Design sketches and sketch design tools

Ellen Yi-Luen Do

Computational Design Laboratory, School of Architecture, Carnegie Mellon University, Margaret Morrison Carnegie Hall 403, 5000 Forbes Ave, 201 CFA, Pittsburgh, PA 15213, USA

Abstract

In early stages of design architects often use sketching and diagramming to perform formal and functional reasoning. Design sketches are an external representation aid for visualization and evaluation of the spatial arrangements of artifacts. Symbols and configurations are used in design sketches to define context and object arrangements. This paper argues the need to study design drawing, reports the findings from empirical studies of design drawings, and describes the software systems implemented to support intention inference and automated activation of knowledge-based design tools to support design.
© 2005 Published by Elsevier B.V.

1. Introduction—motivation

Designers sketch. The ubiquitous cocktail napkin diagrams and tracing paper sketches in architectural folios, exhibits, and their working environment—studios and offices alike, demonstrates the important roles of drawing artifacts and sketching activities in design. Designing is a knowledge-based activity. This creative act involves analyzing, synthesizing and integrating information such as production requirements and constraints. Diagrams and sketches are symbolic representation that designers developed for problem solving and spatial reasoning for their specific domain or discipline. Functional and formal design intentions are often embedded in architectural sketches. Can then, a computer recognize and understand these intentions from designer's sketches and further provide feedback or assistance to the designer? Can a computer provide appropriate knowledge-based design tools at the right time for the tasks at hand?

We are interested in building computational tools to support design reasoning through the interface of freehand sketching. Therefore, it is important to approach the issues from two distinct perspectives: (1) study of design sketches and (2) implementation of sketch design tools. We focus on the designer's drawing conventions that a computer might understand, and the relationship between drawing and design intent. We describe a computer-based freehand sketching environment for design that tries to deliver the right tools at the right time by interpreting a designer's drawings. Rather than asking the designer to find and select tools for specific design tasks, we explore the idea of automatically invoking various computational tools based on the designer's drawing. Developing such a system creates both conceptual and technical problems. If a sketching environment is to present the designers with an appropriate tool, it must recognize what the designer is doing. Conceptually, this requires that there is a link between overt behavior—the marks that the designer makes on the paper or in the computer—and the designer's information needs. Hence, the first part of the paper discusses design studies to understand if there are drawing conventions shared by architectural designers that might be incorporated into a sketching environment. It is argued that designers do share drawing conventions, both at the level of the individual glyph and at the level of the combination of symbols, and that these conventions map onto the tasks that the designers are engaged in. The second part of the paper discusses the technical implementation of the design environment. This environment encompasses several sketch design tools that allows the designers to keep sketches in ambiguous, 'sketchy,' states. It operates on complex

E-mail address: ellendo@cmu.edu.

systems of symbols within sketches, including the topological relationships among symbols. It provides access to a wide range of additional information tools.

The rest of the paper is organized as follows. In Section 2 we argue the importance of sketching activities in conceptual design stages. Section 3 reports empirical studies conducted to investigate how functional and formal intentions are embedded in design sketches and Section 4 presents case studies of architectural design drawings. Section 5 presents freehand sketching software tools implemented to support various knowledge activities in design. Finally, we conclude with discussions and possible future research directions.

2. Why study design drawing

The act of drawing is important not only as a vehicle for communication with others, it actually helps designers see and understand the forms they work with [1]. In the early design process, architects sketch to help themselves to see, to reason, and understand the form they work with, and to explore functional ideas and solutions. Designers—especially architects—are trained to use paper and pencil when developing conceptual designs. Architects are visually oriented and are taught to think graphically [2,3]. They draw to develop ideas graphically, and in the process of drawing, designers communicate their thinking. These drawings are valuable in understanding how designers work. Each drawing marks on paper could represent an outline for a space (room, courtyard) or object (furniture, wall and column) or a path of force (e.g. wind, rain, light ray or circulation).

