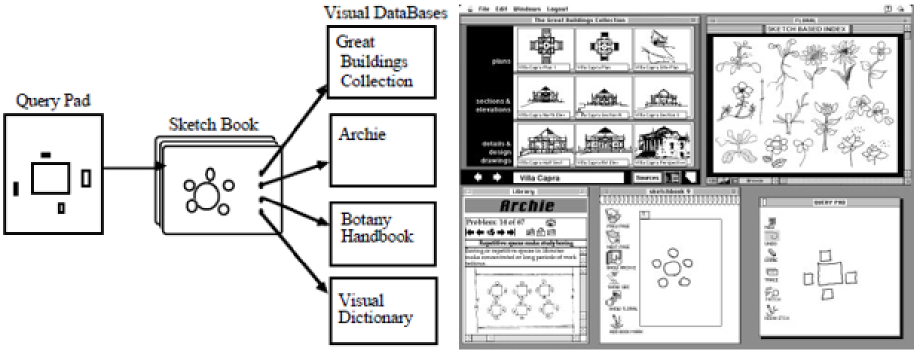


Figure 2.18: User Draws on Query Pad, Most Similar Sketches Identified on Sketch Book and Then Queries Made to Other Databases. [Do and Gross, 1995]

cess by creating a serendipitous nature to the design conception. Saund and Moran present a similar theme in their work on PerSketch in what they call as perceptually supported image editing. [Saund and Moran, 1995] This idea is to give a user direct access to emergent visual objects in a graphic image that reflect the sorts of perceptual objects, they coin the term WYPIWYG (What you perceive is what you get), as is demonstrated in Figure 2.19.

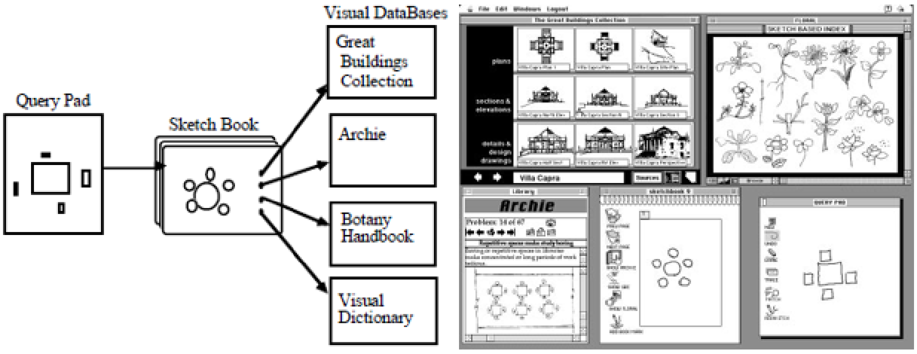


Figure 2.19: PerSketch WYPIWYG (What you percieve is what you get). [Saund and Moran, 1995]

The user performs actions on the screen, the software creates the text description underneath PerSketch follows the "draw/select/modify" metaphor to perform its operation, and they identify the key characteristics of a system that support perceptually enhanced image editors:

1. The task of the system is not to discover "the correct" interpretation for the scene, but rather to prepare and maintain a database of many states that are often conflicting and ambiguous.
2. The system should provide the user with selecting a multitude of visual objects
3. The system must support real time interaction.

They go on to describe a system that enable a "what you perceive is what you get " type image editors that uses perceptual organization, object recognition and better image interpretation methods to a image editing system. This is relevant to the designers and sketching since any software system that enables sketching has to be relevant in this domain. Designers however rarely work alone and more often with other collaborators, so it is relevant to review some of the work done on collaborative designing. Ishii and Kobayashi describe ClearBoard as a interactive board that enables "talking through and drawing on a transparent glass window". [Ishii et al., 1993] They use the metaphors of talking over a table and talking in front of the white board to create a collaborative sketching environment. Of particular interest is ClearBoard 2 and the schematic is shown in Figure 2.20 below. In clear board, the user draws on a screen and the data is then projected on the other user is seen along with video and voice. The authors then use a hybrid drafter mirror setup where the screen is used to draft drawing but also project a visual image of the colleague on the other end. When the authors tested the system with colleagues they seemed to have an increased feeling of intimacy and co-presence.

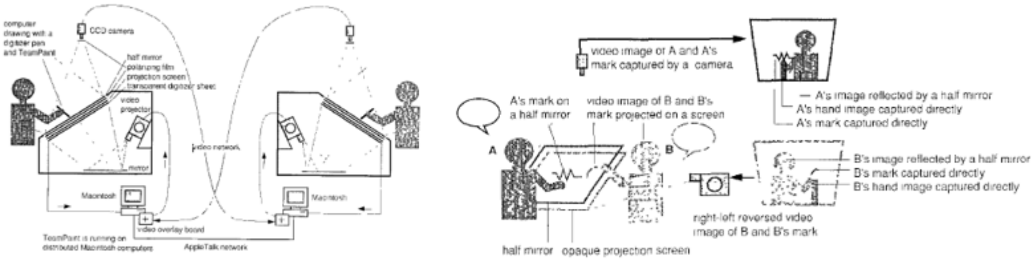


Fig. 8. System architecture of ClearBoard-2.

Fig. 6. How drafter-mirror architecture works.

Figure 2.20: Clearboard 2 System Architecture and Drafter Mirror. [Ishii et al., 1993]

2.11 Conclusion

Most highly detailed drawings and plans start as simple spatial diagrams. The general configuration and arrangements of primitive objects: lines, circles, polygons, arrows remain powerful organizational and communication tools. The purpose of this review was to understand sketching, the process of sketching, the contents of sketching and the key characteristics of sketching tools. The act of creation of a diagram is sketching. This review started with diagrams and explored the cognitive aspects of diagrams and how they are understood by designers. Having reviewed the foundational work of Larkin and Simon and their work on "Why diagrams are (sometimes) worth 10,000 words" this chapter details diagrams and their architectural context and in particular understanding conceptual drawings. This chapter also reviews well-structured and ill structured problems and how design problems are ill structured problems and the role of diagrams in solving ill structured problems. This was followed by a review some of the foundational characteristics of study drawings from an architectural point of view and how they help in early design exploration. In addition, a review of the work of Goldschimdt and that of Schon and Wiggins was conducted to understand how architectural designers go about the process of designing as they sketch and as the sketches develop. Finally, an understanding of the role of diagrams in a digital context is developed and a review of some digital sketching tools that enable diagramming is presented.

Chapter 3

Systems Approach to Design

The systems approach to design rests on the premise that the process of finding a solution to the design problem involves the designer undertake a search and using heuristics to arrive at a satisfactory solution. This view states that design solutions operate on the human problem solving mechanism in a search space. In this context, designing is viewed as a creative problem-solving task.

There has been a lot of interest in this domain and consequently a lot of research has been undertaken in this field. It is beyond the scope of this chapter to review the entire field so the focus here is to review the systems approach in the specific context of early stage conceptual design. The goal is to identify contributions that promote and accommodate early stage design activity from a systems framework point of view. To date, no research appears to have undertaken to combine a systems approach to design and sketching based early stage design. This chapter demonstrates this gap in literature and the opportunity it presents in the context of planning support tools.

The basic premise of a systematic design methodology is to develop systematic methods and tools to carry out logical analysis better and to unburden the designer to focus on the creative aspects of design. [Cross, 1984] The systems approach to planning and design problems necessitates a distinction between the design process and the design content. Separating the two enables a study into each in relative isolation and to make experiments and advances in both. Goel and Prirolli state that design is fundamentally a mental and representational feature of human intelligence. [Goel and Pirolli, 1992] Design problem fits well as an ill-structured problems with poorly defined goals, states and operators. Chapter 2 provides a detailed review of well structured and ill structured problems.

Design problems have no correct answers and can be solved in numerous ways. Solving design problems is therefore very similar to other creative endeavours. Flower et.al present a theory of constructive planning in the context of creative writing in which writers must create a unique network of working goals and they deal with the special problems of integration and "instantiation" that conflict resolution this constructive process entails. [Flower et al., 1992] This can be generalized to design as well and it is this generalization that this chapter attempts to explore in literature. What are the process and mechanics of deisgn?

3.1 Design Methodology

The study of systematic design has been ongoing for decades. Cross [Cross, 1993] details the developments in the field of design methodology and design methods from its initiation with the application of scientific methods to design problems in the 1950's and 60's. The first design methods books also appeared during this period notably Hall [Hall, 1962], Asimow [Asimow, 1962], Alexander [Alexander, 1967] and some other notable ones that came a bit later Archer [Archer, 1984] and Jones [Jones, 1992]. The initial excitement of the 60s led to a general rejection of design methods in the 70's. This was partly due to the fatigue created by attempting to shoe horn a wide number of problems into a logical framework. This sentiment is shared widely in the literature of the time, notably by Rittel and Webber who characterized design problems as fundamentally unmanagable to the the techniques of science and engineering. [Rittel and Webber, 1973]

Rittel succinctly summarizes the design methods phenomenon over the decades and structures it as a generational hierarchy. [Rittel, 1973] This was a way to put structure and context to the growing body of work and also as a way to understand the progress of the field. In Rittel's classification, the first generation of design methods was based on the application of scientific method to design problems. After understanding the limitations of this approach the second generation of methods focused on consensus building for satisfactory solution design problems. The consensus on scientific design method is a way to approach design solutions of problems that are based on the appreciation of the scientific method but also to use intuitive and non-intuitive methods. And finally, the third generation is characterized as one of co-designing and collaboration with public and a participatory process.

The design science method uses scientific knowledge and principles as a way to solve design problems. This was a leap forward since this treats design as a scientific and professional endeavour as opposed to a pre-industrial craft or experience based activity. Therefore the scope of design methods extends not only to the process of design, but also to the design itself which in some sense is a scientific activity. The case for a systems approach to be applied to planning problems came out of the observation that the then existing craft-like approach to planning was not capable of solving planning problems. The key idea of design methodology is to build a "science of design" by using tools to systematically and reliably analyze methods of creation of a design.

Planning problems have almost infinite complexity and uncertainty and to address this a systems approach was developed to make *explicit* the tasks and processes that were *implicit* earlier. Implicit methods were observed to be incapable of handling the problems of planning. Being explicit about the process, the connections between different systems and models of social, scientific phenomenon that were observed in the real world, planning problems could be structured and the design process could be studied. Design methodology therefore attempts to answer questions around which way to design?

Hubka and Eder characterize design science as being to "recognize laws of design and activities and develop rules." [Hubka and Eder, 1987] They identify the important constituents of design science as:

- applied knowledge from natural and human sciences
- theory of technical systems
- theory of design processes
- design methodology

Thus design methodology is necessarily a multi-discipline endeavour that combines different sciences and processes. The research in the design methodology movement did produce a consensus on how design professions are different from non-design professions. There has a been a lot of progress in the field of design methods in the last few years, most notably in the organization and application of systematic tools for design. This progress has been specifically in strategies for executing design projects in terms of the theoretical analysis of the nature of the design activity. In fact, when pursued with purity, it is these techniques that have led to models of cities where quantitative abstraction of the problem at hand is sufficient to model the process of design. The fundamental assumption of a systems approach to planning is that creativity and design "genius" is a exception rather the norm.

3.1.1 Solving Complex Design Problems

The general scientific model for problem solving begins with problem definition and understanding leading to generation of alternatives. These generated alternatives are then analysed for performance and these steps are repeated a number of times until a satisfactory solution is reached. This problem solving activity lies at the core of the design process and can be divided as the following sequence of steps [Goel and Pirolli, 1992]:

- An exploration and decomposition of the problem
- An identification of the interconnection among the components
- The solution of the sub problems in isolation
- The combination of partial solutions into the problem solution (synthesis)

The fundamental assumption of design methods is that activities during the production of a design can be appropriately classified and compared. That the designer goes through a "method" or "process" not too dissimilar from a worker making a widget in a factory. The worker has clear instructions on the process of assembly and there is a specific cycle time that is allocated to the production of design.

Thus design problem solving activities are fundamentally different from non-design problem solving activities. This distinction helps us build a systematic framework around design problem solving. To understand how activities can be classified this way, the "design problem space" needs to be understood. Are there activities that designers perform that are unique to the process of solving a design problem? Goel and Pirolli provide evidence of the problem space and early stage design as having unique characteristics which are summarized below. [Goel and Pirolli, 1992]

The design problem space is where there is a lack of information in the start states, goals states and the transformation function. Solutions to a design problem consist of three phases: preliminary, refinement and detailed design. In this thesis, the focus is on preliminary design since the latter two build on the initial design. The focus is on how does one get to the first design for a complex planning problem since this early stage design has many implications for the later stages.

In the early stages of design, the design solution is not apparent. However the designer in his memory has partial solutions from earlier experiences and he or she may use this to apply to the problem at hand. Therefore internally, the problem is transformed into a problem that is already known to the designer using memory, pattern matching and other heuristics. These solutions are necessarily partial solutions since most design problems are complex and their solution that is built at early stage design is an aggregation of different sub solutions.

Thus a problem is decomposed in having partial solution and the individual solutions are then aggregated. This breaking down of the complex design problem space is a key feature of the early stage problem solving. Due to this decomposition and integration process, there is an iterative process to design much like fitting Lego blocks until a satisfactory arrangement of the sub solutions is found. The iterative process means that there are no set preferences about the solution at an early stage. The designers try multiple solutions without significant commitment to any one thus enabling a “mix and match” solutions.

The designers need to communicate the process of the construction of the design solution as a series of steps and there is a need to document and log the moves that the designer performs to enable communication. At this early stage, the design performance is mostly subjective i.e. the designer stops the process when satisfied with the designs and this is purely personal and subjective. The designers use models and abstractions to represent ideas and concepts and also extensively uses memory to retrieve solutions. Finally, the designers use symbols and diagrams to solve these types of complex problem with an internal hierarchy and methods to manipulate and transform these.

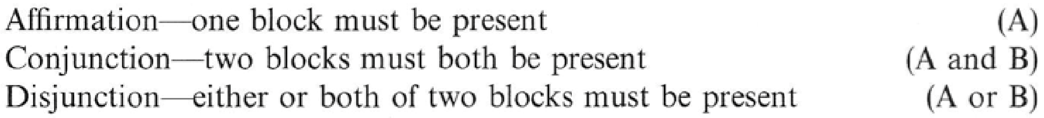
Thus, design problems engender unique activities and actions that are not present in other problem domains. Can these activities now be analysed further from a process point of view? How would one go about classifying and analysing these design activities?

3.2 Designer and the Design Problem

Understanding the mind of the designer is critical to the systems way of designing since the mental process informs the method of design. This understanding will help in developing a model of designers process relations between variables and constraints in multi-dimensional design problems. To develop a broad understanding of this, two perspectives are considered: designing in engineering and designing in architecture and planning. Designing in architecture and designing in engineering highlight two fundamentally different approaches to design methods. This is because the expectation out of engineering design is to develop a solution that is "optimal" and satisfies the requirements. However designing in planning or architecture is as much about creativity as it is about the optimal solutions. Due to this difference of expected output, designers approach design problems in engineering and architecture in a fundamentally different way. Designers have a different mental model and approach to solving these problems and this is because they understand the structure of the design problem differently.

Lawson describes an experiment about a problem that has no correct answer. [Lawson, 1979] In this experiment the subjects were made to discover the structure of the problem and produce a solution. The experiment had four pairs of coloured blocks where two members of each pair are identically shaped but different to all other blocks; the top and bottom of one pair is white, for another pair they are black and for the final pair all the other surfaces are either red or blue. The core task is for the subject to use a full 3x4 plan and use one block from every pair to fill the plan to maximize the amount of either blue or red showing around the external faces. Not all combinations of the blocks were allowed and the subject was not told the rule. (See Figure 3.1) However s/he was allowed to ask if the combination was acceptable or not and a simple yes / no answer was given. The idea is not to ascertain the rules, but to build a solution that the subject thought was acceptable. Therefore the rules are discovered as the design is being built. The rules were classified as Affirmation, Conjunction and Disjunction:

The experiment was carried out among architecture and science student groups. Two



Affirmation—one block must be present	(A)
Conjunction—two blocks must both be present	(A and B)
Disjunction—either or both of two blocks must be present	(A or B)

Figure 3.1: Affirmation, Conjunction and Disjunction in Experiment [Lawson, 1979]

types of errors were considered: A Planning Error and A Structural Error: A Planning error is where the subject does have the optimal solution; they have the correct blocks but they need to be rearranged. Structural error is when the subject has a solution that breaks the rules thus the subject has a lack of structural understanding of the problem. The results of the experiment show that the scientist group did considerably worse than the architecture group for general planning.

Lawson hypothesizes that conjunctive problems allow a smaller choice than disjunctive problems in this experiment. Therefore good planning is critical and also that in a disjunctive problem, the constraint can be fulfilled by swapping one block but for conjunctive problem, the participant has to re-plan from scratch. For structural errors, the architects made more errors than the scientists, where as the scientists excelled in problem structure discovery particularly in case of disjunctive problems.

Overall Lawson observes that there is a lack of structural errors in disjunctive problems by experienced scientists and lack of planning errors for conjunctive problems for senior architectural students. He concludes that science students operated on a problem focusing strategy while architectural students focused on solutions. In general, the problem focusing strategy leads the scientists to make fewer structural errors while the solution focus leads the architects to make fewer planning errors. This is an important conclusion when it comes to design methodology.

In conceptual sketching or early stage design the focus is on finding the structure of the problem and the details can be filled in at a later date. Thus there is an opportunity to take a step back and explore the nature of the problem structure in a scientific way within the design process. What Lawson argues however is that planning and design problems are “wicked” problems that can never lend themselves to thorough analysis and that synthesis can begin before a thorough analysis. This also leads to a view that scientists or engineering designers have models based on analysis of the problem space and after the analysis is complete they move to the synthesis phase, where it is the converse with architects where they focus on solution generation to think about the design problem. Others like Roozenburg and Cross also describe this phenomenon as analysis-synthesis vs. conjecture-analysis model of design. [Roozenburg and Cross, 1991]

Lloyd presents a discipline independent design framework that is useful in understanding the contradictory approaches to design that are presented above. [Lloyd and Scott, 1994] They present a model based on a protocol study of designers the where explanation of design work was classified as generative utterances, deductive utterances or evaluative utterances. The aim of the study was to understand the differences between designers that use the analysis-synthesis approach vs. the conjecture-analysis approach. Generative utterances are expressions that bring something new to the design. Deductive utterances are expressions that help in understanding the needs of the problem. e.g. what sort of light will this window produce? Evaluative utterances are expressions that are general comments on the design. By analyzing these one can link experience of the designer and one can gain insight into the design strategy.

The conjecture-analysis model predicts generative phases before deductive phases that is the ideas are bought in first and then the implications understood.The analysis-synthesis model predicts deductive phases followed by generative phases and finally evaluative phrases; that means that in this model the analysis of the current situation is carried out, then news ideas are bought in and finally evaluated. In this study, Lloyd characterizes designers into two groups: deductors and generators. In this particular experiment, the more experienced designer displays a generative mode of thinking. Less experienced designers used an overall global approach to problem solving while experienced designers used a localized approach and showing capability to decompose the design problem and generate partial solutions.

3.3 Rules in Designing

We have considered the design process and delved into how the designer develops partial solutions and also understands the design problem. How is a design strategy formulated? How are the rules of design synthesis formed? Schn [Schön, 1988] presents an analysis of the patterns of reasoning and the use of design rules by the designer.

The study of rules developed by a designer during the process of designing is useful because it would help in understanding how design knowledge is generated and utilized. It would also lead to an understanding to how these rules are created in the first place.This has implications for ways of designing since there is a correlation between the mental model of design rules and the way the designer chooses to tackle the design problem. Schn takes a very practical view of design away from the process of design or the search of a solution, but more around making of an artefact. According to Schn, design knowledge in such a world-view is expressed in the designer's interaction with the material that he is working with. He describes the knowledge that the designer brings to the design problem and the artefact that is constructed. Types are treated as references to objects that enable a designer to see the design problem: Cave, Pavilion, New English Green etc. are examples of type. Schn argues that there is two way interaction between design types and design worlds: elements of a design world may be assembled to create an artefact that can be called as a type while the components of a design type may provide elements in the design world.

Schn describes an experiment to explore how design rules and types are practised in an experimental setting. They asked a set of designers to analyse the footprint of a library building and give a set of guidelines to architects that will have to design these buildings. The guidelines should detail what the entrance implies as to the whole building and its internal organization. Again the think aloud protocol analysis is used where the designer is asked to verbalize his thoughts as he is working on the problem and these are then recorded and transcribed for analysis. Schn found that most designers reasoned their way from premises to conclusions and the premises took the form of design rules. There were some overlaps between rules but they were subjective from designer to designer. The rules once applied were challenged or corrected. e.g. existing ideas can be used as a standard "to work off" and produce a sequence of designs. In addition, participants used different rules to reach the same conclusion. This study of design types has several implications:

- Skilled designers have a repository of types that hold their design knowledge
- Design types may be codified and formalized into specific rules that may be thought like a science.

- Design types influence the design in aesthetics and political beliefs and also form a basis for collaboration across various disciplines

Thus the study of design types has implications for the building of computational tools and also communication between diverse groups of designers. The fact that design rules are shared and overlapping provides an opportunity for communication and teaching. However not all design rules are the same, some are more significant than others and operate at different levels.

Simmonds presents another study of design making or specifically design decision-making strategy practised by postgraduate students. [Simmonds, 1980] Simmonds identifies levels of a design strategy and he analyses student‘s performance against the context of these three levels of strategy. Simmonds‘ interest is similar to mine in that he reviews performance and strategy formation in both the problem definition and problem solving stage. The activities of the students were classified in to three levels of strategy:

1. Strategic level
2. Operational / process level
3. Basic design skill level.

The first strategic level is around the general themes of decision-making; the second level is about mechanisms for moving between elements of the strategic level. Finally the third level concerns the basic building or design skills and it is more about the sequence of activities that combine to form a design. Are these design hierarchies related? How can a designer define and work through these levels of strategy?

There are really two ways to work in the levels of strategy: top down or bottom up. The top down approach is straightforward: formulate the strategy first and then work down to the operational level.In the engineering design field, Sturges describes a top down function logic decomposition process that is used to represent different functional relationships through out different levels of design. [Sturges et al., 1996] Here the “why” questions are answered by the higher order blocks and the “how” question is answered by the lower levels. Thus the design intent can be captured using these functional relationships independent of the designer.

In contrast, Gero presents a bottom up approach to design synthesis where expected behaviour is generated from a specification of a design problem and actual behaviour from an analysis of a knowledge-base from existing structures. [Gero, 1990] Thus a knowledge representation schema to build designs provides a way to operate between the different levels of strategy. Simmonds found out that the most effective students were the ones who could operate at different hierarchies simultaneously regardless of the approach that was taken. [Simmonds, 1980]

3.4 Complex Systems and Hierarchy

Section 3.1.1 demonstrated why the mechanistic hierarchical view of design can be problematic for a satisfactory solution to real world problems. However all is not lost, for there are aspects of the design problem space that lend themselves very nicely to the application of automation. By developing a hierarchical understanding of the design problem, we can re-classify the complex system as a structure made up of hierarchies. The purpose of this operation is to understand design hierarchy and to gain an insight into the structure of design problems. Understanding or putting a structure to a design problem will enable us to formulate strategies for solution. The work of Herbert Simon and Christopher Alexander is reviewed to understand the nature of complexity in the context of design and also urban design. The key contribution of the hierarchical school of thought is to give methods and tools for early stage structuring of the design problem.

Simon defines a complex system quite simply as a system made up of large number of parts that interact in a non-simple way, so that the whole is more than the sum of the parts, in the sense that it is non-trivial to infer the properties of the whole if the properties of the parts are known. [Simon, 1965] He defines the structure of a complex system as a hierarchy of systems: that is as a complex system composed of subsystems that have further sub systems. Therefore a hierarchic system as a system that is composed of interrelated sub systems, each of them being hierarchic in structure until we reach some level of elementary subsystem beyond which there is no more decomposition.

To illustrate the point further, Simon describes the parable of two watchmakers: Hora and Tempus who were both highly regarded craftsmen and had customers who were constantly calling them. However, only one of them succeeded: Tempus prospered while Hora became poorer and poorer until he went bankrupt. The watches were made of 1000 parts each, Hora had so constructed his assembly that if he had one partly assembled and had to put it down to take a phone call from a customer it fell apart to individual pieces and had to be reassembled. The more the customers called, the more difficult it became for him to have enough time to finish a watch. Tempus meanwhile had the same 1000 parts but he designed them so that they were based on 10 subassemblies, hence when Tempus had to put down his watch to answer a phone call he only lost one sub assembly thus enabling him to complete his work losing only a small fraction of the time as compared to Hora.

This highlights a key characteristic of complex systems: they evolve from simple systems much more rapidly if there are stable intermediate forms and systems. Complex hierarchical systems described this way have a property of near-decomposability where internal sub systems interact in a way that is weak but not negligible. Another aspect of decomposable or hierarchic systems that is apparent from the example above is there is little data loss in representing them. Simon cites the example of a person drawing a complex system like the human face: he would draw the outlines first then fill in the ears, eyes nose etc. Thus many complex systems can be shown as a sum of their parts. Finally Simon introduces the concept of state descriptions and process descriptions where pictures, blueprints, diagrams etc. are state description and recipes, chemical reactions, equations etc. are process descriptions. State descriptions characterize the world as sensed and later characterize the world as acted upon. He concludes that we pose a problem by giving the state description of the solution.

The nature of human problem solving process is characterized as a search through a maze with infinite possibilities but rules can limit the solution space. e.g. Consider a safe with 10 dials numbered from 0 to 99. It would take 10010 possible combinations to open the safe by trial and error. However if there was an audible feedback when the correct number in the dial was pressed, then the total number of combinations required would be drastically less (10x50), thus with this additional context, the task can be converted from a impossible problem to a trivial one. Thus, the design task is then to discover a sequence of processes that will produce the goal state from an initial state. General human problem solving is based on the following: given a blue print find the recipe. Translation from the process description to the state description enables us to recognize when we have succeeded. It is important to understand the nature of complex and hierarchic systems since according to Simon above, they evolve from simplicity and thus can be synthesized and analysed based on the synthesis. [Simon, 1965]

In this case, the audible feedback can be characterized as a constraint and puts structure on the extremely complex problem of finding a combination. Simon describes the process of designing a house: generally considered ill-structured since there is no criteria to test a solution and the problem space is not defined in a meaningful way. Constraints and design rules can be thought of in this context as the needs of the client: the number of rooms, size, budget etc. There are abstractions that also set more constraints: 'general floor plan plus structure', 'structure', to 'support plus roofing plus sheathing plus utilities etc.' Thus a general design problem can be deconstructed into set of requirements and sub systems.

Thus the ill structured problem of designing a house begins to acquire a structure by being decomposed into requirements and components and beings to look like a well structured problem. With all these sub systems, the architect then has an issue of co-ordination between systems. This way we build a hierarchy of systems by applying constraints to address the complex problem of design.

The work of Christopher Alexander on systematic design and "patterns" should be introduced to understand the design patterns based approach to design. Alexander's work builds upon the ideas from cybernetics to put forward a optimistic view of systems approach to design. Alexander's main contribution was in the field of urban planning and architecture and it in this context that his contributions should be considered. Alexander illustrates the lack of sensitivity in design methods to the actual requirements of the environments in which they are designed. [Alexander, 1967] Alexander's central argument is that most modern design methods fail to address the demands placed on them fail to improve the status quo because they have the following problems [Lea, 1994]:

- Inability to balance individual, group, societal, and ecological needs.
- Lack of purpose, order, and human scale.
- Aesthetic and functional failure in adapting to local physical and social environments.

- Development of materials and standardized components that are ill suited for use in any specific application

- Development of materials and standardized components that are ill suited for use in any specific application

- Creation of artefacts that people do not like.

Alexander uses historical precedent to distinguish cities as ones that have arisen more or less spontaneously over many, many years which he calls as natural cities vs cities which have been deliberately created by designers and planners as artificial cities e.g. Siena, Liverpool, Kyoto and Manhattan are examples of natural cities. Levittown, Chandigarh, Brasilia etc. are artificial cities. [Christopher, 1965]

Alexander notes that before the advent of modern architectural methods, most construction was produced without formal models or rules of design and survived and progressed in an evolutionary fashion. Designs went through a process of natural selection to achieve a sense of harmony and equilibrium with the environment and people. As supplement his book Notes on the Synthesis of Form, Alexander also wrote “A Timeless Way of Building” and “A Pattern Language”. Alexander introduces a pattern as set of configurations and artefacts that are commonly present in the world. He lists a set of common patterns and each of them has five parts:

- Name: A short familiar descriptive name usually describing the artefact
- Example: A few pictures and diagrams of the pattern that demonstrate the application domain
- Context: A discussion on why the pattern exists and place where it can be or is used.
- Problem: Constraints on the problem space.
- Solution: Solutions reference and relate other higher and lower level patterns.

Pattern entries have the following properties: [Lea, 1994]

- Encapsulation: Patterns are independent, specific, and precisely formulated enough to make clear when they apply and whether they capture real problems and issues.

- Generativity: Each entry contains a local, self standing process prescription describing how to construct realizations. Pattern entries are written to be usable by all development participants, not merely trained designers.

- Equilibrium: Each pattern identifies a solution space containing an invariant that minimizes conflict among forces and constraints.

- Abstraction: Patterns represent abstractions of empirical experience and everyday knowledge. They are general within the stated context, although not necessarily universal.

- Openness: Patterns may be extended down to arbitrarily fine levels of detail. Like fractals, patterns have no top or bottom - at the lowest levels of any design effort, some are merely opaque and/or fluid (e.g., plaster, concrete).

- Experimentation: with possible variants and examination of the relationships among patterns that together form the whole add constraints, adjustments and situation-specific specializations and refinements.

- Composibilty: Patterns are hierarchically related. Coarse grained patterns are layered on top of, relate, and constrain fine grained ones. These relations include, but are not restricted to various whole-part relations. Most patterns are both upwardly and downwardly de-composible, minimizing interaction with other patterns, making clear when two related patterns must share a third, and admitting maximal variation in sub-patterns. Pattern entries are arranged conceptually as a language that expresses this layering.

By applying the patterns, the design problem is then structured by using specific components that can be aggregated and manipulated by different users. The key to this method is around the formulation of an exhaustive set of requirements to begin with. Indeed Alexander's central premise on the topic of systematic design is around alignment of the design with the fundamental structure of the problem domain. Alexander explores the structure of cities and he postulates that cities are more like a semi-lattice structure but designers abstract that structure to that of a tree. [Christopher, 1965] Another criticism of the design method is around weighing of these different factors:

Alexander suggests that the hardest problems in design need to be solved at the lowest levels of the tree, however, there are other factors entering the solution space at higher levels of the tree and Alexander provides no basis of weighting of factors to resolve this.

Alexander like Simon and others address the lack of order in the design problem by generating a hierarchy through the use of patterns. The common thread that binds this design method is the integration of the design, analysis and evaluation functions into a single entity. This helps in breaking the artificial boundaries and building a more holistic design that is in agreement with the local environment.

3.5 Mechanising Design

The implementation of a mechanistic view of the design process as transformation rules of patterns forms a good basis for workable systems and processes. How can the flow of design of design be mechanized? How can the design process be de-constructed into different steps or stages of design? What abstractions are necessary for automating the workflow? To answer these questions, Newell and Simon introduce the concept of “design states” which are conglomerations of patterns where the designer is able to recognize the patterns contained in a design state, which match those contained within some mental repository of patterns.

Coyne and Gero also state this very succinctly: The model of design as transformation rules acting on patterns within design states requires an understanding of how goal states are achieved. [Coyne and Gero, 1985] Problem-solving activity is therefore goal-directed. The designer tries to find a state that contains a particular pattern, and the process of generation can cease when that pattern is achieved. There may also be ’end states’ that are non-goal states, that is, there are no more rules that can be applied and yet the goal state is not achieved. This also enables exploration and indeed leading to a path of an unsatisfactory end state informs future search and builds on the knowledge-base of the designer. The general mechanism for satisfying goals under such circumstances is backtracking to the point where the solution can be further explored in another direction. This involves a return to an earlier state, where a different rule can be tried. This results in the exploration of alternative solution paths. Design activity is therefore described as a goal-directed search through a space of states or potential design solutions.

In this way design solutions can be characterized by an exploratory search problem within the design state. For a long time, this mechanistic view of design was thought to be insufficient to generate designs, however with the advances in technology, in the proceeding chapters, we will demonstrate how these techniques can be effectively used to generate conceptual designs. Determining the states in a design process as a sequence of actions has a lot of implications for using Artificial Intelligence on the design process. There are some crucial problems with this approach. Therefore, a purely artificial intelligence approach to design poses some fundamental questions on the performance of the design. If the search for a solution is an exploratory process, then there are indeed infinite ways that an exploration can proceed. Is there a way to minimize non useful end states in exploration? Understanding this would lead to a more efficient search and also early rejection of states that are not productive.

Coyne and Gero highlight a design problem shown in the diagram below (Figure 3.2) with the goal being to bridge the canal by connecting A and B given the initial state S and three planks and two pylons. [Coyne and Gero, 1985] A optimizing algorithm may naively reach state M and would consider state N to be “undesirable” or sub optimal. However to achieve state G, necessarily, one has to achieve state N first. This shows that there is a need to explicitly define the intermediate states since they cannot be inferred from end goals explicitly. These take the form of constraints. This state space view of a design problem leads itself well to automation and building a process model for the construction of design. Explicit articulation of design rules enables us to break the design process as a series of steps that are taken to come to an eventual goal. Planning can therefore be characterized as a series of actions that enable the goals to be satisfied. The designer explores the problem space using a search function and transforming the design states to find the solution. However as shown earlier, this design mechanism is unlikely to produce realistic design solutions to real world complex planning problems. To illustrate this, Coyne and Gero discuss the analogy of a car journey between two cities as solved by humans: we do not “search” a map for every street and lane way but rather consider problem solving at a coarse scale first and then resolve the problem at finer levels of details. [Coyne and Gero, 1985] Thus, while purely algorithmic search strategies within the design space can be conceived of it is unrealistic to pro-

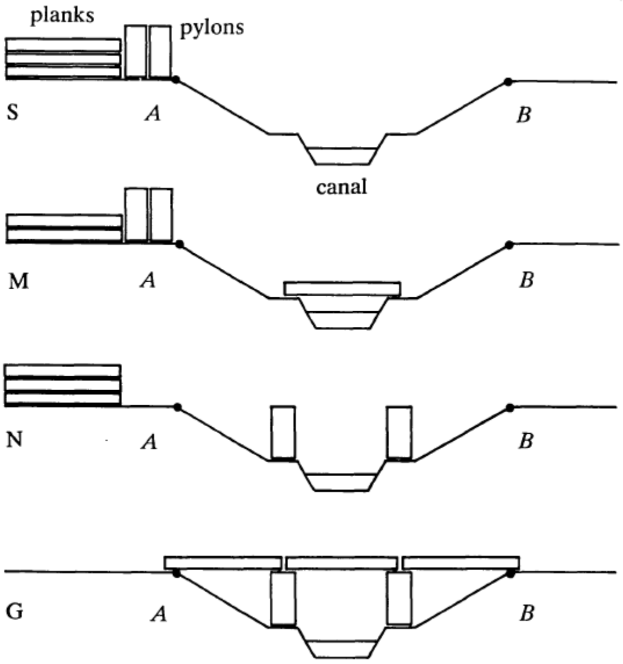


Figure 3.2: States in Bridge Building [Coyne and Gero, 1985]

duce designs that satisfy various human stakeholders. Even considering this limitation, there is a utility of this approach to produce reference designs for the problem. The algorithmic approach leads to standardization of the process and thus objective studies of design performance can be conducted. This is discussed in detail in later chapters. When discussing a process-based or a mechanistic view of design, it is important to understand certain key limitations of this approach. While it is easy to characterize the design process as a series of steps, there are implications for problem solving when these are abstracted out in this fashion. A common criticism of the hierarchical method is that problem decomposition leads to loss of information and simplicity.

3.6 Rational Design

Rational design is a term that is used as to describe the process that is separate from the artefact itself and it is used generally in the context of urban planning. Till about 1950s, planning was a craft: the knowledge was personal and the processes were not documented. In many ways the rational design paradigm came about due to the rise of the design "professional". Rational design is about the use of models and methods that anyone with sufficient formal training would be able to use to develop designs, analyze them and manipulate in to a form. The essence of this process is well captured by Alexander: the importance of the design process is in saying that the building is a reflection of the process that it was designed in. Thus the process is the design. It comes from having knowledge of the subject and indeed this is one of the paradoxes of rational planning. The city or the study area is unbounded in complexity, yet highly rational processes are applied to the study and production of a design. Given the fact that the knowledge-base is almost infinite, it is not possible for a single planner to understand and comprehend in its entirety. Therefore, the skill in planning and design lies in the act of synthesizing this knowledge from various fields to produce a plan.

The process is learned by doing the planning or design activity and is sharpened by practice and experience. In Notes on the Synthesis of Form, Alexander notes that models, processes, context and the artefact are infact the one and the same and modern methods create artificial separations between them thus creating a disjoint in the design process. The design analysis and the artefact are disconnected and this leads to designs that do not satisfy the requirements of the people. Alexander argues that to construct an effective design, artificial models and boundaries must be removed and a method that embraces the requirements and the fractures of the project area must be utilized. Alexander's method of rational design provides a base that helps in development of requirements and assumptions. Alexander argues that a project must start with a comprehensive list of constraints both structural and functional in a project space. Then these constraints are analysed for interactions (either positive or negative), and this algorithm results in groups of requirements that abstract the overall complexity of the design problem. The goal of the algorithm is to arrive at a set of subsystems that mimic the structure of a well-adapted “non-professional” design system.

Therefore the most important way to find a hierarchical structure is to define the relationships of between the various factors decomposed so that the hardest problems are solved first at the bottom of the hierarchy and as the designer moves up, the problem is abstracted and it becomes easier to solve. There have been many attempts to combine these theories of hierarchical systems and requirements sets to construct design machines. We review two techniques to discuss similarities; key features and better understand the systematic design methods. There are many other methods that are in literature. This thesis is focused on methods that have a social aspect to them and also real world practical applicability.

Batty postulates the design problem as a hierarchical problem that imitates Markov chains. [Batty, 1971] He uses the rational design theory to propose a model that is based on search for qualitative rather than quantitative logic in design and a focus on the core of the design problem which is the invention of alternative solutions to the problem. Traditionally it is difficult to rationalize creativity, yet it is the most important piece in terms of the design solution from a systems point of view. In a rational design paradigm, the central premise the same: a through and comprehensive exploration of the design problem is the key to invention of the solution. A good analysis leads to good understanding and therefore it would lead to a better solution. Batty states that design is a choice between conflicting alternatives. Solving X = A+B-C can be achieved in may ways as is demonstrated in Figure 3.3 and a solver can reach to the solution by starting in many ways and working hierarchically. Hierarchic design method has been reviewed earlier in the work of Alexander but in short the designer "solves" simple sub problems first and then as he moves higher in the network, the solution of the sub systems is abstracted as the sub problems are merged.

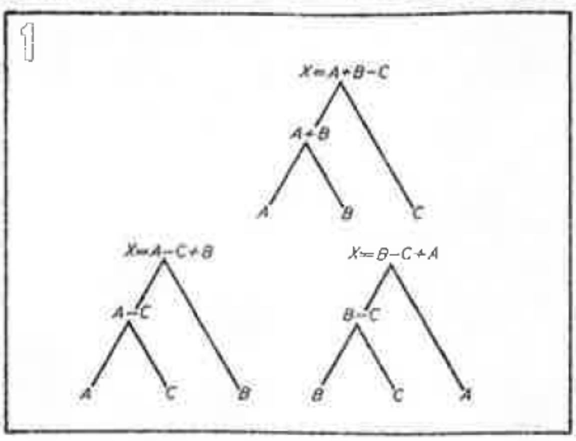


Figure 3.3: Many Ways to Solve a Design Problem [Batty, 1971]

In his theory of rational design, Batty introduces the idea of compromise and averaging procedure between conflicting factors in design as a way to solve the hierarchical problem. If there is a problem that has five factors and there exists some relationship between these factors in a design problem (agreement or conflict), we can build a matrix and a graph of the relationships between these factors as a graph as shown in Figure 3.4.

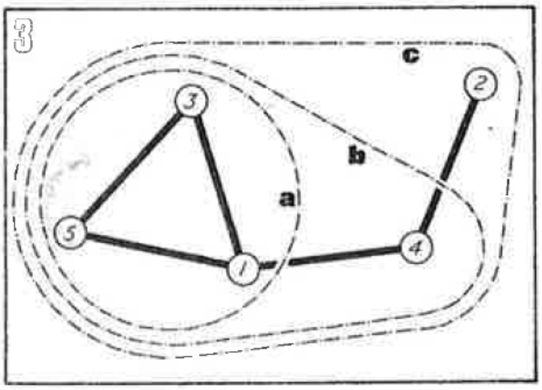


Figure 3.4: Design Relationships Grouped [Batty, 1971]

The design problem can be transformed from a hierarchical structure to one of a graph by linking the various factors of the problem having a interaction with each other. Batty proposes a different way of looking at hierarchical design and to look at design problems in a way that treats hierarchy implicitly rather than explicitly. Imagine that every factor had a designer working on it and we draw a graph that represents the lines of communication between various designers. The communication channel is a way the designer transmits his attitude to to other designers. After the communication has taken place, the designer changes his attitude by taking in to account his position and that of the persons he has communicated with. This averaging process can be compared to a compromise that is achieved in a design. The central premise of this method is the notion of conflict and compromise between different factors until such a time that a final design is arrived at. Design problems structured as graphs (example shown in Figure 3.5) can be classified into three different types of based on the type of graphs that emerge from forming such relationships:

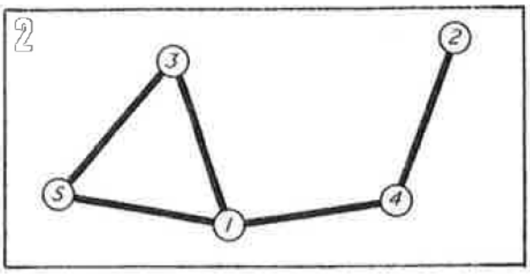


Figure 3.5: Structure of the Design Problem [Batty, 1971]

1. Completely connected graphs: It is a design problem where every factor is related to every other factor in a design problem.

2. Unilaterally connected graphs: It is a design problem where factors are connected in one direction

3. Strongly Connected graphs: The different factors are connected but some of them in direct way

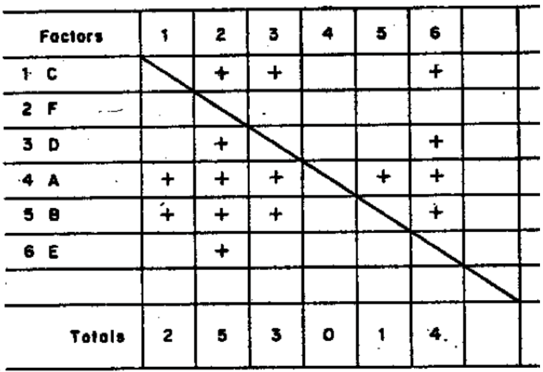
4. Weakly connected graphs: There are some factors that do not have any connections between them

5. Disconnected Graphs: Graphs that are partitioned in to two or more disconnected phases.

The design process is modelled here as Markov system process where the behaviour of the system depends on the previous state of the system where in effect the system lacks memory. While Markovian systems have limited applicability in the sense that real world systems cannot be absolutely classified as either Markovian (or non-Markovian), a design system in this way is useful to compare other design systems. A detailed review of Markov systems is beyond the scope of this chapter but essentially, the idea here is to transform the design problem structure into a directed graph as shown above with interconnected nodes. This transformation enables a design problem to be transformed to a traditional decision making problem.

A similar method of design process was proposed by Jones although it primarily focuses on the engineering design and not on urban planning and architecture. [Jones, 1963] A review of this method provides a good contrast to how a design problem is decomposed in to hierarchies in different domains. Primarily the method is intended to act as a bridge between the “intuition” and “creativity” and rigorous mathematical analysis. Jones's unified method has an aim of reducing the amount of design error, re-design and delay and to make possible more imaginative and advanced designs. He suggests that the method is useful when a large amount of design information is available, design teams have well defined responsibilities and considerable departures from existing designs are called for. The method aims to solve the conflict between logical analysis and creative thought. He defines Systematic Design as primarily a means of keeping logging and imagination separate by external rather than internal means. The method provides a system of notation which records every item of design information outside the memory and keeps the design requirements and solutions completely separate from each other and a systematic means of relating solutions to requirements.

In essence, it consists of the Analysis, Synthesis and Evaluation stages in the design. Analysis is listing of all design requirements and the reduction of these requirements to a set of related performance specifications. Synthesis is the process of finding possible solutions and building up to a complete design with least possible compromise. Evaluation is the evaluation of the designs before the final design is selected. At the beginning of the design process, every member of the team comes up with a list of factors that are critical to the design according to his or her viewpoint. No attempt is made to avoid duplication or omit ideas that are impractical. After all the factors are recorded, the factors are then placed in categories, this categorization is carried out for every factor until we have a case where every category has some factors underneath them. In most design problems there are interactions between various factors and these interactions in the Systematic Design process are marked in the form of a matrix as shown below. For every mark that is put in the matrix (see Figure 3.6), that is for every factor that interacts, there will be a requirement that can be expressed as a performance specification. The totals for these interactions are then added at the bottom of the matrix and also a way to prioritize the different factors can also be produced. Finally, another way of looking at the matrix is to draw a directed graph of the interactions as we have shown earlier and for the matrix above the graph will look like the diagram Figure3.7: After building the interactions and evaluation of the various factors, the Systematic method prescribes producing a set of performance specifications. Performance specifications enable the complete separation of problem from solution and enables a design to be



Factors	1	2	3	4	5	6	
1 C		+	+			+	
2 F							
3 D		+				+	
4 A	+	+	+		+	+	
5 B	+	+	+			+	
6 E		+					
Totals	2	5	3	0	1	4	

Figure 3.6: Factors Matrix [Jones, 1963]

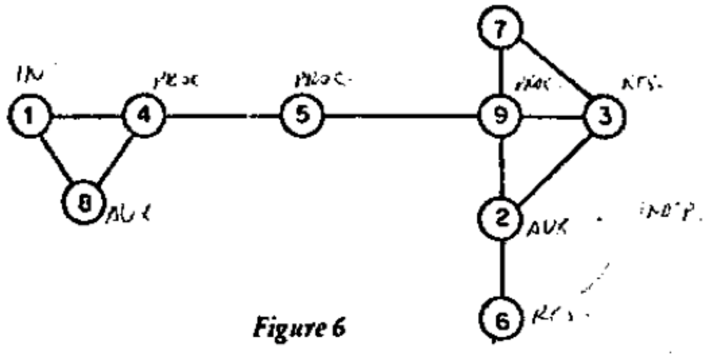
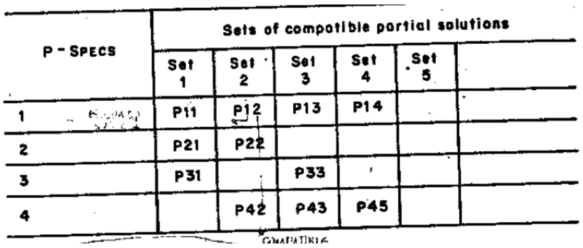


Figure 3.7: Interaction Graph [Jones, 1963]

completely described in terms of its performance. The final two steps of the Systematic Design process are around Synthesis and Evaluation.