'Drawing' in this paper is used to mean the freehand diagrams and sketches designers draw and use in their early design stages. Designers use the term 'drawing' and 'sketches' generally to represent all the kinds of marks they make when designing: ranging from concept sketches to construction drawing. Here, in particular, we are referring to freehand drawings instead of drafting or construction drawings. Drawing serves as external symbol systems to facilitate thinking and support emergent ideas. Fish argues that sketches help designers attend to thought and help trigger short-term memory [4]. Goel argues that drawings are used as 'external symbol systems' to represent real world artifacts which can be manipulated and reasoned with [5]. Mezughi argues that sketching is 'the principal means of visualising design solutions and crystallizing the thinking process' [6].

We also use the term 'drawing' to refer to the making of drawing marks. Designers use the act of drawing to help them discover and explore ideas. The activity of drawing includes both seeing and thinking about the subject being represented. Design drawing is an iterative and interactive act involving recording ideas, recognizing functions and meaning in the drawings. It also involves

finding new forms and adapting them into the design. Designers 'see' and then 'move' the manipulated design objects in their drawings [7]. Schon described the kinds of seeing and their functions as (1) literal visual apprehension of marks on a page, (2) appreciative judgments of quality, and (3) apprehension of spatial gestalts. Goldschmidt views sketching as an operation of design moves and arguments, an 'oscillation of arguments' that brings about a gradual transformation of images [8]. She argued that a designer interacts with drawing with 'seeing as' and 'seeing that' reasoning modalities. Suwa and Tversky claim that designers draw to externalize their concepts and that drawings provide visual cues for revision and refinement of ideas [9].

Recently, we have seen research work and computational systems to support sketching in various domains. Hearst, Landay, Gross and Stahovich outlined sketching systems that support design of user interface, web page, and mechanical device [10]. Landay's system recognizes interface designer's sketches of widget symbols and supports interaction behaviors [11]. In the similar spirit, a military course of action planning can be supported with a simple sketch system [12]. They argued that electronic sketching tools provide designers focus on the task at hand, on spatial relations and structure of the design instead of specific detailed look and feel of the drawing [11,13]. These arguments hold true especially in the domain of architecture where the tool of the trade is drawing [14]. Herbert argues that drawing are more than just a convenient strategy for solving design problems, suggesting that they are 'the designer's principal means of thinking' (p. 1), and that a designer 'must interact with the drawing' (p. 121) [15].

3. Empirical studies of design sketches

To determine whether, and to what extent, it is possible to infer, interpret, or even guess what a designer was thinking about by looking at the drawing she has made, we have conducted several empirical studies on design and drawing. We are interested in how drawings get made, and what specific knowledge and reasoning process they represent. Specifically, we are concerned with the thought processes that underlie the operations comprising a drawing. These controlled studies attempt to answer two questions: (1) What different activities and drawings consistently appear in the conceptual stages of design? and (2) How are symbols and drawing conventions associated with different design activities.

The studies include (1) data analysis of 62 architecture students' concept diagramming, (2) video transcripts and protocol analysis of four architects conducting design of an architect's office. The hypothesis is that designers represent architectural concepts in a consistent and conventional way, using a limited set of diagrammatic elements. In order to

generalize how different designers actually use design diagrams in different contexts and check for consistency, the first empirical study was designed to see how diagrams are related to certain design concerns (represented as problems, responses, and stories from an architecture case library). The experiment asked design students to both draw and interpret a variety of diagrams representing architectural issues derived from post-occupancy data. The purpose of the experiment is to test the feasibility of using diagrams as a way to access design information. The second design drawing experiment was set up to more generally investigate the relations between drawings, their configurations and design intentions in the process of design. The hypothesis is that designers use common drawing conventions when they design. Moreover, the conventions used will depend on the design concerns being considered. If this is true, the drawing conventions used in design concept experiment (first study) would be consistent with the sketches used in a design process (second study). The goals of the empirical studies are thus (1) to verify the findings about drawing conventions, (2) to further investigate design context and intentions as they are reflected in drawing conventions, and (3) to establish a record of the experiment to demonstrate the feasibility of making drawing convention computable.

3.1. Archie diagram story experiment and graphic symbol conventions

The first study used design stories and diagrams from a case-based design aid called Archie ([16–18]). The database library of Archie contains case stories, problems and responses from post-occupancy evaluation data collected in field studies of ten courthouses and libraries. All related items are cross-linked. These case stories include textual descriptions associated with pictures, videos, or diagrams.