Jones elaborates a complete search for solutions can only begin after the performance specifications have been finalized. Jones introduces the idea of partial solutions and links it to the performance specifications through a graphical mechanism as is shown in Figure 3.8. The Systematic Design method advocates the listing of partial solutions to the individual performance specification and many partial solutions are advocated. In general, partial solutions to performance specifications can be conflicting at this stage, and this makes it possible to have combined solutions having the least compromise. A combined solution is a set of partial solutions that form the crux of the design and satisfies the performance specification. When a set of partial solutions are selected they may be plotted as below: Compatibility of partial solutions can be deduced by looking



P - SPECS	Sets of compatible partial solutions					
	Set 1	Set 2	Set 3	Set 4	Set 5	
1	P11	P12	P13	P14		
2	P21	P22				
3	P31		P33			
4		P42	P43	P45		

COMPATIBLE

Figure 3.8: Interaction Nets [Jones, 1963]

at the factor interaction matrix and compatible partial solutions may be plotted as above. As we can see that sometimes some performance measures are not met and in that case, the need is to introduce partial solutions and compromise on existing partial solutions. Finally, then the possible solutions can be plotted in the two dimensional solution space. The characteristics are usually two measures of performance, two measures of shape and a measure of performance and shape of the design. Finally the designs produced by this method of synthesis can then be evaluated in a number of ways:

- Evaluation by performance specification
- Evaluation by judgement

Two methods that apply rational design and systems approach to design each from architecture and planning field and the engineering design field have been demonstrated. These methods show how a planning problem can be de-constructed into a set of requirements and then analyzed until a consensus is reached. Although the application and the outcomes are different, they both follow the basic generalized problem solving method of understanding reality, constructing list of requirements (constraining the design problem) and then going through a process of negotiation in case of planning or analyzing performance in case of engineering design to synthesize a design. The process of synthesis is a process of negotiation between partial solutions and iterations on them. Since partial solutions are fundamental to the process of systematic design, how are these partial solutions reached?

3.7 Partial Solutions and Mental Process of Design

Newell and Simon characterize human problem solving as information processing whereby a set of operators act on patterns to produce solution states not too dissimilar from the way machines process information. [Newell et al., 1972] They use the term “Pattern” in the context of human problem solving: which is a set of characteristics belonging to some object that enables us to recognize similarities in other objects. Experienced designers perform this heuristic all the time when they are designing. In general, patterns need not describe only dimensional attributes of the problem e.g. project area but also topological relationships between elements: color, texture, orientation temperature etc. While humans are really great at recognizing and processing patterns, this has been called as “cognitive map” and is used to describe a network of patterns and associations.

Hertz describes the creative design process using the theory of sets and empiricism on conceptual and subconscious representations. [Hertz, 1992] He describes the design process as a mental model of the following four processes as is shown in Figure 3.9 below.

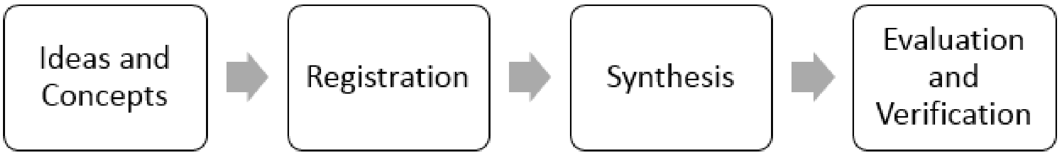


Figure 3.9: Four Step Design Process by Hertz.

Hertz considers a concept as an idea which has been prepared for use by act of will. He considers a design as the total sum of conceptual and subconscious structures related to the design in the memories of all designers involved in the process. Hertz describes the process of registration as the process of placing a set of ideas in an existing structure of the mind. The process of association is where ideas to be incorporated might be described by a given set of ideas. Thus Hertz argues that exploration is the search for possible solutions or new ideas in the space. After registration of ideas, the author describes synthesis as a process where new ideas are made from a set of original ideas and it represents what they have in common. The evaluation is a process of assessing the suitability of a design and also has the synthesis step added to it if in case the design fails the evaluation. And finally verification step is to check whether the design matches the predefined goal. These four processes are then combined into a fundamental creative planning loop below containing the process of registration, synthesis and creation and is shown in Figure 3.10.

3.8 Design Synthesis and Configuration Design

The main criticisms of Alexander and Jones and their systematic methods of design is that they are very prescriptive and do not encourage creativity. The excessive instructions on how the designer should work is one of the main reasons that it is not widely practised. It is important to tackle the excessive focus on process in design because it is the designer who works in the environment. Design is an inherently creative activity and there needs to be space for creativity and it is this aspect of creative design that is at conflict with the systems approach. Any systematic design process should enable flexibility for participants to express their creativity. There are a few techniques that

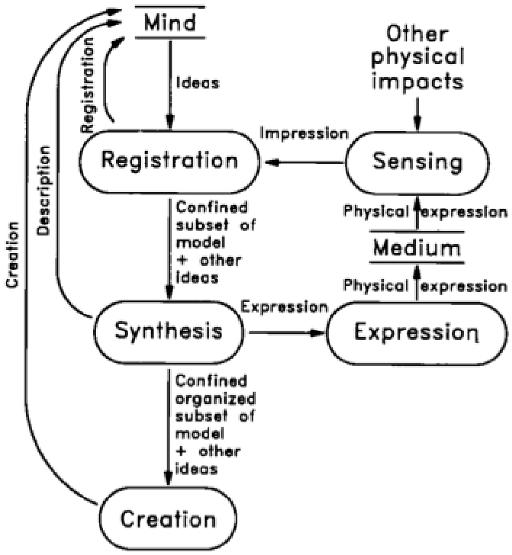


Figure 3.10: Conceptual Design Process [Hertz, 1992]

enable this interaction and a couple of them are reviewed here. By solving this issue of creativity and a systems approach, we solve some of the most fundamental conflicts in design.

Design synthesis models address this drawback by providing a way for design building while preserving the creativity of the designer. As has been demonstrated, design in the form of scientific enquiry is a search through a process involving formulation, synthesis and evaluation of the design. Design formulation is identifying the requirements and specifications of a design, design synthesis is identification of one or more solutions consistent with the requirements and finally evaluation is analyzing the partial or complete solution and a conformance to expected solutions.

Configuration design is a form of design where a set of pre-defined components is given and an assembly of selected components is sought that satisfies a set of requirements and obeys a set of constraints. [Mittal and Frayman, 1989] Configuration design differs from other types of design in that they do not allow for new components to be designed and the set of requirements are assumed to be complete.

As discussed in Simons's work earlier, design problem solving is a search activity where design synthesis involves the search for one or more design solutions through the selection and application of operators. Design evaluation involves assessing whether the goals identified earlier have been satisfied by the synthesis. Design formulation has been reviewed in Chapter 2 but what are the strategies for design synthesis? What are the key requirements to form a effective design synthesis? We have already reviewed the mental and cognitive model of the design process. How are these rules used to produce a design? Design synthesis is most useful in a configuration-design problem based on search. Given that essentially it is a combinatorial problem, how can the search space be constrained so that it is a problem that can be solved with reasonable speed?

Maher presents three models of conceptual design methods that are based on decomposition, case—based reasoning and transformation to come up with a design solution. [Maher, 1990] Each model is a way of representing design knowledge and experience in a formal way by using design rules. (See Figure 3.11) Design synthesis is the focus of Maher's research is in a synthesis process where the design is formulated and the design space contains all the knowledge that is used to develop a solution. Maher presents three strategies for design synthesis:

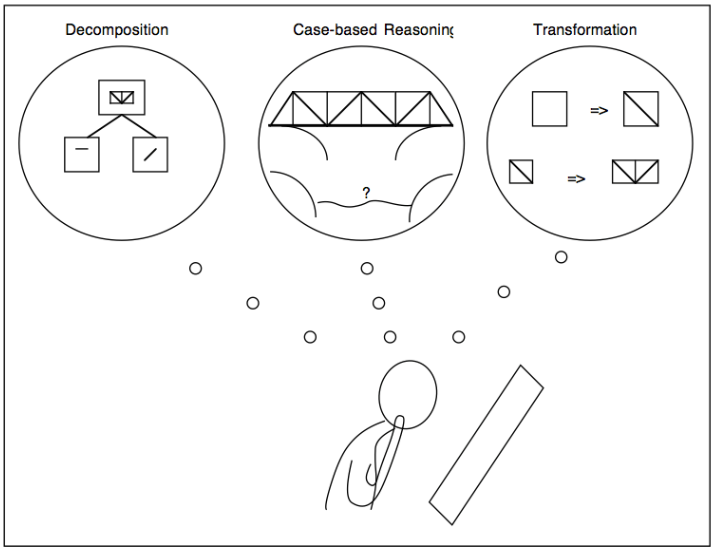


Figure 3.11: Strategies for Design Synthesis [Maher, 1990]

1. Decomposition: The idea of dividing complex problem in to simpler ones is elaborated above in great detail. Problem decomposition has two meanings:
    - Object centred and organized around physical systems: to decompose a domain of design knowledge, example a truss made of beams, bolts, fasteners etc.

   - Functional decomposition: to decompose into the various functions that must be provided for by a design solution, for example, resisting various types of load and providing open space, until a component can be identified that will provide a specified function.

2. Case-Based reasoning: This model is similar to the idea of "types" presented by Schon earlier where the designer users previous design experience as episodes and applies it to the design problem to generate a solution. The model works as follows [Rissland et al., 1998]:

   - recall relevant cases from case memory
   - select the most promising case
   - construct a solution for the new problem
   - test the solution
   - evaluate the results
   - update case memory by storing the new case.

   In the design synthesis domain, the most interesting operations are case retrieval, selection and modification. This assumes that the knowledge about solutions is explicitly represented in the memory of the designers where that knowledge can be from experience or getting help from other experts.

3. Transformation: The transformation model sees shapes and then transform them into new shapes where the design knowledge is expressed as a set of transformational rules. The transformation model follows a theoretical approach to design in which the initial set of design requirements is transformed into a design solution.

Chandrasekaran describes the general Propose, Critique, and Modify (PCM) type common top-level methods to solve design problems. [Chandrasekaran, 1990] This is the classic synthesis technique that has sub tasks of proposing partial or complete solutions, verifying the solutions, critiquing the proposals by identifying causes of failure and modifying proposals to satisfy design goals. Breuker presents detailed models for case-based techniques: structure oriented approach and a resources oriented approach. [Breuker and Van de Velde, 1994] Clearly there is overlap between all these methods of design synthesis. Thus the configuration design problem can be solved through various problem solving approaches: one that is domain independent, uniform method with little background knowledge or the other that is knowledge intensive.

3.9 Conclusion

As demonstrated above, the key criticism of a systems approach to design is that it stifles creativity. This chapter has explored creativity in its role in early stage design. Currently there is no work that bridges these two domains: the systems approach to design and sketching in a comprehensive way. This is the fundamental research question for my work. Can sketching and a systems based approach be used together to produce early stage design? In this chapter, we have reviewed some of the key contributions to the systems approach to design. A understanding of theories and their limitations has been built. This understanding is critical in order to make design a "process" or a method that can be followed or artificial intelligence models can be developed. Additionally, this chapter shows how the problem is seen by the designer and how designers design both cognitively and in working with the artefact. The decomposition of design problems into partial solutions has also been reviewed. In the next chapter, a framework that encompasses this systematic view of design is discussed. This framework accommodates most of the issues presented here and the power of designing in diagrams with various case studies. In the second half of this thesis, a digital implementation of the framework and a series of tests are conducted to show how collaborative design can be achieved with different ways of designing.

Chapter 4

Planning Workflow and Geodesign

4.1 Introduction

After having reviewed designing with diagrams and a systems approach to design, this chapter examines how these approaches are used in practice and in the way of Planning Support Systems. A literature review is conducted on planning support tools and gaps are identified in that there no tools that holistically integrate two domains: of diagramming and the systems approach to design. In addition, the review highlights key reasons as to why planning support tools lack broad acceptance and appeal in practice. This chapter discusses the emerging field of geodesign and also a framework that has been developed by Prof. Carl Steinitz after a number of years of practice experience. This research approaches geodesign from a process perspective and argues that a process-based tool is more effective. After demonstrating the drawbacks and opportunities of planning support tools and reviewing the geodesign framework, an implementation of the framework in a workshop format and this case study is presented. This case study is used to identify opportunities to build planning support tools that integrate the framework, designing through diagrams and systems thinking to help with the problem of regional planning.

Cities often undertake an elaborate planning process that helps them plan and address the complex issues that they face given the population rise, stresses due to climate change and the need for economic development. Given this complexity, the modern planning process is highly opaque and difficult to understand for the common citizen [Burby, 2003] [Arias et al., 2000]; in addition the tools that are currently used as a part of the process do not enable easy comprehension and communication of the problem at hand. The process is also fraught with differing opinions and at times does not promote collaboration or agreement. As a result, stakeholders can miss the vital collective wisdom and knowledge that an effective and efficient collaborative planning process facilitates. While not every planning problem needs to be participatory through stakeholder engagement, particularly at a regional level, collaboration is critical since there are many phenomena working together at the same site. The collaboration need for regional planning is addressed from a planning support system point of view. There is a need for a support system that helps the decision makers better understand the problem and enables experimentation and interactivity that in addition promotes understanding between the different stakeholders. The right tools will help all participants inform the debate and engage with the process in a data driven fashion with the hope that ideologies and opinions take a back seat. This is the ultimate aim of a systems based planning approach where science and creativity inform the design process.

The nature of collaboration can change, it can be collaboration between entities, individuals, citizens, scientists who all have a role to play in the planning process. In his book The Wisdom of the Crowds.[Surowiecki, 2005] author James Surowiecki quotes: "*Diversity and independence are important because the best collective decisions are the product of disagreement and contest.*" The key to a good design therefore is the ability to address different interests and positions of the stakeholders and build a mechanism for negotiation and iteration.

This is a sentiment that finds echoes in many critiques of planning tools and planning process over the last half century and is elaborated below. A participatory planning model can be a great tool to underpin a process where it is easier to get stakeholder buy-in, to bring out problems earlier that are usually not obvious, and to enable rapid scenario testing. These are currently lacking both in planning support tools and the planning process itself.

4.2 Planning Process and Opportunities

The traditional planning physical process emerged in the 1950s from rational decision theory and problem solving. It is structured from problem definition through to analysis and thence plan generation, evaluation and choice of the best plan to be implemented.

The process is invariably real-time and cyclic in that planners and analysts - and indeed any other stakeholders involved in the process - often reiterate this sequence to enable convergence on a best plan. [Brail, 2008] A typical planning structure is laid out in Figure 4.1. In the 1950s and 60s the general systems theory played a very significant role in the development of the planning process. That a general property such as utility or welfare could be optimized with a systems model was the general paradigm. [Harris and Batty, 1993]

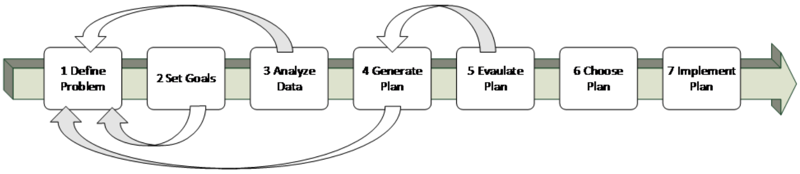


Figure 4.1: The Traditional Planning Process

“Planning support systems” is a term used to collectively label the various tools and processes that a planner deploys when generating and evaluating a plan as described above. The distinction between a planning support system and a decision support system has been blurred with the advances in technology. [Dijst et al., 2003]

Batty presents a framework that contain three primary ideas and functions when combined form the basis of a planning support system:

- The function of the PSS is to generate its own information about the problem and the way it is likely to be alleviated, solved,or resolved. [Batty, 1990]
- The ability of the PSS to capture the essential workings of the system in question. [Batty, 1990]
- to transform basic data into information which in turn is the force behind modelling and design. [Batty, 1990]

The way planners and urban designers think about and communicate ideas relating to urban problems is through visualization based on the following premises [Langendorf, 1993]:

- To understand nearly any subject of consequence it is necessary to consider it from multiple viewpoints, using a variety of information;

- Understanding complex information about urban planning and urban design may be greatly extended if the information is visualized;
- Visualization aids in communicating with others.

So we have complex cities of both physical infrastructure and data and a linear planning process and support tools that are used to enable decision-making. In has been argued that various Geographic Information Systems (GIS), Planning Support Systems (PSS) and Spatial Decision Support Systems (SDSS) and other analytical tools commonly fall short in efficiently supporting design efforts and decision making in implemented and established processes. [Dias et al., 2013] [te Brommelstroet, 2010] [Vonk and Geertman, 2008] However, the sophistication in modeling technologies enables a new family of planning support tools that can address some of the problems around rigidity and accessibility associated with the traditional process in Figure4.1 above. It is this opportunity that merits a re imagination of planning support tools.

The fundamental shortcoming of the planning process presented in Figure 4.1 is that the flow of information and processes tends to be one way and therefore rigid in the sense that previous actions cannot be altered. The sequential nature of the flow mandates a step-by-step approach where the next step in the process cannot be reached without completing the previous one. Additionally, most planning projects are broad and diverse with inputs from multiple stakeholders thus increasing both the cost and importance of communication and collaboration.

Unfortunately, it can be argued that the tools used for planning have been unable to keep pace with these complexities and take a stopgap approach. The general response to additional complexity in the process has been the addition of new features to existing tools or attempts to apply an existing toolset to a new problem. Additionally, very few planning support systems underpin conceptual design and particularly a systems approach to conceptual design. A well thought out design concept goes a long way to developing a good plan. At the conceptual stage, the changes have a lower cost. A more appropriate planning process is cyclical in its initial stages to enable the creation of an optimum plan based on a range of options. This process is cyclical in a number of ways, not only in the speed of the process but also in the output where designs are produced, analyzed and iterated upon.

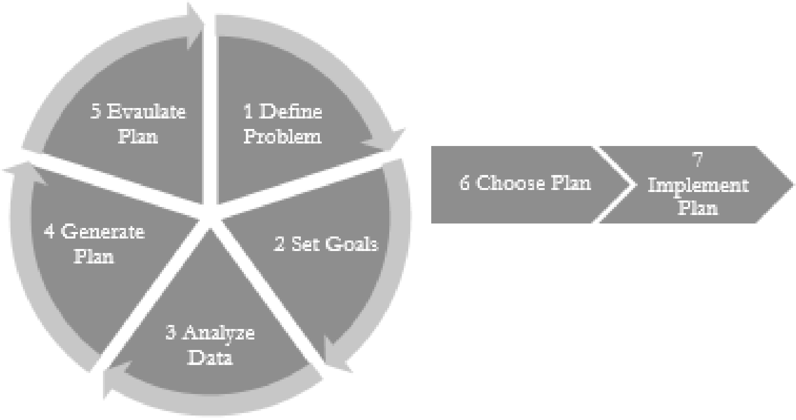


Figure 4.2: A Modified Planning Process

Modeling and analysis, in particular local client side modeling, lies at the heart of this transition. An intuitive natural interface and user friendly spatial planning tools have a significant impact on user satisfaction in a planning process. [Arciniegas et al., 2011] [Arciniegas et al., 2013] [Ligtenberg et al., 2004] As this is explored in more depth,a hybrid design and modeling environment is proposed for use in tools that enable the process in Figure 4.2 above to be implemented. The main reason to introduce this framework is to highlight the work done currently in the domain of planning support systems and its shortcomings and proposes a new way forward. In addition the cyclical nature of the framework enables trailing, quick changes and feedback and also designs that can be built with low commitment. The speed is critical in any planning process and especially in the context of conceptual collaborative planning.

4.3 Planning Support Systems

Geertman defines Planning Support Systems (PSS) as: ‘geo-information technology-based instruments that incorporate a suite of components that collectively support some specific parts of a unique professional planning task’. [Geertman, 2008] In the modern age, PSS generally means the use of computing technology to support the planning process, usually to inform decision-making. From a purely analytic perspective, the idea of a planning support system is to improve the outcome of the planning process by providing rational analysis and scientific insight that leads to better decisions and plans. Some of the highlights of a planning support system are its collaborative nature, and the ability to do collective design. [Klosterman, 1997] In general this domain is called Urban Strategy and is nicely described by Couclelis [Couclelis, 2005]: “it involves actions taken by some to affect the use of land controlled by others, following decisions taken by third parties based on values not shared by all concerned, regarding issues no one fully comprehends, in an attempt to guide events and processes that very likely will not unfold in the time, place, and manner anticipated” (Page 1355)

This multi-stakeholder, multi-disciplinary nature of the planning problem is what planning support systems attempt to address. While this is not a review of the background and history of planning support systems, it is worth highlighting two important aspects of planning support systems that determine success: firstly it is useful to understand the perceived utility and value addition done by planning support tools; and secondly it is important to understand what is preventing broad adoption of digital planning support tools in practice. This will enable the identification of potential opportunities for progress and contribution.

While there have been many planning support tools developed, their uptake has been relatively limited. [Vonk et al., 2005] Generally, the reasons for lack of adoption are around technical issues, usability issues and also around the user, organization and institutional factors . The current tools are inflexible, not compatible with planning tasks or too much focus on analysis. Thus there is a new breed of planning support tools that take the form of ‘information frameworks’ that integrate the full range of information technologies useful for supporting the specific planning context for which they are designed. [Geertman and Stillwell, 2003] [Klosterman, 1997] In general these new tools incorporate spatial decision support systems and planning support systems and are related to planning support tools. Below is a short summary of how these differ (for more information see [Geertman and Stillwell, 2002]):

Planning Support Systems (PSS) generally pay particular attention to long-term problems and strategic issues.

Spatial Decision Support Systems (SDSS) are generally designed to support shorter-term policy making by individuals.

SDSS deal primarily with operational decision-making while PSS focus more on strategic planning activities. Both PSS and SDSS combine tools from participatory geographic information systems (PGIS) with decision support tools, such as multi criteria analysis and visualization tools.

The focus of this work is on strategic planning and the use of planning support systems in that domain. Strategic planning is essentially high level conceptual planning that focuses on strategy building and not so much on the details of a plan. There is a key difference between early and later stage planning. This ties with the discussion presented earlier around sketching and a systems approach to design. Healey deals in detail with the issue of strategic planning characterizing the ambiguous ambition and activity. [Healey, 2006] It is in these domains that planning support systems are the most useful when the goals are harder and fuzzier than in the later stages of planning where the question is more of operational efficiency. Te Brommelstoret offers a good definition of strategic planning [te Brommelstroet, 2010]: "*strategic planning processes can be seen as multilevel group processes in which planning actors work together towards a shared outcome.* "

4.4 Problem with PSS Adoption

The field of tools for planning support is vast and there have been a number of tools that have been built and tested. [Geertman and Stillwell, 2012] [Batty and Densham, 1996] [Hopkins et al., 2004] [Pelzer et al., 2013] [Edamura and Tsuchida, 1999][Guhathakurta, 2002] [Waddell, 2002] They are too many to list and indeed many are being built even today. Research shows that most of the planning support tools are not used widely in professional practice. Vonk provides a good insight into why these tools are not adopted widely. [Vonk et al., 2005] There have been studies that agree that there is a need for more support tools among the planning community to help the planners and designers be more effective. [Bishop, 1998] [Voss et al., 2003] It has been demonstrated that there exist ample opportunities for planning processes to be more collaborative and the need for tools to help in this effort. The acceptance of support tools has been studied as a technology acceptance model by various researchers. Vonk presents the adoption model for planning support systems based on the diffusion of models presented initially by Rogers. This general framework has five steps to adoption of a technology [Rogers, 2010]:

- Generation of awareness of existence of an innovation;

- Persuasion and the formation of an attitude towards the innovation;
- An adoption decision;
- Implementation;
- Confirmation.

This model has been transformed into a “technology acceptance model”. [Frambach and Schillewaert, 2002] The highlight of this approach is the combination of the organizational and individual preferences and factors to determine innovation adoption. Vonk modifies the framework proposed by Frambach to make it more suitable for GIS and SDSS with a specific focus on data and hardware and a simplified schematic is given in Figure 4.3 below. [Vonk et al., 2005] Vonk constructed a web survey using this framework to discover the main bottlenecks in adopting GIS or planning support technology among practitioners, novices and experts. A total of ninety-six responses are categorized into four parts: unimportant, important, very important and don’t know. The three most important bottleneck indicators are experience within the planning organization, user friendliness of system and users awareness of potential of PSS. One of the main bottlenecks to adoption is the lack of information or knowledge of existence of the software. Once users have been informed about PSS, they have a hard time finding them and experimenting with them. If users do manage to find PSS, many of them do not value them and reject the tools immediately. This negative attitude is likely to be partially caused by the image that PSS have among planners as ‘black boxes’ that are difficult to operate. [Vonk et al., 2005] Thus initially, the users do not know about the planning system and if they do know about the tools, then they have a difficult time experimenting with it.

The tools themselves need improving to be able to offer better support for planning tasks so that planners feel that planning support systems offer advantages for their work. Therefore Vonk concludes that there is little awareness among professionals about the existence of the tool, a lack of experience with the PSS and finally there is little intention in the case of planners to use the tools because of lack of support for the PSS. Te Brmmelstroet came to a similar conclusion and in his study 52% of the people stated that not knowing about the software was the main bottleneck. The sec-

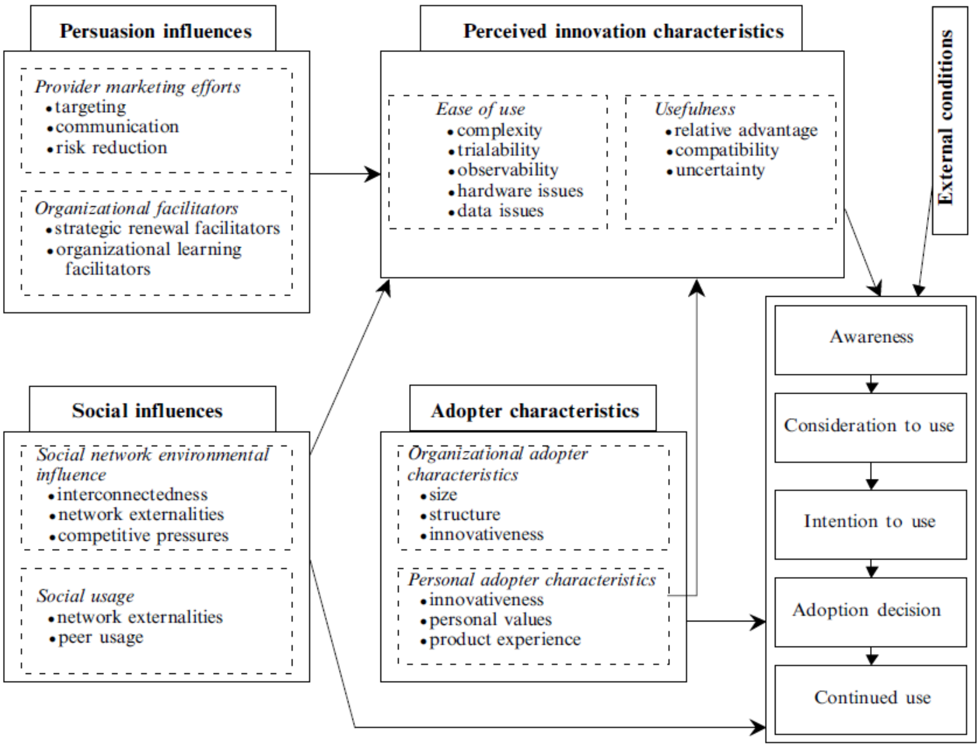


Figure 4.3: Technology Adoption Framework [Frambach and Schillewaert, 2002]

ond major bottleneck was the lack of transparency in the implementation of the system. [te Brommelstroet, 2010] Some other highlights of his study include a lack of a common language between the various tools and collaboration between the stakeholders and the participants.

Fundamentally, the goal of PSS is to improve the planning process and / or the planning outcome. Most studies described above do not provide a systematic way of analyzing PSS, therefore there are no real metrics or scores that can be used to compare different tools and they have to be judged by their perceived utility. Pelzer classifies the utility or the added value in a form of a three level framework which classifies the utility as at: the individual level, group level and outcome level below defined as follows[Pelzer et al., 2014]:

1. Individual Level: At an individual level the value added relates to learning about the object of planning:
    - What is the problem and what are its causes? What is the effect of the intervention etc.?
    - Learning about the perspective of other stakeholders in the planning pro-

cess.

2. Group Level: The additional value at a group level in a PSS is about communication, collaboration, consensus and efficiency.

    - Collaboration is a fundamental aspect of the modern planning process and it involves sharing representations, arguments and arriving at a consensus.
    - Communication is a byproduct of a planning process and the aim of any PSS should be to facilitate communication between participants.
    - Consensus development is a broad goal of collaborative planning and to move forward in process with many stakeholders, consensus is a way to move forward in the process.
    - Efficiency in planning is about doing the planning tasks faster with less time and resources.

3. Outcome level: this is by far the most difficult metric to measure in a planning process. Pelzer argues that the most important aspect of added value lies in adding to the internal agreement or internally consistent with the logic of how plans work. In summary, the added value of PSS at the outcome level is conceived as “better informed plans and decisions”.

This demonstrates that the central value as perceived by practitioners in a planning support system is around communication and collaboration. Therefore the central research question is around how can a planning support tool improve efficiency, communication, collaboration and consensus?

4.5 Multi-objective PSS

There has been extensive research in multi-objective, multi-stakeholder planning support tools and the aim of this section is to do a quick review to identify key findings and opportunities to put a context to this work. Carver extends the use of GIS with the use of multicriteria analysis (MCA) techniques. [Carver, 1991] Similar studies have been conducted by others to analyze alternative design solutions against each other. [Jansen and Rietveld, 1990] [Pereira and Duckstein, 1993] [Janssen, 1992] In such a case, usually, the optimal solution is created by the system using multi-objective linear programming. [Aerts et al., 2003] [Williams and Re Velle, 1996] [Eikelboom and Janssen, 2015] In addition, Stewart has used genetic algorithm techniques to construct designs using multi-objective optimization techniques. Brouns et. al. demonstrate a study where spatially explicit information was used to formulate strategy for peatland management and validated using stakeholder workshops. [Brouns et al., 2015] Feng et al. demonstrate a integrated land use and transport planning model that uses a multi-objective programming and a genetic algorithm. [Feng and Lin, 1999] In all of these studies alternatives are considered and a new design is “generated” by algorithms. This thesis attempts to further this line of research but taking a approach of diagramming and digital design synthesis. This thesis focuses on building synthesized designs ‘hierarchically’ using simple shapes and symbols. These synthesized designs lend to advanced multicriteria analysis that accommodates the techniques described above. This work explores this relationship in a geodesign context digitally with fast design creation and versioning and its implication on multicriteria analysis.

4.6 The Opportunity in Planning Support Tools

To summarize, the key issues that hamper broad acceptance of planning support tools is that they do not fit the workflow of the designers in that they operate on the black box model. [Vonk et al., 2005] If we look at the perceived value i.e. what is valuable from a professionals point of view, the following things emerge: enhanced collaboration, understanding of the problem and learning about different stakeholders and understanding the mechanics of the plan itself. If the problem is that of understanding and communication, then we have demonstrated earlier how sketching and early stage sketching can help in communicating concepts. In addition, the key values that participants perceive from the planning tool context is best served at the early stages of the design when there is a lot of room for flexibility and changing of ideas. Chapter 2 demonstrated how early stage design is exploratory in nature. Finally a systematic approach to problem solving that is generic enough to encourage different disciplines would foster collaboration and communication.

Harris et. al identify two key requirements of a PSS [Harris and Batty, 1993]:

- the search for good plans must be by a informed way of trial and error

- planning and policy making need extensive tools for tracing out the consequences to evaluate the alternatives

Another consideration is that the tool should work with the existing workflow that is used by planner. This means that there should be support for all the file formats, technologies and nomenclature that professionals use. Is there a systems thinking design framework that can be applied in the planning context that will support the designers with the planning process and also address some of the shortcomings that we discussed above?

4.7 Geodesign and Geodesign Workflow

GIS has a long history and has evolved as a tool for performing spatial analysis, managing spatial assets and a platform for automating the cartographic process and displaying information in map form. While this paradigm has served us well, there is an increasing awareness of the fragility of our planet and a trend to expand the GIS terminology to a much larger design domains. Traditionally these include architecture and landscape architecture but additionally there is a need to expand to other disciplines. Geodesign came out of a need and realization that analysis of geographical information is not sufficient and needs to be extended to include design. Traditionally, landscape architects, planners and architects do not use the geospatial technologies to design and geodesign aims to fill the gap as the next generation technology that aim to take the field beyond GIS as identified by Harris [Harris, 1989]

The concept of geodesign is not new, it aims to address the problems faced by large planning processes that have multiple stakeholders, difficulty in identifying the key issues on a site and multiple sources of data and experts. Geodesign differs from traditional spatial optimization models of planning or allocation of land use in that it deals with collaborative design where the computers respond to changes in design as it is being built by various stakeholders. Cartography is a core element of geodesign. However in geodesign, cartography plays a supporting role since the other or the more dominant part of the domain is in design. The concept of geodesign can be traced out of a movement in the late 60s of integrating science and design into a single process. Harris [Harris, 1960] [Harris, 1965] proposed the use of sketching and sketch planning in the planning process as a part of the planning support tools domain and the use of modelling to analyze the designs as a part of a single process. Using sketch planning as an idea has been explored in literature as reviewed earlier and the interest of this thesis is in applying sketch planning in a systems approach. Batty [Batty, 2013] characterizes the planning process as one of science, design, technics and politics and the way they interlock. In his article "On planning process" [Batty, 2013], Batty represents this interaction of science and design in a feedback loop that enables the evaluation of designs and a re-generation of alternatives.

Figure 4.4: Integrating Design and Analysis in One Process. [Batty, 2013]

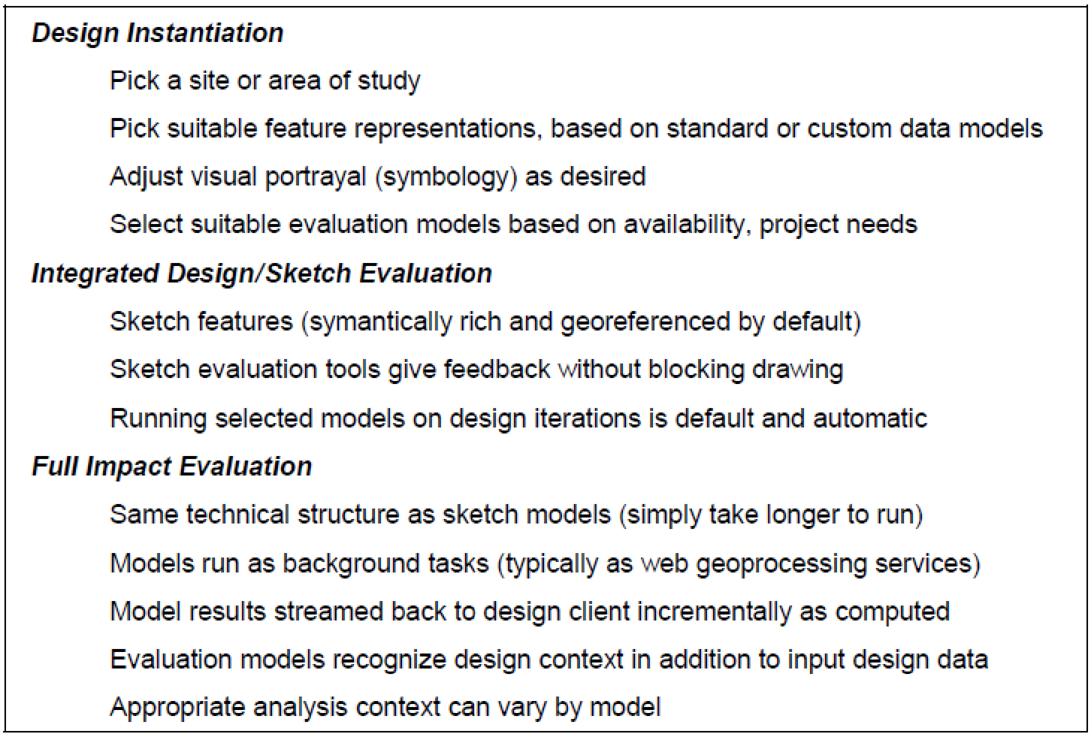
These ideas are not new, they have been around with us since the 60s and 70s when the technology at the time was not up to the mark in terms of data processing, storage and computation power. Therefore true integration was not possible. The pace of technological change is rapid and most modern computers are now comparable to early super computers in terms of their power. This along with the advent of the internet provides an ideal platform for revisiting this paradigm. Can geodesign be used to build tools that use GIS as a foundation and aid in design? The theory of geodesign is able to approach design problems in a systems framework. While additionally there are aspects to geodesign that support early stage planning and collaboration. It is useful to discuss what makes geodesign fundamentally different: the geodesign workflow. While one can argue that professionals have been practicing geodesign and holistic collaborative design for a number of years, geodesign introduces a new workflow that is unique to the field. This in my mind is what makes it ideally suited for a planning support type role. Flaxman [Flaxman, 2010] provides a great motivation for the need of geodesign by highlighting three major issues associated with Geodesign and traditional design workflow and symbology:

- How to use the designers graphical skills to generate representations that are understood broadly, communicated and shared.

- How to depict different systems: natural and human as a part of a integrated process.

- How to make these accessible and open to a broad number of people so that they can participate and bring other subtle knowledge such as art, culture etc. into the planning process.

Fundamentally these questions lie at the heart of geodesign and solving these complex questions should be goal of a geodesign tool. In the solution also lie answers to some of the problems associated with collaboration and communication that exist in the current planning support tools. Analysis and evaluation of design in a traditional GIS workflow is concerned around digitization and drawing of polygons and once they are drawn, they are then evaluated. This workflow is very similar to the sequential workflow of planning that was presented earlier. Flaxman [Flaxman, 2010] provides a good alternative workflow for Geodesign below. (Figure 4.5)



Design Instantiation

Pick a site or area of study
Pick suitable feature representations, based on standard or custom data models
Adjust visual portrayal (symbology) as desired
Select suitable evaluation models based on availability, project needs

Integrated Design/Sketch Evaluation

Sketch features (symantically rich and georeferenced by default)
Sketch evaluation tools give feedback without blocking drawing
Running selected models on design iterations is default and automatic

Full Impact Evaluation

Same technical structure as sketch models (simply take longer to run)
Models run as background tasks (typically as web geoprocessing services)
Model results streamed back to design client incrementally as computed
Evaluation models recognize design context in addition to input design data
Appropriate analysis context can vary by model

Figure 4.5: Components of the Geodesign Workflow [Flaxman, 2010]

It differs substantially from the traditional GIS workflow in a couple of ways: firstly in the integrated design / sketch evaluation where the designs are evaluated as they are sketched at the same time. This activity of sketching and evaluation forms the core loop of the workflow. It is understood that GIS is not solely for planning and has other applications as well. However for this research GIS is considered in the context of planning.

Finally there is a two-step evaluation of the sketch where initially there is a quick evaluation and then it is submitted for final full evaluation. The evaluation process should be seamless and not block the design process. Dias [Dias et al., 2013] puts this succinctly: in a traditional design workflow the analytical assessment happens after designs are produced while in a geodesign workflow they need to happen at every stage of the design. Thus we move away from the sequential workflow to a rapid iterative cycle of design and testing.

The workflow above implies a nice "sketch and analyze" process in realtime. The core idea that design gets better as the designer iterates over the initial idea is in agreement with how designers build on their ideas and make changes and iterate over the design concept using sketching. This way of design in the geodesign context makes the production of different alternatives an integral component of the design process. Traditional tools and workflow do not accommodate for this way of building a plan just because of the amount of data processing and the computing support infrastructure that is required. Additionally, most traditional planning support tools require a large amount of investment on the part of the designer to design and broadly do not support free form sketching. With this way of working, traditional tools are found lacking where the focus of the tools is to produce one design and then analyze it.

This workflow enables rapid iteration so the time required to produce a design is reduced drastically as compared to traditional design methods. By having a shorter cycle time, the geodesign workflow enables the designers to make smaller design move. A huge benefit of this is the fact that the designer can then move back in his design process and revert back to the previous step. This design style of making small changes and keeping track of all changes is what the designer does as a part of the design process. Most of the literature in planning support systems focuses on the details of the tools, the usability of the tool, the clarity of information presented etc. as is reviewed in 5 but there is very little work done on the workflow of design and how a design comes to be and how do can tools support the design process. The area of the design workflow is the primary focus of this work and in the preceding chapters, the thesis will elaborate on the workflow and show examples of how digital tools can facilitate the workflow of geodesign. These will involve: How does one go about building a digital tool that supports early stage planning processes? And can communication and collaboration be achieved using geodesign based planning support tools that enable quick iteration and rapid design creation?

4.8 Framework for Geodesign

Steinitz developed a model of landscape change that enables design and assessment of alternative futures. [Steinitz, 1990] [Steinitz, 2012] The framework takes a multi-system approach to problems that are novel both from a design and from an analysis perspective. The "Steinitz Framework" has been put in practice for a number of years on large landscape change problems and in the form of intense two or three day workshops where participants from diverse academic and professional backgrounds and levels of experience come together and go through the process to build a design iteratively in a compressed timeframe. [Steinitz, 2011] [Steinitz et al., 1996] [Steinitz et al., 2005] In the context of the work of Steinitz as noted earlier, 'design' is both a verb and a noun; as a verb design is about asking questions and as a noun design is the content of the answers. [Steinitz, 2012] [Steinitz, 1990]

Therefore geodesign covers this integrated activity of design, and the workflow introduced earlier focuses more on the design as a verb where the participants are taught how to think about a problem. This has also been a finding as a part of this research where by going through a process of a geodesign workflow, the participants in a workshop not only develop designs but also develop a way of thinking about the problem that is holistic and takes in to consideration many aspects of the problem space. Steinitz [Steinitz, 2012] presents a framework to address the design problems for a geographic area. (Figure 4.6) Most geographic problems and design problems are ill-structured problems as discussed earlier and the workflow and the framework provided help in providing a structure and a systematic way to think about the design problem.

Steinitz [Steinitz, 2012] presents four stakeholders that are key to collaboration in design in a geo-design context:

1. Information technologists: With the widespread availability of GIS and other technologies the IT / computing and modeling professionals play a important role in not only making available the data and content for a study but also organizing and helping in the analysis of the designs produced. In addition they also act as a bridge to the other people in the project.

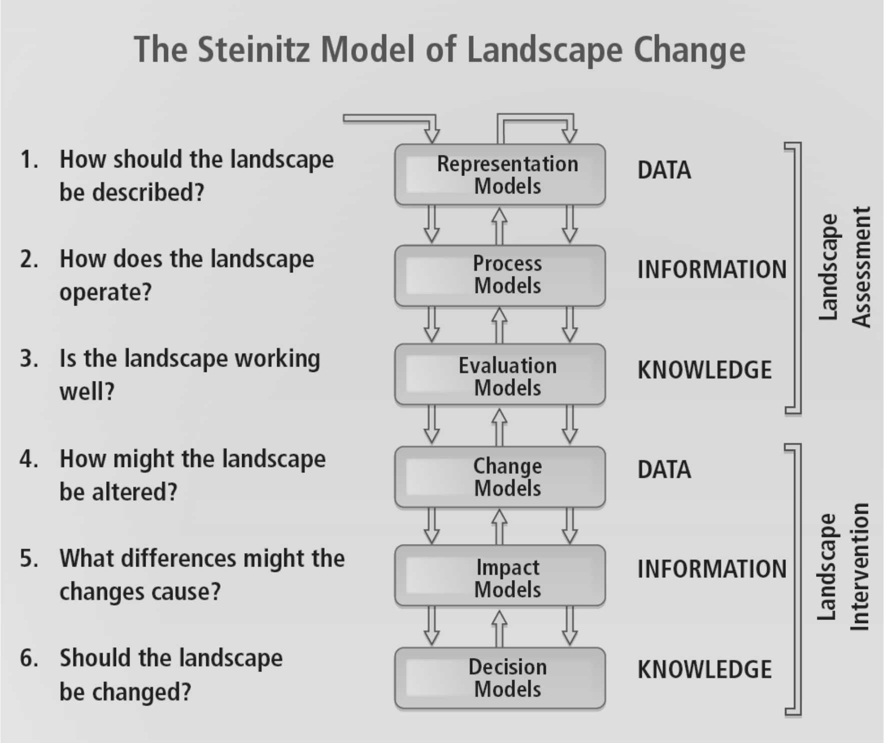


Figure 4.6: Steinitz Model for Landscape Change

2. Design professionals: The designers obviously play a critical role in the context of the geodesign framework, they bring a large repository of skills, experience and knowledge into the study. In addition to informing the design decisions, they also work with the other participants and stakeholders to bring their expertise and build the actual interventions.

3. Geographic Science professionals bring their skills around data, geographical models and other GIS related technologies to the study. They play a critical role in building the evaluation and other models in addition to contributing to the analysis of designs produced.

4. People of the place: Finally, arguably the most important group of people who live in the area and also have to live with the interventions proposed. In addition, the people of the place bring in local knowledge, culture and other softer aspects of the study area. They are critical in the decision-making and evaluation phases since their values and ideas about the future critically changes the outcome of the design process.

It should be noted that this is a collaborative activity and every stakeholder brings a unique perspective to the study and in some ways a good study is where the sum is better than the parts. Also in a collaborative setting there are rules of collaboration and no individual loses his or her identity in the process.

The design process for a geographic study area should be organized to respond to six questions:

1. How should the study area be described?
    - Representation models or available data on the site answers this question and with the recent trends with big data, open data etc. these are relatively widespread and easy to acquire digitally.
    - It also includes deciding the actual study area, its boundaries, the different entities and jurisdiction that encompass the study area. These models obviously have an implication on the data and other models, the selection of the site has a large influence on the study itself so some of the major questions are [Steinitz, 2012]:
        - What are the boundaries of the study area and the different systems?
        - What is the physical, economic and social geography of the study area?
        - What are the data / databases available and how can they be accessed / studied?
    - These initial questions help in scoping the study and the area for a project. Most planning and design studies operate on a large geography and very complex projects and thus the way the project is setup and defined is absolutely critical.
2. How does the study area function?
    - Process models answer this question: the answer to this question is critical to the understanding of how different components and parts link and interact.
    - The primary aim of this step is to understand the scope better and also to decide on what should be included (or excluded) in a study. This scoping of existing processes is critical to understand what actions need to be performed or areas where some work is needed. Process models can also be

built or imported from widely available GIS toolset to suit the study area in case there is a lack of available data. Some sample questions are [Steinitz, 2012]:

    - What are the major physical, ecological and human processes?
    - How are they linked?

3. Is the current study area working well?

    - Evaluation models answer this question. Once the representation and process models are finalized and understood, decisions have to be made on how the study area is working and what parts of the study are working well and others not so well.
    - It is recommended that people of the place build evaluation models. It is nuanced activity that includes scientific evaluation coupled with social, economic and cultural aspects of the place that the people of the place are most familiar with. A level of familiarity with the study area is required and this can only be gained through experience in the area over a number of years. Some questions that need to be answered as a part of building the evaluation models are [Steinitz, 2012]:
        - Is a particular area seen attractive or vulnerable?
        - What are the current environmental or other problems in the area?
        - How badly an area is performing with respect to others?

4. How might the study area be altered?

    - Change models answer the question about the intervention to be planned. This part of the framework deals with the actual process of designing an intervention.
    - Change models are highly dependent on the many stakeholders and in particular the people of the place. What are the values of the people? How do they see the future and is their vision of the future different from existing conditions? What are the other changes that are going to happen (e.g. climate change) to the region regardless and what is the preference of the

people to tackle these changes. Some questions answered in this stage are [Steinitz, 2012]:

  - What are the major changes foreseen in this region?
  - Are they related to growth / development / conservation / decline or any number of combinations of these?
  - What other pressures are anticipated in the future?

5. What difference might the changes cause?

   - Impact models answer the question about the performance of the interventions: how does the intervention perform as compared against the evaluation model.
   - Assessing the impacts of proposed changes is both important and tricky. There are computational tools available that measure the impact but in addition to the technical problems that are a part of dynamic evaluation there is also the other issue of measuring social or economic impact of the designs. The impact assessment of designs is critical to inform the design process. As mentioned before, the traditional way of measuring impact is in the last phases of the design process. However given the iterative nature of the framework, evaluation at every stage is critical. Some questions answered by this stage are [Steinitz, 2012]:
     - In which ways are the changes beneficial or harmful?
     - Are the impacts seen as serious and reversible?
     - What is the cost of the impacts?

6. How should the study area be changed?

   - Finally the decision models deal with the position of the decision makers and take into account the historical and cultural preferences upon which decisions around the intervention are made.
   - The different stakeholders have a role to play in the decision-making and priority setting. Decision making is a vast field of research and a detailed exploration is beyond the scope of this thesis. However there is extensive

research undertaken in group decision making that makes tackling issues relatively seamlessly. Some questions as far as the decision model is concerned are: [Steinitz, 2012]

  - Who are the major stakeholders?
  - Are they from the public or private sector?
  - Is their position known?
  - Are they in conflict?
  - What changes and their consequences are considered most important?

These six questions (Refer figure 4.6) form the central building blocks around which tasks can be built and linked as a way to tackle a geodesign study to be performed on an area. The first three questions relate to assessing the existing conditions in the landscape and the answers to the next three questions deal with how the interventions can be managed and agreed on. All of this happens during the design process and is done by many participants in the form of a workshop. Thus within this framework a number of tasks or questions can be formulated that enable a systematic study to be undertaken for any geography. Steinitz [Steinitz, 2012] summarizes some of the actions or questions nicely:

1. Representation Models
    - Obtain needed data
    - Organize them in a appropriate technology
    - Visualize the data over space and time
    - Organize them to be shared among the members of the team.
2. Process Models
    - Implement, calibrate and test the process models
    - Link them to each other as appropriate
    - Link them to the expected change models
3. Evaluation Models

- Evaluate past and present conditions
- Visualize and communicate the results

4. Change Models
    - Propose and/or simulate future changes
    - Represent them as data
    - Visualize and communicate them

5. Impact Models:
    - Assess and compare the impacts of each change model
    - Visualize and communicate the results

6. Decision Models
    - Compare the impacts and decide on a way to proceed.

At any point in the study, these questions should be revisited based on feedback and new inputs must be accommodated, thus while systematic the framework is non-linear. The core idea is to start the study and then iterate over the course of the study until we have some consensus about the designs produced (based on the decision model). At questions 1,2,3, existing technologies like GIS and the geographic sciences dominate. There is an extensive library of models that are mature and available broadly and they enable production and analysis of these models. These questions also relate to the description of the landscape and there are many other aspects to these that are not necessarily answered by geographical sciences; in particular they are to do with the cultural, economic and other “soft” knowledge that cannot be represented in a form of data or model. The last three questions deal with the role of the information technologies and the designers. Designers have a lot of experience in the process of design and the creation of that which is new. Similarly, the designers have to be supported by technologies and other professions to assess the impact of their designs. Finally the decision models space is the domain of the decision makers: who makes the decisions and how are they made? There are many stakeholders in a large and complex study but there should be a set of common values that inform the decision making process.

It can be seen how after starting with these six questions, Steinitz assigns specific tasks at each stage that can help in preparing the study and arrive at a design decision. An important area of research in the context of the framework is the domain of questions 4,5,6. For the earlier questions, as mentioned earlier, the GIS and geographical sciences have been able to provide solutions, however, there is a huge opportunity for research and investigation into the latter three questions and in particular how designers and technologists, people of the place and the decision makers can collaborate to produce designs. This is the core topic of this research and it is described in the later chapters. But before that, there is a exploration of the framework in action.

4.9 Lisbon Experiment

To understand the geodesign workflow and its context in a planning support system, it is useful to review the workflow and framework in practice. The key issue here surrounds the utility of the framework as collaboration and design support mechanism. As previously discussed, the key drawback of most planning support systems is around a lack of understanding and also the inability to fit in the existing workflow. Can digital support be implemented on the geodesign framework that addresses some of the key drawbacks of the traditional planning support tools identified earlier? If so can the digital support tool facilitate collaboration and communication? I want to review how the workflow operates without any digital support to highlight key aspects and identify how digital support might be able to solve the issues around collaboration.

The following paragraphs detail a workshop that was conducted on the 1st of February 2014. The study area is the Tagus river estuary in the Lisbon area and the framework described above was applied to the study area over the course of four days in a workshop format. The primary participants were faculty and students at the Lisbon University with a diverse expertise in architecture, landscape architecture, urban planning and related professions such as economics and others. This workshop was conducted solely with pen and paper. It is useful to understand the workflow in this fashion to understand the implications of introducing digital technology and the correct place to introduce it. Far too often, as it has been demonstrated in the review earlier, the tools are not consistent with the workflow. Additionally, by reviewing a non—digital workshop, key concepts of the geodesign workflow can be identified and we are approaching the tool building problem in the opposite direction from most existing tools. There is a non-digital workflow, how does one digitize it? as opposed to, there is a tool, how does it fit on to an existing workflow.

The workshop focused on the Tagus estuary as a cultural and historical landscape for potential nomination and list as the UNESCO World Heritage site. It is from the area that early Portuguese explorers set sail to discover India and other new worlds and therefore the area is suitable to be nominated for its role in Portugal's age of discovery. The Lisbon Metropolitan Area consists of about 32,500 hectares of tidal area, surrounded by urban areas that include about a million inhabitants. Lisbon serves as Portugal's capital city in addition to an important economic, industrial and cultural center for modern Portugal. Although, industrialization in the 20th century has left toxic sediments in the lower estuary, the upper estuary has survived and is a biodiversity haven. It in this context that the workshop was conducted to answer the design problem as to whether the area can or should be nominated as the World Heritage site and the implications of its nomination to the area's economic prospects. The figure below shows the Satellite map and also the land cover map of the geographic area. The workshop was structured as a four-day event where the first day was a visit to the site to observe the study area and included a boat trip across the estuary.

4.9.1 Representation Models

The question of Representation models is answered by the figures above; a clear boundary is shown for the study area, enclosed in a white box, covering the area of interest. In addition, there exists a land cover map that details the land use that is published by the city and county council. It is useful to note here that these maps are printed out and a basemap with transparencies created to be used as a reference layer. The boundaries for this project are around the Lisbon estuary area and include the downtown part of Lisbon, the towns and area across the bay including the area of Almada, Seixal, Barreiro, Moita, Montijo. Downtown Lisbon is famous for its many historical and cultural monuments in addition to supporting the capital city of Portugal with many administration and government, universities and other institutions. Downtown Lisbon and the

Figure 4.7: Lisbon Study Representation Models: Basemap and Land Use Map.

greater Lisbon area north of the river has many attractions and places to visit and see and it is experiencing a population increase. On the southern part of the estuary, there are various towns and settlements that have been variously inhabited by industry and residential houses. There are old ports and ecological areas that are at work in the area and also form a part of the landscape. In addition to having satellite imagery, land-use data, there is also data available about the transport and road network. Thus we have a good idea of the representation models in the framework.

4.9.2 Process Models

Process models are important since they identify the key processes working in the study area. The process models identified for this study were:

Biodiversity Biodiversity is a key area of concern in the greater Lisbon region. There are various bird and fish species that are endemic to the estuary. Any plan of development, conservation or construction in the area in the future will impact their habitats and should be taken into consideration. A focus on economic development risks the habitat of these species and could lead to species loss in addition to a loss in tourism potential and also a risk of flooding.

Visual The Lisbon area is famed for its architecture and its hills provide views both for tourists and also from historical and cultural perspective. These need to be either protected or conserved when taking into account any development on either side of the river system.

Heritage The Lisbon region has a long history and has many cultural and historical landmarks that form the basis of the geography. It is from this estuary that the Portuguese "Age of Discovery" started.

Flood Hazard The upper part of the estuary is prone to annual flooding, which poses a risk to Lisbon and surrounding areas. Any future development of the southern towns will have to consider the impact of flooding.

Land Value Lisbon, also being the economic capital of Portugal, has a lot of competition for land and development. The land value in the southern cities is generally less since they are considered less attractive than central Lisbon and the northern part of the region. To enable migration or building of new communities in the southern region would involve increasing the land value of the region as a whole.

Agriculture There are some communities still in the area, particularly in the east, that rely on agriculture as a key source of income. Agriculture also increases the visual preferences and is predominantly practiced in the southern part of the region as is visible from the base map.

Transport Small Cars are the primary mode of transport in the southern region which lacks a proper transport plan. Alternatives such as bikes, trams etc. can also be considered as a part of the design. Consideration for both small and large transport is the key requirements for future plans.

Transport Large There are bridges and trains that connect the Lisbon area to the southern region including new bridges that link the two regions. A second airport that could be built on an existing military landing base could provide tourism incentives for the southern areas as well. Ship and ferry transport can also be considered as a part of this requirement that help in ferrying passengers across the estuary to the various cities on the southern side.

Employment The Lisbon region is going to experience population growth and there will be pressure for employment, commerce and industry across the area. Currently, the northern area and Lisbon proper are the main areas for employment and attract people into the city commuting from the southern areas. Employment also has implication for land value and population growth.

Tourism / Recreation Finally there is a huge opportunity to generate and enhance tourism in the region beyond what is already a popular destination for tourists. Increasing tourism will lead to more economic growth and employment prospects in the region. However increased tourism also has an impact on agriculture and endemic species in the area.

These ten systems were identified as key process models for the region and clearly they are interlinked. There is a huge tourism and heritage and visual preference requirement that needs to be addressed from a historical and cultural heritage point of view. In addition there is the threat of flooding and agriculture that has implications on biodiversity in the broader region. Finally the large and small transportation is interlinked with employment and economic growth and also requires large capital investments. Thus we can see how these are interlinked and against this background is the question of nomination, as the World Heritage site should be put in context. The region is also under threat from climate change and population increase so a successful (or unsuccessful) result has impacts on the broader economic and cultural consequences.

4.9.3 Evaluation Models

The participants were divided into smaller groups and the groups were assigned to evaluate the performance of these systems and assess spatially how these systems were performing. The groups were pre-determined and consisted of an expert in the domain e.g. a person who is an agriculture and a biodiversity expert would be assigned to the agriculture team along other cross disciplinary members to evaluate the performance of the system. In order to standardize the evaluation across all the systems a pre-defined color set of red and green was utilized, where the red would mean that the system is performing well and a green would mean that that improvement or intervention is needed. (Figure 4.8) These analyses were sketched out by hand using the base maps in the first morning and below is a photo of evaluations drawn by hand using the base of the ten systems.

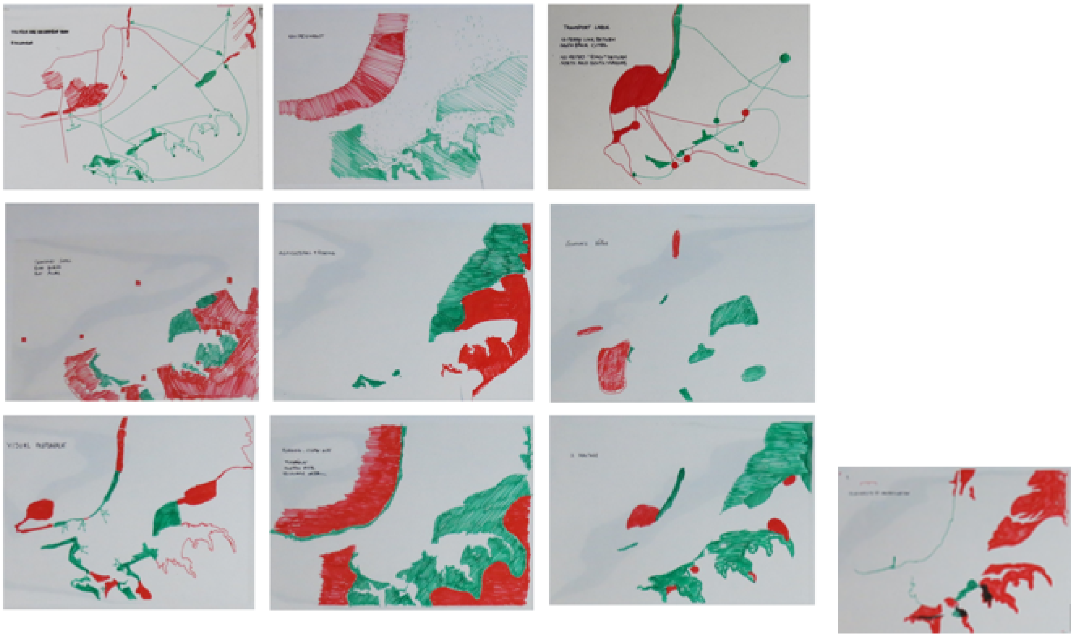


Figure 4.8: Evaluation Models Sketched by Hand

As can be seen the different teams adopt different ways to sketch out the evaluation and every system now has a way to communicate performance as compared to any other system in the project. This technique of using same colors and a predefined basemap has tremendous implications for multi-system tool building. This way most evaluations of the different process models are standardized.

4.9.4 Change Models

The next step in the framework is the development of change models. Given these sets of process and evaluation models, the teams are tasked to develop change / intervention ideas on transparencies and sketch them using the basemap. The teams are given a limited time to build these ideas and are encouraged to come up with about ten ideas and rank them by preference. With help of the experts who build and develop these ideas, the teams sketch out the ideas taking into consideration issues relevant to the system such as growth, development, conservation etc. In addition, any idea which is considered to be relevant from a current and future point of view, is also added to the set. The Figure below shows a set of diagrams and their evaluation model that are sketched for four requirements. The building of change models is a team effort and a democratic activity in that the ideas themselves are presented to the group and there is discussion as to the validity of the ideas and its usefulness. (Figure 4.9)

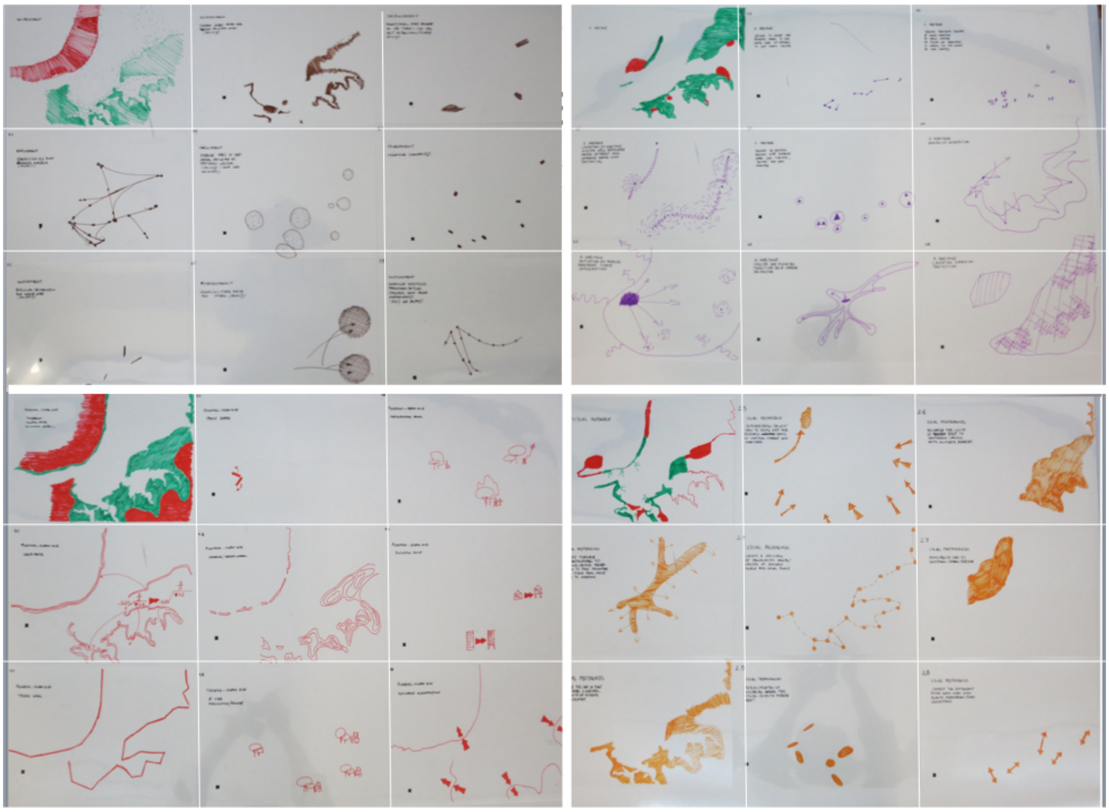


Figure 4.9: Change Models for Lisbon Workshop

The drawings are rank ordered in the sense that the best idea (according to the team) is placed at the top of the pile and then the second best and so on and finally these are laid out in the table as shown below so that all the systems, evaluation models and change models that are built using the representation models are shown together in one set. The numbering and ranking here is important and needs to be preserved since it has an impact on design strategy and the selection of diagrams.

After the diagrams were drawn, six interest groups were formed to build the change models. (Figure 4.10) Interest groups are formed and six teams were formed to represent different interest groups: World Heritage Nomination Advocates, Nature Conser-

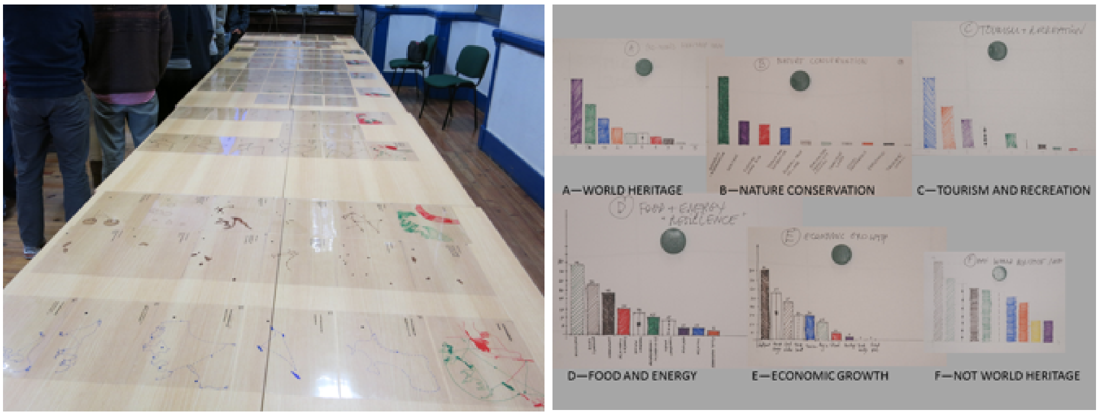


Figure 4.10: Change Models and Decision Models

vationists, Tourism and Recreation promoters, Food and Energy producers, Economic Growth promoters, and Landscape Planners not considering World Heritage potential. The change teams represent a certain viewpoint and they are formed by shuffling the teams during the final phases of the workshop. Each change team then has to vote internally to decide on priorities and rank order their preference (or lack of) towards process models. The core idea is to build a collaborative decision making framework. At the workshop, we manually simulated the Delphi method to ensure equal representation, randomization and accurate preferences between the team members. The different interest groups built their decision model as a bar chart representing their preferences and the figure below shows the decision model of the six interest groups or change teams.

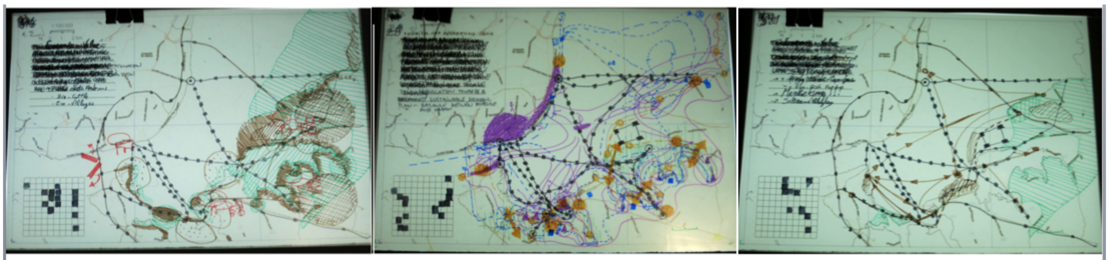
As is quite apparent here, the tourism and recreation team place a high value for the Tourism and Recreation process model and the visual preference model. In the same way the economic development team placed a higher value on the land value and the transportation requirements. Thus we can see a broad level of interests and conflicts within the different change teams. The idea of this exercise is to help the teams build a strategy for their design and also be able to communicate their strategy in a language that can be understood by all the other members in the workshop. After the decision model was built, the next step was to do the actual design, where the task was to build a design based on the selection of the different diagrams using the decision model as map or guide to the selection process. For example the Nature conservation team placed Bio-diversity as their number 1 preference so they would inspect very closely all the change models that are build for that requirement and select the best ideas for their design, in a similar fashion, they do not place a high value on the employment requirements so ideas or diagrams under that requirement are not given a high priority and thus may or may not be selected to be included as a part of the final design.

The task of the change teams is to review the diagrams placed on the table and to build a design using them overlaying them on top of other. The diagrams are laid out on a common table and the participants select the ones they like by reviewing the contents of the diagram and having an internal discussion on the merits of adding / removing that diagram in the design. The process is fairly quick and it enables design synthesis at a very rapid pace. (refer Figure 4.11) The teams are given a limited time to select and choose their diagrams and then are expected to produce a design for review.

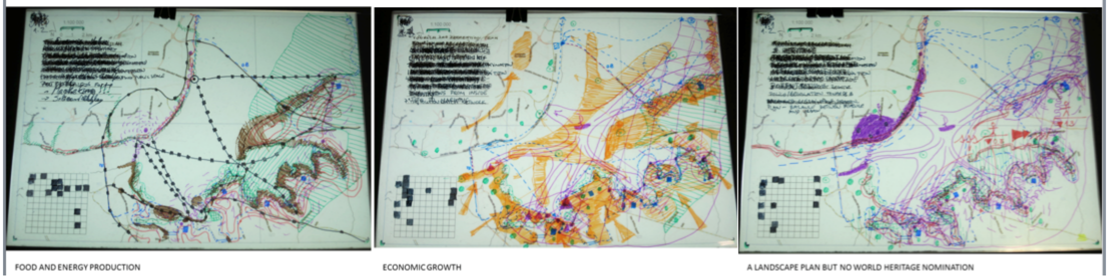
Figure 4.11: Design Synthesis and Diagram Selection

4.9.5 Impact Models

At every stage of the selection process, the designs are assessed over the evaluation models for the requirement by placing a transparency of the red / green evaluation model on top of the design. This way the change team can assess visually if the diagram falls on the red or the green part of the evaluation and determine if this is a suitable project or policy for their objective. This simple technique of overlays has been in use for a number of years in the GIS world and was done in an analog fashion at the workshop. The impacts however in this case are mostly visual and imprecise. Whether the impacts are serious or reversible is a decision that is made by the team that produces the diagram and also the design team. At this stage, new diagrams are added to the set that either modify an existing idea or add totally new one based on the initial design analysis.



WORLD HERITAGE NOMINATION NATURE CONSERVATION TOURISM AND RECREATION



FOOD AND ENERGY PRODUCTION ECONOMIC GROWTH A LANDSCAPE PLAN BUT NO WORLD HERITAGE NOMINATION

Figure 4.12: Comparing Synthesis

4.9.6 Decision Models

Once the teams produce a version of the design, the next step in this process is to compare the designs produced by various teams. Primarily there are three techniques that were used in the workshop to compare designs:

Design Score based on Impact The designs are compared by a simple competition and scoring by impacts. The designs are judged by each change team with respect to their performance for each requirement and also the overall "score" of how well or poorly they perform.

Spatial Agreement In this case, all the designs produced are overlayed on top of each other and held against a projector to see what light is actually emitted. Muddled colors usually mean that there is disagreement with the teams around what

Figure 4.13: Overlay All Synthesis

should be done for that area, on the other hands primary colors mean that there is agreement. E.g. in the Figure 4.13, there is broad agreement on the transport plans and the plan for the upstream habitat restoration. (Figure 4.12)

However, there is significant disagreement on what needs to be done in the lower region where there are inhabitants and existing buildings. Thus this simple technique of agreement can help in understanding the position of the various participants in the design.

Project and Policy Frequency: In this type of design comparison, the most popular projects and policies selected form the basis of the design, with this type of design producing a sort of a popularity contest of the designs used and thus ensures that every team is satisfied. (Figure 4.13)

Finally, the most difficult and interesting of the comparisons is a sociogram experiment where the teams and their designs are quizzed on their acceptability to work with one another. Thus alliances can be formed and the multiple designs can be transformed into one design. An example of this might be that the pro World Heritage team might want to work with the biodiversity and the heritage team while the economic development team might want to partner with some of the other teams such as the food team to produce a plan. Thus at the end of three-day workshop we started with little data or minimal data, and through a workflow, were able to produce designs for a large city-region from scratch. This analog workflow enables an integrated systematic design process and gives us the opportunity to collaborate with peers to produce a design. Thus in the space of four days, participants were able to work through the framework and build a set of competing designs, understand key values of different stakeholders and critically understand the logic behind a design.

4.10 Observations on the Workshop

Some observations on the geodesign process and the workshop are documented here. Some of these are adapted from Steinitz. [Steinitz, 2014] Geodesign problems are very hard and complex in nature. There is no easy or obvious solution to a problem at a scale and size of the one described above. However, in order to tackle it the problem can be distilled to about eight or ten systems that are acting on the study area. The eight to ten number comes from experience and could be even more than ten but human cognition is difficult for more than ten systems simultaneously. This multi-system approach is critical to a successful design solution to a complex problem as is demonstrated in the study. Participants in the workshop above routinely jumped across various systems to build their plan and in the process, they got an understanding of the key issues and solutions across systems. This cross system understanding of the problem is unique to the workflow of geodesign and is the key to collaboration. There were experts from various fields who would use the evaluation maps and understand the impact of their designs and decisions over domains that they were not familiar with. The reason why participants could cross systems and understand the diagrams and build the designs is because of the fact that there is a shared language and symbology that glues the entire process together; each system is represented by a specific color and also all the diagrams in the system are shown in the particular color. Additionally, every diagram is numbered and is a part of the grid, thus it is easy to see where in the grid the diagram fits. This structure of the diagram‘s grid and the color of the diagram joins the workflow together. In a lot of ways, the diagrams are the currency of the system that are used and traded to produce a design. Just like a bank note, a diagram can be reused, passed to different teams and be used as an instrument for negotiation. A diagram is also a partial solution to a problem. This way the complex problem of flooding is solved by using a set of partial solutions or diagrams during the course of the workshop. In many cases, diagrams are used in conjunction with other diagrams in the sense that they are paired since they are found to complement each other, so transactions, negotiation and selection can happen to sets of diagrams rather than just one individually. Thus the diagrams form sub-systems across various domains and act as a partial solution to the design; for example the placement of a new housing diagram goes together with the diagram for new road. Impact assessment can be done at any stage of the design although in this workshop we did the assessment at the end of the design process because of the time constraints. The impact of a selection of a diagram can then be assessed across various systems and teams.

The workshop and the workflow provided a methodology to get a group of people together to come up with a design when none existed. Thus using diagrams and basic synthesis techniques, the participants were able to not only produce design, they were also able to negotiate on a design and iterate on it using the same set of diagrams and new ones being added to the set constantly. The process of the workshop and the entire workflow itself is collaborative: teams are expected to rely on individual expertise and their ability to collaborate to build a design and get agreement from the others. In that sense the most collaborative team can be the one who would produce a design that has input and acceptance from all the other teams. The process of comparison of the diagrams was quite time consuming but also the most interesting. The designs that are built by various groups needed to be compared in way that differences and positions are clear but also leave room to negotiate and form alliances. Revisions to the designs were quite difficult to make since it involved making a completely new diagram and adding it to the grid. The workshop is very interactive and all participants have a role to play in the workshop session. There was very little time that the participants were not doing anything and the workflow forced a systematic and step-by-step approach to design.

4.11 Research Questions and Conclusion

There are a number of interesting phenomena relating to the design process that were observed in the workshop. The design process is a non-linear process, participants were going back and forth in their design trailing different combinations, analyzing the impacts and having a discussion on the best strategy. The change teams had a general overall strategy or goal. However, the way they achieved the goal was in an organic fashion. There were a set of operations that were performed by the participants: creating diagrams, inspecting all available options, picking some and analyzing them in the process of design creation. In the design creation stage, almost every team had a different strategy to attack the grid which led to divergence in the selection of diagrams and designs. However, in the final stages of the workshop these divergent participants were bought together to form a single design based on compromises and collaboration. Thus the participants were able to have different decision models, spatial strategies and projects and following a sequence of actions were able to come together to form a design. This is shown in Figure 4.14 below.

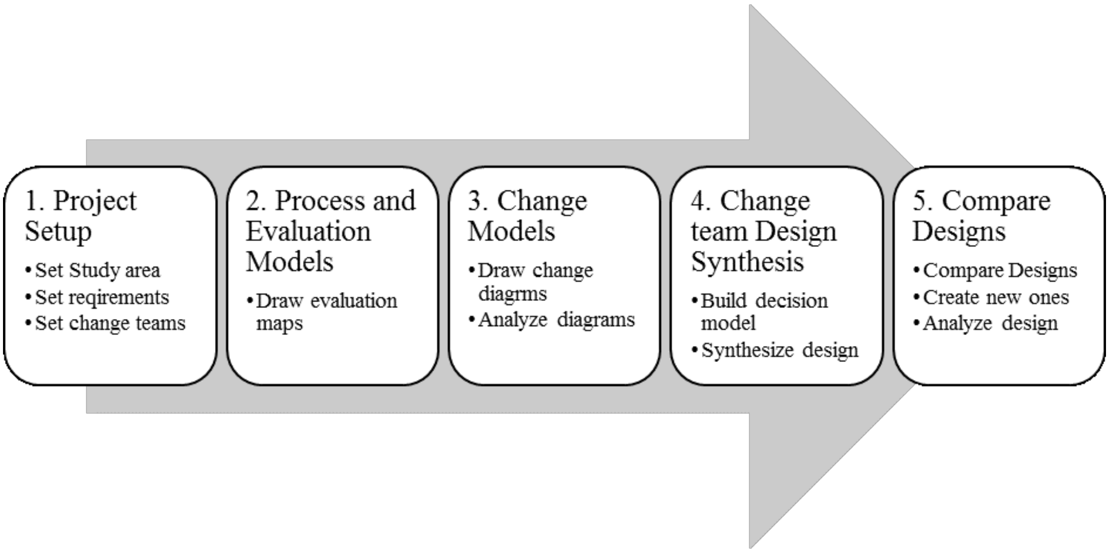


Figure 4.14: Basic Workshop Sequence

The project starts with requirement, study area and change team identification done prior to the workshop and can be called a “setup” phase. In this phase, the participants are informed and key process models are also identified. The change teams are also discussed and finalized. This forms the basic structure of the project. Once the workshop starts, as is documented above, the participants build the evaluation and change models and perform the synthesis as they progress through the workshop. While it is depicted as a linear process above, in reality it is anything but: participants go back and forth between various stages at different times as is shown in Figure 4.15. Key actions performed by users are shown in Figure 4.16. Indeed, according to the method, this process has to be done at least three times to generate satisfactory designs.

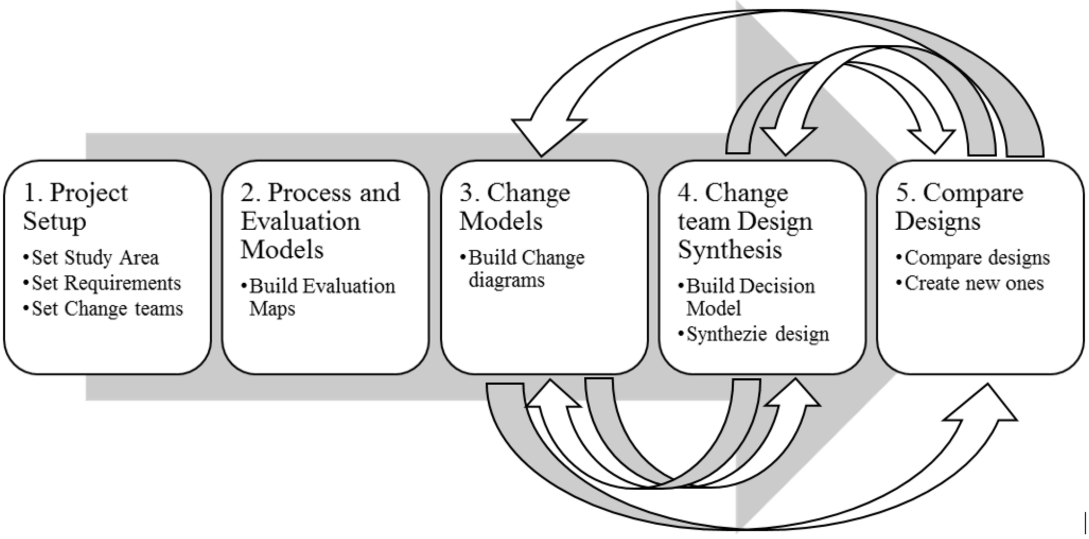


Figure 4.15: Participants Go Back and Forward Between Various Stages

In this context the planning workflow in particular is addressed with digital tools and a planning support workflow. This workshop was conducted in a fully "analog" environment without the use of a single computer or GIS tool. This is significantly different from traditional research in that it is trying to recreate a workflow that has worked for a number of years without a computer. This is a much more difficult problem to solve since being analog has enabled the method and workflow to be adaptable to different styles of designing and collaboration. Being analog also enables the participants to progress quickly in the framework and produce designs. The question here is would converting this method to a digital format degrade the effectiveness of the method? Digital tools, because they are programmed, have a logic behind them that usually constrains the actions that can be done within them. Designing is fundamentally a creative activity, therefore in theory, digitizing the workflow should hinder creativity. Can a digital workflow support free form design? Would it be quick and fast enough for immediate feedback that is critical in the process of design? Will it enable the participants to move quickly through the method and produce consensus designs?

Noted above are characteristics unique to the method and the geodesign framework. From a planning support perspective, this poses a number of challenges for any tool that may be used to replace the analog process. The tool has to accommodate a number of systems, enable the users to perform a set of operations, provide the ability to compare and analyze designs. Finally, most crucially, the tool has to be flexible enough to accommodate different designing styles and be fast.

This is the key research question: What features should be available digitally to enable these operations? Most digital tools are conceived by developers and implemented and then feedback is taken from stakeholders to "tweak" them. As the research shows above, this method is not suitable for broad acceptance. In an ideal situation if a designer is able to code the tool, it will come out as the closest one to match the workflow. In that sense, this approach of taking an analog process and digitizing is novel in planning support tools research. One drawback of this approach is that by mimicking the analog workflow, we are missing out on various "features" that all digital tools enable. This is not necessarily a negative thing since they can always be added at a later date. The workflow uses all the ideas around systems analysis, use of diagramming and sketching and design synthesis that was demonstrated earlier. The utility in strategic and conceptual planning is clear with the added notion of collaboration and communication between different stakeholders. In that sense, the idea is to build a planning support tool to enable this workshop using a computer and computerized drafting tools. Computing is near ubiquitous now and tools are available that enable professionals to create designs that are highly sophisticated. As we have seen above, the designing of diagrams can be achieved in most computers fairly easily and therefore that is not the key area of interest; however there exists little research on how more than two or three people collaborate at the same time. Can a planning support tool be built? How would it perform and what are the specifications that are necessary to enable collaborative design workflow?

The first place to start with this is around building a support system and workflow that enables digital collaboration and design production using the workflow. 4.16 above shows the various actions taken by the users as a part of the workshop. Any digital support tool should enable these actions.

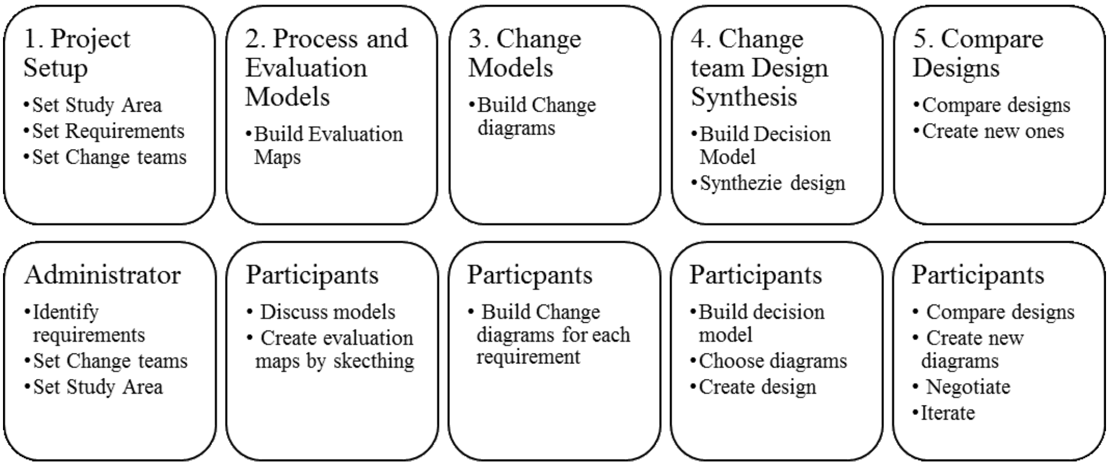


Figure 4.16: Workshop Flow (top) and Key Actions Performed by Participants (bottom) at Different Stages of the Workshop

One key area of research is analyzing multiple systems at the same time. This approach to problem solving is crucial to the systems approach to design and planning. The cornerstone of the geodesign framework is around the ability to analyze multiple systems at the same time and that to me is the way to have a broad multi system approach to solving complex problems. A simultaneous multi-system analysis tool in the context of the workflow is not present currently and this effort would contribute to that body of research. Multi-system approach lends itself very well to the complex and ill defined nature of design problems. A multi-system approach puts a comprehensive set of constraints to solve the problem of design in its early stages. The other aspect of design from a geodesign point of view is that of design-analysis. While the analysis tools and technologies are capable and well tested, there is very little research and work done on early stage design tools in a multi-system approach. In that sense beyond building a tool, the core research idea is to test the framework in an even more pressurized and digital fashion and doing analysis across different systems at the same time.

Another aspect of this workflow that needs research is around collaboration. In the example above, we observe how groups of people get together and use diagrams and other structures to collaborate and produce a design, would that still work in a digital context? In addition, at times in the workshop there was competition among teams, where “deals” and compromises were made by the participants to come to an agreement. This is a fundamental aspect of the planning process. Can a shared language and structure be produced in a digital setting that can be understood and grasped by a large group of people in front of a screen? Thus the mechanics of digital collaboration and in particular in the age of Skype, Instant Messaging, and Photo sharing etc. what is or is not useful is a critical research question.

All planning processes hinge on collaboration and effective communication and therefore this collaboration question has tremendous implications for the future of planning. Can people from different disciplines collaborate to build plans and designs using a shared language? And if they can, what are the key considerations to be had so that planning studies can be devised better and designed for collaboration is an open question. Tied to the collaboration question is also the question of user interface and the appropriate technology for that. Are cell phones better? Are tablets better? How do you enable collaboration on a broader scale with commonly available computing platforms. What input method suits the best? Is it the mouse, is it the touch pad / fingers? These need to be explored in the multisystem point of view. In addition, presentation of advanced analysis information to diverse group of stakeholders also has a lot of questions for research: Do the participants understand the data? Is it useful? Is it clear? etc. The evaluation and impact assessments of designs and diagrams are something that has been done and well understood in the GIS and other geographical fields. But what has not been tested is using the same approach in a multisystem environment that has up to ten systems. Would participants be able to understand the impacts and their results? How would designs be built once it is understood how they are synthesized. There exists a large body of work in the urban modeling domain and scientists and researchers have created very elaborate models for impact analysis of designs. It would be very interesting if these can be linked digitally to the workflow to understand live implications of a design decision.

While the synthesis process in geodesign workflow is not linear, the different teams are approaching the problem and producing a design by synthesizing in various different ways and what kind of a workflow supports digital synthesis is a key question for research. In addition, as in the case of the workshop, the key consideration is around strategic early stage design using a systems framework. Thus the challenge for the tool is to organize around produce design at the early stages of the planning process. In the literature, these problems are solved in isolation. However the framework presents a way to solve it holistically.

Finally this workshop raises very interesting research questions on design methods and ways of designing. What are the different ways of designing? Which ones are best suited for a particular type of geography. Understanding these digitally would have a lot of implications on the process of design itself and also how design studies are constructed. This would also have implications on the complexity of data provided: In the age of Big Data etc. what is the minimum amount of data that is required to enable participants to produce a design using a particular design method and how does using a method of design over other impact the designs themselves and their performance. What implications would making a digital version of the tool have on the ways of designing? Would it be easier to do these studies? Can we crowdsource a design and how would the design itself change when done digitally in a crowdsourced fashion?

Chapter 5 documents the key technical features that are needed to be in place for a digital system that enables this workflow. The chapter covers its structural underpinnings and also describe a series of tests in the form of workshop that were conducted to test the research questions above. Chapter 6 details the technical implementation of how this process was converted in a digital form and document workshops conducted into a digital form. Chapter 6 also shares the early results around these questions.

Chapter 5

Digitizing the Geodesign Workflow

Since software development is both an art and a science, this review does not specify a particular way to build software tools. Instead, the focus here is on the technical specification for a multi system analysis tool that facilitates the geodesign workflow. In the previous chapter, a workshop conducted without any digital support was described and this forms the template for a tool that can be used in a workshop setting for end-to-end geodesign. Digital support to the design synthesis in the context of geodesign is non-existent and research into it is an immediate priority. [Ervin, 2011] This work addresses the research priority and it is novel in that it extends a framework [Steinitz, 2012] into a digital domain and implements it as a software systems specification. By documenting key user features and in a digital fashion, the framework can be understood at a much deeper level and it also opens up a way to enable innovation in multi-system planning support tools. The latter part of the chapter discusses fundamental software engineering concepts around versioning and version control and its role in the digitization. Application of techniques commonplace in the software engineering world to planning support tools open up a number of scenarios for further research of planning support tools. There exist a number of guidelines around good software specification documents. [Lamsweerde, 2009] [Cusumano and Selby, 1997] [Walz et al., 1993] In this case a template provided for a Requirements Engineering class [Marchese, Francis, 2013] is used as a helper to specify functional and engineering requirements of a tool.

Functional specifications are very common in the engineering design domain and they help engineers understand the requirements and build systems. A critical feature in a requirement specification document is that it is implementation free: the programmers have the freedom to implement the specifications in a number of ways.[Karlsson,Goran

, 2009] A good requirement specification also enables comparisons of various implementations and detailed performance analysis can also be conducted. Another additional advantage of a requirement specification is that while it lays out clear guidelines for critical functions, it stays away from what functions are provided, how a function should be written or what technology needs to be used. This ensures that the specification is true to the framework and multiple implementations are possible.

This document is intended for software developers, or mixed teams of software developers and planners who understand the urban design process and are familiar with the geodesign framework. The intention of this document is to provide engineers with guidance on how to start converting a framework into software structures and for planners and designers to gain a deeper understanding of the workflow and the framework. For academics and planners, this document provides a deeper more technical understanding of the geodesign workflow. It is also relevant to other domains where this document can be used to understand the mechanics of multi system software and the complexities around it. In Chapter 6, experiments conducted with one implementation of this specification and its implications on future research are described. This approach to building support tools will stimulate discussion and insight into the technical underpinnings for geodesign support systems. The ideas expressed in this document extend our existing understanding of planning support tools that are not necessarily used in a geodesign context.

5.1 Research Question and Why Digitize?

The fundamental question to ask is why there is a need to digitize an analog workflow in this framework. What opportunities does a digital workflow present that are not possible without it? The method prescribed by the Steinitz Framework has been used in practice for a number of years in the form of hands—on workshops, sometimes with no digital support. Digitizing the workflow and the process gives a number of benefits in a design research context. Firstly, the method is mature having being used quite extensively over the past number of years and there are a number of reference case studies that have been published. The results from these case studies can be studied and appropriate performance benchmarks can be constructed. Also the framework and method although codified recently, has been in use for a number of decades, so in that sense it is not new. Therefore digitizing it is a natural progression of the framework in the same way the gradual use of IT and computer systems occurs in all aspects of personal and professional work. The reason digitization has not been done earlier, is because this is a hard technical and engineering problem that has not been solved in an elegant fashion. While there have been numerous attempts to build geodesign support tools, see Eikelboom[Eikelboom and Janssen, 2015] for short review, there does not exist any tool that supports multiple users performing geodesign as prescribed by the Steinitz Framework.

Digitizing the workflow will provide the foundation to conduct many tests of the framework that are currently not possible. Currently, conducting a workshop is a time consuming task with days, if not weeks, of organization and setup. By digitizing the framework, the process of setup and organization can be automated and thereby more tests can be performed. Research carried out on design methods in a purely digital form for a given problem can also be compared to previous work done in an analog fashion to compare performance. Digital design brings with it all the benefits that any other digitization has bought about: speed, power of detailed analysis and so on.

Given the analog nature of the workflow, collaboration was not possible beyond those present in the same room at the time of the workshop. However there are many digital technologies that enable collaboration in the modern world: Skype, Google Docs etc. These technologies could be leveraged to expand the collaboration with people joining in from different places. The other aspect of collaboration is that of scale. How many people can simultaneously design? Can there be a plan that has input of every resident in a community? A purely digital implementation of the framework can potentially scale up support for these types of scenarios.

There is a growing trend of digitization as a broader trend in information technology penetration. There are datasets that have been already digitized and a digital implementaiton of the method would be able to leverage these and utilize them seamlessly in various studies.