This study focuses on diagrams that explain design issues of environmental forces, building components, and human responses. The term 'diagram' is used here to mean a drawing that uses geometric elements to abstractly represent natural and artificial phenomena such as sound, light, wind, and rain; building components such as walls, windows, doors and furniture; and human behavior such as sight, perception of privacy, and circulation, as well as territorial boundaries of spaces or rooms.

3.1.1. Experiment sequences and test materials

Sixty-two undergraduate design students participated in the experiment. They were divided into four groups, each of which had a different task sequence (Table 1). The tasks included (1) making diagrams from stories, (2) writing stories from given diagrams, (3) pairing diagrams and stories, and (4) commenting on existing Archie diagram–story pairs.

Twenty-four Archie text-diagram story pairs were selected for the four tasks of this experiment. Each task

Table 1
Groups and their respective test variations

Group	Task sequence	Story titles	Participants
A	1–2–3–4	Yes	17
B	1–2–3–4	No	17
C	2–1–3–4	Yes	11
D	2–1–3–4	No	17

has six sub-tasks, and each sub-task used a different story. Each participant was given four tasks (Table 2). In each task, the first three sub-tasks were concerned with architecturally problematic situations (problems), and the second three sub-tasks with possible design responses to an architectural problem (responses). The time spent by participants on all tasks ranged from 30 min to 1 hour.

The first task (1) asked participants to illustrate given text describing an architectural story. For example, Fig. 1 shows the text from a (response) sub-task of task 1:

Wall as Acoustic Insulation
Use thick walls between courtrooms and public areas to reduce sound transmission.

Fig. 1. Example material for task 1, diagram-making task.

The second task (2) asked participants to write a brief text description for a given architectural diagram. Fig. 2 below shows a (problem) diagram for task 2 with its title.

The third task (3) asked participants to match six diagrams with six textual descriptions. Two sets of three diagrams and three text paragraphs were arranged in rows and the participants were asked to pair them. Fig. 3 shows one example page.

The fourth and final task (4) asked participants to simply comment on six diagram–text pairs taken from the Archie case library. For example, Fig. 4 shows a (response) diagram–text pair from this task.

3.1.2. Experiment results

This study revealed four significant features of design diagram making [19]. First, participants used only a limited set of symbols to represent design concepts. Second, concepts suggest sectional or plan preferences. Third, keywords were used as text labels in plan diagrams. Fourth, there is consistent interpretation of diagrams among designers.

Table 2
Standard task sequence in a test (for group A and B)

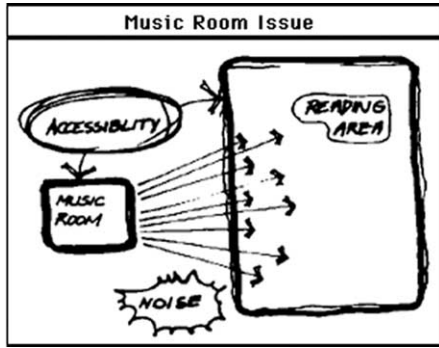| Task sequence	Tasks
Pre-test questionnaire	Background information
Task 1	Illustrating texts
Task 2	Interpreting diagrams
Task 3	Pairing diagrams and texts
Task 4	Commenting archie diagram–text pairs
Post-test questionnaire	Comments and suggestions about the experiment

Fig. 2. Example material for task 2, a diagram illustrating architectural problem with a text title.

3.1.2.1. Graphic symbols represent design concepts. From the experiment, we found that designers use graphic symbols to represent certain 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. The basic drawing elements—the lines, arrows, and geometric shapes—the 'primitives' are used in diagrams in a variety of different domains, and are not limited to architectural design. When primitives are combined, they can form symbols to represent architectural objects such as walls and windows or to illustrate natural phenomena such as sun and human figures. Fig. 5 shows graphic symbols used by the participants to represent human figure, sun with sun rays, walls and windows.