Finally digitization will enable fundamental research into the performance of a multi system analysis tool on a regional size planning problem. The question of scale and design is an old one in the planning domain. What type of design methods work at what scale? Experimentation is required for this and the geodesign framework can address these very effectively. Digital support would make setting up and conducting experiments easy. How do the methods that work on regional level problems perform on lower or higher level planning problems? Experimentation is the only way to test and answer these. However, these experiments are very difficult to carry out without digital tool support.

5.2 Scope

Figure 4.16 details the actions that a participant performs in a workshop. The design process is not linear and the participants switch between different actions as they proceed in the workflow. However for successful implementation of the workshop digitally, these actions need to be supported in a digital fashion. In this chapter, these user actions are transformed into a system specification for features that need to be implemented on a tool level and also at a system level. This specification aims to be as generic as possible and stay away from individual data and models that are used in the tool since the aim is to build an open flexible system that can handle the myriad of data and models that are available to be used in the context of geodesign. The data and models are called content here. Digital content is usually in the form of big data, urban models, sketches etc. and any workshop and project presumes that some base data would be available in a digital format. Therefore the specification assumes that data import and export is a necessary feature that needs to be implemented.

In the Lisbon workshop, the participants used many techniques to build their design and the diagrams: tracing, using free hand symbols, using existing landuse data etc. How should these inputs be implemented digitally? Any geodesign system should allow for multiple ways to design given that the activity is necessarily collaborative and each participant has their own method of designing. In the geodesign workflow context, the focus is to do with conceptual design at a very early stage of the design process. Therefore the expectation is to not have highly realistic designs with a very detailed fit and finish and minute intricate details of a design are out of scope for this specification. This document specifies conceptual design and use of systems thinking in developing that design using a process that is repeatable. This systems thinking is critical for the geodesign workflow and it is implicit in this specification, in the sense that non-systems approach to design is out of scope and designs done within the frame work and workshop are in scope.

Generally, change models as were demonstrated in the Lisbon project, consist of either projects or policies and a combination of projects and policies should be sufficiently able to demonstrate an intervention. The most important aspect of geodesign processes is the people and the participants of the workshop. The participants play various roles as they progress in the framework: team conductors, subject matter experts, negotiators, design builders etc. A digital implementation necessarily needs to accommodate these different roles. There are many ways to run a project but for this document, a workshop setting is implied. Further research needs to be done on how the workflow of geodesign can be implemented perhaps in a non-workshop setting and that is out of scope of this document.

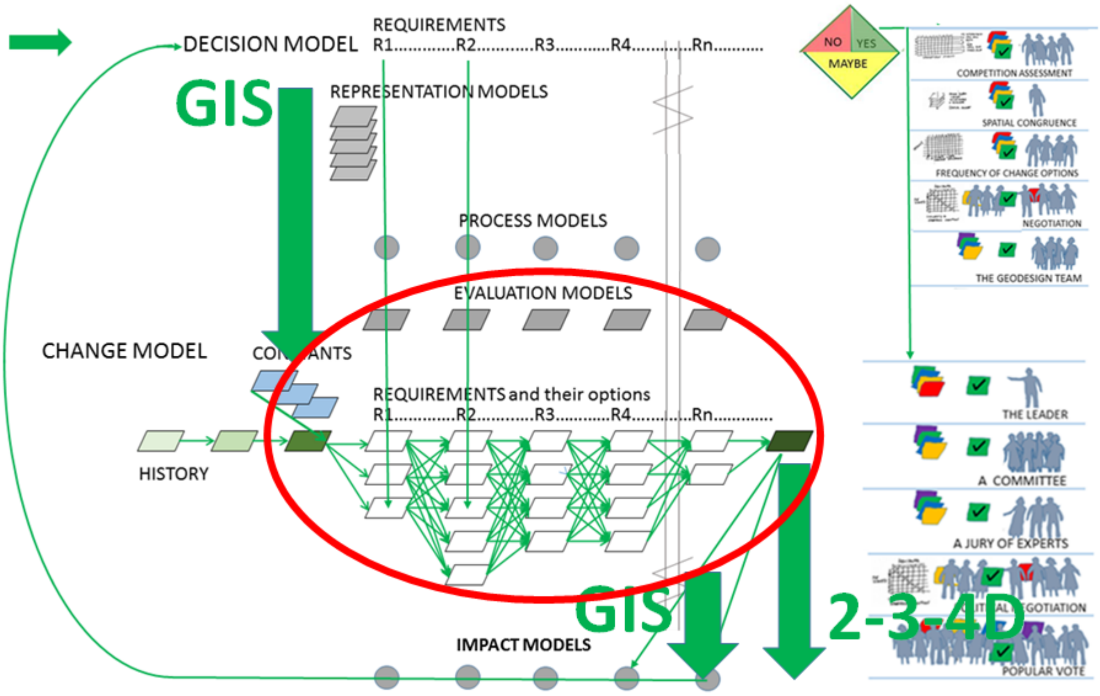


Figure 5.1: Tool Scope

From an output perspective, the aim of this is to enable the workshop that is presented earlier to be able to be conducted digitally using commonly available digital technologies. Thus all the models of the geodesign framework: Process, Evaluation, Change, Impact and Decision models need to be accommodated along with the design synthesis and the possibility to conduct various designs in a short time. Thus the goal is to build a tool that digitizes the entire workflow from start to finish and enables broad collaboration taking a multi systems approach to the problem. Figure 5.1 depicts this in detail.

The difference phases of the Lisbon workshop earlier can be converted to individual user actions and subsequently key tool features can be identified (Figure 5.2 below)

Workshop Phase	User Actions	Tool Features
Project Setup: • setup study area • setup Requirements, • setup change teams	Defined by project organizers	• Ability to set project area • Add requirements, set types • Set change teams
Process and Evaluation Models: Participants assigned to teams build Evaluation maps	• Discuss models • Create Evaluation maps by sketching	• Ability to add evaluation maps for requirements • Standardized colors
Change Diagrams: Participants build Change Ideas for each requirement	• Add a diagram • Describe, rank it • Sketch features (color coded) • Up to 10 diagrams	• Ability to add / edit features to diagrams • Sketching support • Assign diagrams to a requirement
Change teams and Decision Model: Participants split into teams and build decision model for their team.	• Participants shuffled into new teams • Discuss priorities • Delphi method	• Participants can form a team • Participants can form a decision model based on requirements

Design Generation and synthesis: Change teams build a design by selecting individual diagrams based on their decision model.	Change teams build a design by selecting individual diagrams based on their decision model and these diagrams are noted.	• Ability to select a diagram for addition in a design • Ability for a team to create multiple designs.
Design Comparison and iterations: Designs are compared (and new ones generated)	• Compare designs • Negotiate with other teams • Add new diagrams • Iterate	• Ability to perform different types of comparisons on built synthesis

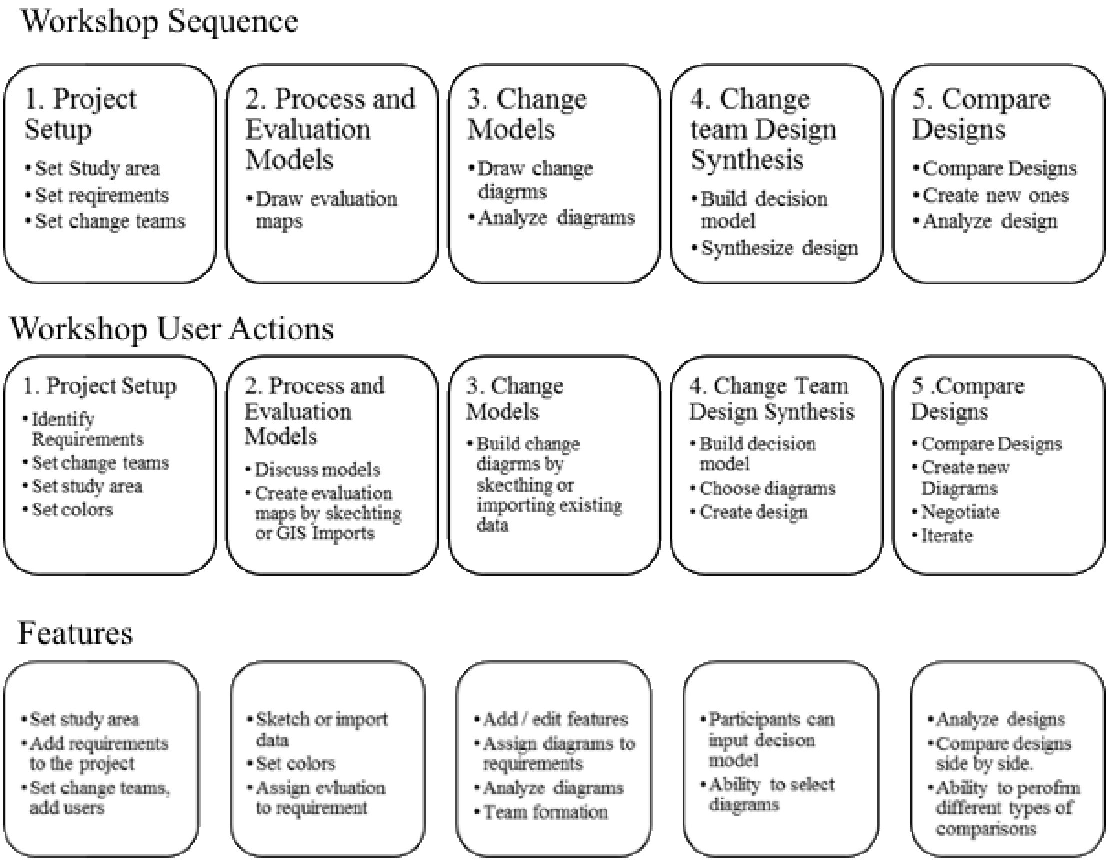


Figure 5.2: Workshop Flow (top) Related User Actions (middle) and Tool Features (bottom)

5.3 Context

GIS and other technologies are well established, and most people have had a number of years of experience with them. There exist innumerable models that produce data and maps being developed by various groups. Indeed Big Data is a research trend. Almost all of urban planning and design and most geodesign project work are carried out in this environment of existing data and computer models. It is critical for the planning support tool to be open and be compatible with existing and future data formats. Therefore while the design environment is self-contained, the data and the different models that interact with the tool through it, the content, should be interchangeable. In that sense, the system has to interact with a number of data formats and also export to different formats for use in other visualization technologies once the design is created.

The geodesign framework is targeted toward a broad audience of professionals. There are a diverse array of models and data that are relevant to a particular profession, also future developments in models and modeling cannot be specified so the system should be able to take in as input different models represented in the form of a map and diagrams that are either drawn within the tool or pre-existing ones imported into the tool so that a broad level of engagement is possible. While there are extensive studies conducted on the GIS and data and modeling part of the process shown in Figure 5.1, very little research is being conducted on the process of design itself, so the tool in some ways is a design tool first and should have a focus on design. There have been tremendous advances in visualization technologies, 3D technologies that show a lot of potential. [Shiode, 2000] [Wu et al., 2010] [Köninger and Bartel, 1998] [Isikdag and Zlatanova, 2010] [Hu et al., 2003] They are proving to be extremely effective communication mechanisms and therefore the ability to export the designs in that format are crucial. Given that the intended audience is that of designs are architects, planners, and policy makers the export functionality is important since they can take the design generated and use it in their respective tools.

There exist tools and data to build representation, process and evaluation models and also tools to visualize design, but there are no tools that help in digital synthesis of these designs. Therefore this work sits in between the GIS world and the visualization world. GIS can handle the data side very well with a number of tools for data analysis, modeling etc. and the information visualization side is well handled by a number of visualization tools. However the process of designing i.e. the process of allocating things at the correct place is not and it is that void that the workflow aims to address.

This is demonstrated in Figure 5.1 above. The core design synthesis aspect of the workflow is still not digital while there exists digital support for the models and visualization. Digital support for change synthesis will enable a seamless geodesign workflow that is fully digital.

Given the fact that the system sits in the middle, it makes the workflow inherently dependent on input from the participants and the data produced will have to be exported into visualization tools. Therefore it is important and a prerequisite that the tool is compatible with most popular data types. The ability to include all the possible models and methods that can be produced by these participants is the key to the system. Since a core value proposition of the workshop is around collaboration, there should not be a situation where a particular profession or a group of scientists cannot participate in the process. The core audiences of the software are described in Steinitz [Steinitz, 2012]:

- people of the place
- geographic professionals
- design professionals
- IT professionals

Given the need for different types of geographic data, GeoJSON [Butler et al., 2008] and Shapefiles were selected as the standardized data formats. One common complaint of most planning support tools and workflow is the inability to have compatible data and therefore supporting the most commonly used formats should be the goal of any geodesign workflow. Given that the design synthesis stage interfaces with GIS and visualization tools, it is crucial that inter-operability is maintained.

5.4 Technology Requirements

The Steinitz framework and the geodesign workflow mandate that the users contribute to the design process in a tangible fashion: they need to know how to operate a mouse and keyboard and in addition are able to explore maps on the screen. Often most planning support tools overestimate the technical capabilities of the users. To mitigate that, it is assumed that the users will have basic familiarity and an understanding of computer and computer operations. A web based environment is assumed for this tool. Browser and browser capability has improved dramatically in the past few years and given that collaboration is the critical piece of the workflow, a browser provides a terrific platform for collaborative tools. Since mouse and keyboard provide precise inputs to the users doing design work, it is preferred over touch inputs. Since the users of the tool are varied and diverse, a browser makes the most sense from a technology point of view.

Obviously, for browser based collaborative tools, users should have access to wireless or wired internet. The quality of internet connection varies considerably between geography, the network, wired or wireless connection, the number of people using the network etc. However the assumption here is that most people with normal broadband should be able to use the tool. Of course the faster the internet connection the better it is from a tool point of view. However, for general purpose use a standard internet connection is assumed.

From a hardware view point, most modern laptops should suffice. There is a large amount of data presented in the workshop with almost 100+ maps and data as is shown in Chapter 4. In the Lisbon experiment, the maps are laid out on long tables for the users to see and select the ones they preferred and for a digital metaphor to work, the screen resolution is a critical factor. Thus there is a preference for higher screen resolution monitors and display.

5.5 Dependencies and Constraints

5.5.1 Network Connections

In the context of a collaborative workflow, there is a core dependency around the network connection and the browser capability. The Lisbon workshop demonstrated that a lot of data is presented and analysis is carried out on that data in almost real-time in the course of the workshop. The real-time nature of the analysis assists in the flow of the workshop and framework. In a digital setting, not only is the network connection critical but also the ability to perform quick analysis calculations. At a given time, there are a number of operations that need to be performed by the server including geo-spatial computing and data processing and the results of these operations need to be streamed in real time to the clients to show them the results of the computation. Therefore the server infrastructure is as critical as the front end user facing module. These two back end and front end systems have to work together to ensure that the data is presented and analysis is done at near real-time. (Figure 5.3)

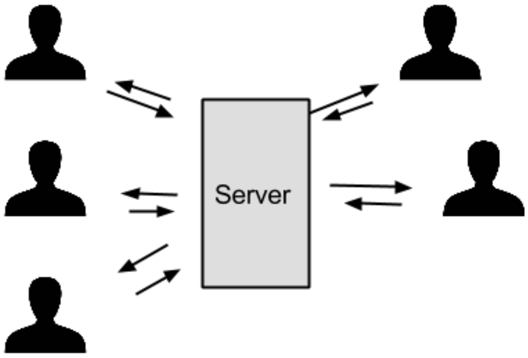


Figure 5.3: Real Time Communication Between Users Working on Same Project

5.5.2 Data Processing

Since the tool is designed to be an open system where the participants and others bring their own data into the tool, the ability to read multiple formats and convert them into one "specified" format on the server is important. Not only is the content be in different formats: scanned images, GeoJSON, Shapefiles etc., when they are imported into the system, they only need to be translated internally into a representation that standardizes over these formats. Therefore a module that reads and understands geospatial data is a critical dependency of the system and this can be in the form of a PostGIS webserver or R programming package. This "data processing engine" also deals with import and export of data in and out of the system. In addition, this module performs spatial analysis on these data. Therefore it should also contain most of the geospatial data, the required GIS or other modules to do the analysis such as unions and intersection of geometric features that needs to be implemented.

5.5.3 Data Management and Backup

In a digital environment, there are three types of data:

1. Existing basemaps, landuse information etc. that is used by the participants in the course of the design.
2. Data is either imported using files that participants have or is being sketched in by the participants.
3. Data that is used as design aids and are evaluation maps and the existing land use maps and in addition sometimes there are regulatory requirements that prohibit certain types of action. These should be provided as additional constraints to the design teams.

These have to be inputted into the tool and the following section details some necessary requirements and best practices with respect to data management. Once a data file is uploaded, the information needs to be parsed, validated and if valid needs to be transformed into an internal format - in this case GeoJSON. In general data should be shared within the project but not outside of it. Therefore internally data should be properly managed with relevant permissions and privileges associated with it. All data pertaining to the diagrams should be available and accessible to the participants of the workshop. The entity holding the data in the database should be a diagram object and the actual data can either be stored in the file system or in a database like PostGIS itself. Data should also be saved in an offsite or synced out of the server for backup and protected accordingly. Data should be retained during the life of the project and only after the project is complete and data taken out can the original data be removed or deleted. In addition to the data being imported, the changes to the data such as a change in a diagram description should be stored in the database and propagated using the sync framework across all the participants in the workshop. For the scale and size of most of the projects for geodesign (regional level) a decimal precision up to four or five should suffice for most geographical co-ordinates such as latitude and longitude.

Data in a diagram can be a number of things: features, doodles, representations, symbols etc. This is shown in Figure 4.9 in Chapter4. Therefore data is considered as a generic representation mechanism of any geospatial file format. In the case of geospatial data, sketching the data can be effectively represented by primitives of lines, polygons or multipolygons or points and in the common file formats. The data in this case is a mixture of geo-referenced symbols and geospatial data from existing data sources such as shapefiles. Of course geospatial analysis can be conducted on geocoded data, while the use of open symbols such as arrows and so on can also be coded to form a language of smart diagrams and digitized. The data management module therefore should also act a translator of data between different formats once that become common internally. (see Figure 5.4)

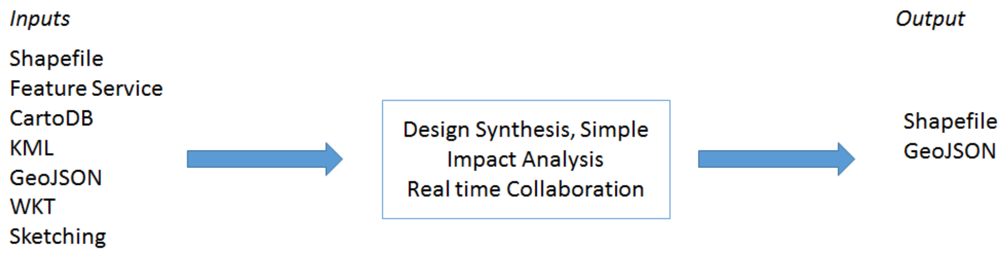


Figure 5.4: System Inputs Output Overviews

Backing up data is important since these are user created diagrams and there should be no data loss. Backup should be performed regularly and a copy of the data should be maintained outside of the server in a cloud service that is secure.

5.5.4 Real-time Communications

There is a large dependency on the "real-time" aspect of the tool and therefore extensive work needs to be done on enabling performance of calculation so that they are performed quickly and results generated can be transmitted to the user and also between clients that are connected to the project. This intercommunication between clients functionality should be built in and cannot be bolted on at a later stage. Therefore is a critical first step along with the data processing module. Every client should be able to work with every other client connected to the project for this is the heart of the collaborative aspect of the tool. The different participants should form a peer-network that are talking to each other and collaborating in real time on the design process.

5.5.5 Data Limits

There is huge dependency on the data or the content that is used in the tool. Traditionally, GIS files are files with a large amount of data in them and while it is suitable for desktop class application, it is difficult to collaborate among a broad group of participants (>30 people working on a project) and therefore the data size is a major constraint. There needs to be a maximum file size limit at least initially to ensure that data can be synced without major issues across clients. The framework is very data intensive with different models: evaluation, process and impact.

Given that the data is used primarily as a design aid, there is a delicate balance between the data resolution and load on the data processing engine. In the conceptual stages of a design, data need not be extremely detailed and aggregation may be applied to the data to limit the size. Traditional GIS is primarily aimed at experts and professionals but given the broad user base and skills, simplification of data is not only recommended it is necessary. The tradeoff of data simplification is a broad based collaboration and by simplifying the underlying data presented, it can be ensured that a broad group of people can participate and understand the data. File size is also to do with the performance and understanding of the system, while larger file sizes means that the performance is slow and the time taken by the system is long and thus degrading the user experience. At some point, a tradeoff has to be made between the file size and performance for real-time processing; this also means that there is a need for simplification of the data before it is entered into the system.

The limits on the data complexity and size are due to technical limitations and user comprehension. However, it is easy to envision a time when technology would be sufficiently powerful to accommodate any data without simplification. There is still an issue of user comprehension of detailed data.

5.6 Frontend and Backend Structures

Having reviewed key constraints and dependencies of the tool, the following section details the key requirements for the tool. Key requirements are grouped into two main types of classifications that help in understanding the scope and all the features required to digitize the workflow: the back end and the front end. The backend includes key objects and procedures to be built on the server and the front-end to detail user interface actions and also suggested reading and literature references help in the building of the user interface. The front end and the back end system together constitute the workflow and are important in their own way and they are to be designed together to work in conjunction with each other.

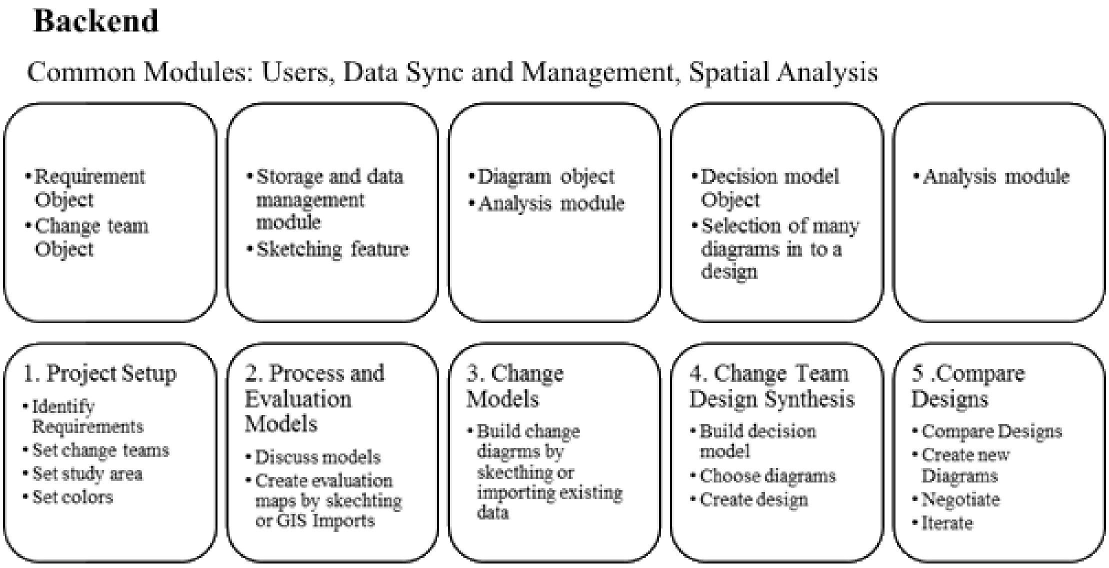


Figure 5.5: Backend Structure (top) and Workshop Flow (bottom)

5.6.1 Backend Design

Figure 5.5 details the key database and backed objects to be constructed on the server database for the workflow the objects are categorized per the actions taken by the user. The following details the key specification for each object.

5.6.2 Diagram

The basic unit in the system is a diagram. This is shown on in the third box in the top row in Figure 5.5. The geodesign workflow operates on diagrams and the figure below shows examples of diagrams that are used in the Lisbon workshop as reference. It is observed that there are two types of diagrams (refer Figure 5.6):

- A evaluation diagram shown in red and green
- A design idea representing a project or a policy in the form of features sketched out by hand in orange.

In addition, the diagram also has a name describing the content of the diagram (to others) and whether it represents a project or policy and additionally it has a rank. The rank of the diagram gives an indication of its perceived importance in the set of diagrams. Diagrams can be renamed or re-ranked and also removed from the project as is seen fit by the conductor and users. There are two ways data can be added in a diagram:

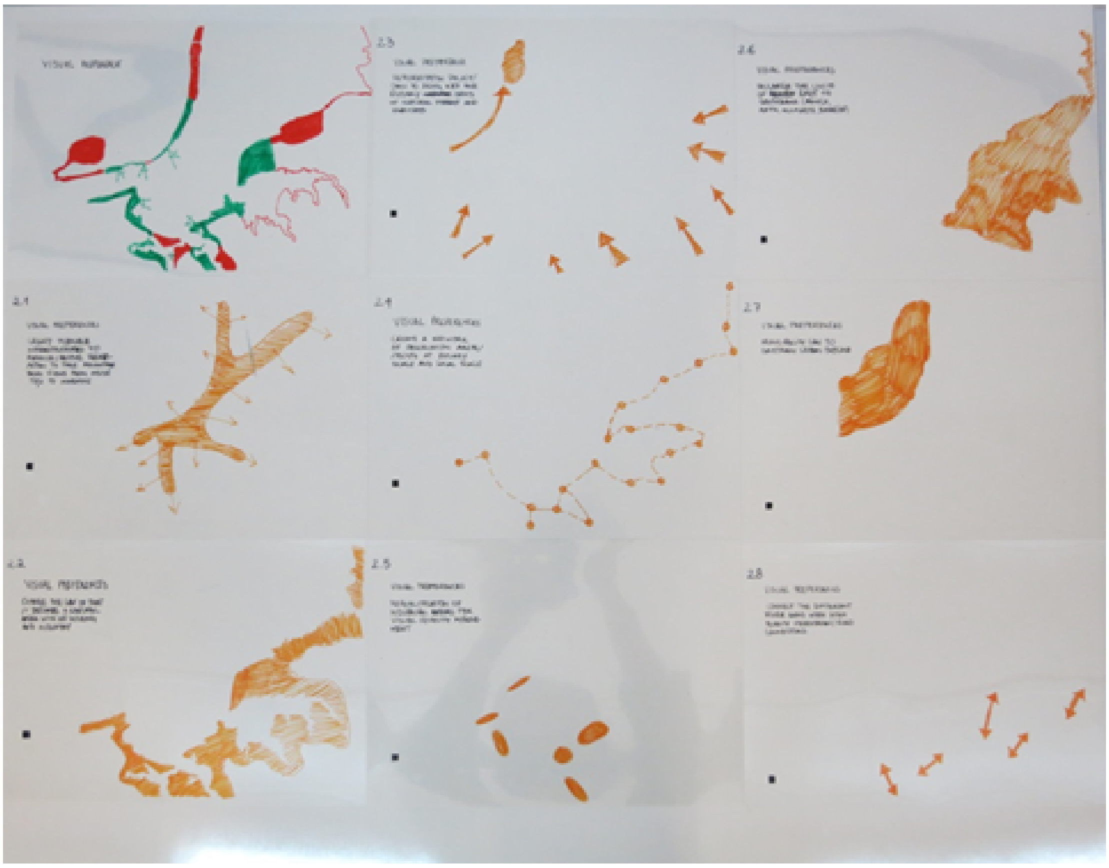


Figure 5.6: Diagram Examples. Diagrams Share the Same Color as the Requirement.

- uploading existing data
- sketching by hand

In the Lisbon workshop, the diagram is drawn by hand as shown below but as discussed earlier, in the conceptual design phase, the ability to sketch a diagram or import existing data into the object is important. In a number of geodesign projects, there will be existing data already available and therefore the diagram object must have the ability to reference user uploads within them. The generic diagram object should also accommodate geo—spatial data within it and this data should be accessible for the data analysis module. When the user is sketching the diagram, the diagram and its changes should be tracked as it is being developed, and just like a document with version control, the evolution of a diagram should be tracked. Similar to editing tools, there should be mechanisms to add / remove or edit features already drawn, and in some ways all the features available in modern photo editing or vector editing tools. When drawing the author should start with a blank canvas and by the end of the drawing / importing process the diagrams should look not too different from the hand drawn ones shown in Figure 5.6 above. Therefore the edit tool should have the ability to draw lines and polygons and fill them with a color. The evaluation diagram in red and green is also similar to the standard diagram however, and the red and green colors depict an assessment conducted about the requirement. Most modern GIS software are capable of advanced modeling that can produce a map with two or three colors and it is feasible that this data could be added as an evaluation map. Therefore the evaluation map can be a static map generated through a GIS process or directly linked to a dynamic model. Indeed in the experiments described in the later chapters, evaluation maps are built from output of GIS models. Further work needs to be done in standardizing these to a format to generate the evaluation map, and this is discussed in detail in Chapter 7.

Even though there are different ways of inputting information, internally the representation of this data should be standardized e.g. in the form of a shapefile. This format allows flexibility in that any type of spatial data set can be converted into it (and out to any format as well).

Finally, a diagram is always part of a requirement i.e. a diagram must always be linked to a requirement object, and there is no scope of diagrams without any requirements. Conversely, every requirement has an evaluation or assessment diagram (in red and green) and a series of diagrams that are in that requirement. The diagrams should be attached to the requirements in a one-to-many relationship i.e. a requirement can have many diagrams associated with it and a diagram can only ever be a part of one system. In that sense, moving diagrams across systems is not permissible. In the workshop, when new diagrams were added or removed, they were done on a requirement basis but diagrams are not allowed to cross requirements. A diagram for a requirement is only at that requirement.

5.6.3 Requirement

The concept of a requirement was just introduced, it needs to be elaborated. In this thesis the words Requirement and System are used interchangeably. In a systems view of design, a design problem has to be broken down in a set of requirements and smaller entities. In a regional scale problem, this is even more important since there are many systems working simultaneously. Designers tackle a design problem by adding constraints; constraints put structure on the design problem and it is this constraint that we are referring to in the context of a requirement object. The requirement is a misnomer here, and in fact it should be called a system. In a regional scale problem there are many systems at play: groundwater, surface water, transport, housing, commerce, industry etc. Any design that is produced needs to accommodate these "systems" and therefore it can be considered as a design requirement.

The requirement object has to be generic enough to have any number of systems from different to domains accommodate it. A requirement usually has detailed models associated with it and if there exists a model that can produce a three or five color (Red / Yellow / Green) map, then the model needs to be accommodated in this object. This requirements object represents the column headers or one of the ten systems that are analyzed in the workshop. In the case of Lisbon example earlier, it would be the following: Biodiversity, Visual, Heritage, Flood Hazard, Land Value, Agriculture, Transport—large and small and Employment and Tourism.

Not only does the requirements object have to accommodate different professional and academic domains, they also should have the context of the domain and an understanding of what kind of system it is. For example, is it a requirement that values spatial attractiveness or environmental vulnerability? In the planning domain, there are broadly two types of systems that are in action on a site:

- The first type is around allocating land use in terms of attractiveness. For example, the land with good road connectivity is a more attractive location for a commercial mall or a residential estate. This type of attractiveness requirement specifies how attractive (or unattractive) a location is for a particular type of land use.

- A second type of requirement is an assessment based on vulnerability. Vulnerability is related to conservation; how vulnerable are the areas near the sea shore to climate change? The assessment of this model is around making a judgment of high risk and low risk areas.

Attractiveness requirements usually have a target: e.g. in our plan we need 50 hectares of additional housing or 25 hectares of commercial area. These are common targets that are achieved as a part of the planning process and usually decided before the plan or the project starts. The vulnerability type requirement may or may not have a target. Should there be a number of species we need to save? How much coastline can be lost? What is the target for Visual Preference of a landscape? From a data structure viewpoint, these systems can have targets but they may not be specified or be implied in the project.

Finally, the requirements object should have a unique color associated with it and all diagrams under the requirement inherit the color. Standardizing around color provides a way to form a language of communication between various stakeholders and is an integral part of the framework.

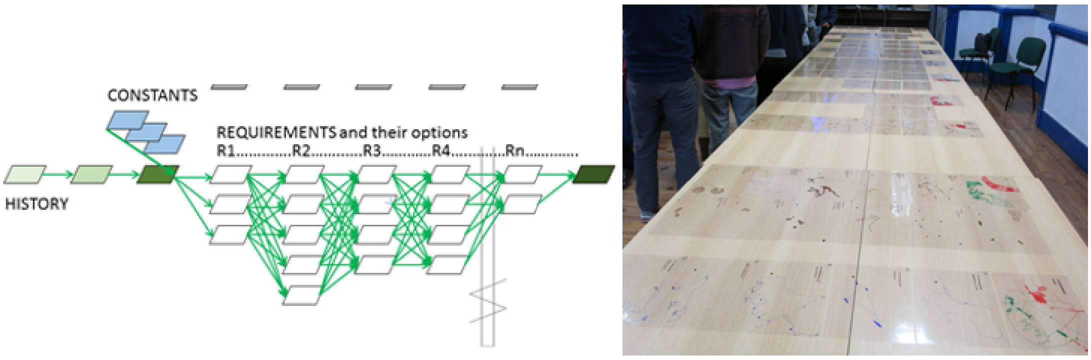


Figure 5.7: The Requirement and the Diagrams Grid Conceptual and in the Workshop

Together, the requirements the diagram object form the core of the synthesis system, this is shown in Figure 5.7. The left hand figure shows the grid of requirements in a top row (R1, R2 etc.) and the individual diagrams underneath every requirement in a similar fashion, the requirement and diagrams are arranged on long tables in the workshop with the evaluation layer at the very top and a series of diagrams underneath it. Technically, there are no limits to the number of requirements but usually they should be limited to eight to ten since that is the limit that most participants can process and it is closer to the seven +/- two target that is the threshold for human processing.

5.6.4 Users

The people participating in the workshop need to be addressed in the database. Besides the participants themselves, there are conductors and administrators that need to be incorporated in the system as well. In that sense, a user is a unique person and represents a participant in a workshop in different capacities. The user object can be used to authorize profiles and enable people to join the project and work on a set of diagrams, perform administrative operations on the project. Broadly, a user should be able to add / edit diagrams, be able to communicate with other users, and also be able to access the requirements systems grid.

In the Lisbon workshop, there were three kinds of users: regular participant, a leader or a conductor of a change team, and an overall workshop conductor. The hierarchy is artificial but it reflects the reality in a workshop situation: not all people are truly equal in skills, abilities, talent and interest. Some people are more comfortable leading, some are more comfortable as individual contributors. Thus, the conductors would have special privileges to create and submit a design etc. This structure mimics the structure of an organization where the CEO for example has privileges over the others. However it should be noted that from the geodesign and workshop context, every member is treated equally. This is especially important since there is a large social implication around power and authority and it is important that the egalitarian nature of the process be intact since one of the fundamental underpinnings of geodesign and indeed any such endeavor is that anyone can design. Identifying and working with team leaders and conductors in a workshop environment is a critical aspect of collaboration, else it is an unstructured conversation that will not lead to collaboration and knowledge sharing.

5.6.5 Change teams

In the Lisbon experiment, the task of the participants is to separate into different interest groups called change teams and build a design that follows their agenda. For example, the economic development team builds a design that is suited to their agenda by picking the diagrams that they want from the set of all the diagrams in the grid. A team can create many designs during the process of the going through the workshop. The designs themselves are a subset of diagrams so a design in that sense is a one-to-many relationship with the diagrams object. There should also exist a one-to-many relationship with the change team and users so that many users can be a part of a change team. However a user can only be part of one change team in a project.

A team may or may not have conductor since there are occasions that a conductor may be decided at a later time. While not critical, the decision model is a key component of the way teams operate. The decision model is a way for the participants to prioritize the requirements and attack the design problem within the team. The decision can be linked to the requirement object and set a priority for each input by the team members. The model is an average of the inputted preference amount. There are many ways to approach a decision model. Broadly they are preferences shared by the various members of the team towards different requirements.

5.6.6 Design Creation

Creating a design synthesis should be a simple process. A synthesis or design synthesis in particular is a compound object that is a set of diagrams selected by a change team. In the workshop participants selected a set of diagrams and overlay the diagram transparencies on top of each other to form the synthesis, and in the same way, the tool needs to enable selection of a set of diagrams and at some point the selected diagrams must be sent to the server for analysis. A team can create multiple synthesis and therefore all creations should be versioned and the ability to browse through various synthesis diagrams should be available by switching through a list. The basic characteristics of the backend system have been defined: User, Requirements, Diagrams, Change Teams and the ability to select multiple diagrams to create a synthesis. With these four objects, one can create a system that is capable of handling the basic structure of the workshop.

5.6.7 Geographic Bounds

Every project is based on a study area. The study area is represented by geographic bounds that are static throughout the project. This is the study area of the project and all diagrams, requirements and spatial analysis inherit these bounds and clip the map or the tiles to the object. By bounding the project provides a way to reduce the data operations that are required and can increase performance. In addition, bounds also constrain the problem space by using a boundary from a geographical context.

5.6.8 Data layers and Data import / export

Design activity does not happen in a vacuum, and usually there are data sets that already exist to help in aiding the design activity e.g. existing land use, terrain, hydrology, protected landscapes etc. These form a critical part of the design. Every project and site has its own set of constraints that are specific to the area. For example, there may exist a conservation law that mandates certain areas be protected or there might be a preference not to destroy and build on existing structures. These types of data should also be included in the design activity since they are critical to the successful completion and acceptance of a new design.

Any design activity should involve the existing land use, the satellite view and the constraints view. Together these four combined with evaluation layers would help in building good design using the appropriate constraints. The goal is to build an open system, and the ability to import and export most common spatial data formats is a requirement that should be met. The data layers specified above are available most commonly in the following formats and therefore should be should be supported. They are:

- Shapefile
- Tilelayers
- GeoJSON / TopoJSON
- CSV
- KMZ/KML
- WKT
- GPX
- WMS

By allowing the import of these common data formats and enabling export to Shapefiles ensures compatibility with other commonly used tools in the urban planning domain.

5.6.9 Version Control

Geodesign differs from the traditional design process in that the cycle time for creating a design is much shorter. In the software development world, there exist mature tools to handle changes to source control code and can be effectively used here. Version controlling a software project ensures that changes in the code base, merging of different work and conflict resolution is solved. Version control has been prevalent in most software development projects and it has come a long way. Version control enables collaborative software development. The concepts of version control can be effectively applied to enable the geodesign workflow.

Therefore, underpinning all of the actions of the tool should be a version control system that tracks the changes in the files themselves. The act of sketching and early stage design as we have discussed earlier involves numerous attempts to reach solution, backtracking and solving around a problem space. This means that participants and designers create different versions of their idea, each one slightly different from the previous. In the non-digital world, designers, usually sketch, create multiple sketches, modify these and iterate on the drawings until a satisfactory solution is reached. This process is very hard to mimic purely in a digital world. However, modern version control provides the best analogue to this process. Version control enables software engineers to work with source code efficiently tracking and merging changes to the code as they collaborate. To enable the design workflow in the workshop and track all the changes, it is recommended that version control be implemented for diagrams so that every change made in the diagram is tracked and potentially can be reverted.

Not having access to the design‘s “history” is a detrimental to the solution formulation as has been discussed earlier. It is important to go through different iterations of the sketch and work off them and therefore the ability to have a history is critical. All potential solutions should be available easily for the designer so that he/she can “hone in” on the most satisfactory one. This application of a version control system to store geospatial features also provides some critical benefits. Version control used in software projects is used to execute commands such as diff and merge work and manage changes to the codebase. These can effectively be applied to the design as well. The ability to diff and merge between objects to build composite diagrams and also identify potential conflicts in the ideas is thus essential. In addition, version controlling spatial data, can also lead to other GIS like operations that can be performed on the repository. This operation on geospatial data has implications on the workflow. In the Lisbon workshop, it was observed that the participants would copy one diagram and add another data to it or remove some part so that it suits their plan better, this operation is handled very well by source control and is similar to the merge operation. For example as shown in the Figure 5.8, the figure on the left is the original diagram and the figure on the right is a diagram that takes the old figure and extends the green feature. It will be trivial to conduct a diff and merge of these diagrams using source control in addition to reverting to an older version.

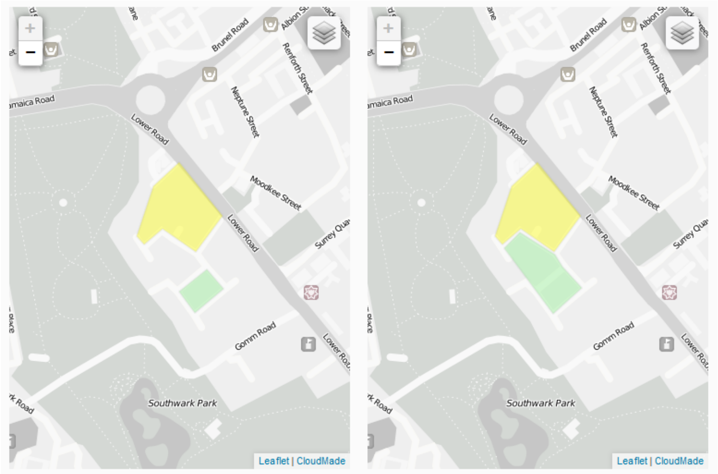


Figure 5.8: Versioning and Two Versions of a Diagram

There are many version control systems that are both open source and easily accessible. Some of the more popular ones that can be recommended are Mercurial and Git. A diagram under version control would look like the following where the operations on a diagram are easier. For example in the figure below are creating a new version of the diagram v4 that on the left is a combination of the v3 and v1 of a different diagram, similarly on the right we have a v4 that is a combination of v3 of the original diagram and v2 of a different diagram. (see Figures 5.8 and 5.9)

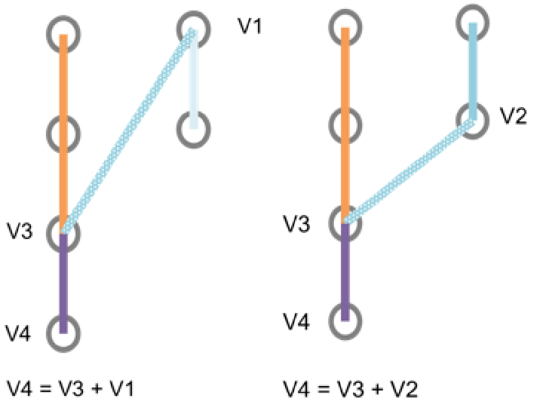


Figure 5.9: Merge Operations for Diagrams under Version Control

These types of operations are routinely performed in the workshop and by designers and using version control is a nice way to keep track of the changes and enable these operations in a fairly robust fashion. The versioning system should be considered as a replacement of the file system for the data used in the project. In addition using version control gives a lot of benefit in terms of data organization and logging for changes in the project, by the end of the project there were more than 150 diagrams, that were created which is normal in most projects.

5.6.10 Diagram Analysis

The ability to do impact calculations in the design process is critical. This is one way that geodesign differs from existing processes and this focus on design and analysis is elaborated earlier in the previous chapters. This process of analysis should be very fast and almost immediate to ensure that the user experience is not suffering. Every time a diagram is added to the workshop data, it should be analyzed for its impacts in real-time and additionally these results should be stored for reference and future use. The analysis is essentially an intersection operation in GIS to evaluate where on the evaluation map for the requirement the drawn diagram fits to determine the suitability of the location of the project or policy.

This is done routinely in an analog fashion in the workshop: the participants overlay the diagram sheet over the evaluation sheet for the areas that overlap. To explain this process, consider the digital version of an evaluation and a diagram as shown in Figure 5.10 below. The figure on the left shows the evaluation of the requirement and the figure on the right shows a diagram.

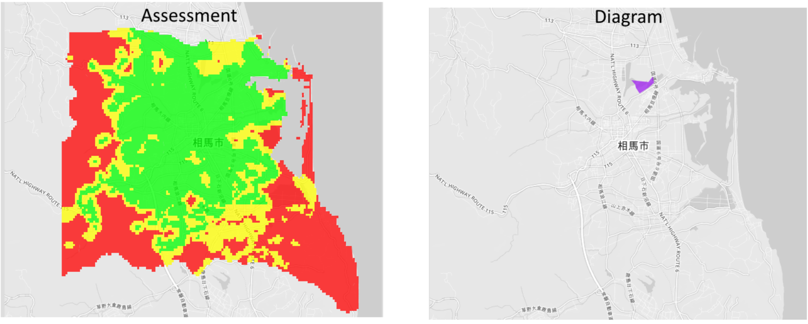


Figure 5.10: Assessment and Diagram

This diagram on the right can be as shown earlier as hand drawn, imported from a GIS or other existing data. The Assessment, Diagram and the two together and its intersection are showed below in Figure 5.11. It can be observed in Figure 5.11 that the diagram overlaps the "green" area of the assessment (Green area means: low risk / high attraction). If a polygon falls under the green area it means for that requirement, there is low risk and high attraction and probably is a good policy or project.

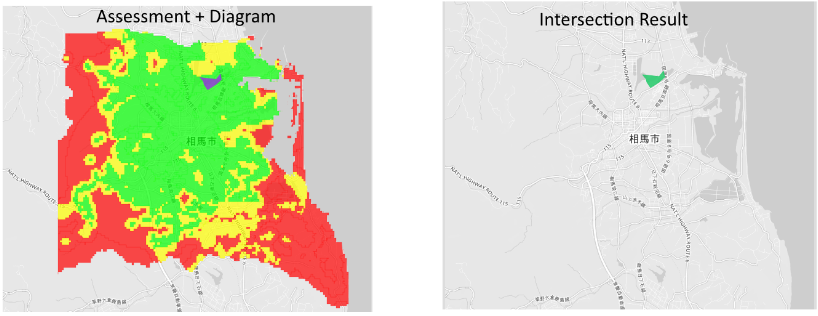


Figure 5.11: Assessment and Diagram Overlaid (left) and Result of Intersection of the Diagram on the Evaluation (right).

This process and computation has to be performed for every diagram and every assessments, and therefore every diagram should be capable of detailed assessment. This is a computationally intensive task and the time taken is directly proportional to the complexity of the assessment data and the computational power available. However, the central premise of geodesign is to show dynamic analysis of changes and successful implementation of this is critical to the functioning of the system.

In the workshop context it was not possible to quantify this accurately given the analogue nature of the diagrams and assessments. During diagram section for addition to a design, most of the participants overlaid the diagram over its evaluation to see if the diagram is on the "Green" portion of the assessment or the Red part of the evaluation. It is this behavior that is mimicked.

At the most basic level, this is the impact that needs to be calculated. However there are other type of impact calculations that can also be computed. For e.g. an impact index can be developed where not only is the polygon intersection area calculated but a judgment is made of how bad the impact really is by calculating where the impact is: e.g. it is in a protected area, or its impacts towards endangered species or the type of project proposed in the diagram. There are a couple of ways to calculate the impact index as far as the framework is concerned. One way to build a index is to look at the decision models, since the preferences that the different teams assign to each of the systems is not the same, a index can be generated that emphasizes the impact of changes on a high priority system more than one that is of low importance for that change team. Another way to develop a impact index is to examine the kind of change a system represents. Is it large construction, small construction, agriculture, paved roads etc. Each of these changes have different impact on the study area and depending on the cultural preferences or even scientific analysis a index can be developed.

5.6.11 Miscellaneous Backend Features

The workshop and framework is most effective when there is a strict time table that is followed from the start to the end. All participants of the workshop were aware of what stage of the workshop they were in. This helps in facilitating collaboration and the participants could easily check at what stage other teams were to assess if they are performing fast or slow. Thus there is a necessity to have a workflow manager or a step by step process that tells the users where they are in the process.

Another key aspect of the diagram drawing is to go back and correct errors. This happens at various different places: first when sketching diagrams if an error is made, since it is made with marker, it can be easily erased. Secondly, in the design synthesis phase of the workshop, if an incorrect diagram is picked, it is very easy to run to the table, pick the correct one and move forward. This ability to undo an action is a constraint that is very common in a design process, where the designers go forward and back on ideas while designing. In a digital setting, this means that every action taken in the design process has to be logged and audited. This can be either in log files or custom data structures that log every step in the process. The ability to undo a move in the front end and support in the backend is critical.

Just as individual diagrams are analyzed for their impacts synthesis created by change teams are analyzed in the same fashion. Thus the process of impact analysis is done on an individual diagram level as well as on a set of diagrams that form a design synthesis. The logic is exactly the same as described above, just the number of the diagrams are dependent on how many the team has chosen. In general, there may be about fifteen or twenty diagrams that may be chosen for analysis. This analysis is useful when comparing different synthesis and designs at the end of the workshop when judging design quality across different change teams.

5.6.12 Frontend Design

In addition to the back end system, there are front end features that are required by the system to perform the workshop. (see Figure 5.12) Front end design has to do with user interfaces and ease of use by participants. This section details references and papers in literature that are relevant to front design of GIS enabled design systems. The primary task of users in the workshop is to review the assessments, add diagrams and analyze them and select a set of diagrams to create a design. This is done repetitively till a satisfactory design is reached. Once all the teams reach a satisfactory design, their designs are then compared. Therefore, there are two main parts of the system front end: the Diagrams Grid and Synthesis comparison. Figure 5.12

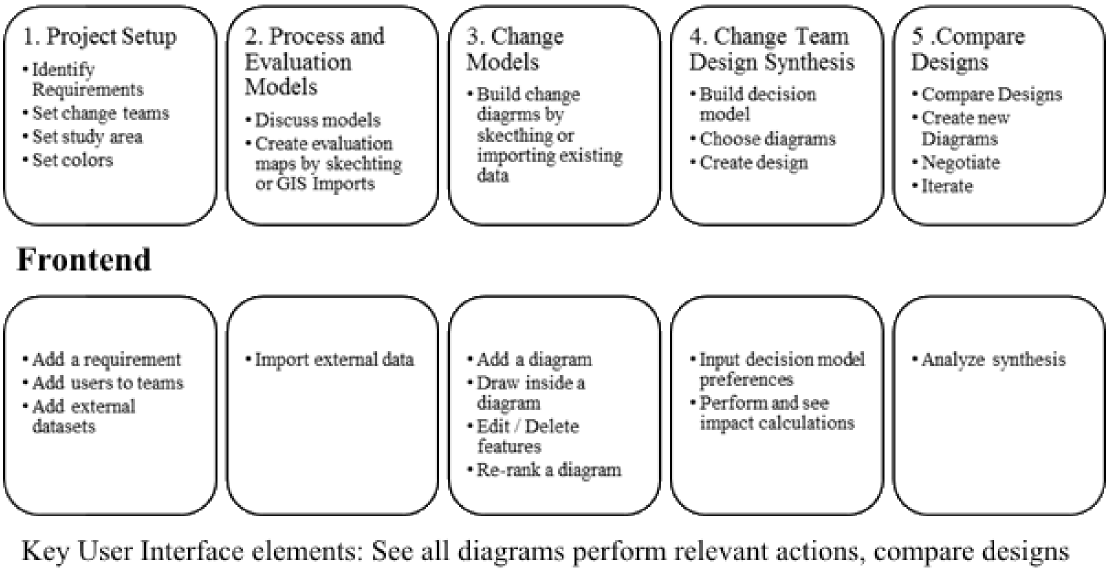


Figure 5.12: Workshop flow (top) and Key Front End Modules (bottom)

In addition to the back end system, there are front end features that are required by the system to perform the workshop. Front end design has to do with user interfaces and ease of use by participants. This section details references and papers in the literature that are relevant to front design of GIS enabled design systems. The primary task of users in the workshop is to review the assessments, add diagrams and analyze them and select a set of diagrams to create a design. This is done repetitively until a satisfactory design is reached. Once all the teams reach a satisfactory design, their designs are then compared. Therefore, there are two main parts of the system front end: the Diagrams Grid and Synthesis comparison.

Diagrams Grid: Once a project is setup and the study area finalized, the users would use the diagrams grid structure to see the data on project. This data would include all the diagrams, and the assessments in one form. This is like seeing all the diagrams and evaluations together on one large table as in the photo depicted earlier. The diagrams grid is the main workbench for all the actions of the user and it is here that the user adds, reviews and interacts with the diagrams.

Synthesis Comparison: The second data presentation item that needs to be created is the comparison module where the synthesis created are compared by showing them side by side and compared against the same metric as all the others. The different synthesis should be loaded side by side for visual and other comparisons that are described earlier in the chapter. In general there are three types of design comparisons that can be undertaken:

1. Feature Overlays: In this type of comparison all the diagrams selected are overlaid one on top of the other at 50% transparency and the overlays should show visually the agreement / disagreement with the design. When the designs are in agreement, we would see primary colors and when there is conflict, we would see muddied or brown color as shown below in the analog version.

2. Impact Assessments: Impact assessments that are aggregated for all the synthesis shown side by side is also pertinent here. Easy visual comparison should be possible by aggregating the red / yellow / green areas.

3. Frequency of Diagram Use: Just as in the Lisbon example described earlier the selection of diagram frequency is an important way to measure popularity of a diagram. A diagram by more teams shows that it probably is a good idea in that it has a lot of buy—in and acceptance among teams.

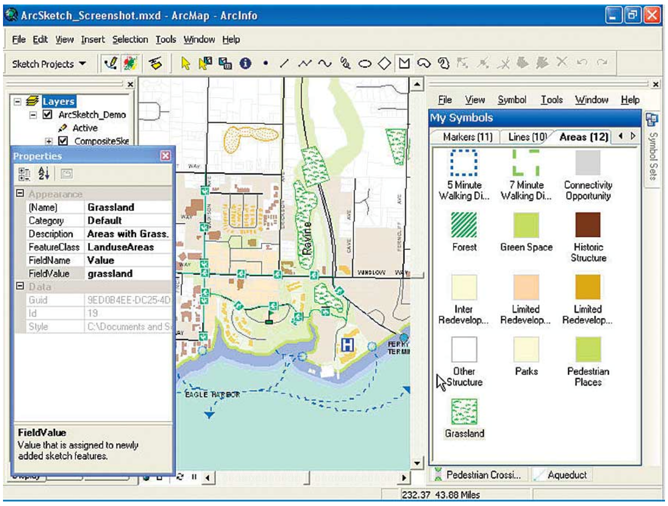
These two modules are the two key front end objects that need to be created: a workbench to review, add/remove diagrams and a comparison module to compare different designs side by side.

5.6.13 Users should be able to add a diagram

The users at any point should be able to add a diagram to the grid and this addition should be shared between all users connected. The participants contribute all diagrams therefore when a diagram is added to the grid, it should appear on the grid of all participants in the workshop along with the features that are sketched out or imported.

5.6.14 Users should be able to draw inside a diagram

This is a basic function that needs to be performed in the front end. The project should have many diagrams just like the Lisbon example; the user should select any diagram and be able to draw features into the diagram using a mouse, commonly called as “sketching”. A sample sketching interface is shown below in Figure 5.13. In addition to sketching on the interface, the user should be able to import existing data from different data formats using the front end of the system. So using a few mouse clicks, the user should be able to import their data into the system. The following sub-features should be provided in the drawing tools:



(Name)	Grassland
Category	Default
Description	Areas with Grass.
FeatureClass	LanduseAreas
FieldName	Value
FieldValue	grassland
Guid	9ED0B4EE-DC25-4D
Id	19
Style	C:\Documents and S

FieldValue
Value that is assigned to newly added sketch features.

Figure 5.13: A Example Sketching Interface, ESRI ArcSketch

- Edit a Feature: The user should be able to edit a feature once it is drawn
- Delete a Feature: The use should be able to remove a feature from the diagram once it is drawn

- Clear all Features: The user should be able empty a diagram by clearing all features of the diagram.

- All of these features are used frequently by designers in the Lisbon workshop and are involved around diagram creation and editing.

- Track every change in the features as they are being built so that the user can revert to a sprevious one

5.6.15 The User should be able to re-rank a diagram

The ranking of diagrams is important since it tells the change teams what diagrams are more important than others. Re-ranking also helps the change team to understand the “expert‘s view”. In the Lisbon workshop, the experts ranked the diagrams by their preference and it helped the change teams to formulate a strategy of diagram selection. Therefore changes to the diagram rank are important and any ranking change should be propagated to all the participants

5.6.16 Synthesis Building

Once the diagrams are added and the grid is populated, the user should be able to construct a synthesis by going through a process of selection of multiple diagrams to create a constructed diagram that is an aggregation of the selections in the same way, diagrams can be removed from the synthesis by unselecting a diagram.

5.6.17 Impacts Analysis

After a set of diagrams are selected, the user should be able to see the impact of those selections against the evaluations as discussed earlier on the screen in order to assess whether the selections perform well. This can be either on-demand as the design is being built or at the press of the button.

5.6.18 Users should be able save designs for synthesis

Once the users select a set of diagrams, they should be able to store the selections as a synthesized design. This synthesized design should have a user friendly text associated with it that describes the synthesis. The impacts of the synthesis also should be saved for future use.

5.6.19 New Requirements should be able to be added to the project

Sometimes mid way during a workshop, there maybe a need to add new requirements to the project. This should be done through a “management” panel and the addition of the requirement should be propagated to all the participants.

5.6.20 Evaluation layers should be able to be added by the project administrator

As a part of the setup of the project, every requirement should have an evaluation layer that is built using existing data. This evaluation layer is a three to five color layer that is used throughout the workshop. This layer is added to the “evaluation” type diagram and should be locked for modification from others.

5.6.21 Project Administrator should be able to add / remove move participants from different change teams

Change teams are teams that take on a role playing agenda and in a digital setting, the users or participants of the workshop should be able to be added or removed from a team. This nature of team-based collaboration is a critical feature of the tool and ties with the change team model described earlier.

The project administrator should be able to see progress in an administrator‘s console type interface. Since the workshop is a series of different stages, the progression to the next stage is only possible when all the actions and requirements of the existing stage are fully completed. For example, before moving into the synthesis comparison stage, the conductor should be able to check if all the teams have indeed created a synthesis and that there are no errors in the synthesis creation.

5.7 User Interface

User Interface of planning support systems is a vast and deep topic. The aim here is not to conduct a review of the literature on this but to help in understanding the key concerns with user interfaces, information processing and ease of use if concerned. Effective user interface facilitates communication and collaboration and reviewing the literature to highlight what makes an effective interface is the goal of this section. The issue of user interfaces can be framed in the context of a communication problem in that they should facilitate a shared knowledge and understanding of the problem at hand. Therefore user interfaces of planning support tools should be judged by:

1. How well the participatory planning instruments enable users to carry out the intended tasks / understand information?
2. How well the instruments fit the capabilities and demands on intended users?

This is the central question when it comes to building user interfaces of planning support tools. Given that we intend to mimic or replicate the process that was used in the workshop, the interface goals for this document are to explore how building a digital interface impacts the performance of the user in a workshop. This is an area for further research but the following sources summarizes the key contributions to the user interface literature for planning support systems that can be used by developers to build a interface for the workshop.

Category	Contribution Summary	Source
Usefulness / Clarity of interface	Public Participation done with non-technical users, farmers and local small industry people. Spatial information and results from a spatially explicit dynamic pollution model (AgNPS) for previously prepared scenarios were presented. Questionnaires were administered at four different times during the workshops to test participants‘ reactions to, and opinions of, the information provided. Participants were able to understand and react to the spatial information despite their lack of previous exposure to such materials. Both visualization and discussion caused major shifts in the perception of the problem and suggestions for solutions. Participatory visualization of scenarios enhanced perception and increased understanding of the water pollution problem caused by intensive pig farming and stimulated the collective search for solutions.	[Andrienko and Andrienko, 2003] [Bacic et al., 2006]

Usefulness / Clarity of interface	The focus is on the concept of Usability Engineering for GIS —a set of techniques and methods that are especially suitable for evaluating the usability of GIS applications which can be deployed as part of the development process. To demonstrate how the framework of Usability Engineering for GIS can be used in reality, a screenshot study is described. Users were asked to provide a screenshot of their GIS during their working day.	[Haklay and Zafiri, 2008]
Usefulness / Clarity of Interface	The research provides evidence from two case studies where Environmental Decision Support Systems (EDSS) were used in participatory water management that end-user employment is correlated with perceptions of EDSS effectiveness. Both studies provided statistically significant results suggesting that end-users employed in or directly affected by policy decisions perceived the EDSSs used as being more effective than end users from research or engineering backgrounds. A seven-point Likert scale used to measure end-users‘ agreement with perceived effectiveness statements is used in the evaluation instruments in the two case studies.	[Inman et al., 2011]
Usefulness / Clarity of Interface	Survey based technique (web and in person), experts and students were surveyed on their understanding of mapping information and contains specific recommendations on how to develop interfaces for communicating information to experts and non experts.	[Pettit et al., 2011]

Usefulness / Clarity of Interface	A comparison of different planning support tools and scores on presentation involves the user understanding what is important and asking if the PSS does what it is supposed to do.	[Uran and Janssen, 2003]
Usefulness /Clarity of Interface	A comparison of participatory modelling to other frameworks and modelling approaches such as companion modelling, participatory simulations, participatory decision analysis etc. that involve stakeholder participation is required.	[Voinov and Bousquet, 2010]
Linking frontend to backend	Describes an XML framework to describe environmental applications. Integration of management activities, and also of the modelling undertaken to support management, has become a high priority. To solve the problems of application and integration, knowledge encapsulation in models is being undertaken in a way that both meets the needs for good science, and also provides the conceptual and technical structures required for broader and more integrated application of that knowledge by managers. To support this modelling, tools and technologies from computer science and software engineering are transferred to applied environmental science fields, and a range of new modelling and software development approaches are being pursued.	[Argent, 2004]
Usefulness and Clarity of information	New scales for two specific variables: perceived usefulness and perceived ease of use, which are hypothesized to be fundamental determinants of user acceptance were examined and studied for and elaborated.	[Davis, 1989]

General Background on Planning Support Systems	A general review of PSS and details the way the PSS side of things evolved and how it became fragmented over time. Gives a background on the use of computers in PSS. Starts with early graphical user interfaces, and how early PSS started with Google Maps etc. Types of PSS: 1. Long Term Forecasting at the Strategic Level: Visualizing Land Use and Transportation. 2. Immediate Forecasting at the Local Level: Visualizing the Impact of Air Pollution Using a Virtual City Model 3. Describing and Exploring Spatial Data: Tools to Enhance the Understanding of Urban Problems	[Batty, 2007b]
Consensus Measurement / Effectiveness	Consensus measuring technique. Discussions on the map as a commenting platform.	[Boroushaki and Malczewski, 2010]

Case Study	A case detailing using a PPGIS in the context of a wetland management project. From experiences with the development of the two decision support efforts. The first tool uses spatial multi-criteria analysis techniques, to enable a structured analysis of the diversity of the water management issues. The second tool focuses on interactive design and spatial negotiation. It is concluded that application of this category of tools can be promising in early phases of decision-making. Their main contribution is to help to overcome unnecessary conflicts, to stimulate collaborative planning, to structure the problem and to provide insight in values and preferences of stakeholders involved.	[Goosen et al., 2007]
Case Study	A study that compared three scenarios using photos and then had a participatory discussion on the reactions to the images.	[Tress and Tress, 2003]

User Experience	Usability techniques in public participatory GIS, There are four identifiable human computer interaction and usability evaluation techniques that were reviewed: • the reliance on chauffeurs to drive the software, • the use of software to record the interactions between the users and the system, • the instruction to facilitators to encourage participants to verbalize their thoughts regarding the interactions and the development of a task list to guide the process • the use of tasks or scenarios to obtain information about users performance and attitudes towards the system.	[Haklay and Tobón, 2003]

User Experience / Clarity	This paper quantitatively evaluates the usability of a Web-based public participatory GIS (Web-PPGIS) and the degree of public engagement in the context of a real-world spatial planning application. The public participatory decision-making process utilizes ArgooMap to support local residents in an online procedure for determining the best location for a new parking facility in Canmore, Alberta, Canada. UsaProxy is employed to automatically collect the data sets on the system usability and the degree of public engagement. This research shows that the degree of public engagement depends significantly on the system usability measured in terms of the system efficiency and effectiveness and the participants satisfaction with using the system. In this study, participants are encouraged to design the best parking lot location for that town and come up with the most suitable / acceptable location	[Meng and Malczewski, 2010]
User Experience / Clarity	A case where participants were chosen at random and then asked to start comments / discussion on a map. Aspects that were studied were: • learnability, • memorability, and • satisfaction of case-study participants	[Sidlar and Rinner, 2007]
Participatory modelling	Two methodologies: Groundwater flow model and Bayesian belief network were studied in a regional context where the participants built models and analyzed geography.	[Salter et al., 2009]

Data presentation and 3D	Community Viz participatory modelling software was used along with immersive 3D visualization.	[Sheppard and Meitner, 2005]
Clarity of information	SWOT analysis in terms of fit of the planning task to the technology to the user.	[Vonk et al., 2007]
Applicability of PSS	Key drawbacks of the planning support system interface and implications of combining design and analysis into a single function.	[Van Kouwen et al., 2007]
Collaboration in a Planning Support System	Implications for building a collaborative interface	[Vonk and Ligtenberg, 2010]

5.8 Key Modules

To improve code maintainability, the application should be as modularized as possible and following are some of the key modules in the system and their brief description.

- Diagram Operations: This module is the core module to handle all diagram operations such as addition, editing, deleting etc. in the workflow. In addition to managing these operations, the diagram module also does the work of writing diagram data into a file for future use and also the reading of data from the file.

- Requirements Manager: The requirements module handles all functions related to the requirements such as adding of requirements, setting the requirement type, color, and setting a requirement target etc.

- Change Team Manager: This module handles the operations around change teams such as adding users, removing users, creating new change teams etc.

- Sync Manager: This module manages the synchronization between the different participants connected to the workshop. It manages the state of the data and syncs this state across all the clients connected.

- Analysis Module: Once the diagrams are selected and submitted for analysis, this module does the analysis and it includes GIS like spatial functions that perform the actual union and intersection of the features fast. This module may sit on a separate server from that of the others given the processing power that is needed.

- Data Manager: This module acts as the core data manager and handles all the different file formats and also reads and writes the information to the diagram files. The Data manager also works with the Sync manager to communicate the state of the data to ensure that all changes are properly synced with others.
- Import / Export Manager: The import / export manager is a module that converts between different file formats seamlessly and also enables data validation and checks on the data. It works with the data manager module to pass on validated data for it to write.
- User Module: The user module handles all functions with the User object and its related functions: authentication, profile, language preferences etc.
- Versioning Manager: The versioning manager works with the data manager to manage and handle changes to the data: new versions, cloning / copying between versions etc. are handled by this module. In addition, this module tracks change logs, change sets and also performs analysis on the different changes.
- Logging module: The logging module logs and keeps track of system or functional messages around errors, warning etc. The logging module also provides a detailed analysis of the crashes, crash reports etc. to help debug the code.
- Administrator module: The administrator module maintains the administrator functions such as checking synthesis progress, validity of different diagrams etc.

The tool should enable different types of collaboration, each with its own security model as described below:

- Team based: Every user is a part of a team that in some ways collaborates or competes with the others in the workshop. Therefore a way to authorize a user could be to inherit the privileges from the team that the user is a part of.
- Open Collaboration: In some cases the user is not a part of any team and therefore they should not be able to create a synthesis. However they should be able collaborate and see the data since they are still a part of the workshop.

To enable the different type of collaborations, there should be three types of users in the system: A project administrator, team conductor and also a regular participant. The project administrator is the super user of the system. He / she creates and manages the projects, adds / removes change teams and also has control over other users in the sense that they can add who leads the individual change teams. The second level of user privilege is the team conductor: A team conductor leads the individual team in some cases the requirements team also and they coordinate the way the design synthesis is built on the system. They can add other team members in the change team as well.

5.9 Performance and Capacity

This section describes basic performance characteristics of the system and quantifies the range of performance criteria for successful application of the tool in a real life workshop setting. There may be upto thirty people working on a large complex planning problem. At any given time, the server should be able to support upto 30 users logging in the system and interacting with the data. The users will perform the key operations as described above, while simultaneously computing impacts of their designs.

The server has to synchronize the addition and removal, changes to the diagrams and other objects across all participants in real-time. When a user joins a project, the user should have the most recent copy of the data. The amount of data can vary between users and it depends on the stage at which they join the project. For example a user may join from the beginning of the project and some other user may join at a stage when some initial data has already been created. Thus the server should manage incremental data history and provide it to the user at any time that is desired.

Every project should have about eight to ten requirements. For most projects the number of requirements will vary between these numbers and therefore will have to be linked to eight or ten different models in real time. Since the goal is to build an open system, there may not be any control on the performance of the linked models. However there should be a requirement that all computation with linked models be performed within a range of 5-30 seconds.

The users should have a near real-time synchronization of the actions performed by other users on the project. If a user adds a diagram, that addition should be synchronized across all the participants connected to the workshop. GIS operations can be computationally intensive and since we are doing primarily intersection and union operations, there should be some amount of caching for performance improvements so that the users do not have to wait for a long period (more than 15 seconds) for the results. In general, an asynchronous framework should be used on the client side to enable asynchronous processing and updates to the interface so that the main thread is not waiting for data and locking the user interface which makes for a bad user experience.

5.10 Monitoring and Maintainence

As with all modern applications, the load on the computer that performs the GIS operations should be monitored for performance. Some GIS operations can be very compute intensive primarily because of the data that used and also the intended outcome. A way to minimize the server load is to simplify the features, reduce the feature count and cache some of the data for future use. In addition, errors pertaining to impact analysis should be monitored and logged since they are used to determine the performance of a design and are a critical function of the tool. Standard logging practice using logging levels should be implemented:

DEBUG Low level system information for debugging purposes

INFO General system information

WARNING Information describing a minor problem that has occurred.

ERROR Information describing a major problem that has occurred.

CRITICAL Information describing a critical problem that has occurred.

For most operations on the system logging is essential in debugging and identifying the problem. Some sample operations on the tool are: When an external file is added or the user draws the diagram, this links a diagram to an external model or an evaluation layer or imports Shapefile etc. These operations can generate a number of errors since we are dealing with external data. There is no way to sanitize or ignore these errors and the application should be able to handle exceptions gracefully and also alert the user in case there is an issue with the source data. Finally logging is important to ensure system performance is maintained. Errors should be detected on the imported data first and the threshold for data to be inputted should be high, that is, data that does not meet the error threshold for example data having invalid geometries should not be allowed to be imported in the system. In addition, errors related to synchronization or different clients having different states should be logged and acted upon appropriately. Synchronization errors are particularly difficult to debug so they should be logged with extra precaution so that remedial action can be taken appropriately.

5.11 Operations Summarized

Some key operations are described here and having an operation focused view of the system helps in organizing the modules and also in development of class abstractions within the modules. This is to be referred to in conjunction with the user operations on the front end.

- Save / edit: The save / edit / delete operations handles the data that is inputted in to the diagram object and also notifies the sync module to sync the changes across all the connected clients.

- Add blank diagram: Similar to the operation above, a participant can add a diagram using the front end and initially the diagram is blank. This diagram needs to be synced across all the participants.

- Re-rank diagram: The user can re-rank a diagram or change the rank of the diagram in the list to make it more important. Any changes to the diagram have to be propagated across all the participants.

- Select a diagram for synthesis: In the front end the user needs to select a diagram for addition to a synthesis map.

- Create synthesis: The create synthesis operation takes in a set of diagrams and submits them to the server for analysis and stores them in a version that stores the diagram state and analysis information.

- Get diagram information: This operation reads the data contained in the diagram such as features, points etc. and shares them with the requesting module.

- Analyze synthesis: Once a set of synthesis diagrams are submitted to be saved, they are analyzed against the assessments and the impacts saved.

5.12 Security and Authorization

Participants of the workshop and connecting to the tool need to be authorized to connect to the data. Therefore an authentication interface is required. The users should not be able to access certain data such as the basemaps or the constraints because these are common and should be shared with all. The administrator needs to invite the participants using a special email to the project and only then can the participant see the data. Some data may be proprietary and not for sharing; therefore access should be limited to the people who are authorized to see it

5.13 Summary

This chapter serves as a specification that can be handed to a software developer to help them create an implementation of the geodesign workflow. Key system objects, system parameters, and the backend and frontend structure have been described. The goal is to build a multi system planning support tool where the users are able to bring their own data. Any model can be connected and the impacts of selections on the front end can be computed in near real-time at the backend.

This specification contributes to the planning support tool literature by laying out software guidelines for this new class of real-time planning support tools. In the following chapters, an implementation of this specification and results of five workshops that were carried out in 2014-2015 digitally using the same workflow as a non-digital workshop will be discussed.

Chapter 6

Experiments with Digital Design Synthesis

6.1 Introduction

Chapter 5 detailed a specification that highlights key modules and components for building a planning support system that supports the geodesign workflow. To review, Geodesign borrows from a number of different domains: architecture, engineering, landscape architecture, urban planning, traditional sciences etc. [Dangermond, 2010] and takes a holistic and complementary view on the design process by incorporating different stakeholders. The promise of Geodesign when used in a digital environment differs from traditional design done digitally in the way it can be implemented. Traditionally, digital design involves the use of spatial optimization models of planning or allocation of land use to build a plan. Additionally, the traditional workflow is around digitization and the drawing of plan objects, which constitute design in a serial fashion, and once they are drawn they are then evaluated for performance. However in the context of geodesign, design deals with a collaborative process where the computers respond to changes in design as the various stakeholders are building it. Thus what makes geodesign fundamentally different from traditional design process is the workflow or the process of creation of a design. The ability to create a design collaboratively and measure impacts of the creation as you proceed is embedded in a platform for collaboration and communication which forms the basis of the geodesign workflow. Fast iteration and quick design cycles are also ways in which the geodesign workflow differs significantly from a traditional one.

Carl Steinitz, Professor Emeritus of Landscape Architecture and Planning at Harvard University, developed some early and fundamental ideas about the geodesign workflow. Steinitz developed a model of landscape change that enables design and assessment of alternative futures. The "Steinitz Framework" has been put in practice for a number of years on large landscape change problems and in the form of intense two or three day workshops where participants from diverse academic and professional backgrounds and levels of experience come together and go through the process to build a design iteratively in a compressed timeframe. The framework takes a multi system approach to problems that are novel from a design and from an analysis point of view.

This chapter details a set of experiments carried out in 2014-2015 using a reference implementation of the specification described in Chapter 5. Two different types of experiments were carried out:

- A set that used data from an existing workshop that was conducted in 2013 in Japan and was partially digital
- And secondly, an independent experiment without any prior data availability and all data was generated in the week of the workshop.

Similar to the Lisbon experiment, a workshop conducted earlier in 2013 at Soma city in Japan is considered. In this workshop, unlike the Lisbon study, digital technology was used at all stages except the design synthesis stage. There was extensive use of GIS technology in the process, evaluation models and impact models. However the change models were built by hand sketching on transparencies and then digitized by hand. Therefore the data from this workshop proved ideal content to build a new tool based on the workflow and test its utility and effectiveness. Using the specification described earlier, the goal was to build a system that can handle the workshop data created like the one in Lisbon and eventually conduct a workshop from scratch with the workflow to prove the central research question: What kind of digital change synthesis support is required for geodesign? The reference implementation and the experiments of the workflow provide an insight into this question. The following sections detail the workshop data, the study context and the design problem.

6.2 Soma City Case Study and Background

On the 11th of March 2011, a magnitude 9.0 under-sea quake occurred off the Pacific coast of Tohoku in Japan. The epicenter of the earthquake was approximately 70 kilometers off the Oshika Peninsula of Tohoku. The earthquake is also known as the Great East Japan Earthquake and the most powerful earthquake ever recorded to have hit Japan and the fourth most powerful earthquake since modern record keeping began in 1900. It was so powerful that the earthquake moved Honshu, Japan‘s main island 2.5 meters east and trigged powerful Tsunami waves that reached heights up to 40.5 meters. Up to 15889 people died across twenty prefectures with 127,290 buildings totally collapsed. The earthquake caused severe structural damage across Northeastern Japan including heavy damage to roads, railways etc. In addition the Tsunami caused a level 7 nuclear meltdown at the three reactors in the Fukushima Daiichi Nuclear Power Plant. Residents in a 20 km. radius of the power plant were evacuated and the associated evacuation zones impacted hundreds of thousands of residents as is shown in the Figure 6.1.

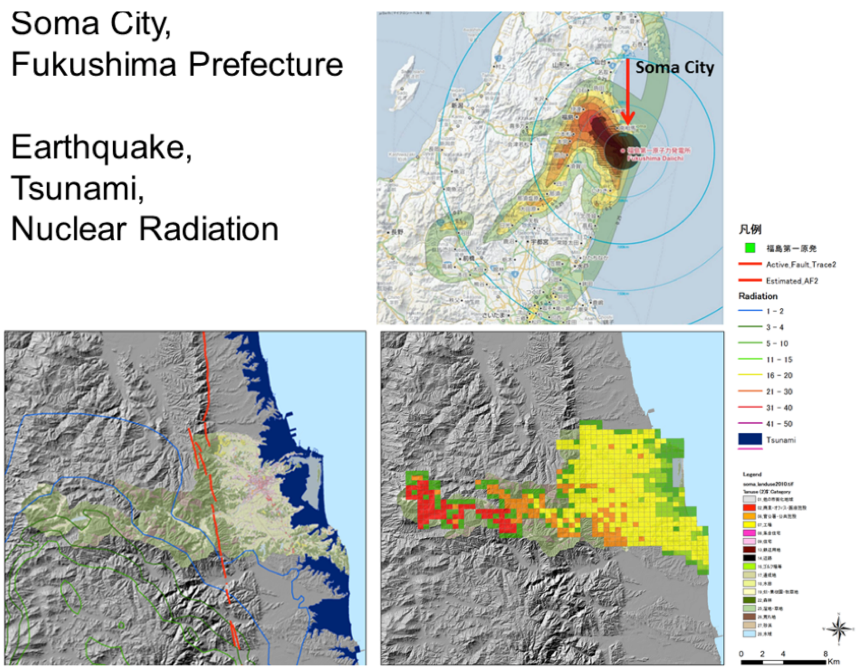


Figure 6.1: Tsunami, Earthquake and Nuclear Radiation in Soma City

Soma is a city located in Fukushima Prefecture about 45 km. north of Fukushima Daiichi Nuclear Power plant and suffered tremendously due to the earthquake and the resulting Tsunami. The eastern portion of the city was inundated with the floodwaters reaching up to 4 km. inland and causing death and destruction in its wake. [2011 Tohoku earthquake and tsunami, 2011] Figures 6.2 and 6.3 show some photos related to the disaster. The environmental disaster and the loss of life is of great concern and residents are sheltered in temporary prefabricated residences, a temporary Tsunami barrier has been rebuilt, some of the contaminated soil has been moved and there has been a restoration of electricity and basic services. Some people have returned to the city but a lot of young people have not.

The Mayor of Soma City requested faculty and colleagues at Tohoku University to organize a workshop to build a plan for Soma city and recommend projects and policies to restore the city to its prior condition and transform itself in the future. The Soma workshop was conducted during 27 February through 1 March 2013. All participants had previously visited the city, in most cases on the days immediately preceding the three-day workshop. The workshop was based on a mix of analog and digital models and extensive GIS modeling was used. The participants where students from Tohoku University, faculty and they were experts in GIS and other related modeling technologies.

Figure 6.2: Soma City Devastation and Temporary Tsunami Barrier

Figure 6.3: Soma City Inner Core and Temporary Housing

6.2.1 Representation Models

The main area that is of concern is the area around Soma City (Figure 6.4), the bay and the areas surrounding the city. There are traditional agricultural and historic landmarks and shrines near the city that need to be preserved in addition to the natural beauty of the area. The city itself is in the center of the geography and on the west inland are mountains and to the east is the ocean. Sendai, the largest city in the area, is also towards the North, Fukushima and the nuclear reactor is to the South. In addition, there is a North—South highway that also serves as an evacuation route. The forests and soil on the mountain side have been irradiated and are a NO—GO zone. There is extensive land use and land cover data that is available for the city and the region since they have been using GIS for a number of years.

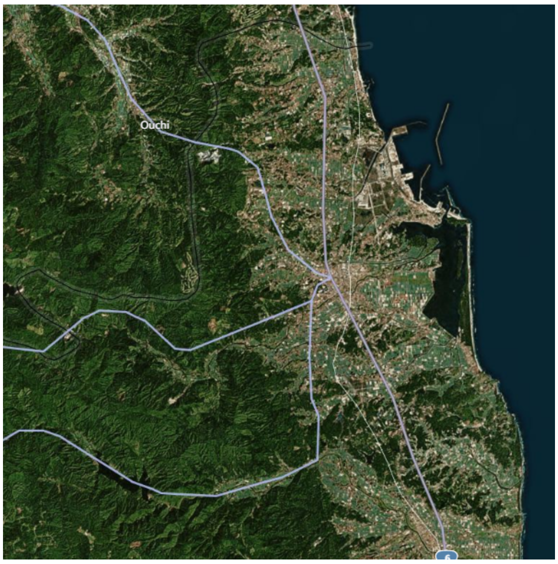


Figure 6.4: Geography of Soma and the Study Area, City Center in the Middle.

6.2.2 Process Models

On the first day of the workshop the teams were asked to identify major issues that would influence the decisions regarding the future of the city. This is the workshop setup step and the following ten systems were identified:

1. Ecology: The ecological and heritage quality relates to identifying the places and regions that have important natural, historical and cultural significance such

as farms, temples, places of ecological or natural beauty. The region is known for its forests and shrines and there is a deep interest locally to preserve that area and the traditional lifestyle. This is a vulnerability type system that identifies the most risky to the least risky areas.

2. Quake: The earthquake requirement relates to the identification of places that are at most risk due to an earthquake in the region. Typically these are the area where evacuation is most difficult. The area has suffered a massive earthquake recently as well so that gives a good indication of the riskiest geographies in the region.

3. Flood: This requirement is around identifying places that are most at risk due to flooding or a Tsunami. There are two rivers that drain into the ocean here and in addition, the recent Tsunami flooded a large portion of the coastline and damaged it.

4. Nuclear: The nuclear requirement relates to identifying places that are most at risk in case of another nuclear accident. The Fukushima Dai Ichi and Ni nuclear reactors that were compromised as result of the Tsunami and earthquake are about 70 kilometers of South of the geography. However, the forests and soils in and around the area are also at risk given that radioactive material is absorbed by these systems and stays there for a longer period of time.

5. Evacuation: This requirement deals with identifying places that are at risk of not being able be evacuated on time in case of a natural disaster like a Tsunami and floods where roads are a primary evacuation route on the land. There is a train station and a railway line as well that serves as connections but it is of no use during the earthquake etc. so we are considering the road network.

6. Replacement housing: This requirement is an attractiveness type requirement that deals with identifying places that are most attractive for housing families who have lost their homes because of the Tsunami and the nuclear disaster.

7. High Density Housing: This requirement is around finding suitable locations that are most (or least) attractive for high-density housing: detached housing or apartments. This might be most suited for younger population and the mayor has

identified that bringing in the young people into the town as a key priority of the city.

8. Low Density Housing: This requirement is around finding locations for low-density detached homes with gardens / garden farms.
9. Commerce: This requirement deals with finding suitable locations for neighborhood commerce and the central business district in the town. The key idea is to attract tourists and shoppers into the town since after the Tsunami and earthquake young people have not come back in to the town and it is a major problem for the Mayor and the town in the long term.
10. Industry: This requirement relates to ranking the most suitable places for the marine processing industry and other inland industries. Having local jobs is also a critical part of the future long-term economic sustainability of the town and involves repopulating the town center.

These are the ten major physical, ecological and human processes that were identified as being important to the study area. Of course there are many other systems that are at work in the area. However this selection constrains the design problem and also puts structure into a really complex problem.

To summarize, there is a need to conserve some of the natural, cultural beauty in the area, in addition to addressing concerns around evacuation, flooding and nuclear accident risk. There are areas inland that are irradiated and need to be addressed. In addition, housing commerce and industry needs to be allocated suitably to ensure people are coming back and having jobs. Ten teams were created and assigned to each of these ten systems and given a task to produce a GIS process model, an accompanying evaluation model and an impact model that would be used to determine the performance of the designs.

6.2.3 Evaluation Models

The evaluation models are visualized on a five-color scale. For the two types of systems, the color scheme is as shown below in Figure 6.5 for the attractiveness type requirement, the areas in red are the areas of lowest attraction or the highest risk and the areas in green are the highest attraction or the least vulnerable. The teams used standard GIS modeling techniques to produce the maps and they are shown below. Most of the participants were advanced GIS students and were familiar with the key techniques and software operations of modern GIS packages. (Figure 6.6 for all of these maps) The following details the key consideration for each of these evaluations, starting with the "vulnerability" type requirements:

Figure 6.5: Color Scheme for the Attractiveness Type Requirements (left) and the Vulnerability Type Requirements (right)

1. Ecology: The ecological heritage quality requirement was developed by judging the distance a particular area is with respect to forests and or cultural sites nearby. If there exists forests or cultural sites nearby, the area is judged to be red and then it is at a highest risk while a green area is at a lower risk. This analysis was conducted on the dataset of existing land use provided by the City Mayor.

2. Earthquake: The earthquake risk was judged by assessing the distance from the major geological fault lines in the region, the weakness of the ground and the slope of the terrain. The areas in green are the lowest risk and the ones in red have the highest risk.

3. Tsunami and flood: The Tsunami and flood vulnerability was computed by aggregating two different measures: distance from the coastline, the altitude and the size of the Tsunami, while for flooding, the risk was calculated by using the landform classification and the distance from the river.

4. Nuclear Radiation: The nuclear map was computed by exposure in terms of microSievert /year with the forests and the soil by the mountain being classified as the highest exposed.

5. Evacuation: The evacuation map was computed by doing a network analysis of percentage of people in a safety zone within five minutes.

For the "attractiveness" type requirements the maps were generated with the following analysis:

1. Replacement housing: The evaluation map for replacement housing was generating by putting a weight on how far a location is when compared to convenience to school, welfare medical and welfare facilities. This weight estimates the preference of residents to the housing.

2. High Density housing: The attractiveness of high density housing is determined by the walking time to the train station and bus stop and the walking time to the hospital and elementary school.

3. Low Density Housing: The attractiveness of low-density housing was computed as a hybrid measure of convenience, surrounding environment and land price.

4. Commerce: The commercial requirement was computed using a model that takes into account the distance from Soma Station, the population the vicinity of the ring road and accessibility of the ring road. These factors were used to construct an attractiveness map

5. Industry: The industrial attractiveness map was calculated by assessing the distance to key transport routes for inland industry and closeness to the shore for the marine industry.

6.2.4 Decision Model

The chief planner of Soma City Mr. Tadano Soichi was asked to rank the importance of the ten systems to the people of the area. This was accomplished by his assignment of 50 small magnets to the list of concerns, and his judgment was accepted as the basis for the decision model, thus in this case a single person devised the decision model and this was used in the entire workshop.

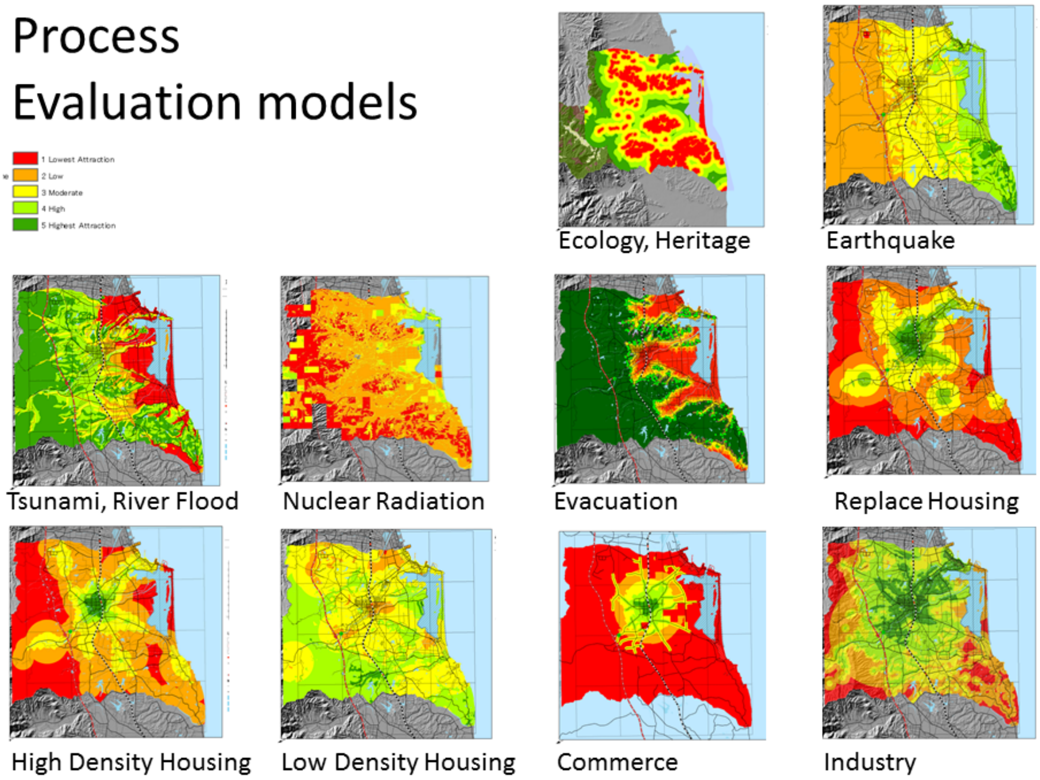


Figure 6.6: All Soma Evaluation Models

6.2.5 Change Models

After the assessment maps were created, the teams then designed recommendations that could mitigate or improve the state of their processes. These would be handdrawn, colorcoded diagrams on clear plastic and numbered in the rank order with which they are recommended. Figure 6.7 is a sample of the diagrams, their photos, and text and description are below. These are scanned copies of individual diagrams and their translated descriptions are below.

Figure 6.7: Change Diagrams (left) and Diagrams Displayed on a White Board for review. (right)

On the second day of the workshop the participants were organized into six change teams organized on different primary objectives and they were:

1. TREND: The primary objective was to forecast land use change with no policy changes and no relocations
2. RPLAN: Elaborate existing restoration plan by the city
3. SHRINK: Smart shrinking towards a compact city
4. TRAD: Maintain traditional lifestyle
5. SUBCEN: Maintain population by attracting new industry and creating a sub center
6. COMMUT: Maintain population by attracting commuters to the Sendai Metro area.

Change teams used the constraining and combinatorial method to build their initial designs by selecting about 10 -15 of these diagrams. The teams were instructed to use the appropriate diagrams that satisfy their policy change objective. The way to do this is to select the different diagrams of plastic sheets, make a "sandwich" by overlaying them on top of each other, and taking a photograph of this. These designs would then be geo-referenced and digitized for use at a later stage of the workshop.

6.2.6 Impact Models

Once all the teams had a set of designs they were digitized and assessed for impact by the ten process models. The process is the same: each design was overlayed on the more attractive or less vulnerable locations, after which a second iteration was carried out on the designs and tested for impacts. The change designs were compared across all the ten impact models as shown in the Figure 6.8 below. Finally the designs were presented to a broad audience of faculty, students, participants and representatives for Soma city for review in the form of detailed presentations. Experts from different fields who had personal experience of working in the area and knowledge then evaluated the designs.

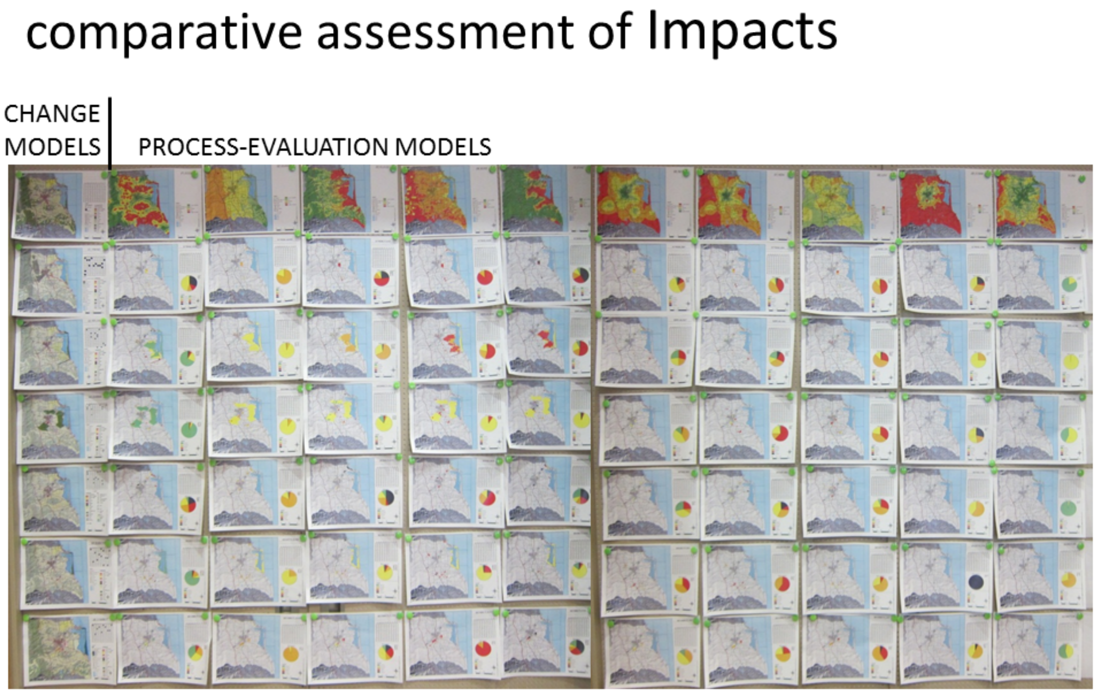


Figure 6.8: Comparing Six Change Designs across Ten Systems for Impact.

6.3 Observations and Change Synthesis Workflow

This workshop is an application of the framework in a partially-digital environment. The process models and evaluation models and maps were built by computers and GIS and then the actual process of design synthesis was conducted in an analog fashion using transparencies, overlays and the impact assessments again done in GIS. Digitizing the design synthesis portion would enable a fully digital end-to-end geodesign worlflow in a way that is not being done to date. This new digital workflow will consume GIS analysis and data and outputs a design that can be used in different software packages. As discussed in the previous chapter and demonstrated in the Lisbon case study, the key actions that need to be taken by the user in this environment are:

1. The users need to add a diagram
2. The users need to edit a diagram once added
3. The users need to re-rank a diagram

4. The users need to select a few diagrams for synthesis
5. The users need to compute the impact of their selections
6. The users need to be able to save a set of diagrams as a design
7. The users need to be able to go back to the design and make changes and save as a new version.

Using this data and the specification documentation mentioned in Chapter 5 a new tool was built. In the following sections, key user interface features are documented in addition to results of experiments carried out with the tool on the Soma workshop data.

6.4 Tool Introduction

A web based tool was built that implements the specification mentioned earlier. The Geodesign Study tool can be accessed through www.geodesignstudy.com and it is an application written in Python. The site can be accessed using all modern browsers and also supports mobile and tablet—based browsers. All interaction is controlled using touch or mouse—based input depending on the method the site is accessed. Once the user logs in they are presented with two screens: Diagrams and Compare. The tool uses modern web technologies and support import of open data to build diagrams, synthesize them and perform analysis across different synthesis. Users can collaborate to build the diagrams, decision models and synthesis in real-time using standard off the shelf hardware such as laptops at a relatively low cost with all the advantages of a web-based environment. Primarily, the tool is to be used in a workshop setting in conjunction with the Steinitz Framework and the geodesign workflow.

The key aim of the tool is to enable affordable world-class geodesign workflow for simultaneous design and analysis for regional sized problems. The goal of this tool is to enable experiments using the technology to test the geodesign framework and identify areas of further research. Using the tool the users can conduct advanced impact studies, cost modeling and other performance measures on their designs.

The advances in browser and web technology offer the ideal opportunity for users to interact with an intuitive interface. The analysis and calculations are performed on a webserver and the associated data stored securely in the cloud in a PostGIS enabled GeoDjango database doing the spatial computations. OpenStreetMap provide the mapping layers and map tile information in the tool.

The tool is built using modern web technologies and by designing the decoupled modular database and storage structure, the architecture is robust and scalable and has no single point of failure. After logging in, the users use the Diagrams screen to build the diagrams and synthesize a design and they use the Compare screen to analyze the synthesis that built. For a thorough review of the backend and frontend modules and objects, please refer Chapter 5

6.4.1 The Diagrams Screen

Figure 6.9 below details the diagrams screen. It is the first screen that is displayed once the user logs on to the tool and joins the project. With a focus on minimal controls and inputs, there is a grid-like interface that has three main sections: The Assessment Maps, the five-color maps that show the performance of different systems as a map of three colors. The second section is the diagrams section that is also in a form of a grid on which the individual diagrams or partial design ideas are added. The user can explore multiple diagrams simultaneously, add / edit diagrams to the grid and in addition to seeing diagram descriptions, expanding the diagrams etc.

When a user adds a new map, a blank canvas is loaded on their screen on which they can draw their design idea that can be a project or a proposal. The user draws these features by the simple sketching and editing tools that are provided with the application. There are basic tools to draw, polygons, lines or points that represent one-hectare land use. These features are stored in the backend and the metadata information is also stored for use and analysis later. Users can build a number of diagrams using this simple interface and see them simultaneously on a screen. Using these basic and simple controls very quickly, quite complicated diagrams can be built with as is highlighted in the case study below. Once diagrams are built, the next step in the workflow is to select a few of them for synthesis and analyze them for performance over multiple systems

Additionally, the tool provides basic customizations such as setting colors, notifying people joined the project about actions on the grid and also plotting the impacts of

Figure 6.9: Diagrams Screen with Different Diagrams

various selections on the assessments. In addition there is a way to show decision models and set priorities over different requirements by the members of the team.

6.4.2 Diagrams Screen User Interface

The primary goal here is not to develop the most suitable or appropriate interface, the idea here is to build an interface that adequately supports the basic actions that are needed to perform design synthesis. In the following section, the user interface screens are described. These screens enable the basic commands and user actions that are identified in the previous section.

6.4.3 Adding a Diagram

1. Step 1: In the “Diagrams” page, click on “Add a diagram” link. (Figure 6.10)
2. Step 2: Select a requirement under which the diagram will be added. (Figure 6.11)
3. Step 3: Finally, enter a small description for the diagram, this description should

reflect the content of the diagram and is shared with everyone. (Figure 6.12)

4. Step 4: Once Add Diagram is clicked, the diagram will be added to the grid in the appropriate requirement column. In addition everyone will see a map with green border. This way participants of the workshop will know that a diagram is new. (Figure 6.13)

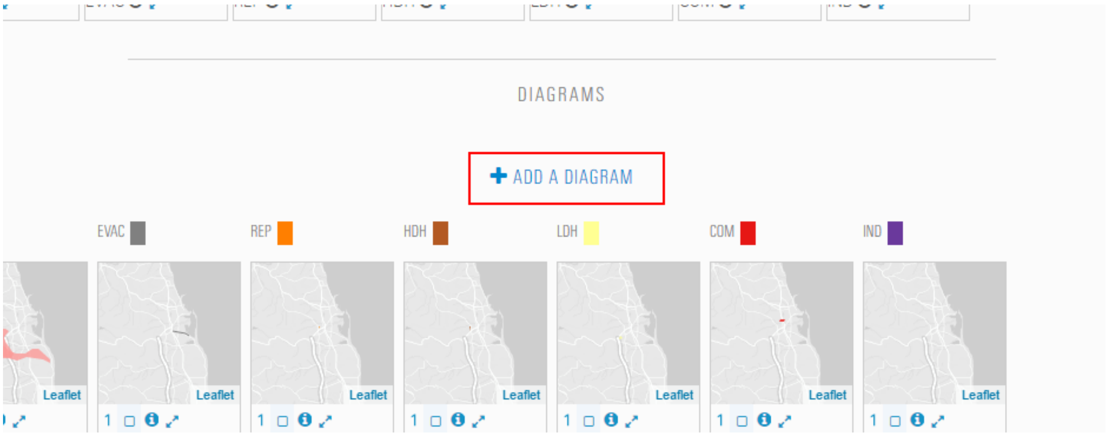
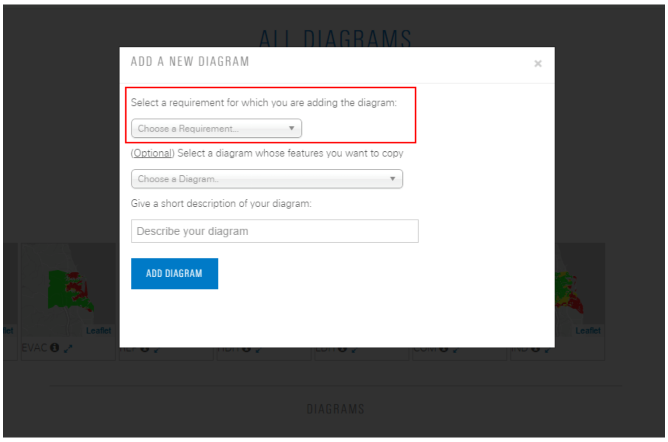


Figure 6.10: Add a Diagram



Select a requirement for which you are adding the diagram:

(Optional) Select a diagram whose features you want to copy

Give a short description of your diagram:

Figure 6.11: Add Diagram Details

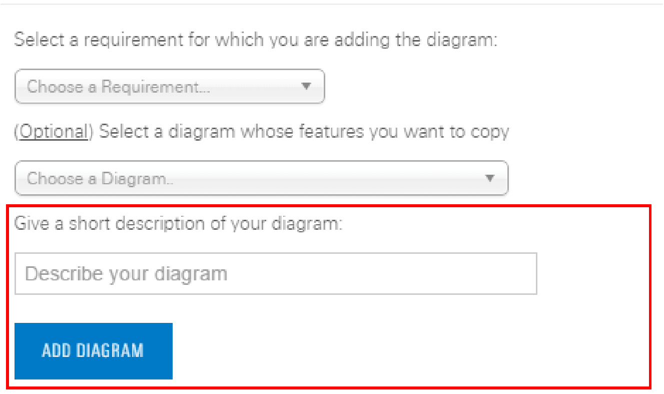
6.4.4 Edit/Add features in a diagram

1. Step 1: Enlarge a diagram. (Figure 6.14)

2. Step 2: Once the diagram is enlarged, click Edit. (Figure 6.15)

3. Step 3: A menu will appear on the right. (Figure6.16)

4. Step 4: Click on the polygon



Select a requirement for which you are adding the diagram:

Choose a Requirement...

(Optional) Select a diagram whose features you want to copy

Choose a Diagram...

Give a short description of your diagram:

Describe your diagram

Figure 6.12: Add Diagram Description

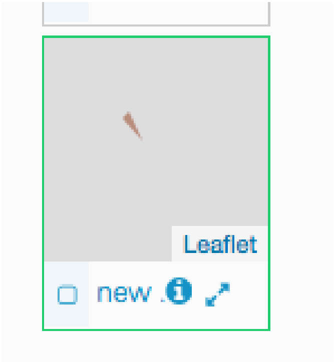


Figure 6.13: New Diagram Added

5. Step 5: Choose a polygon to draw and complete drawing. (Figure 6.17)

6. Step 6: Once edits are complete, Save. (Figure6.18)

Figure 6.14: Enlarge a diagram

6.4.5 Synthesize a design

This section demonstrates how complex designs can be synthesized using simple diagrams digitally. The designer is expected to review all the available diagrams and

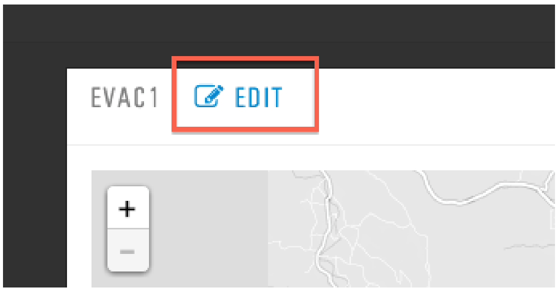


Figure 6.15: Edit Enlarged Diagram

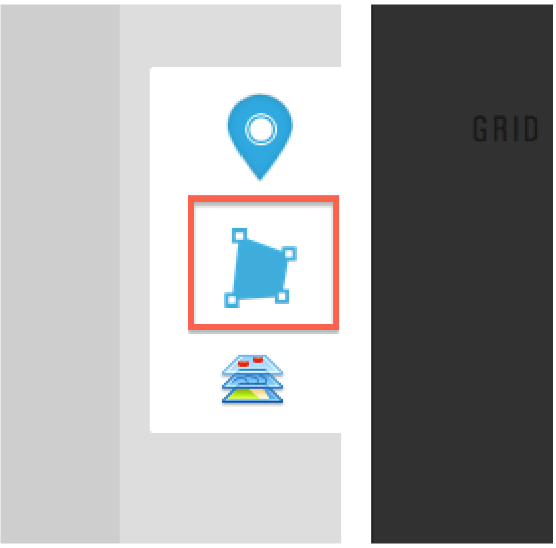


Figure 6.16: Edit Diagram Menu

understand the key elements within them. Then the designer must pick and choose individual diagrams from the set that best fit their design idea and their “client”. In the workshop, all the diagrams created by all participants are available to be selected. The designer can collaborate, ask questions, make modifications to the idea and select the diagram that they prefer. (Figure 6.19)

1. This “selection” of a diagram for addition to their design is enabled by checking the selection box. (Figure 6.20)

2. Once the diagram is selected, the user can see the diagram in the changes map and also in the list of selected diagrams. This changes map is the composite map of all the selections in a design. (Figure 6.21)

3. The selected designs are also shown in a grid. The rank and the requirement of the selection are shown in the grid. The user can hover over the grid to show the details of the diagrams selected. In this way any number of diagrams can be

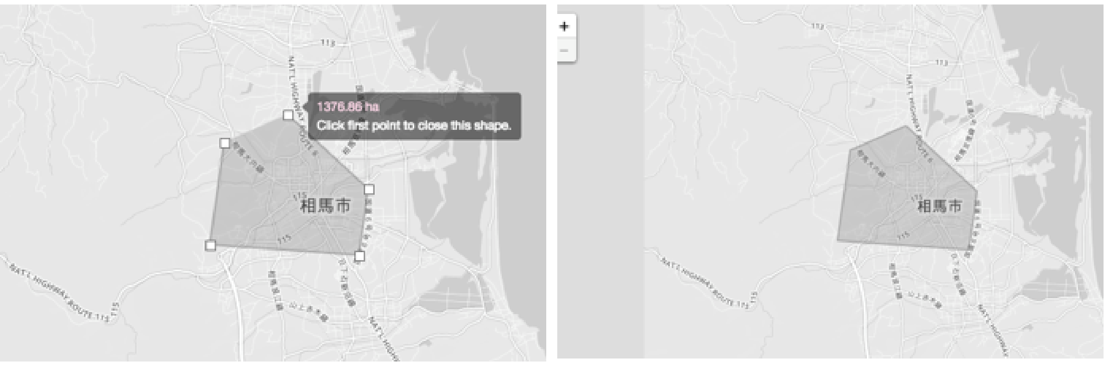


Figure 6.17: Drawing Feature

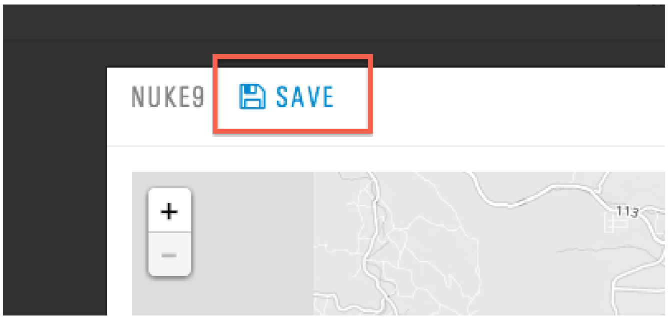


Figure 6.18: Save Feature

selected. (Figure 6.22)

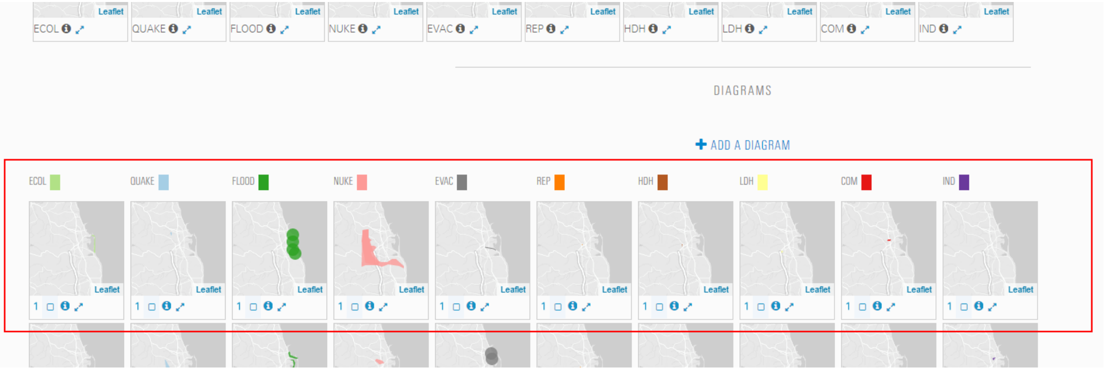


Figure 6.19: Diagrams Grid

6.4.6 Impact Calculations

Impact calculations were described in detail in Chapter 5. Here the user interface is demonstrated to show how these impacts can be calculated.

The evaluation map, the diagram and the two together and their intersection are showed in Figures6.23 and 6.24. It is seen that the diagram overlaps the “green” area of the assessment. The green area means: low risk / high attraction. If a polygon falls

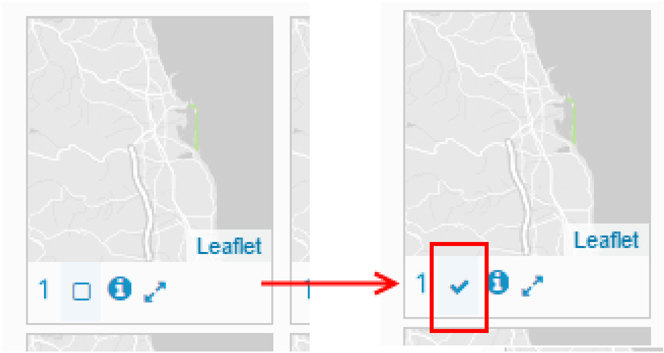


Figure 6.20: Select a diagram

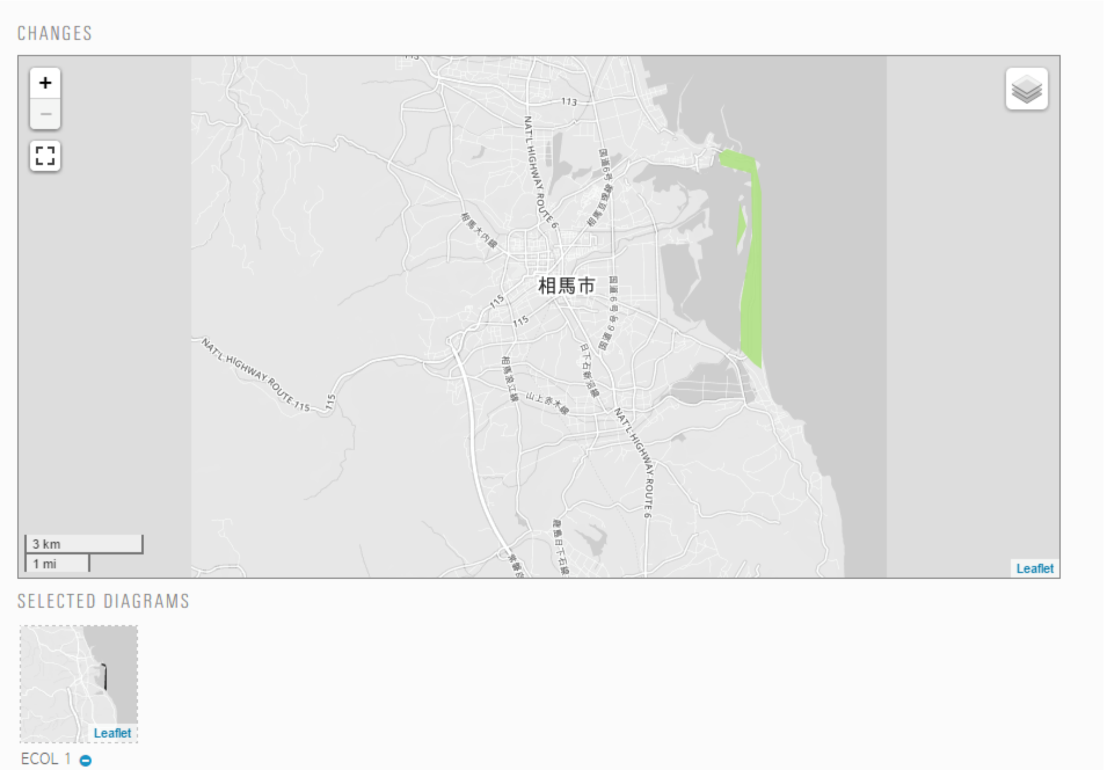


Figure 6.21: Diagram Appears

under the green area it means for that requirement there is low risk and high attraction and probably it is a good policy or project. This way intersections are then aggregated to show the cumulative impacts split by the requirements.

This impact analysis can also be done for multiple diagram selections and the synthesis itself. Once a set of diagrams has been selected , the users can click on the “Compute Impacts” button as below to see how the design performs against the different assessments. The process sends this information to the server and the users can visualize the performance of their design in realtime. (Figure 6.25)


DESIGN GRID

ECOL	QUAK	FLOO	NUKE	EVAC	REP	HDH	LD
1 1							

Figure 6.22: Selected Diagrams Grid

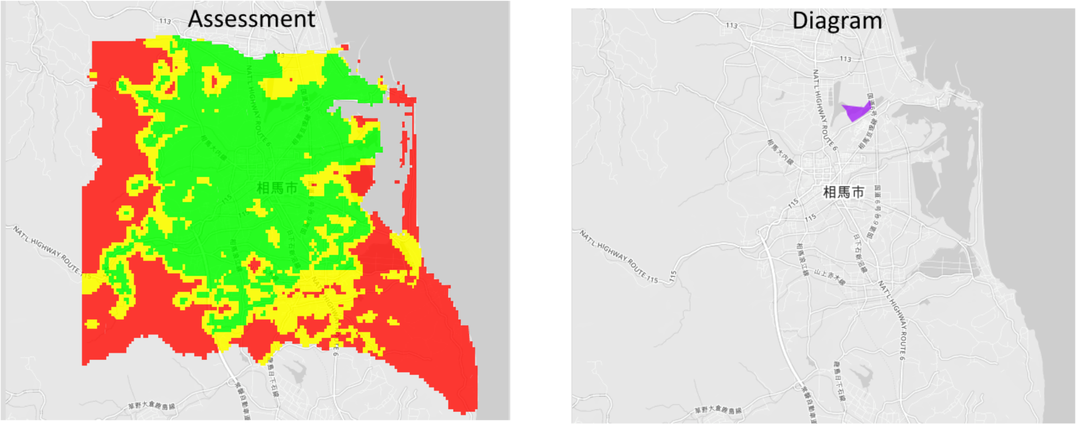


Figure 6.23: Impact Assessments and Diagrams

6.4.7 Understanding Impact Calculations

Once the user presses the Compute Impacts button (Figure 6.25), the diagram and evaluation information is sent to the server for processing. The processing time depends on the diagram and evaluation layer complexity and it may take between 15-40 seconds to perform these computations. Once the computations are complete, the user is presented with a series of charts and maps to show in detail the performance of their design as shown in Figure 6.26. The goal of impacts analysis is to analyze the performance of the design selections against all the systems. The following section details the individual impacts type and the data.

Target vs Achieved This is the first chart, Figure 6.27 details the target for the requirement (set by the administrator). A target is usually a land use target that needs to be met in a design. For example 50 ha. of high density housing is a target and that needs to be met through the different diagram selections. When the user selects diagrams, the tool adds the land use information from that diagram to show the total target. The user

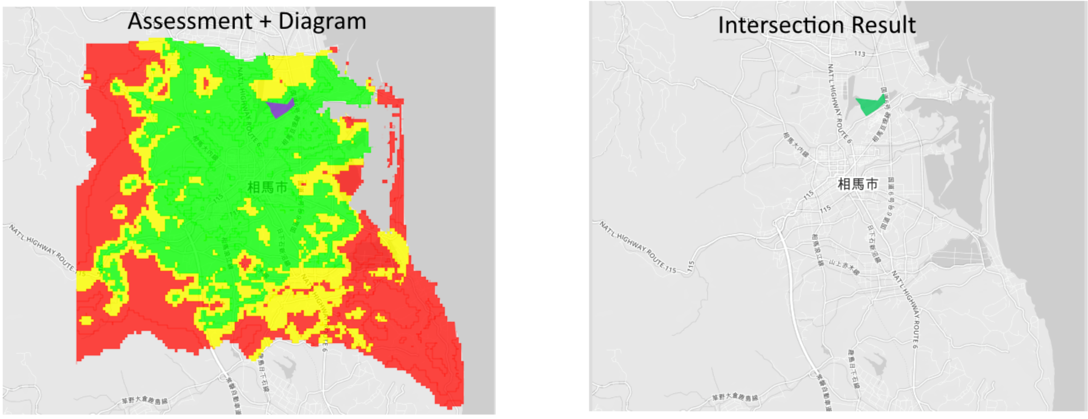


Figure 6.24: Impact Intersection and results

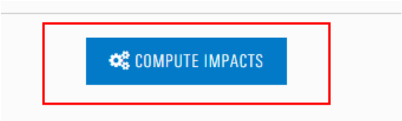


Figure 6.25: Calculate Impacts

can edit existing diagrams or add new diagrams to make sure that you are as close as possible to the target.

Self Impact In this chart the user can see the impacts of the diagrams selected under a requirement on itself (Figure 6.28). If a requirement has an assessment map, the diagrams selected in the synthesis that fall under the requirement will be assessed for impact. The impact is a simple overlap of the diagram over the red, yellow or green of the assessment. For example if the user selects a diagram, the tool will look up what requirement the diagram falls under and then execute an intersection analysis to show how this diagram performs against the assessment. If there are multiple diagrams selected under a requirement, they will be aggregated together and the impacts shown on the map. The self-impacts are shown in a chart format in Figure 6.29, where there are two ways to show any data in the system, in a map or in a bar chart. It is shown in a chart here, the area is exactly same in red / yellow / green format as is shown on the map.

Impacts across requirements This map is the cumulative impacts map (Figure 6.30)and it shows the impact of all the diagrams selected in the synthesis on a particular requirement. This calculation takes into account all the designs that are selected and evaluates the impact of those designs on the requirement. It will give a good sense of how good a design (all the diagrams selected) performs for a particular requirement.

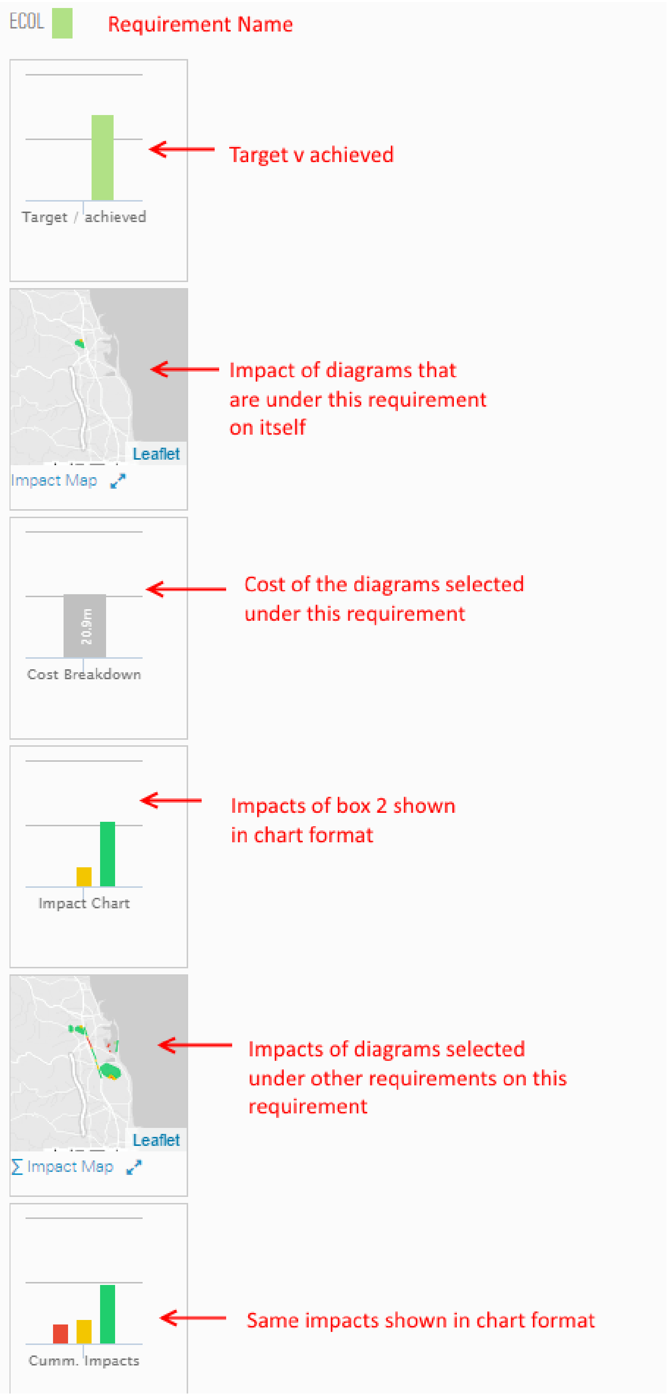


Figure 6.26: Impact Calculations Summarized

If there are a large number of red areas, it means that the design is not satisfying this requirement well. There will always be tradeoffs and this way you can see the performance of your design. Information about this is also shown in a chart format (Figure 6.31).

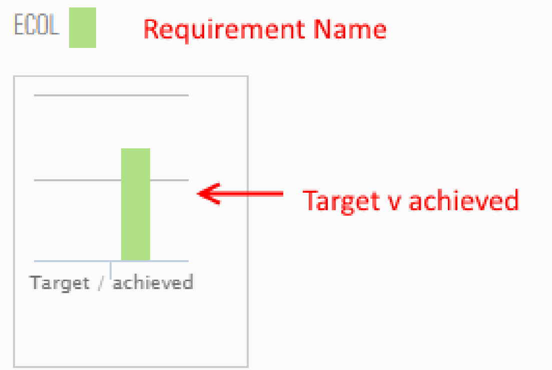


Figure 6.27: Target and Achieved

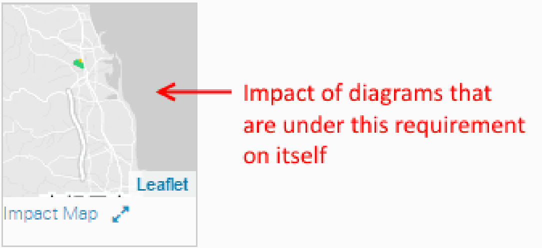


Figure 6.28: Self Impact

6.4.8 Compare Screen

Once a synthesis is built and saved, users can compare different syntheses created by using the compare screen. The software enables three different ways of comparing (Figure 6.32):

1. Comparing impacts of the synthesis
2. Full design overlay
3. A frequency count of diagrams.

There is also a provision to navigate different versions of a synthesis and understand the progression of a design from a comparison and impact point of view.

Comparing Impacts This involves map of all the designs selected overlaid on a basemap. This is the oldest type of comparison that has been used in non-digital workshops. Here the idea is to construct a purely visual way to compare different designs. The more muddy the color, the more there is a difference of opinion on what should happen to the area. On the other hand, primary colors indicate

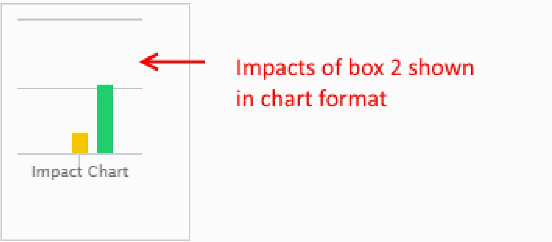


Figure 6.29: Self Impact in a Chart

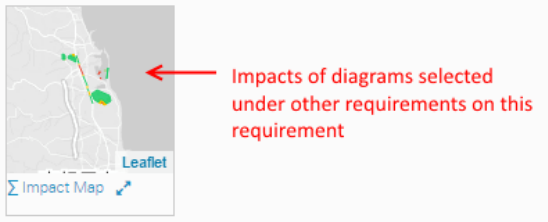


Figure 6.30: Cross Requirement Impacts

that there is agreement among the participants on what should happen. This technique is a very nice and simple way to compare agreement / disagreement between different teams.

Full Design Overlay The second way in which the compare page analyzes design is around computing the impact of the design, when a design performance is calculated as a measure of its impacts on the red or the green area of an assessment map. Thus the designs with more overlap in the red area as compared to green would perform worse. This way is a bit more of an objective method but does not guarantee good design selection since the overlaps can be gamed at a certain level.

Frequency Count of Diagrams Finally the compare screen also enables comparison of different diagrams by frequency count. The number of times a diagram is selected across all the designs is an important measure to judge the popularity of a diagram. All of these calculations are done in real-time on the server.

6.4.9 Miscellaneous Comments

The ability to build diagrams quickly and analyze them, synthesize the design and then compare the synthesis form the core of the system and indeed it is the crux of the geodesign workflow. The average time to build and add a diagram is in seconds. The tool presents this information to decision makers and participants in a way that is easy to

Figure 6.31: Cross Requirement Impact Chart

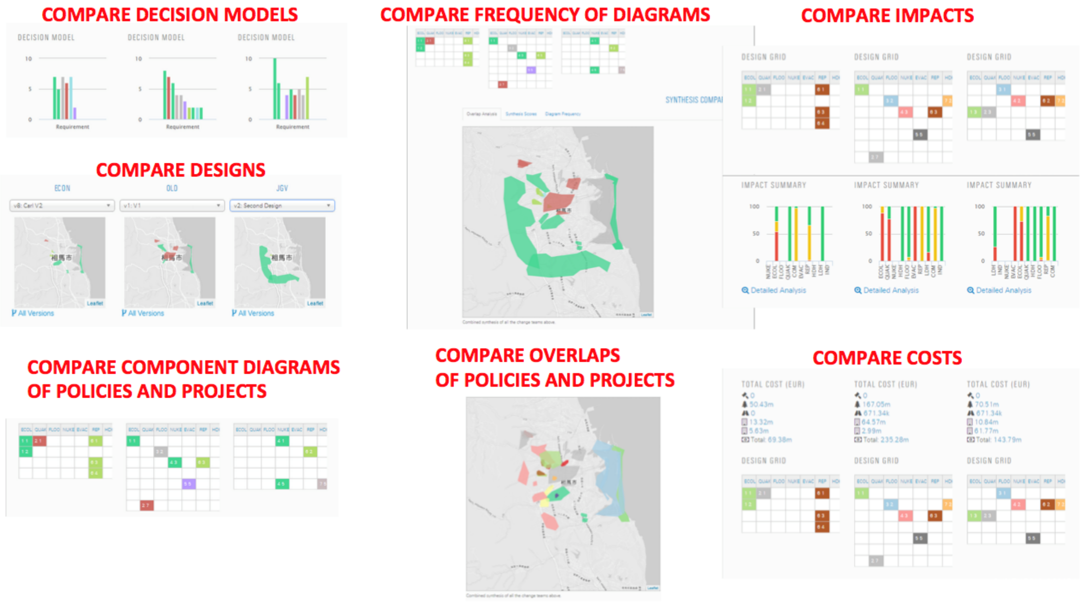


Figure 6.32: Compare Screen

understand. Since this is the first time that the geodesign workflow has been converted in to a digital form, data from the Soma workshop described above was used to conduct a series of four experiments to finalize the workflow and iron out the bugs. Finally the experiments concluded with a workshop conducted at the University of Georgia as an independent case study to prove the performance of the workflow to produce designs on a real world problem starting with no prior data preparation work. All the data that are generated and stored on the tool can be downloaded for use with other tools such as Shapefiles or GeoJSON files.

6.5 Experiments and Results

The digital form of the workflow was tested in a number of workshops starting in July 2014. This section details the various experiments that were conducted with the workflow with different audiences. The core objective of the experiments was two fold:

1. First to put the workflow in a real world stress test and see how it performs in

a non-linear design process and if indeed workshops similar to the Lisbon and Soma documented in Chapter 4 and Chapter 5 would be possible.

2. And secondly to gather feedback on what is working and what is not from a technology and interface point of view thus understanding the important characteristics of a digital environment.

Four experiments were conducted in July, September, October and November 2014 using a single dataset—that of Soma. The test involved advanced students, faculty, senior researchers and professionals from different universities. The change model synthesis process that was carried out in an analog fashion at the Soma workshop was tested in a digital format. In these tests, the evaluation models and the change models were inherited from the Soma workshop in the form of shapefiles and TIFF files. Along with this data that was received from the colleagues in Japan, other supplementary data such as base maps, the evaluation models and the scanned copies of the change diagrams was also received. The change diagrams were digitized by hand and were entered into the tool so that users logged on could see the diagrams and compare page.

At the beginning of the workshop, the participants were introduced to the screens in the form of a short video and presentation. A short tutorial on the tool and key actions were demonstrated to the users, the participants then familiarized themselves with the diagrams and the data, after which the participants were separated into six different change teams. They were:

- Soma Local Government: The local government of Soma city needs a plan to rebuild the city and revive the economy.
- Japanese National Government: The national government needs to respond to the natural disaster and the failure of the nuclear power plant. It has to undertake one of the largest cleanups in modern history after the disaster.
- Property Developers: There is a need to build new housing after the Tsunami and the nuclear disaster. Property developers can help in building housing and generating local jobs.
- Older people: Older people are primarily interested in maintaining and preserving the traditional lifestyle and heritage of the place.

- Young people: Since the disaster, a lot of the young people have left the city and the city and it has a skewed demographic. Young people need jobs, things to do, shopping / sports etc.

- NGOs: Japanese public support remains strong for environmental protection, conservation and renewable energy. A poll in June 2011 by the Asahi newspaper found that 74 percent of the public was in favor of abolishing nuclear power after a phase-out period.

The participants in all these workshops were asked to take the personas in their change team and construct a decision model that suits their interest group. Then the participants were asked to collaborate amongst themselves to produce a design. Finally the designs were compared and discussion took place after the workshop. The participants went through a design process and were asked to provide feedback on the screens, ease of use, complexity and data provided. In addition the users were asked to fill out the user impressions questionnaire that asked the users about the over all impression of the workflow, the things they liked / disliked, and other feedback.

The workshops helped in fine-tuning the code base and also in conducting innovative experiments that a purely digital workflow enables. The workshops were able to push the limits of the geodesign framework by adding people and having teams work remotely from different places.

A standard structure and format was pursued for the workshops:

Time	Content
09:30 10:00	Personal Introductions
1000 1100	Carl Steinitz: Description of Study Area and Organization of Workshop.
1100 1130	Hrishikesh Ballal: Overview of the tool and demo: Synthesis and comparison.
11:30 12:30	Form Process evaluation teams review diagrams, create new ones.
12:30 13:30	Lunch
13:30 14:00	Process Teams Build Decision Models

14:00 14:30	Synthesis: Change Version 1
14:30 15:00	Assess Impacts of Change Version 1
15:00- 15:30	Revise to create Change Version 2
15:30- 16:00	Assess Impacts of Change Version 2
16:00 16:30	Conclusions and Debrief.

For some of the workshops, the schedule was compressed even more with the entire workshop being finished in three / four hours. This was the case specially for the internet versions.

Figure 6.33: Workshop 1 at UCL 24 July 2014

6.5.1 Experiment 1

The first real test of the workflow was held at UCL CASA on July 24th 2014 (Figure 6.33). The main participants of the workshop were colleagues at the Center for Advanced Spatial Analysis and a couple of colleagues joined from Free University of Amsterdam, the workshop was held at a lab within University College London. Participants used lab computers to join and use the workshop data.

Participants in the workshop were able to draw diagrams although the drawing tools were primitive; they were able to select designs for synthesis and draw diagrams. The workshop started per schedule and there were issues around saving designs for synthesis. After the workshop, the participants were asked in a survey format the key pieces of feedback on the user interface and what they thought was missing from the tool. The participants really liked that all the diagrams were on one screen and that the interface was clean and simple. The reaction to the excessive scrolling was mixed with some participants not minding it. A few asked for advanced drawing tools since they were experts in GIS. Given that this was the first workshop, there were a number of areas that needed improvement and the following are some of the key ones that stand out:

- Loading time: The tool was very slow and needed a lot of time to load the data. The main feedback from this workshop was to speed up the loading time and make the tool more responsive. Because of the slow loading time, there were complaints of not having enough time for rapid progress.
- When diagrams were selected, they were not remembered on the server so participants had to reselect all the diagrams in case of screen refreshes.
- There was not enough context or training provided for participants to understand the data, since the data and diagrams were inherited from the colleagues in Japan and given that we had relatively little time, this was a common complaint.

Since this was the first test of the workshop, it was a difficult one from both the data and diagrams point of view as it was the first time that the data was digitized and the evaluation maps handled. In addition at this workshop, there was an issue in the workflow. The creation of synthesis was problematic so the workshop had to be cut short. Following this workshop the following key changes were made to the implementation:

- Implemented a better pairing and data processing and analysis system at the backend so that the impacts and other processing time was reduced.
- Implemented a user selection module that stores users selection of diagrams so that users do not lose their selections once they refresh or reload the page.
- A better initial training and user tutorial was built so that participants could understand the key systems, user actions. A video tutorial was also made that the participants could access at any time for future reference.
- In addition several improvements on performance, and particularly screen load times were implemented at the front end and on the server.

6.5.2 Experiment 2

Figure 6.34: Workshop 2 Geodesign Summit Europe, Delft September 2014

The second test of the workflow was conducted at the European Geodesign Summit on September 10th 2014 in Delft, The Netherlands (Figure 6.34). Participants were again invited to a daylong workshop one prior to the conference event and followed the same structure as the first workshop: the data was inherited from the Soma workshop and participants were formed in teams and were asked to do a design synthesis for their change team following their agenda and decision model.

The workshop went satisfactorily and the participants could build do the basic tasks described above: to add a diagram, the edit it and build a design synthesis and then finally compare different synthesis at the same time. The participants were in the same room and the teams were on different tables sitting together, everyone had their laptop and were connected to the workflow using their own hardware. They went through the process of the design selection and created one or two versions of their design and finally these designs were compared.

Overall the feedback was overwhelmingly positive including good feedback on the training improvements. The improved training meant that the tutorial was “live” and users followed a PowerPoint deck in “show and tell” fashion that the participants could act interactively and simultaneously. Also included in this workshop was a rudimentary cost model that computes the cost of a design as it is being built that was useful and got good feedback. However, following are the key challenges that participants bought out:

- The server was too slow to refresh. There was no syncing capability, so participants had to refresh their page to load new data on their screen and the wait times depended on how many were requesting the data from the server. There was a large delay in getting the data on the screen, and participants were shown a “loading” screen.

- Another major piece of feedback from this workshop was that the editing and the selection screens were separate. There was a separate editing screen and the participants had to navigate to a different page to do the selection for synthesis. This was a navigation issue that needed to be fixed.

- The final piece of feedback was around the understanding of impacts and the impact maps. Participants found it difficult to understand the various impacts and impact maps sometimes refreshed without any user action leading to confusion.

- Users mentioned that they could not identify who had added the diagram. In addition, there was feedback on clarifying the definitions in the tool since they were unclear to users.

While the over all experience of the users was positive from this workshop a couple of key points became apparent: the editing screen and the selection screen needed to be combined so that the workflow would become seamless and there would be less page navigation between different elements. This was a large undertaking since editing and creation of a diagram is a very complicated process and needed to be re—thought. The second key change that was decided was to reduce the data load times even more by doing re—architecture on the server so that clients were always connected in real time to the server and communication was live and synchronized. This is a huge task technically since the server then has to maintain several connections simultaneously and additionally synchronize data and changes very quickly.

Figure 6.35: Workshop 3 CASA UCL October 2 2014

6.5.3 Experiment 3

The third workshop test using the data was held at UCL CASA on October 2 2104, with the same participants that attended the workshop 1 (Figure 6.35). However, this time given that the changes were made to the workflow the participants, instead of being in a same room, were asked to be on their respective desks in their offices. In addition, participants joined in from Amsterdam and Oxford. All of the participants were either Masters or PhD students in the planning field with a number of years of experience with urban design. Communication and training and were organized via Skype and there was screen sharing using Skype. This was a very novel experiment with participants using standard hardware and a freely available communication platform to co-ordinate making a design. The change teams module was tweaked so there were now coordinators for each change team who then worked on a separate Skype group chat along with the main channel with all participants.

This was the first time to do training and introduction of the data and workshop methodology over Skype but the response was broadly as positive, participants could understand the methodology and the introduction. They were able to add, edit diagrams and also able to do synthesis and save their designs. Communication over Skype went well and there were no crashes. Some key pieces of feedback:

- Skype quality was sometimes problematic with some participants a bit nervous initially the roles were not clear but this was to do with my training and introduction.

- Participants requested better logging of actions on the tool since given the distance they were not sure who performed what action and it was difficult to keep track of the changes.
- Participants also requested that they be able to share their selections to their teammates.
- The diagrams were too small to see the features and the users wanted to copy/paste between diagrams. The small size had to do with the limited screen size

The participants agreed that training was needed for the tool but the recommendation was to shorten it even more from 20 minutes to less than 10. In addition, the overall feedback was that collaboration over a distance is difficult and not ideal and in this case the workshop was even shorter than the original scheduled. In a distance workshop setting, the shorter the workshop, the better it is for the participants joining in remotely. This is one of the key learnings from this workshop. When done remotely or over a distance, the workshop and the frame—work has to be compressed and the participants need to move quickly between the different stages.

6.5.4 Experiment 4

The final test in this series with the Soma dataset was carried out on at the end of November; in this case the intention was to do design synthesis over the Internet across a very large area to see how this workflow can be extended. (Figure 6.36 and Figure 6.37) The participants included very senior academics in Japan who had provided the original dataset and teams based in London, Lisbon, Boston, Amsterdam, Beijing, Hong Kong and different parts of Japan spanning 11 locations and 9017 miles (figure below). Just like all the previous experiments, the participants were given an introduction and a tutorial about the problem and the change teams. In addition a condensed tutorial over the Internet about the key software functions described above was given to the various participants. The participants then used Skype to collaborate using audio, video and screen-sharing. The workshop lasted for about three and half hours and participants were able to add diagrams, edit existing ones, create a design synthesis and also compare the first version of the design amongst each other in near realtime across large geographical distances.

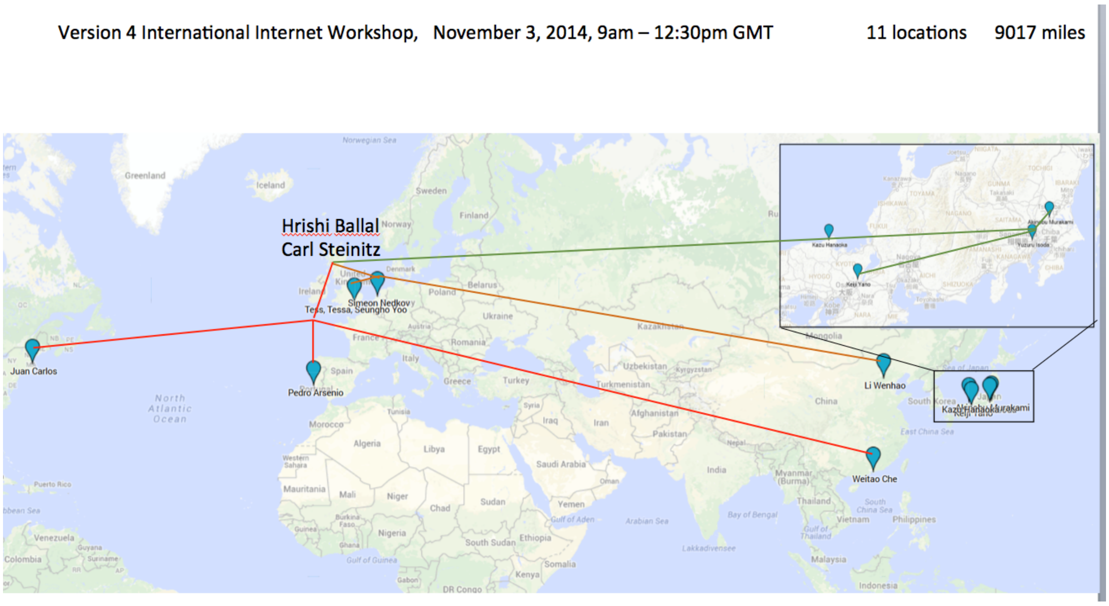


Figure 6.36: Workshop 4 Remote Workshop November 2014

The workshop went according to plan and all the tasks were accomplished. There were couple of areas of improvement that were suggested in the workshop:

- There was a bug in the workflow around data syncing and this caused some of the participants web pages to be unresponsive and they needed to refresh the page.
- There was confusion initially as to the task itself since the participants were not able to understand the instructions over Skype.
- There were numerous comments on not knowing the background about the area enough to make a design.
- A piece of feedback was to be able to compare the designs between team members and there were a lot of requests for the ability to import team members designs into the participants designs.

These four experiments proved that a digital implementation of the design synthesis phase of the geodesign framework worked and that collaboration and communication was indeed possible between participants in the same room and over the internet. In

Figure 6.37: Workshop 4 Participants at Different Locations

addition, the experiments also showed that the specification document is indeed complete and covers all the scenarios that are required for collaborative design synthesis using existing data in a planning problem. The final test of the workflow was an independent test setup at the University of Georgia where there were no existing models or diagrams and the participants added the diagrams in real time and conducted a design synthesis.

The next section describes this final test. All the data and models in the test were built of data that was provided by the staff at the university. Almost six weeks of preparatory work went into the workshop to produce the process models and evaluation maps. A novel aspect of this test was that the software was used on two different scales: one at a county level and a second site that is a state park within the county. Thus in this case, teams were working in real time at two different scales. The main objective of this test was to determine if the workflow would be able to handle a large geography and a planning problem that is at two different scales. There were not predefined models and in that sense we were starting from a blank slate and building to a final design. Therefore this workshop was a complete end-to-end test of the tool in that sense.

Figure 6.38: University of Georgia Workshop and Collaboration

6.5.5 Experiment 5

The workshop was held at the University of Georgia campus in Athens Georgia over the course of three days, the first two days were focused on going through the framework and producing the design synthesis. (Figure 6.38) The final day was spent on preparing a presentation of the design. The following section describes the design problem and the study area.

6.5.5.1 UGA Workshop Introduction

Savannah is the oldest city in the State of Georgia and is the seat of Chatham county. Established in 1733, Savannahs downtown area including the Savannah Historic District, the Savannah Victorian Historic District and 22 parklike squares, is one of the largest National Historic Landmark Districts in the United States. Downtown Savannah largely retains the original town plan prescribed by founder James Oglethorpe a design now known as the Oglethorpe Plan. [Savannah, Georgia, 2015] The beauty and the historic nature of the city have resulted in extensive preservation and it also supports a thriving tourism industry. The coastal ecosystems of Chatham County are among the most productive in the United States. They serve as nursery grounds for fish and shellfish, thus supporting extensive commercial fisheries.

Savannah is already the fourth-busiest container port in the United States. When its river is dredged to accommodate Post-Panamax ships it will see significant commercial/industrial development. Without dredging the port will lose business to Norfolk, VA and Baltimore, MD. Wormsloe State Park is an important tourism attraction and its Live Oak allee is the most photographed view in Georgia. It is a major ecological research station managed by the University of Georgia. On-going sea-level changes are already creating disruptions to natural systems. Sporadic intense storms and the forcing effects of climate change put pressure on natural and man-made systems to adapt and accommodate. Pressures to change are impacting Chatham County and Savannah, with substantial implications for their precious historical, cultural, natural beauty and ecological resources. Far-reaching and far-sighted planning is necessary to ensure that anticipated changes can be accommodated with minimum risk to these valuable resources. Given this problem the following process models were in play at the site. The workshop was setup assuming the following conditions: The port capacity will double, the port is spending USD 706 million on a expansion project that will also dredge thirty two miles of the harbor navigation channel of which eighteen miles of the Savannah River downstream to its mouth, and fourteen miles of the Atlantic Ocean entrance channel from 42 to 47 feet to attract and accommodate Post-Panamax ships.

The population of the county will double at a higher density because of this increase in industrial activity. In addition there would be a four fold increase in tourism given the population rise and increase in commerce and industry. Finally there is a risk of sea level rise and the region is on the path of hurricanes. A strong storm has the potential to cause significant damage to the area.

6.5.5.2 Process Models

The ten process models are described here briefly. The teams before the workshop identified these and after identifying key model and data sources for these, evaluation maps were created using standard GIS technology. The evaluation maps were of three colors built by sophisticated models.

Climate : The areas of potential threat from natural hazards and long-term sea level rise scenarios need to be identified. The current 50 year projections for the area predict a 3 ft sea level rise and in addition there are FEMA declared flood zones that are prone to flooding from the sea and the rivers that drain into the county.

Ecology/Nature : Identify habitats with high priority for conservation, existing conserved lands and improve connectivity among existing and future protected lands (for vegetation, wildlife habitats, and associated water and land movement needs)

Ground and Surface Water : For groundwater identify key areas or drinking supply well locations that could be at risk by saltwater intrusion, urban encroachment, or other threats. These could also be close to groundwater recharge areas. For surface water, there is a need to preserve the existing water bodies and also take remedial measures to replenish some of the most at risk sites.

Historic and Cultural : The region has many historical and cultural attractions that need to be protected. In addition promotion of tourism in this region is a key driver for future economic growth and is linked to this process model.

Visual and Tourism : There are areas in the region that people like to see for visual beauty and they need to be protected, and there are others that need to be developed and are not a part of the public access network. The historic and cultural process model is directly linked to the process model.

Agriculture / Forestry : The key objective of this system is to prevent land use conflicts, and land conversion from areas suitable or under existing agricultural or forestry use from other land uses (e.g. urban, industrial). Export of wood from agriculture and forestry is a major industry in the region and it is one of the key drivers of the growth of the Savannah port.

Housing : The increase in population in the county will put pressure on the housing areas and there is a need to densify existing housing and also identify new areas suitable for housing.

Industry and Commercial : Identify suitable places for industry and tourism. With the growth of the port and there would be pressure on the area to accommodate industrial and commercial activity around logistics, repackaging etc. and there is a need to identify suitable areas that would support this system.

Transport : Transportation is a key catalyst for the economic and tourism growth in the region.

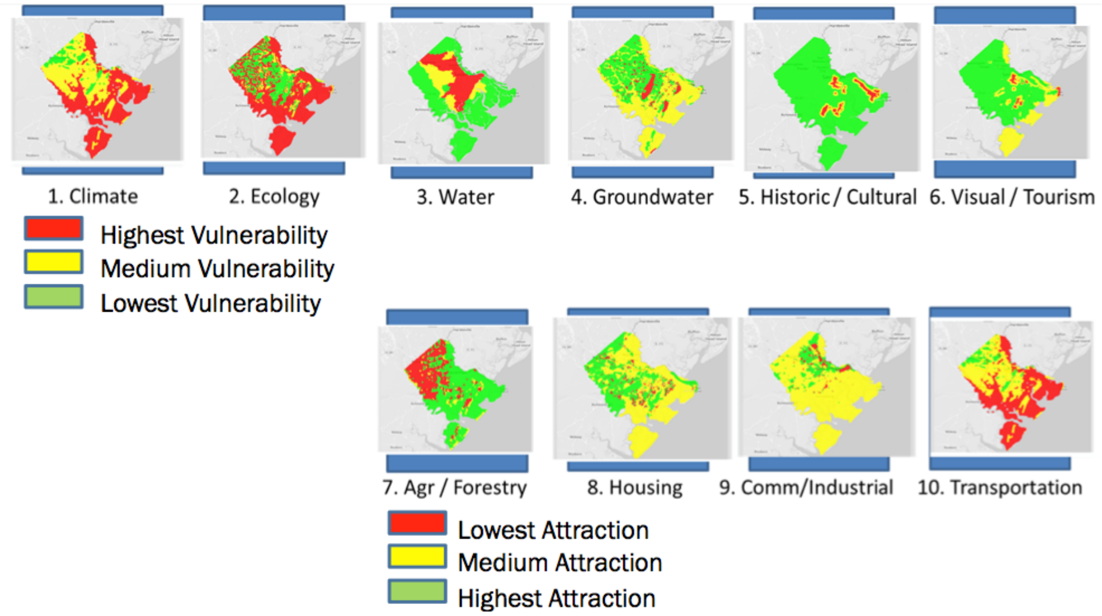


Figure 6.39: Evaluation Maps for the Ten Systems

The evaluation maps were uploaded to the tool and on the first day of the workshop the participants were given a brief tutorial for the key operations that users perform on the screens and some questions were answered. (Figure 6.39) The tutorial was short and consisted of showing key actions and the participants joined in along with me as the instructor. In the first half of the day, the participants sketched out ideas or solutions for the different systems, and a sample of some of the drawings are given below. (Figure 6.40)

The participants sketched out the diagrams and collaborated between them to discuss the ideas and sketch them using the sketching tool. A total of about 270 diagrams were added in the workshop by the end of the exercise. These diagrams were synchronized across all the connections to the project and participants were able to see the diagrams being added dynamically. The participants were then divided into five change teams representing different interest groups, and the change teams were:

Developers : The key agenda for the developers was to promote development of industry, commerce and transportation in addition to economic development in the area.

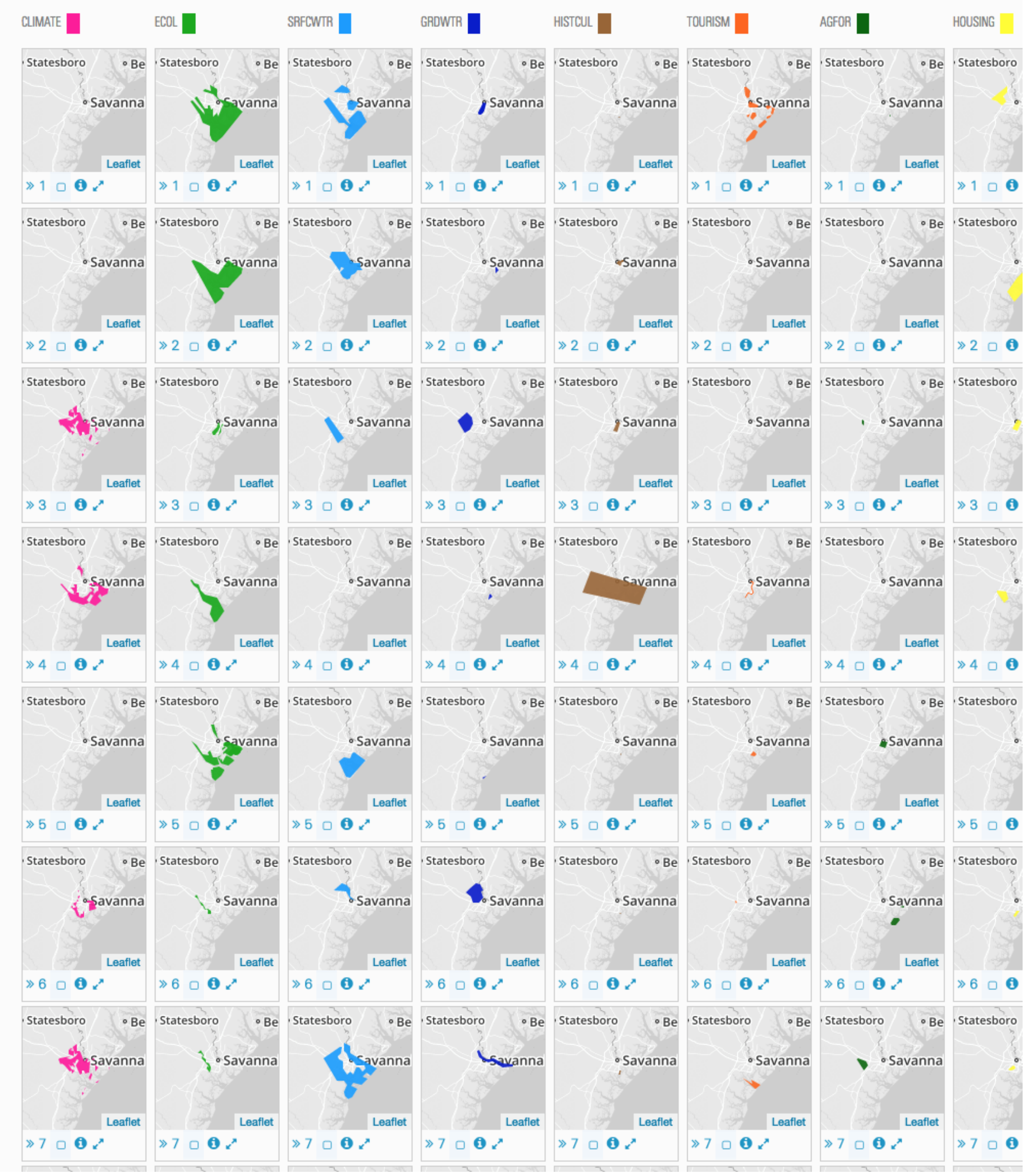


Figure 6.40: Diagrams Drawn by Participants

Climate Change : The key objective for the climate change team was to mitigate the risk of climate change to the area and also prepare a design that addresses the risks posed by rising sea level and the threat of a hurricane.

Environmentalists : The key objective for this team was to preserve and conserve the green spaces and increase the environmental aspects of the region.

Planners : The regional planners are tasked with building a comprehensive regional plan taking into account the positions and considerations at a regional level.

Wormsloe : The Wormsloe team worked on a smaller scale and their task was to produce a plan for Wormsloe in the context of the county. This was the first time the workflow was being tested on two different scales.

The teams were asked to build a plan for 2030 and 2050 and in another task the teams were asked to build a plan considering the worst case for 2030 and 2050. The task was to select a group of projects and policies that satisfied their interest group. The participants were able to select individual diagrams and design plans for their group at a rapid place. (Figure 6.41)

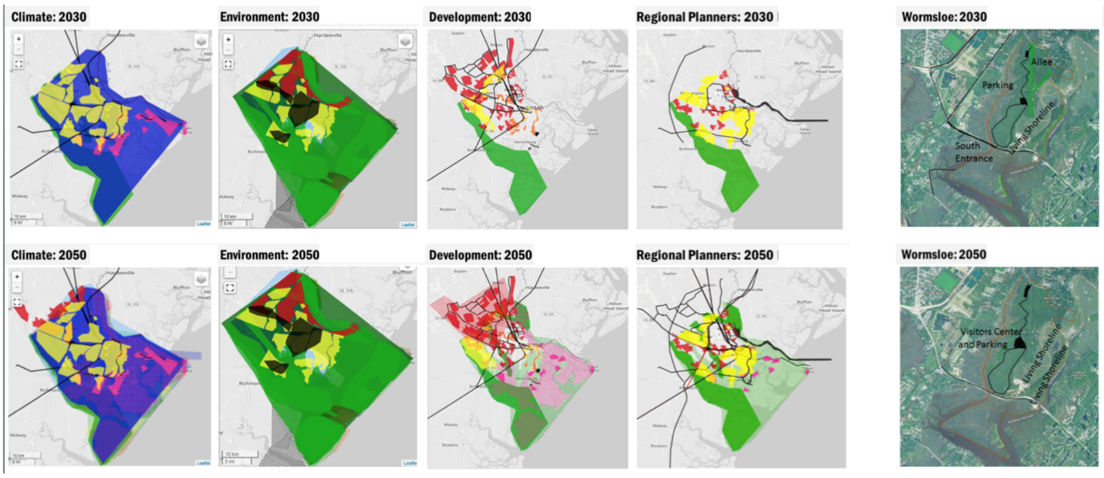


Figure 6.41: Plans Built by Different Interest Groups.

Figure: plans constructed by different interest groups. The key issues that were bought up by the participants during this workshop were:

- The participants were very advanced and some of them had their own data in different formats. Thus we had turned off import of some data formats to ensure a better experience.
- There were bugs in the workflow when the participants tried to re-rank the diagrams and this activity had to be turned off after a short time.
- There was feedback around the ability to make composite diagrams or diagrams that are made of two different diagrams and have the system add and maintain these and add then them to the grid.

Figure 6.42 shows a list of participants and their professions and areas of expertise. It should be noted that they included very senior planners, students, academics and

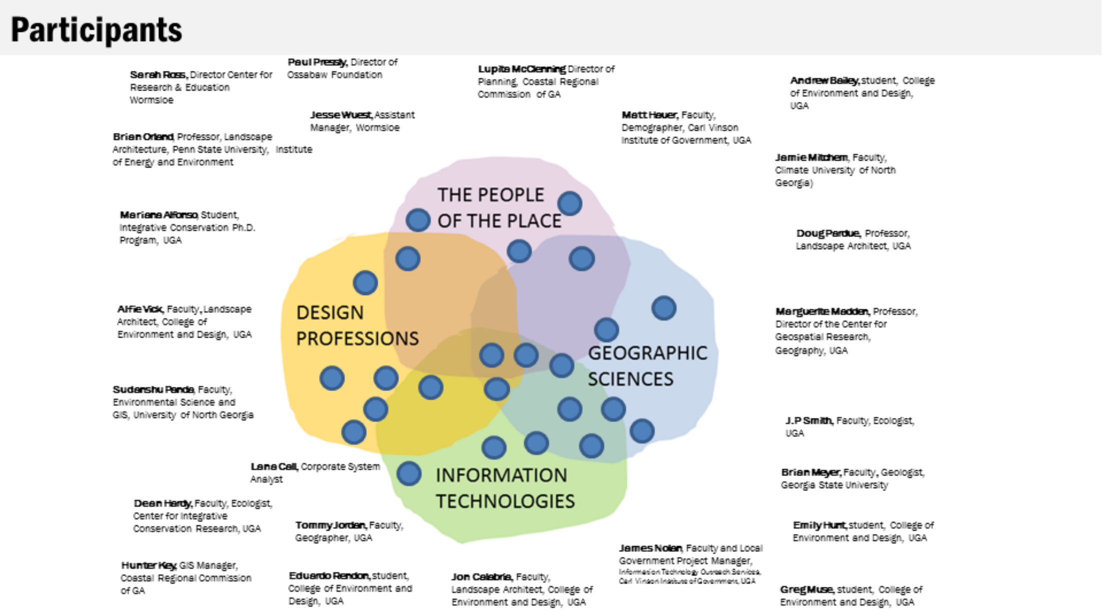


Figure 6.42: Workshop participants and professions.

professionals. By enabling this diverse group of people to work together in a workshop setting, it can be tentatively concluded that collaboration is possible. In addition, the participants have varied level of experience from the novice designer to the some who were very experienced senior designers. Based on verbal feedback, they communicated that shared understanding and learning was possible between them. However, a more detailed and thorough experiment needs to be carried out to understand the effectiveness of the tool in promoting (or discouraging) collaboration. Given that a varied number of professions are shown above, it is a matter of further research if more professions can be included in this list. The only way to do this is to conduct more workshops and studies. Overall, this test proved that a thorough and detailed regional level study could be carried out using the workflow with no prior availability of data. The setup of the tool was conducted from scratch and the participants provided positive feedback regarding the tool and the methodology.

6.6 Conclusion

A software that implements the geodesign workflow specification has been tested in a number of experiments with real world data. In these experiments participants were able to collaborate and conduct geodesign synthesis in real-time and in a very compressed timeframe. Over the course of the last year, the experiments with this workflow have demonstrated that this workflow supports the promise of geodesign and can be used to collaborative build designs. By conducting a number of repeated experiments, there have been demonstrable improvements in the design and performance and also considerable confidence in proving that the framework and methodology can indeed be extended digitally.

Chapter 7

Discussion and Future Work

7.1 Introduction

Problems at the regional level need new methods and tools to tackle them. This is because these problems are significantly different than problems at a local, household level or at the global level. Most regional planning problems deal with complex multi system issues with a large number of stakeholders. They require modelling and computer support, and the input of experts from different domains working symbiotically with people who have local knowledge. Sound regional planning has impacts beyond the region itself and it is through these interfaces that a holistic attempt to mitigate some of the adverse impacts of the man made and natural systems can be mitigated. It is at this level that there is an urgent need for research and development. The focus of this thesis is to further the state of the art for regional planning problems using the geodesign framework. In a sense it is about providing tools and methods for systematic regional planning using diagrams and enabling collaboration among different participants.

There are no easy solutions to problems of planning and it has to be tackled from many different angles.Providing the tools, technology and the embedded methods for the solution is the main contribution of this work to this issue. The aim of the work is to bridge the classical way designers work with diagrams and marry them with a systems approach to design all in a thoroughly modern digital synthesis workflow. To accomplish this, one requires an understanding of how designers work, a strong systems engineering background and in addition the ability to build software. It is at the intersection of these three domains that this work sits.

The research is focused on strategic early stage design problems for the regional scale. This work attempts to answer “how” and “what” questions at this scale: How does one begin a design? What are the key factors that are at play in the study are? “Well begun is half done” is an idiom that is particularly relevant here. Most regional studies and projects are long (multi-month / multi-year) projects. This work is focused on providing the right foundation for planning projects that are complex and that necessitate collaboration. This work aims to help start the projects in a sound fashion by giving scientific basis and systematic framework for design conceptualization. Furthermore, a digital platform gives the ability to conduct many experiments relatively cheaply. These experiments enable the participants to quickly test scenarios and variables to come to an informed conclusion around the effectiveness of a specific design method.

The advances in information technology are well known and documented. Smartphones, tablets, PCs etc. now have computing power that is more than sufficient power for most compute intensive spatial analysis tasks. In addition, the growth of the internet and cloud technologies have enabled a whole new class of applications that empower the individuals and facilitate communication. This computing revolution is a terrific opportunity for the planning domain and particularly in the context of planning support tools to address the issue of regional planning. There is scope in both research and practice to push the boundaries for collaboration on planning projects using the internet and modern technologies so that planning tools are available and accessible to all.

In the experiments documented earlier, participants generated designs that have broad acceptance, are data driven and have a systematic assessments of impacts. This activity is crucial given the complex nature of the planning problem and is the primary value proposition of the work as a planning support tool. In the literature, there is little research on collaborative early stage design in a multi-system approach for regional sized problem. This work uses the geodesign framework to build such a tool to enable collaboration and address this issue. Bringing together early stage design techniques, like sketching with collaborative planning support tool in the regional context is the key contribution of this work.

The existing open source or commercially available tools were found to be inadequate when used in conjunction with the geodesign framework. Therefore a new platform and specification had to be documented to build a truly collaborative design tool. Since the tool is custom built, there is no equivalent software available with which it can be compared. The specification document identifies the key functionality and features required to enable collaboration between participants.

Using collaborative techniques in early stage design, this work helps identify key factors and build broad consensus among the different stake—holders. Conceptual design is just that: a rough concept where the idea here is to further use the designs from the workshop and conduct advanced analysis and "fit and finish" type work on them. The promise of 3D and other advanced visualization techniques can be realized only when you have the designed objects spatially allocated correctly: a location that is informed by data and analysis. A design that has consensus and agreement between various conflicting stakeholders has the most likely chance for a buyin. In addition a collaborative consensus needs to be reached when discussing policies to pursue. The framework and experiments documented provide a platform to do both. The mixture of projects and policies usually form the basis of a plan and systematically identifying priorities has been the hallmark of the workflow.

7.2 Summary of Research

This thesis identifies critical gaps in planning support tools and addresses them by implementing a tool based on the geodesign framework. This tool was then tested in a series of experiments conducted over a period of a year among diverse participants. The software uses the power of diagrams to help in collaboration and communication. Diagrams are graphics and abstract representation of ideas or real world spatial phenomenon. This abstraction promotes understanding and comprehension of elements, relations, ideas and concepts. Designers extensively practice designing with diagrams in many stages of the work for it is the classical way of how designers design. In the context of architecture and planning, the purpose of this early sketching activity is primarily to avail oneself of potentially meaningful clues while designing. Early stage sketching is sketching done by the designer before the problem space is crystallized and is a mix of exploration of the problem space and also a search for a potential solution. If properly structured, these clues can be used to form and to inform emerging design concepts in a dramatic way. Therefore diagrams are a powerful way to communicate ideas quickly to people who do not have the context to the problem. Diagrams drawn digitally provide the opportunity to transfer all these features in a digital environment. Digital sketching is important for concept generation as is demonstrated in detail in Chapter 2 .

In Chapter 1 a comprehensive review of the cognitive structures of the mind of the designer has been conducted. Hence any digital planning support tool for early stage design needs to implement free form sketching. The core idea of a systems approach to solving problems is to decouple the process of design from the creativity of design. Most design problems are unique in that they are “ill-defined” problems and have no correct answer. The application of systematic tools and methods unburdens the designer and enables him to carry out the analysis of the design while focusing his energies on creativity. A systematic process breaks down the complex problem into smaller sub systems that can be understood and tackled individually and then aggregated to the larger problem at hand. The design activity is then described as a goal-directed search through a space of states or potential design solutions. In this way design solutions can be characterized by an exploratory search problem within the design state.

This thesis also reviews frameworks and theories to solve the problem of design as a rational set of moves or steps that can be quantified and categorized. This “hierarchical” design paradigm presents a number of ways to tackle a design problem particularly with the use of technology. This decomposition of the design problem into sub problems is the essence of a systems approach to design since it is only then that methodical analysis can be done to the partial solutions.

A review of planning support tools is conducted with the specific goal of identifing why planning support tools are not widely used and the key barriers to their broad adoption. Some of the reasons for lack of adoption are the inability of the tool to fit in the planning work-flow, lack of awareness of the tool and in addition the black box approach that most tools take to are key bottlenecks to broad adoption. This research approaches the field of geodesign from a process and a workflow point of view. Chapter 4 demonstrates how geodesign is fundamentally different from a process and output view point. To understand the concepts of the workflow and the framework better a three day workshop using the framework that used no digital tools was reviewed.

The Lisbon workshop that is documented helps in understanding the process specific qualities of geodesign and the opportunities for digital tool support. The key features of the framework are apparent from the workshop: it is very practical, sketch based and oriented to the design deliverable, it fits in well with early stage design and a systems approach to planning problems. Converting an analog process to a digital one is one of the key contributions of this work. A specification document for digital support for geodesign change synthesis is then provided. This specification aims to define the system parameters to enable the digitization process both from a technology and a user point of view. In addition to writing the specification, a reference implementation was also built. This in itself is not a trivial task given that it has not been done to date at this level of complexity.

This reference implementation was put to test in a series of experiments on a dataset that was used in Japan. The workshop conducted in Japan was all digital expect for the change synthesis portion of the framework. Once the tool was built, a series of experiments in the form of workshops were conducted to test whether communication and collaboration was possible. The series of workshops tested the performance of the tool in a digital setting leading up to a final independent test at the University of Georgia.

In all of the workshops documented, participants came in with little or no knowledge of the framework and the technology. They were able to synthesize designs and conduct analysis on their designs and based on the analysis make improvements on their designs over a very short time frame. Over the course of the six workshops that were conducted, the training became shorter and shorter to the point where by the end of it the training lasted less than 10 minutes. The training aspect is important because this tool was built from scratch and presented to experts and professionals with a lot of experience. The open nature of the platform meant that data could bought in by the participants. The participants were familiar with their data and it was the key to quick learning and acceptance. This also means that once extensive documentation is developed for the tool it can be self-contained and be taught and picked up fairly quickly. Indeed, it was observed that in a number of cases, users were able to teach each other the operations of the tool.

The work is aimed at demonstrating the viability of planning support that is based on the geodesign framework. The tool uses the concepts studied for early stage design and a systems approach to design to develop a planning support tool that is engaging and participatory. In addition to the participants bringing in their own data, the designs can be taken out for further analysis as well. It is hoped that this research paves the way for a new generation of tools that enable systems thinking in design and broad collaboration over the internet.

7.3 Characterizing Research and Contribution

It is important to characterize the research contribution and put it in perspective. The ideas of a systems approach to design and design methods and design thinking have been around for a number of years. Similarly, planning support tools and development of planning support tools is an area of a lot of activity as well. These are two completely separate fields as far as the current state of the art is concerned as has been demonstrated in the literature review. A number of studies in the literature advocate a holistic thinking and a multi stakeholder collaborative approach to planning problem solving. They highlight the importance of good communication in plan building but there are very few tools that enable this efficiently. Planning support tools used on this sized problem have been tested with a broad group of people but without supporting a multi-system or a process oriented approach. Similar work in the planning literature usually takes already existing software either commercially available or open source and conducts the relevant studies and tests on it. These have problems as well in that they are inflexible to different design styles and usually confine the user to a particular type of designing. In addition they are based on a single system tool where it is not possible to accommodate different systems. Thus, the existing tools are not suitable for regional level problems where multiple factors are at play simultaneously. Therefore proper and thorough tests using the multi-system approach using sketches have not been possible till date.

Indeed, a new tool had to be built specifically for this so that a multi-system collaborative design test could be performed. There now exists a detailed specification and an implementation that bridges these two domains: planning support tools and systems approach to design in a seamless fashion using the “Steinitz Framework”.

The “Steinitz Framework” is uniquely suited to a digital approach. Geodesign given its short design cycle times lends itself very nicely to a structured design process that the Steinitz framework advocates. A unique characteristic of the framework is that it enables asynchronous collaboration. The participants come together and diverge and come back together again to build designs. The process focus makes this orchestration possible and in addition it works on early stage design. The multi-system approach to design is at the heart of systems thinking when applied to designs and especially with a regional sized problems. The Steinitz framework and geodesign specially assumes it as a default. There are many other systems theories and frameworks and some have been reviewed earlier but this research demonstrates that when it comes to collaborative design, the key is for the tool to be as flexible as possible to the various design styles and accomodate differing and conflicting veiw points.

The software code and the functions are not documented as a part of this thesis. This is deliberate, for code is especially is a live entity constantly evolving and changing. However, the thesis does document the key modules and features that are necessary for a multi-system design support tool and these concepts and ideas will not change. The codebase that has more than half a million lines and the orchestration of different technologies to support planning operations over 9000+ miles, it is an not a trivial problem. Therefore this work is not merely a thought exercise of how systems approach to design could marry with planning support tools. It is also a documentation of the results of workshops and actual experiments in design. In that sense this work is truly original and no one else has performed test and studies like the ones documented in this thesis.

The second aspect to this research is the open and flexible nature of the planning support tool that was tested. The software is inherently open and flexible and in some ways can be thought of as a “grid of empty boxes”. This is the true power of the tool and the method and enables it to position itself between GIS and visualization as a designing aid. Due to the open nature of the system, there are no format or data specifications to adhere to and participants can add almost any geo-spatial data format. This “bring your own data” paradigm is novel given where the tool sits in the broader context of the technology trends.

Similar to the “bring your own device” trend in information technology, the future of design lies in tools that play well with existing data and enable users to design in the way they are most familiar with. In that sense, it is essential that any planning support tool works with existing data because as discussed in earlier chapters designers use abductive design to build their plans. Most abductive design needs existing data to work with and a process where designers infer from existing conditions. The bring-your-data nature of the tool means that we are just at the tip of what is possible with this from an experimentation point of view of comparing different designs in different places. This paradigm opens future collaboration and research possibilities with different datasets and groups on the same design problem. The flexibility was tested in the various experiments described earlier.

The “Steinitz Framework” has evolved out of number a of years of practice and experience. The work can also be considered as a digital test for the framework. Previously, the framework was partially digitized: some portions of the workshops were done with digital tools while the critical change model and change model synthesis were done manually. One of the reasons it was not converted digitally earlier is because it is a very difficult technical and engineering problem, in addition to it being a design problem. The reference implementation was able to co-ordinate a large number of diagrams and synthesize them in a way that is simple and uses non-specialized (ubiquitous) technologies.

There are very few design tools that focus on sketching and particularly in the context of regional planning and multi system domain. The sketching tools primarily focus on sketching itself or one system at a time or if they are not well suited for multi system analysis. An operational view of the framework was taken into account to build a multi-system sketching and analysis integrated into one tool. This is the main reason why a framework test is possible in an integrated fashion. Apart from multi-system analysis, another feature that makes the work unique is that the tool can be used by anyone with a laptop, a Skype connection over the internet. The use of ubiquitous technology to access and use the tool is a crucial element of this work and in fact is a huge technical challenge. This opens up a large number of possibilities for the tool itself and our ability to conduct tests. In the modern world, almost everyone has a laptop and a browser installed on it. As long as Skype and the browser works, the participant can join the workflow and be a part of the design team. This is very powerful since using this method, we can conduct studies in the developing world or in places where expensive hardware is not available. This enables these places to “leapfrog” their skill and understanding around urban and regional problems. Arguably it is in the data poor and technically constrained environments that these methods and techniques are most required and useful. All of these factors have a huge impact on the potential for the future of this technology and the workflow.

7.4 Discussion

The fundamental tension in this research is about compromise. This work and method trades simplicity for detailed modelling to gain an holistic approach to design. Simplicity means a number of things in this context. The models and diagrams that were used were simplified versions of the ideas and concepts they represent. Each diagram can in itself be a yearlong multi person project that works on the details of the concept. However details are not useful when communicating the essence of an idea to a broad audience.

This compromise sits uncomfortably with many experts who were using the tool. Indeed, there has been a lot of personal feedback on the simplification process and the reluctance of experts to simplify it after a certain point because “one cannot perform a real study at this level of coarseness” The modern professional or academic deals with a tremendous amount of data and there exist highly complex and detailed models that are specific to a field. A lot of data is necessary to develop deep expertise in a field. However the more complex the model and data, the more difficult it is for people in other fields to understand it. The simplification and standardization of the map data and assessments enables people from very diverse disciplines to have a conversation about issues, and provide input. At the early stages of the design, the concept development is the key.The tool is primarily meant for collaboration and communication in early stage conceptual design. Therefore the focus of the data and the content is around concepts and not about detailed fit and finish of these concepts. In Chapters 2 and 3 theories and studies about early stage sketching and how designers think about design have been documented. By undertaking the process of sketching and creating variations of an idea, the idea of the design crystallizes in the mind of the designer. This is a classic case of "learning by doing". In the process of going through the framework, the designer will build a good model for the key issues of the area and the problem at hand and be able to negotiate and communicate with others. It is the power of conceptual design produced by using the framework. In the very early stages of the design, details are not important or even necessary. Thus simplicity and small data are a feature since it focuses the participants on the design itself rather than getting lost in the details.

It is at the intersection of different professions that innovative design happens and the only way to do this is to break down the silos of specialization by building something that enables communication and understanding. The other aspect to this simplification is technological. Large datasets, complex files and models hurt the performance of the system. Some models take hours or days to run and it is simply not possible to use them in a workshop setting.

In line with the broader technology trends this technology will evolve as well. Just a few years ago there were limited mailboxes, a maximum allowed size for an attachment etc. and as the technology progresses, these limits were removed. There will come a time when the coarseness limit due to the technical specification will go away. When computers are powerful enough and everyone has good internet connectivity, then the limitations on the data size will not be present. We however still have to deal with the issue of collaboration and communication and for that simplification is the key.

The ability to simplify is necessary, but it is also useful when the method and framework are applied in data—poor environments. All of the workshops that were conducted were conducted in a data rich environment with a lot of data available. In addition a number of sophisticated models were available and also staff and scientists who would work on them regularly. One powerful application of the tool and technology is in the context of data-poor environments. Given the low technical knowledge and data availability threshold, this tool opens up the world of systematic planning to environments that were inaccessible before. There are a number of places and projects where there is very little or no data and the existing methods that require large datasets cannot be used for these problems. Sometimes data is not available or does not exist, the tool and the workflow needs to work in these situations as well. Indeed in the Lisbon experiment the assessments were drawn by hand and the workshop was able to produce the designs.

Experience shows that having too much or too detailed data is also a distraction from the problem at hand. In the Georgia workshop, it was observed that the data available was at a parcel level for the entire county for certain systems. This data is very important and necessary to conduct very detailed and thorough studies by experts. However, in the context of the workflow and the workshops, a system is just one of many and participants who are not necessarily experts are required to look at the map and understand it relatively quickly. Therefore for collaboration to happen, the simplification is necessary: it is only then that experts and participants of other fields can collaborate. Simplification is also necessary since the framework and the tool is best used in a compressed timeframe. This has a number of applications in the real world: disaster planning, rescue planning or in situations where an intervention is required immediately.

7.5 Holistic Design and the Future

This section is about broader regulatory trends in planning that will have implications for this research and practice in the future. According to the latest World Urbanization Prospects report in 2011 more than 52% of the global population now resides in urban areas, a percentage expected to reach 56% by 2020. [DESA,] Cities and regions therefore have to face the enormous challenge of responding to these dramatic demographic changes. The scale of the challenge necessitates a new way of approaching urban planning, decision making and the planning process in general. The practice of urban and regional planning is changing very rapidly due to the pressures from government, advances in information technology and also the attitudes of the broad population. In the European context, as recently as the year 2000, European countries signed what is known as the Florence Convention [Steinitz, 2012] and it is aimed at the protection, management and planning of all landscapes and raising awareness of the value of a living landscape. In this case the landscape is defined as natural, rural, peri-urban, urban, land, inland water and marine areas. In addition, they cover all types of landscapes: outstanding, everyday and degraded landscapes as well. The Florence convention is a way to think about planning and design that might well be adapted to other non-

European countries. In essence, the convention places an obligation on the member states and ratified signatories:

- integrating landscape into their regional, town planning, cultural, environmental, agricultural, social and economic policies.
- establishing and implementing landscape policies aimed at landscape protection, management and planning
- increasing awareness of the value of landscapes, their role and changes to them

There is already a large push for the planning and design field to be more collaborative, to think holistically and to bring together different stakeholders in the planning process and regulations like these codify them. The European model is likely to be emulated in many geographies and it is prudent to anticipate laws and regulations modelled around collaboration and participant input at an early stage.

This regulatory environment codifies the requirement to collaborate being placed at every level of the planning process. The digital workflow enables a level of collaboration that is simply not present in the current tool set specifically in early stage conceptual design. The experiments with geodesign synthesis have demonstrated participants collaborating over the internet over thousands of miles and also over the same room. The systems based framework and the software were able to bring people together to do collaborative design using the currency of diagrams. Given the legislative, social and political environment, these tools and processes will become mandatory in the future and more research needs to be conducted on tools that can be used in practice.

7.6 Ways of Designing

One important research implication of this work is around the process of design creation. The digital workflow opens up significant areas where fundamental research can be undertaken in to the ways of designing. This was not possible earlier because the tools were simply not present to conduct experiments and analyze the results in a comprehensive fashion. In addition to building tools for geodesign synthesis support the other objective of this work was to explore if creative aspect of designing and the planning process can be supported or enhanced. Given the limited time and the fact that the experiments conducted focused on the workflow and the mechanics of collaboration, more experiments need to be conducted on the creativity aspect of the process and there exist a foundation on which to build and design these experiments. Therefore it is too early to make a comment on this research objective but it is something that needs to be explored in detail in the future.

The experiments have already demonstrated seven out of the eight ways of designing from the “Steinitz Framework”. There are many ways to approach the change synthesis grid that is described earlier. This work contributes significantly on the broader topic of design methods in a collaborative context with experts and non-experts together.

There is no “correct” method except that many people follow one of these methods out of personal preference, efficiency etc. Sometimes the participants used these methods without conscious knowledge of them during the process of design. In practice there are infinite number of future possibilities or change models that be achieved as a part of the planning process. However these methods help in managing these seemingly infinite options to a select few that are manageable. In geodesign workshops usually change synthesis is done in a combination of a number of methods but a couple of methods dominate within a change team. With the digital workflow, these methods of design and research are reinvigorated since there now exists a platform to conduct these tests very rapidly with the use of computers and humans and this platform can generate quantitative data about the method itself.

In a “Framework for Geodesign” [Steinitz, 2012], Steinitz identifies eight ways of designing. Designing is a very personal activity and this work has a number of implications on design flexibility in a tool development context. A flexible design tool is necessary for large complex design problems. The following section documents how these different techniques were accommodated in the experiments conducted.

Anticipatory : The anticipatory method is based on a designers experience and expertise. A experienced designer can provide a solution to a design problem by recalling from a mental model or past project to design a solution. After having reviewed the condition of the study area the designer can add diagrams and select the correct one and use his experience to devise a solution by selecting a set of diagrams. In the remote workshop that there was a single person change team who built the design own their own and finally shared it with the rest of the group. This was a seamless process and the flexibility allows experts to join the workflow from remote locations to create a design for the region. This opens up a lot of possibilities for collaborative design from very experienced experts in cases where they cannot physically make the journey to the study area or workshop site.

Participatory : In the participatory design method, the process assumes that there is more than one designer and each will have their own idea about how the future design should look like. In the case of the workflow there is a relatively simple way of achieving this way to design. In experiments not documented we had about eighty people joining a project and selecting their set of diagrams for the best design as envisioned by them. Since the selections are tracked in the tool, we can then do a summary design of diagrams that are selected by 80% of the people for example but more than 50% of the participants. This way designs can be synthesized by any number of selections in the grid and potentially we can have a large number of people joining over the internet and select a design. There is a huge area of research that opens up with respect to participatory design and in particular done over the internet.

Sequential : In the sequential approach, the designer makes a series of confident choices that systematically develop the design; that is, select a set of diagrams in a certain sequence because the sequence of selection is important. Every step has an impact on the next step. In the workflow, analysis of selections is done in real time across all the systems, the evaluations are updated every time a new design is added to the list and the updates directly co-relate to how the new designs are added. This type of designing problem is most interesting in cases where there is a need for remediation and development. For example, in the Soma city case, does one clear the soil around the mountains first and then develop downtown to get more people in or does one wait until more people get in and the remedy the mountain side. This type of design not only has budgetary implications but also impact on project management, time and schedule. This method can be very easily used in the workflow and is an avenue for further research.

Constraining : The constraining method is useful when the teams and their clients do not have a good understanding of the priorities and the decision model. It is a case where the design has to be built first to understand the key questions and issues of the site. This is not uncommon in very complex city systems. Given the speed with which the design can be made using the workflow these types of experiments can be performed very quickly and easily. On the internet based workshops, teams were able to build a design in a matter of hours and iterate on them so by the end of three hours we had teams with three or four iterations of their design. Thus the workflow provides a very good platform to pursue this type of designing.

Combinatorial : In the combinatorial approach the designer or the client is not sure of what the best combinations or sequence of decisions are to create a design. For example, it may be that two or three requirements are equally important and solving them together as one system is the only way to solve the problem at hand. In this case the selections will have to be grouped as a set of diagrams per requirement. There maybe a set of requirements of top priority, and another set with equal weights that are second priority. This is requirement while similar to the combinatorial one, it is one of the most difficult to manage since the designer has to deal with a set or two or three systems and their impacts at the same time. The cognitive processing load is very high for this and it is demonstrated in the feedback.

Rule Based : In some ways rule based systems and optimized designs are the most exciting for research in a digital context. In a rule based way of designing the designer or the team sets a set of rules for design. E.g do not build 200 m from the beach is a rule that can be used in a design project. The digital workflow supports the rule based design naturally since the analysis of impacts and the selection of diagrams is all digital, so rules can be very easily implemented as threshold or constraints to select or not select a diagram. For example, in one of the workshops, a rule was implemented that said to build a design that does not intersect with any red areas of the assessments. The idea here is to select a set of diagrams that produce the least “damage”. These types of rules can be easily created in a digital environment and run very quickly. This type of design may not be very practical but would give really great baseline measures to compare the designs of other teams. It would present a scientific way to discuss the pros and cons of a design. The man-vs-machine made design also has implications on the nature of design itself and has potential to revolutionize the field if we can incorporate artificial intelligence etc.

Optimized : The optimized approach is similar to the rule based approach where it requires the designer to understand the importance of each requirement and also its decision criteria. An example of an optimized one could be one that gets most of the votes or one that can have the lowest cost. A lowest cost design algorithm was implemented and tested in the digital workflow and it builds a design after selecting diagrams that had the lowest cost of implementation based on a cost model. This costing function is very important since in a number of ways it is the primary vector that drives the decision from decision makers. The digital workflow is especially suited for this type of activity and again can be used to make reference designs for projects.

Agent—based : The agent-based design was the only one that was not tested in this work and is an area of future research. In an agent based design, the algorithm takes into account the interactions of policy and project interactions and makes a decision on landuse. The Agents themselves could be stakeholders, people of the place, decision makers etc. The agent-based models are necessarily complex and computer based and takes a lot of time to setup for a project and implement the algorithm.

The digital workflow has the potential to integrate a number of computer based design methods and opens up a very interesting platform for research. Tests around what design method suits what type of problem or geography, how can one technique used in one study area be used in a different study context etc. can now be thoroughly tested. These further tests when conducted will contribute to the body of work around applications or suitability of design methods for classes of problems. This type of work was not possible before since the change workflow was not digital and it did not fit the collaboration model well.

There now exists a way to generate a design in an all-digital format with all the evaluations and impacts also being computed in a digital environment, in real time and shared across all the participants. Given a set of diagrams and grids that have been built, algorithms using different parameters and modeling techniques could be linked to the grid to be able to read and understand the diagrams and create the designs. The digital nature of the design process lend itself very easily to logging and analysis of the design creation process.

In an analog process of making a design, there is too much activity amongst the team members and it is difficult to keep track of the different changes in the process. Therefore detailed analysis is not possible. Indeed many design studies either rely on taking video camera and recording the process, or interviewing or "think out loud" type exercises. Given the digital nature of this workflow, all actions can be tracked to build an analysis of the design process. The logging is therefore inbuilt, so potentially one can deconstruct a design step by step to understand the exact point where the design performed a certain way for a particular criteria. This way of analyzing the design method is novel and can only be done using a digital tool. Thus fundamental research into ways of designing can now be performed both from a process and design content level across different problems.

7.7 Areas of Further Research

This work opens up a number of exciting possibilities for research and further investigation. There now exists a way to conduct experiments and workshops using the geodesign framework totally digitally using ubiquitous computing tools and relatively modest requirements for Internet access. Work at this scale has not been done earlier digitally in a cohesive fashion. The demonstration of a multi-system approach along with the use of ubiquitous computing and relatively easy learning curves are the ideal combination to broad acceptance of using a systems framework for regional planning.

This work demonstrates what is possible using a simple user interface and non-specialized hardware. The ideas and concepts are borrowed from the analog world that have worked for a number of years, they can show how collaborative planning can function in the future. The workflow was demonstrated to work seamlessly both when participants were joining in person or completely remotely from different locations. In addition to enabling remote workshops, the key innovation of the digital change synthesis method in the context of the geodesign framework is that it is multi-system and enables near real-time impacts analysis over the network. It is a tool that accommodates diverse systems and stakeholders without the stakeholders having had to compromise their identity and expertise. Seven key areas for future research have been identified and some early work has already started on this:

1. Plugins and an API
2. Linking into dynamic models
3. Smart Diagrams
4. Design Methods and Scales
5. Crowdsourced Design
6. Design in Data Poor Environments
7. User Interfaces for Planning Support Tools
8. Artificial Intelligence

1. Plugins and an API: Just as with any other platform, an API can be built for the core functionality of design synthesis in the tool to enable development and contributions of plugins by different companies. For example, in the tool, there is a very basic costing model in place, a robust and complete API will enable vendors to build or integrate their own costing / finance model into the tool. The open and flexible nature of the tool works well with this concept and a number of future collaborations can be envisioned when plugins or adapters are developed between the tool and other platforms. The second area of research and development is around plugins and an API to the workflow. This ties nicely to the first key area of building an Assessment format specification. While the core task of the workflow is around design synthesis, there are many other tasks that a final design needs to perform that is beyond the synthesis itself. Indeed the idea here is to have a conceptual design that then needs to be further analyzed for performance and other characteristics. A good example is computing costs of a design. Once a design

is synthesized, the cost of implementation needs to be calculated. Every project has a different model of computing costs that is specific to the project, the geography and the financial model. While there exists a simple cost model, an API would be a great way for the more sophisticated costing and financial models to interoperate with the designs. Similarly, one can imagine a small marketplace of services that interact with the design synthesis to compute costs and any other things that are relevant in a design analysis situation: carbon impacts, impacts on ecosystem services etc. Building this public API to the workflow and collaborating with others to help in performing advanced calculations on the design itself is important. One other example that can be used from an API point of view is around visualization and fit and finish. There are many 3D visualization technologies and the design that is synthesized may be outputted to any of these tools for advanced visualization processing. There are so many possibilities of building a tools agnostic API that warrants further research.

2. Linking into dynamic models: A major area for future work is to link dynamic process and evaluation models in the workflow. Most labs, research groups and government institutions have elaborate models that are built and used by them to investigate a phenomenon or area of study. These models can run on super—computers and large computing infrastructures or even small servers. The assessments maps that we used in the experiments were static shapefiles or similar data that was provided by the different groups who use these models to generate the map.

The increased sophistication of GIS software, internet mapping technologies and networking technologies have enabled advances in using models and related analytics in many public planning forums. [Klosterman, 1997] [Shiffer, 1995] [Guhathakurta, 1999] Modelling in urban planning has evolved over the past few decades from what initially started as simple models, thence developing in complex cellular automata and agent based models based on discrete choice and micro-simulation. [Harris and Batty, 1993]

In contrast to this tradition of making simple models more complex, there has also been a less organized effort to develop models that are simpler than their predecessors. This has proceeded by decoupling sub-models and developing these in more detail or by fashioning their different elements into individual models or modules that can be used as elements in a toolbox of techniques. Many planning-support systems are constructed in this fashion [Brail, 2008], although the quest to develop simpler models is dwarfed by the wider trend of extending models to embrace new information technologies and richer sources of data. Models thus act as important instruments that enable researchers and planners to simplify, to make predictions and to plan prior to "acting" on the world in some irrevocable way. [Batty, 2007a] Lowry and others observed that models could be classified in terms of the media used to relate to the world they sought to simulate, the formalization or type of abstractions used, and their representation in terms of description or prediction of existing or new forms of the reality they related to. [Lowry, 1965]

Urban modeling has moved away from aggregate, cross-sectional models to more disaggregate, agent-based structures that depend on representing more individual-based data. There are some interesting models that can be dynamically linked in the design process that have proven to be useful as far as regional planning is concerned. In literature, there are a number of studies that detail the utility of regional planning models and its significance in research. [Verburg et al., 2002] [Valbuena et al., 2010] [Koomen et al., 2011]

In some of the workshops, dynamic updates to the assessment maps were demonstrated. However, the ability to link the large computing infrastructure and models directly into the workflow is the first area of research. When a user selects a policy or a project in the grid, the information about that policy or project is shared or sent to the advanced model and the model is re run to produce a new assessment after the addition of the project and updated. For example, if there is an area that is not working from an evacuation point, the assessment of that map shows red. If the participant selects a project to build a road, the assessment should be dynamically changed taking into consideration the road being built. These dynamic changes are in fact the next step of research and would tremendously help the design process. However, this is a much deeper work than appears and needs to be explored in more detail in collaboration with the model authors.

Since the workflow accommodates almost any type of model that can produce a map, there needs to be a standard that specifies the format of the assessment maps and how the assessment map model service interacts with the broad set of geodesign tools. Standardization of the assessment maps and evaluation models will enable many tools to inter operate and also tool makers to provide flexibility in terms of the models that are supported. The second issue to solve is the speed of modeling: there are models that take seconds to run and there are model that take days. In a workshop format it is simply not possible to wait for hours for the model to return the data so there needs to be a specification on what is an acceptable time and how fast should the model run to be useful in this setting. The writing of an Assessment specification is one of the key research priorities since this also has the additional benefit of making available a whole body of models for use and analysis.

3. Smart Diagrams: Diagramming in general has been done on pen and paper many years. As has been reviewed earlier, designers use symbols, arrows and other simple representations to communicate their ideas using diagrams. Since the workflow enables digital diagramming, one area of research is to develop artificial intelligence type rules to understand a diagram beyond the polygons, polylines etc. One can imagine a case where the computer interprets the intent of the designer and the necessary impact changes are made. If a designer draws a circle and arrow pointing to the right and writes for example “move” and this is shown to another person, the second person understands what the diagram means, it means to move the area in the circle to the right. In the same way if it is drawn as a diagram for spatial allocation, the computer should be able to understand the intent of the diagram and take necessary actions. Some sample actions could be: “Align”, “Divide”, “Increase”, “Integrate”, “Move”, “Rotate” or “Split”. Most experienced designers can view diagrams with these texts or symbols and understand what they mean in a planning context but doing the same with the grid and the workflow, opens a lot of possibilities for further research. A diagram interpretation module could be architected that interprets the diagrams and then takes actions either spatially or in the synthesis stage to come up with designs that not only understand the actions of the diagram but also implements it in the design synthesis. This is a important area of research and will address a tension in this work. While the figures drawn by the participants are technically not abstract diagrams in that they are spatially explicit precise figures, further work has to be carried out in this field. This work should involve not only how the figures are drawn using digital sketching tools and also how they are represented in the system. For example the concept of fuzziness is relevant here. A designer can draw a circular shape and annotate it saying build a housing “in this general

area" and the software understands the spatial allocation associated with that figure. Chapter 2 details some advances and software examples done in this area. While foundational steps have been taken, further work is necessary in this area and the bridge between freeform sketching and diagramming and spatial understanding remains to be built.

4. Design Methods and Scales: Most complex regional problems can be broken down into "sub-problems". These sub-problems can be at a street level or a neighbourhood level. A more interesting research question is around scale and the way to design. The framework and the workflow has been tested on one and two scales in a workshop setting. Can it be done for three scales? How do the design methods and organization change for three scales or more scales. How does one set up a project with more than two scales? These are all very relevant research questions and an answer to these would help shed light on which design method is most effective a particular scale. Also testing the scales hypothesis would have implications on design of the planning study in particular how is the scope of the planning study defined?

5. Crowdsourced Design: is a relatively new trend that is changing the way a lot of things work in the world. Input from a broader public should be sought using simple tools to help solve a problem. Crowd sourcing has been used to translate content, raise funds for products and also conduct mundane tasks. A similar approach could be taken in design. Can a community design a plan for themselves? Can designs be generated without the input of experts or planning or architecture firms? In the experiments, a way to conduct crowd sourced designs using the workflow has been demonstrated. How much farther can this be stretched? Since it is all available using a internet connection, can the residents of one county come with crowd sourced design for their neighbouring county (and vice versa) and how would the designs look? These types of interesting question need to be researched. Also as mentioned earlier, broad inclusion of the community is embedded in the law in some jurisdictions and it is a trend that it will be more and more prevalent in most countries as well. The crowdsourcing approach also challenges the technical limitation of the workflow. How many people can design at the same time? What are the technical server requirements to enable this?

6. Design in data poor environments: Another area of research and collaboration is to conduct design in data—poor environments. Arguably the regions and areas of the

world that need this type of thinking, tools and techniques the most are the ones with least access. One priority for research is to understand how the framework and method will work in data—poor environments. In some ways by doing the workshop in a non-digital format proves that the framework works well but would the digital implementation work just as well? Would it be quicker or faster or would the designs change if the quality of the models are sub-optimal or the available assessments are not up to quality. Would the design methods change if the data quality were poor? How do the final designs look and perform as compared to the ones built with elaborate data?

7. User Interfaces for Planning Support Tools: On a technical level, research can done on the user interface for multi-system planning support tools. Experiments to answer fundamental maps specific user interface questions can now be conducted. For example What properties of tools that trigger exploratory attitudes? In addition since the interface is used by diverse participants with very different levels of skills and understanding, studies can be done on interface effectiveness and the ability to communicate and understand the information presented.

8. Artificial Intelligence: For a long time researchers and academics have envisioned an expert system that automatically designs for a region by itself using the existing knowledge. While an agent—based system is one example of a fully automatic computer generated drawing system there are many others that can be designed using the systematic framework. Given the collaborative nature of the tool and that all diagrams are added by participants, we can envision an artificial intelligence adding diagrams to find a optimal solution for a problem and then synthesizing its designs. Some of this has already been implemented in the workflow in the form of optimizing or rule based design methods. Artificial intelligence could also be applied different projects to understand the key characteristics of the designs and the conditions, thus creating a meta regional knowledge that is shared across geographies. For example what does the Seattle watershed have in common with the Savannah watershed and can these common things be applied to a design to be built for the Thames estuary region. These type of advanced analyses would be possible with the support of artificial intelligence and a systematic design process. While a bulk of this work falls in the domain of computer science, there are interesting comparisons to be made for an AI generated design vs an experienced designer making a design.

7.8 Practice and Education

This last section discusses the implications for practice and particularly for education. The core problem that is solved by the digital design synthesis workflow using diagrams is that of a systematic way to approach conceptual design. This has significant implications for practice. Most planning problems handled by professionals are complex problems with a number of simultaneous systems in play and it is very difficult to understand and comprehend the key issues.

This is where the workflow is most useful, by enabling a quick and fast exploration in a workshop setting using real and available data, the participants are able to create a set of designs for various interest groups. The preliminary designs form the base of advanced designs that can be worked on and iterated over and over. This form of quick testing of solutions is valuable in practice. In fact in the world of software development this is very common. There exist many software packages particularly when it comes to designing interfaces etc. that help designers and developers test out interface ideas using sketching and doodling. Interfaces are built very quickly using these tools, shared with users for feedback and then iterated on. This is a very common way of building interfaces for most software products. The workflow intends to do the same for planning practice. The ability to build quick prototype designs informed by real data is a powerful way to build a final design. Prototyping helps save time and budgets and also enables ideas to be parsed and filtered. This type of rapid prototyping is the gap that the workflow attempts to fill.

Given that it is on the internet, the data and the prototype designs can easily be shared with other people, while feedback can be recorded about it. Thus from a practice point of view, this is a tool for building wireframes and ideas about design. In addition, the workflow enables broad collaboration between experts relatively easily. A flooding expert in Japan can collaborate easily with a project in London where his expertise is needed. Since this can be done on a per project basis, the cost of engagement can be bought down drastically. The workflow opens up avenues for collaboration between professionals in a way that was not possible before and a practice can use the workflow to participate in projects and increase their revenue stream. The technology and the workflow democratizes expertise and design experience. People from different backgrounds and cultures can come and design together quite easily using the tool and inevitably it will lead to knowledge exchange and the exchange of expertise. This I think will change the way practice runs fundamentally and the true power of the internet in flattening the world will be demonstrated by the workflow.

In a similar fashion, the workflow acts as an education tool to teach students about multisystem planning and analysis. Using diagrams and diagram synthesis, students will learn a systems approach to design and the methods for design. The workflow can be added to the various geodesign curricula as a way to be introduced to complex regional planning projects. When students build a plan together, the shared learning experience will be most effective from a teaching point of view. In addition to the theory of building the design, collaboration, expertise would be taught to the student. The workflow and the frame work is a very "hands on" and the students practical knowledge would be enhanced by using the workflow. They will learn about the tradeoff and the methods of design using the tool. Thus it presents a way for universities to move away from simpler design projects to teaching students about conceptual design in a regional planning context.

7.9 Conclusion

We are living in times of rapid change on the planet with rapid urbanization, population growth and climate change. Our society and the way people live on this planet has material impacts on the artificial and natural systems that surround us. There is a growing recognition that the current trajectory is unsustainable and a change should be brought about to help mitigate some of the most disastrous consequences of the human civilization. Population in growth is putting a lot of pressure on governments and a strain on our resources. There is a lot of pressure to promote industry, jobs and economic growth thereby speeding up the depletion of natural resources. Also this adds to the adverse impact of humanity on the planet. Smart management of resources and systematic planning is a way to counter or mitigate these issues. The issues and the impacts are not hypothetical ones that will occur at some abstract time in the future, they are being felt by communities today. Planning professionals, urban planners, scientists and academics have a significant contribution to make given their position and expertise. As intermediaries, thought leaders and professionals interact with various entities including government, society and environment. Therefore this places the profession in a unique situation to make a contribution to this effort and be a medium for positive change. To enable these solutions, collaboration and communication between different disciplines is critical. It is at the regional level that the various stakeholders, scientists and engineers that can contribute most effectively since this level overlaps the different domains.

This thesis has demonstrated the effectiveness of a collaborative, internet based urban design technology using the geodesign framework. This workflow is novel in that it supports a systems approach to designing through diagrams, real-time analysis and collaboration over the internet using ubiquitous technologies. The experiments described earlier were the first that were carried out using in a fully digital fashion. The aim of this work is to advance the state of the art in early stage conceptual design and rapid iteration of the design prototypes. The experiments show the tool to be a very useful early stage design tool to complex planning problems. There are many open questions and avenues for further research and this is just the beginning of a long journey with Geodesign and solving complex design problems using the technology.

Bibliography

[2011 Tohoku earthquake and tsunami, 2011] 2011 Tohoku earthquake and tsunami (2011). 2011 tohoku earthquake and tsunami — Wikipedia, the free encyclopedia. `http://en.wikipedia.org/wiki/2011_Tohoku_earthquake_and_tsunami`. [Online; accessed 21-February-2015].

[Aerts et al., 2003] Aerts, J. C., Eisinger, E., Heuvelink, G., and Stewart, T. J. (2003). Using linear integer programming for multi-site land-use allocation. *Geographical Analysis*, 35(2):148–169.

[Ahmed et al., 2003] Ahmed, S., Wallace, K. M., and Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, 14(1):1–11.

[Alexander, 1967] Alexander, C. (1967). *Notes on the Synthesis of Form*. Harvard University Press Cambridge.

[Amabile, 1983] Amabile, T. M. (1983). The social psychology of creativity: A componential conceptualization. *Journal of Personality and Social psychology*, 45(2):357.

[Anderson, 1982] Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review*, 89(4):369.

[Andrienko and Andrienko, 2003] Andrienko, N. and Andrienko, G. (2003). Informed spatial decisions through coordinated views. *Information Visualization*, 2(4):270–285.

[Anzai and Simon, 1979] Anzai, Y. and Simon, H. A. (1979). The theory of learning by doing. *Psychological Review*, 86(2):124.

[Archer, 1984] Archer, L. B. (1984). Systematic method for designers. *Developments in design methodology*, 1.

[Arciniegas et al., 2011] Arciniegas, G., Janssen, R., and Omtzigt, N. (2011). Map-based multicriteria analysis to support interactive land use allocation. *International Journal of Geographical Information Science*, 25(12):1931–1947.

[Arciniegas et al., 2013] Arciniegas, G., Janssen, R., and Rietveld, P. (2013). Effectiveness of collaborative map-based decision support tools: Results of an experiment. *Environmental modelling & software*, 39:159–175.

[Argent, 2004] Argent, R. M. (2004). An overview of model integration for environmental applicationscomponents, frameworks and semantics. *Environmental Modelling & Software*, 19(3):219–234.

[Arias et al., 2000] Arias, E., Eden, H., Fischer, G., Gorman, A., and Scharff, E. (2000). Transcending the individual human mindcreating shared understanding through collaborative design. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 7(1):84–113.

[Asimow, 1962] Asimow, M. (1962). *Introduction to Design*, volume 394. Prentice-Hall Englewood Cliffs, NJ.

[Atman et al., 1999] Atman, C. J., Chimka, J. R., Bursic, K. M., and Nachtmann, H. L. (1999). A comparison of freshman and senior engineering design processes. *Design Studies*, 20(2):131–152.

[Bacic et al., 2006] Bacic, I. L. Z., Rossiter, D. G., and Bregt, A. K. (2006). Using spatial information to improve collective understanding of shared environmental problems at watershed level. *Landscape and Urban Planning*, 77(1):54–66.

[Batty, 1971] Batty, M. (1971). An approach to rational design: Part 1: The structure of design problems. *Architectural Design*, 41:436–439.

[Batty, 1990] Batty, M. (1990). Informative planning: The intelligent use of information systems in the policy-making process.

[Batty, 2007a] Batty, M. (2007a). Model cities. *The Town Planning Review*, pages 125–151.

[Batty, 2007b] Batty, M. (2007b). Planning support systems: progress, predictions, and speculations on the shape of things to come. (122):1–25.

[Batty, 2013] Batty, M. (2013). On planning processes. *Resources and Planning*, pages 17–45.

[Batty and Densham, 1996] Batty, M. and Densham, P. J. (1996). Decision support, gis, and urban planning. *Sistema Terra*, 5(1):72–76.

[Bauer and Johnson-Laird, 1993] Bauer, M. I. and Johnson-Laird, P. N. (1993). How diagrams can improve reasoning. *Psychological Science*, 4(6):372–378.

[Bishop, 1998] Bishop, I. D. (1998). Planning support: hardware and software in search of a system. *Computers, Environment and Urban Systems*, 22(3):189–202.

[Boroushaki and Malczewski, 2010] Boroushaki, S. and Malczewski, J. (2010). Measuring consensus for collaborative decision-making: A gis-based approach. *Computers, Environment and Urban Systems*, 34(4):322–332.

[Box, 1979] Box, G. E. (1979). Robustness in the strategy of scientific model building. *Robustness in statistics*, 1:201–236.

[Brail, 2008] Brail, R. K. (2008). *Planning Support Systems for Cities and Regions*. Lincoln Inst of Land Policy.

[Breuker and Van de Velde, 1994] Breuker, J. and Van de Velde, W. (1994). *CommonKADS library for expertise modelling: reusable problem solving components*, volume 21. IOS press.

[Brewer, 1973] Brewer, G. D. (1973). *Politicians, bureaucrats, and the consultant: a critique of urban problem solving*. Basic Books New York.

[Brouns et al., 2015] Brouns, K., Eikelboom, T., Jansen, P. C., Janssen, R., Kwakernaak, C., van den Akker, J. J., and Verhoeven, J. T. (2015). Spatial analysis of soil subsidence in peat meadow areas in friesland in relation to land and water management, climate change, and adaptation. *Environmental management*, 55(2):360–372.

[Burby, 2003] Burby, R. J. (2003). Making plans that matter: Citizen involvement and government action. *Journal of the American Planning Association*, 69(1):33–49.

[Butler et al., 2008] Butler, H., Daly, M., Doyle, A., Gillies, S., Schaub, T., and Schmidt, C. (2008). The geojson format specification. *Rapport Technique*, page 67.

[Carver, 1991] Carver, S. J. (1991). Integrating multi-criteria evaluation with geographical information systems. *International Journal of Geographical Information System*, 5(3):321–339.

[Chandrasekaran, 1990] Chandrasekaran, B. (1990). Design problem solving: A task analysis. *AI Magazine*, 11(4):59.

[Cheng et al., 2001] Cheng, P. C.-H., Lowe, R. K., and Scaife, M. (2001). Cognitive science approaches to understanding diagrammatic representations. *Artificial Intelligence Review*, 15(1-2):79–94.

[Christiaans and Dorst, 1992] Christiaans, H. and Dorst, K. H. (1992). Cognitive models in industrial design engineering: a protocol study. *Design Theory and Methodology*, 42:131–140.

[Christopher, 1965] Christopher, A. (1965). A city is not a tree. In *Architectural forum*, volume 122, pages 58–62.

[Couclelis, 2005] Couclelis, H. (2005). " where has the future gone?" rethinking the role of integrated land-use models in spatial planning. *Environment and Planning A*, 37(8):1353.

[Coyne and Gero, 1985] Coyne, R. D. and Gero, J. S. (1985). Design knowledge and sequential plans. *Environment and Planning B: Planning and Design*, 12(4):401–418.

[Cross, 1984] Cross, N. (1984). *Developments in Design Methodology*. John Wiley & Sons.

[Cross, 1990] Cross, N. (1990). The nature and nurture of design ability. *Design Studies*, 11(3):127–140.

[Cross, 1993] Cross, N. (1993). Science and design methodology: A review. *Research in Engineering Design*, 5(2):63–69.

[Cross, 2004] Cross, N. (2004). Expertise in design: an overview. *Design Studies*, 25(5):427–441.

[Cross, 2006] Cross, N. (2006). *Designerly ways of knowing*. Springer.

[Csikszentmihalyi, 1988] Csikszentmihalyi, M. (1988). *Society, Culture, and Person: A Systems View of Creativity.* Cambridge University Press.

[Cusumano and Selby, 1997] Cusumano, M. A. and Selby, R. W. (1997). How microsoft builds software. *Communications of the ACM*, 40(6):53–61.

[Dangermond, 2010] Dangermond, J. (2010). Geodesign and gis–designing our futures. *Peer Reviewed Proceedings of Digital Landscape Architecture, Anhalt University of Applied Science, Germany*.

[Davis, 1989] Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, pages 319–340.

[DESA,] DESA, U. United nations, department of economic and social affairs, population division: World urbanization prospects, the 2009 revision: Highlights. `http://esa.un.org/unpd/wup/Highlights/WUP2014-Highlights.pdf`.

[Dias et al., 2013] Dias, E., Linde, M., Rafiee, A., Koomen, E., and Scholten, H. (2013). Beauty and brains: Integrating easy spatial design and advanced urban sustainability models. In *Planning Support Systems for Sustainable Urban Development*, pages 469–484. Springer.

[Dijst et al., 2003] Dijst, M., Schot, P., de Jong, K., and te Utrecht, R. (2003). *Framing Land Use Dynamics: Integrating Knowledge on Spatial Dynamics in Socio-economic and Environmental Systems: International Conference 16-18 April 2003; Utrecht University, The Netherlands; Reviewed Abstracts*. Utrecht University.

[Do, 2002] Do, E. Y.-L. (2002). Functional and formal reasoning in architectural sketches. In *Sketch Understanding, Papers from the 2002 AAAI Spring Symposium*, pages 37–44.

[Do, 2005] Do, E. Y.-L. (2005). Design sketches and sketch design tools. *Knowledge-Based Systems*, 18(8):383–405.

[Do and Gross, 1995] Do, E. Y.-L. and Gross, M. D. (1995). Drawing analogies: Finding visual references by sketching. In *Proc. Association of Computer-Aided Design in Architecture, National Conf*, pages 35–52.

[Do and Gross, 2001] Do, E. Y.-L. and Gross, M. D. (2001). Thinking with diagrams in architectural design. In *Thinking with Diagrams*, pages 135–149. Springer.

[Dogan and Nersessian, 2002] Dogan, F. and Nersessian, N. J. (2002). Conceptual diagrams: representing ideas in design. In *Diagrammatic Representation and Inference*, pages 353–355. Springer.

[Dorst and Cross, 2001] Dorst, K. and Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies*, 22(5):425–437.

[Edamura and Tsuchida, 1999] Edamura, T. and Tsuchida, T. (1999). Planning support system for an urban environment improvement project. *Environment and Planning B: Planning and Design*, 26(3):381–391.

[Eikelboom and Janssen, 2015] Eikelboom, T. and Janssen, R. (2015). Comparison of geodesign tools to communicate stakeholder values. *Group Decision and Negotiation*, pages 1–23.

[Ellis, 1999] Ellis, W. D. (1999). *A source book of Gestalt psychology*, volume 2. Psychology Press.

[Ervin, 2011] Ervin, S. (2011). A system for geodesign. *Proceedings of Digital Landscape Architecture, Anhalt University of Applied Science*, pages 145–154.

[Feng and Lin, 1999] Feng, C.-M. and Lin, J.-J. (1999). Using a genetic algorithm to generate alternative sketch maps for urban planning. *Computers, Environment and Urban Systems*, 23(2):91–108.

[Fish, 1996] Fish, J. C. (1996). *How sketches work: a cognitive theory for improved system design*. PhD thesis, Loughborough University.

[Flaxman, 2010] Flaxman, M. (2010). Fundamentals of geodesign. *Proceedings of Digital Landscape Architecture, Anhalt University of Applied Science*.

[Flower et al., 1992] Flower, L., Schriver, K. A., Carey, L., Haas, C., and Hayes, J. R. (1992). Planning in writing: The cognition of a constructive process. *A Rhetoric of Doing: Essays on Written Discourse in Honor of James L. Kinneavy*, pages 181–243.

[Forbus et al., 2001] Forbus, K. D., Ferguson, R. W., and Usher, J. M. (2001). Towards a computational model of sketching. In *Proceedings of the 6th International Conference on Intelligent User Interfaces*, pages 77–83. ACM.

[Frambach and Schillewaert, 2002] Frambach, R. T. and Schillewaert, N. (2002). Organizational innovation adoption: A multi-level framework of determinants and opportunities for future research. *Journal of Business Research*, 55(2):163–176.

[Fricke, 1996] Fricke, G. (1996). Successful individual approaches in engineering design. *Research in Engineering Design*, 8(3):151–165.

[Galle and Kovács, 1992] Galle, P. and Kovács, L. B. (1992). Introspective observations of sketch design. *Design Studies*, 13(3):229–272.

[Geertman, 2008] Geertman, S. (2008). Planning support systems: A planners perspective. *Planning Support Systems for Cities and Regions*, pages 213–230.

[Geertman and Stillwell, 2002] Geertman, S. and Stillwell, J. (2002). *Planning support systems in practice*. Springer Science & Business Media.

[Geertman and Stillwell, 2003] Geertman, S. and Stillwell, J. (2003). Planning support systems: an introduction. In *Planning Support Systems in Practice*, pages 3–22. Springer.

[Geertman and Stillwell, 2012] Geertman, S. and Stillwell, J. (2012). *Planning Support Systems in Practice*. Springer Science & Business Media.

[Gero, 1990] Gero, J. S. (1990). Design prototypes: a knowledge representation schema for design. *AI Magazine*, 11(4):26.

[Goel, 1992] Goel, V. (1992). Ill-structured representations" for ill-structured problems. In *Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society*, volume 14, pages 130–135.

[Goel, 1995] Goel, V. (1995). *Sketches of Thought*. MIT Press.

[Goel and Pirolli, 1992] Goel, V. and Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science*, 16(3):395–429.

[Goldschmidt, 1991] Goldschmidt, G. (1991). The dialectics of sketching. *Creativity Research Journal*, 4(2):123–143.

[Goldschmidt, 1994] Goldschmidt, G. (1994). On visual design thinking: the vis kids of architecture. *Design Studies*, 15(2):158–174.

[Goodman, 1976] Goodman, N. (1976). *Languages of Art: An Approach to a Theory of Symbols*. Hackett publishing.

[Goosen et al., 2007] Goosen, H., Janssen, R., and Vermaat, J. E. (2007). Decision support for participatory wetland decision-making. *Ecological Engineering*, 30(2):187–199.

[Graves, 1978] Graves, M. (1978). Referential drawings. *Journal of Architectural Education*, 32(1):24–27.

[Gross, 1996] Gross, M. D. (1996). The electronic cocktail napkina computational environment for working with design diagrams. *Design Studies*, 17(1):53–69.

[Gross and Do, 1996] Gross, M. D. and Do, E. Y.-L. (1996). Ambiguous intentions: a paper-like interface for creative design. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology*, pages 183–192. ACM.

[Gross et al., 1988] Gross, M. D., Ervin, S. M., Anderson, J. A., and Fleisher, A. (1988). Constraints: knowledge representation in design. *Design Studies*, 9(3):133–143.

[Gruber and Barrett, 1974] Gruber, H. E. and Barrett, P. H. (1974). *Darwin on Man: A Psychological Study of Scientific Creativity*. EP Dutton.

[Guhathakurta, 1999] Guhathakurta, S. (1999). Urban modeling and contemporary planning theory: Is there a common ground? *Journal of Planning Education and Research*, 18(4):281–292.

[Guhathakurta, 2002] Guhathakurta, S. (2002). Urban modeling as storytelling: using simulation models as a narrative. *Environment and Planning B: Planning and Design*, 29(6):895–911.

[Haklay and Tobón, 2003] Haklay, M. and Tobón, C. (2003). Usability evaluation and ppgis: towards a user-centred design approach. *International Journal of Geographical Information Science*, 17(6):577–592.

[Haklay and Zafiri, 2008] Haklay, M. and Zafiri, A. (2008). Usability engineering for gis: learning from a screenshot. *The Cartographic Journal*, 45(2):87–97.

[Hall, 1962] Hall, A. D. (1962). *A Methodology for Systems Engineering*. van Nostrand.

[Harris, 1960] Harris, B. (1960). Plan or projection: an examination of the use of models in planning. *Journal of the American Institute of Planners*, 26(4):265–272.

[Harris, 1965] Harris, B. (1965). New tools for planning. *Journal of the American Institute of Planners*, 31(2):90–95.

[Harris, 1989] Harris, B. (1989). Beyond geographic information systems. *Journal of the American Planning Association*, 55(1):85–90.

[Harris and Batty, 1993] Harris, B. and Batty, M. (1993). Locational models, geographic information and planning support systems. *Journal of Planning Education and Research*, 12(3):184–198.

[Healey, 2006] Healey, P. (2006). *Urban Complexity and Spatial Strategies: Towards a Relational Planning for Our Times*. Routledge.

[Herbert, 1988] Herbert, D. M. (1988). Study drawings in architectural design: Their properties as a graphic medium. *Journal of Architectural Education*, 41(2):26–38.

[Hertz, 1992] Hertz, K. (1992). A coherent description of the process of design. *Design Studies*, 13(4):393–410.

[Hopkins et al., 2004] Hopkins, L. D., Ramanathan, R., and Pallathucheril, V. G. (2004). Interface for a sketch-planning workbench. *Computers, Environment and Urban Systems*, 28(6):653–666.

[Hu et al., 2003] Hu, J., You, S., and Neumann, U. (2003). Approaches to large-scale urban modeling. *Computer Graphics and Applications, IEEE*, 23(6):62–69.

[Hubka and Eder, 1987] Hubka, V. and Eder, W. E. (1987). A scientific approach to engineering design. *Design Studies*, 8(3):123–137.

[Inman et al., 2011] Inman, D., Blind, M., Ribarova, I., Krause, A., Roosenschoon, O., Kassahun, A., Scholten, H., Arampatzis, G., Abrami, G., Mcintosh, B., et al. (2011). Perceived effectiveness of environmental decision support systems in participatory planning: Evidence from small groups of end-users. *Environmental Modelling & Software*, 26(3):302–309.

[Ishii et al., 1993] Ishii, H., Kobayashi, M., and Grudin, J. (1993). Integration of interpersonal space and shared workspace: Clearboard design and experiments. *ACM Transactions on Information Systems (TOIS)*, 11(4):349–375.

[Isikdag and Zlatanova, 2010] Isikdag, U. and Zlatanova, S. (2010). Interactive modelling of buildings in google earth: A 3d tool for urban planning. In *Developments in 3D Geo-Information Sciences*, pages 52–70. Springer.

[Jansen and Rietveld, 1990] Jansen, R. and Rietveld, P. (1990). Multicriteria analysis and gis: an application to agricultural use in the netherlands. *Geographic Information System for Urban and Regional Planning*.

[Janssen, 1992] Janssen, R. (1992). *Multiobjective decision support for environmental management*, volume 2. Springer Science & Business Media.

[Jones, 1963] Jones, J. C. (1963). A method of systematic design. In *Conference on Design Methods*, pages 53–73. Pergamon Press, Oxford/New York.

[Jones, 1992] Jones, J. C. (1992). *Design Methods*. John Wiley & Sons.

[Karlsson,Goran , 2009] Karlsson,Goran (2009). The 8 characteristics of good user requirements. `http://www.slideshare.net/guest24d72f/8-characteristics-of-good-user-requirements-presentation"`, note =.

[Kavakli and Gero, 2001] Kavakli, M. and Gero, J. S. (2001). Sketching as mental imagery processing. *Design Studies*, 22(4):347–364.

[Kavakli and Gero, 2002] Kavakli, M. and Gero, J. S. (2002). The structure of concurrent cognitive actions: a case study on novice and expert designers. *Design Studies*, 23(1):25–40.

[Kavakli and Gero, 2003] Kavakli, M. and Gero, J. S. (2003). Strategic knowledge differences between an expert and a novice designer. In *Human Behaviour in Design*, pages 42–52. Springer.

[Kavakli et al., 1999] Kavakli, M., Suwa, M., Gero, J., and Purcell, T. (1999). Sketching interpretation in novice and expert designers. In *Visual and Spatial Reasoning in Design*, volume 99, pages 209–219.

[Klosterman, 1997] Klosterman, R. E. (1997). Planning support systems: a new perspective on computer-aided planning. *Journal of Planning education and research*, 17(1):45–54.

[Köninger and Bartel, 1998] Köninger, A. and Bartel, S. (1998). 3d-gis for urban purposes. *Geoinformatica*, 2(1):79–103.

[Koomen et al., 2011] Koomen, E., Koekoek, A., and Dijk, E. (2011). Simulating land-use change in a regional planning context. *Applied spatial analysis and policy*, 4(4):223–247.

[Kramer, 1994] Kramer, A. (1994). Translucent patchesdissolving windows. In *Proceedings of the 7th Annual ACM Symposium on User Interface Software and Technology*, pages 121–130. ACM.

[Lamsweerde, 2009] Lamsweerde, A. (2009). *Requirements engineering : from system goals to UML models to software specifications*. John Wiley, Chichester, England Hoboken, NJ.

[Landay and Myers, 2001] Landay, J. A. and Myers, B. A. (2001). Sketching interfaces: Toward more human interface design. *Computer*, 34(3):56–64.

[Langendorf, 1993] Langendorf, R. (1993). The 1990s: information systems and computer visualization for urban design, planning, and management. *Environment and Planning B*, 19:723–723.

[Larkin and Simon, 1987] Larkin, J. H. and Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11(1):65–100.

[Lawson, 2006] Lawson, B. (2006). *How designers think: the design process demystified*. Routledge.

[Lawson, 1979] Lawson, B. R. (1979). Cognitive strategies in architectural design. *Ergonomics*, 22(1):59–68.

[Lea, 1994] Lea, D. (1994). Christopher alexander: An introduction for object-oriented designers. *ACM SIGSOFT Software Engineering Notes*, 19(1):39–46.

[Lee Jr, 1973] Lee Jr, D. B. (1973). Requiem for large-scale models. *Journal of the American Institute of Planners*, 39(3):163–178.

[Ligtenberg et al., 2004] Ligtenberg, A., Wachowicz, M., Bregt, A. K., Beulens, A., and Kettenis, D. L. (2004). A design and application of a multi-agent system for simulation of multi-actor spatial planning. *Journal of Environmental Management*, 72(1):43–55.

[Liu, 1995] Liu, Y.-T. (1995). Some phenomena of seeing shapes in design. *Design Studies*, 16(3):367–385.

[Lloyd and Scott, 1994] Lloyd, P. and Scott, P. (1994). Discovering the design problem. *Design Studies*, 15(2):125–140.

[Lowry, 1965] Lowry, I. S. (1965). A short course in model design. *Journal of the American Institute of Planners*, 31(2):158–166.

[Maher, 1990] Maher, M. L. (1990). Process models for design synthesis. *AI Magazine*, 11(4):49.

[Marchese, Francis, 2013] Marchese, Francis (2013). Requirements specification version 1.0. `http://csis.pace.edu/~marchese/CS775/RequirementsSpecificationTemplate.doc`. [Online; accessed 21-February-2015].

[Menezes and Lawson, 2006] Menezes, A. and Lawson, B. (2006). How designers perceive sketches. *Design Studies*, 27(5):571–585.

[Meng and Malczewski, 2010] Meng, Y. and Malczewski, J. (2010). Web-ppgis usability and public engagement: A case study in canmore, alberta, canada. *URISA Journal*, 22(1):5.

[Mezughi, 1996] Mezughi, M. M. (1996). *The Integral Role of Drawing in Architectural Conception.* PhD thesis, University of Glasgow.

[Mittal and Frayman, 1989] Mittal, S. and Frayman, F. (1989). Towards a generic model of configuration tasks. In *IJCAI*, volume 89, pages 1395–1401.

[Newell et al., 1958] Newell, A., Shaw, J. C., and Simon, H. A. (1958). Elements of a theory of human problem solving. *Psychological Review*, 65(3):151.

[Newell et al., 1972] Newell, A., Simon, H. A., et al. (1972). *Human problem solving*, volume 104. Prentice-Hall Englewood Cliffs, NJ.

[Norman, 1988] Norman, D. A. (1988). *The Psychology of Everyday Things*. Basic books.

[Pelzer et al., 2013] Pelzer, P., Arciniegas, G., Geertman, S., and de Kroes, J. (2013). Using maptable® to learn about sustainable urban development. In *Planning support systems for sustainable urban development*, pages 167–186. Springer.

[Pelzer et al., 2014] Pelzer, P., Geertman, S., van der Heijden, R., and Rouwette, E. (2014). The added value of planning support systems: A practitioners perspective. *Computers, Environment and Urban Systems*, 48:16–27.

[Pereira and Duckstein, 1993] Pereira, J. M. and Duckstein, L. (1993). A multiple criteria decision-making approach to gis-based land suitability evaluation. *International Journal of Geographical Information Science*, 7(5):407–424.

[Pettit et al., 2011] Pettit, C. J., Raymond, C. M., Bryan, B. A., and Lewis, H. (2011). Identifying strengths and weaknesses of landscape visualisation for effective communication of future alternatives. *Landscape and Urban Planning*, 100(3):231–241.

[Purcell and Gero, 1998] Purcell, A. and Gero, J. S. (1998). Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies*, 19(4):389–430.

[Reed, 1974] Reed, S. K. (1974). Structural descriptions and the limitations of visual images*. *Memory & Cognition*, 2(2):329–336.

[Rissland et al., 1998] Rissland, E. L., Kolodner, J., and Waltz, D. (1998). Case-based reasoning from darpa:machine learning program plan. *Proceedings of the Case-Based ReasoningWorkshop. San Mateo, CA: Morgan Kaufmann*, pages 1–13.

[Rittel, 1973] Rittel, H. (1973). The state of the art in design methods. *Design Research and Methods*, 7(2):143–147.

[Rittel and Webber, 1973] Rittel, H. W. and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, 4(2):155–169.

[Rogers, 2010] Rogers, E. M. (2010). *Diffusion of Innovations*. Simon and Schuster.

[Roozenburg and Cross, 1991] Roozenburg, N. and Cross, N. (1991). Models of the design process: Integrating across the disciplines. *Design Studies*, 12(4):215–220.

[Salter et al., 2009] Salter, J. D., Campbell, C., Journeay, M., and Sheppard, S. R. (2009). The digital workshop: Exploring the use of interactive and immersive visualisation tools in participatory planning. *Journal of Environmental Management*, 90(6):2090–2101.

[Saund and Moran, 1995] Saund, E. and Moran, T. P. (1995). Perceptual organization in an interactive sketch editing application. In *Computer Vision, 1995. Proceedings., Fifth International Conference on*, pages 597–604. IEEE.

[Savannah, Georgia, 2015] Savannah, Georgia (2015). Savannah, georgia — Wikipedia, the free encyclopedia. `http://en.wikipedia.org/wiki/Savannah,_Georgia`. [Online; accessed 21-February-2015].

[Scaife and Rogers, 1996] Scaife, M. and Rogers, Y. (1996). External cognition: how do graphical representations work? *International Journal of Human-Computer Studies*, 45(2):185–213.

[Schön, 1988] Schön, D. A. (1988). Designing: Rules, types and words. *Design Studies*, 9(3):181–190.

[Schon and Wiggins, 1992] Schon, D. A. and Wiggins, G. (1992). Kinds of seeing and their functions in designing. *Design Studies*, 13(2):135–156.

[Schooler and Engstler-Schooler, 1990] Schooler, J. W. and Engstler-Schooler, T. Y. (1990). Verbal overshadowing of visual memories: Some things are better left unsaid. *Cognitive Psychology*, 22(1):36–71.

[Sheppard and Meitner, 2005] Sheppard, S. R. and Meitner, M. (2005). Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. *Forest Ecology and Management*, 207(1):171–187.

[Shiffer, 1995] Shiffer, M. J. (1995). Interactive multimedia planning support: moving from stand-alone systems to the world wide web. *Environment and Planning B*, 22:649–664.

[Shiode, 2000] Shiode, N. (2000). 3d urban models: recent developments in the digital modelling of urban environments in three-dimensions. *GeoJournal*, 52(3):263–269.

[Sidlar and Rinner, 2007] Sidlar, C. L. and Rinner, C. (2007). Analyzing the usability of an argumentation map as a participatory spatial decision support tool. *URISA-WASHINGTON DC-*, 19(1):47.

[Simmonds, 1980] Simmonds, R. (1980). Limitations in the decision strategies of design students. *Design Studies*, 1(6):358–364.

[Simon, 1965] Simon, H. A. (1965). The architecture of complexity. *General Systems*, 10(1965):63–76.

[Simon, 1977] Simon, H. A. (1977). The structure of ill-structured problems. In *Models of Discovery*, pages 304–325. Springer.

[Steinitz, 1990] Steinitz, C. (1990). A framework for theory applicable to the education of landscape architects (and other environmental design professionals). *Landscape journal*, 9(2):136–143.

[Steinitz, 2011] Steinitz, C. (2011). getting started–teaching in a collaborative multidisciplinary framework.

[Steinitz, 2012] Steinitz, C. (2012). *A framework for geodesign : changing geography by design*. Esri, Redlands, Calf.

[Steinitz, 2014] Steinitz, C. (2014). Notes on geodesign. Unpublished Personal Correspondence.

[Steinitz et al., 1996] Steinitz, C., Binford, M., Cote, P., Edwards Jr, T., and Ervin, S. (1996). Biodiversity and landscape planning: alternative futures for the region of camp pendleton, california. Technical report, DTIC Document.

[Steinitz et al., 2005] Steinitz, C., Faris, R., Vargas-Moreno, J. C., Huang, G., Lu, S.-Y., Arizpe, O., Angeles, M., Santiago, F., Ivanova, A., Gámez, A. E., et al. (2005). Alternative futures for the region of loreto, baja california sur, mexico. *report from Harvard Universitys Graduate School of Design/Universidad Autónoma de Baja California Sur/University of Arizona/cibnor/San Die go State University/Scripps Institute of Oceanography/Municipality of Loreto, BCS, November*, 17.

[Sturges et al., 1996] Sturges, R. H., O'Shaughnessy, K., and Kilani, M. I. (1996). Computational model for conceptual design based on extended function logic. *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, 10(04):255–274.

[Surowiecki, 2005] Surowiecki, J. (2005). *The wisdom of crowds*. Anchor.

[Sutherland, 1968] Sutherland, N. (1968). Outlines of a theory of visual pattern recognition in animals and man. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 171(1024):297–317.

[Suwa et al., 2000] Suwa, M., Gero, J., and Purcell, T. (2000). Unexpected discoveries and s-invention of design requirements: important vehicles for a design process. *Design Studies*, 21(6):539–567.

[Suwa et al., 1998] Suwa, M., Purcell, T., and Gero, J. (1998). Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies*, 19(4):455–483.

[Suwa and Tversky, 1996] Suwa, M. and Tversky, B. (1996). What architects see in their sketches: Implications for design tools. In *Conference Companion on Human Factors in Computing Systems*, pages 191–192. ACM.

[te Brommelstroet, 2010] te Brommelstroet, M. (2010). Equip the warrior instead of manning the equipment: land use and transport planning support in the netherlands. *Journal of Transport and Land Use*, 3(1).

[Tovey, 1989] Tovey, M. (1989). Drawing and cad in industrial design. *Design Studies*, 10(1):24–39.

[Tovey et al., 2003] Tovey, M., Porter, S., and Newman, R. (2003). Sketching, concept development and automotive design. *Design Studies*, 24(2):135–153.

[Tress and Tress, 2003] Tress, B. and Tress, G. (2003). Scenario visualisation for participatory landscape planninga study from denmark. *Landscape and Urban Planning*, 64(3):161–178.

[Uran and Janssen, 2003] Uran, O. and Janssen, R. (2003). Why are spatial decision support systems not used? some experiences from the netherlands. *Computers, Environment and Urban Systems*, 27(5):511–526.

[Valbuena et al., 2010] Valbuena, D., Verburg, P. H., Bregt, A. K., and Ligtenberg, A. (2010). An agent-based approach to model land-use change at a regional scale. *Landscape Ecology*, 25(2):185–199.

[Van Kouwen et al., 2007] Van Kouwen, F., Dieperink, C., Schot, P., and Wassen, M. (2007). Applicability of decision support systems for integrated coastal zone management. *Coastal Management*, 36(1):19–34.

[Verburg et al., 2002] Verburg, P. H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., and Mastura, S. S. (2002). Modeling the spatial dynamics of regional land use: the clue-s model. *Environmental management*, 30(3):391–405.

[Voinov and Bousquet, 2010] Voinov, A. and Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software*, 25(11):1268–1281.

[Vonk and Geertman, 2008] Vonk, G. and Geertman, S. (2008). Improving the adoption and use of planning support systems in practice. *Applied Spatial Analysis and Policy*, 1(3):153–173.

[Vonk et al., 2005] Vonk, G., Geertman, S., and Schot, P. (2005). Bottlenecks blocking widespread usage of planning support systems. *Environment and Planning A*, 37(5):909–924.

[Vonk et al., 2007] Vonk, G., Geertman, S., and Schot, P. (2007). A swot analysis of planning support systems. *Environment and Planning A*, 39:1699–1714.

[Vonk and Ligtenberg, 2010] Vonk, G. and Ligtenberg, A. (2010). Socio-technical pss development to improve functionality and usabilitysketch planning using a maptable. *Landscape and Urban Planning*, 94(3):166–174.

[Voss et al., 2003] Voss, A., Voss, H., Gatalsky, P., and Oppor, L. (2003). “prototype and further requirements of a real participatory gis”. In *Proceedings of the 6th AGILE Conference on Geographic Information Science (Presses Polytechniques et Universitaires Romandes, Lausanne) pp*, pages 613–622.

[Waddell, 2002] Waddell, P. (2002). Urbansim: Modeling urban development for land use, transportation, and environmental planning. *Journal of the American Planning Association*, 68(3):297–314.

[Walz et al., 1993] Walz, D. B., Elam, J. J., and Curtis, B. (1993). Inside a software design team: Knowledge acquisition, sharing, and integration. *Communications of the ACM*, 36(10):63–77.

[Wegener, 1994] Wegener, M. (1994). Operational urban models state of the art. *Journal of the American Planning Association*, 60(1):17–29.

[Williams and Re Velle, 1996] Williams, J. and Re Velle, C. (1996). A 0-1 programming approach to delineating protected reserves. *Environment and Planning B*, 23:607–624.

[Wilson, 1994] Wilson, T. D. (1994). The proper protocol: Validity and completeness of verbal reports. *Psychological Science*, 5(5):249–252.

[Wu et al., 2010] Wu, H., He, Z., and Gong, J. (2010). A virtual globe-based 3d visualization and interactive framework for public participation in urban planning processes. *Computers, Environment and Urban Systems*, 34(4):291–298.