3.1.2.2. Design concepts suggest sectional or plan preferences. Results from task 1 showed that participants seem to share a preference for using plans or sections to illustrate certain architectural concepts. For example, most participants chose a plan view to illustrate relations between different functional spaces and acoustics, but chose a sectional view to illustrate lighting conditions and sight lines. Table 3 below shows that (except for task 5) each of the six sub-tasks in task 1 resulted in a strong preference for either plan or section diagrams.
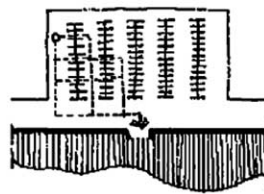
Fig. 6 shows a pattern of preference for plan and section diagrams was found from the experiment results. Functional problems suggest the use of plans, whereas lighting or sight line problems suggest the use of sections. Problems 1, 3, and response 1 dealt with functional placement of spaces, and used plan-based representation. Problem 2, and response 3 concerning natural lighting lead to the use of sectional diagrams with symbols for light and sectional walls. Response 2 was about visual contact to the children's area, which involved both the arrangement of functional spaces and consideration of visual sigh lines, and hence resulted in a mix of plan and section diagrams.

3.1.2.3. Keywords as text labels in plan diagrams. From the experiment we found that participants were more likely to include keywords from the given text as labels in plan diagrams than in sections. The descriptions about noise and privacy resulted in plan diagrams produced a higher percentage of diagrams with label. The tasks that involved lighting and sight lines produced a higher percentage of section drawings without labels. Functional spaces were mostly labeled by placing text inside a shape (oval, blob, or rectangle), occasionally beside the shape with an arrow or line pointing to the shape. In contrast, concept labels such as 'supervise,' or labels of material, such as 'walls,' 'frosted glass' were usually placed beside the shapes with or without a pointer (line or arrows). Fig. 7 shows diagrams using keyword such as map room (problem 1), courtroom and public area (response 1) as labels. No surprisingly, labels in the diagrams were used by the participants in writing the interpretive texts.

3.1.2.4. Consistent diagram interpretation among designers. The results from all tasks demonstrated that participants shared similar and consistent interpretations of the diagrams. For example, when given diagrams consisting of bubbles with labels and arrow lines (about the relation of noise and accessibility to a music room and reading area), participants introduced the concept of separation, writing that accessibility leads to adjacency of the two areas and noting that concerns about noise transmission should be addressed by a soundproof buffer. Participants performed
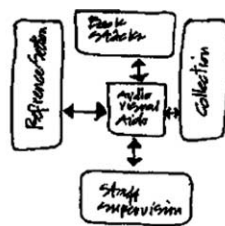
Fig. 3. Example page for pairing test, task 3, diagrams on top row, and texts on bottom row with different sequence.
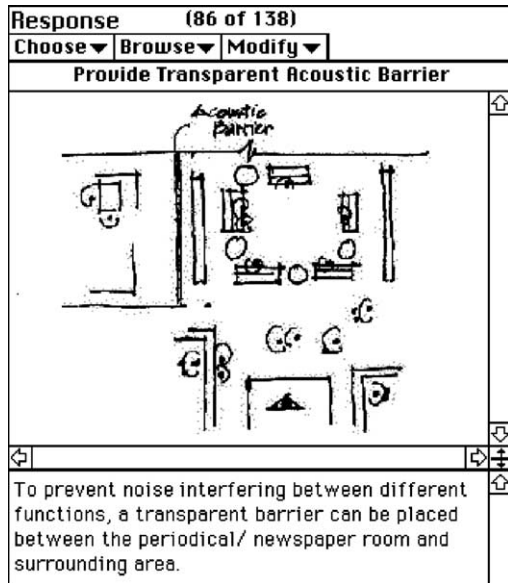
Fig. 4. Example material for task 4, an architectural response diagram–text set from Archie.

the diagram–text pairing exercises (task 3) with ease and most participants agreed with the Archie diagram–text pairs (task 4). They interpreted other designer's diagrams or texts as they were intended. This suggests that designers mostly agree with each other's diagrams.

The experiment results support the hypothesis that diagrams are used in a consistent way to represent different issues in architecture. They shared an understanding of the definition of diagram, only used a small set of symbols in their drawings and arranged them in conventional and consistent ways.

3.2. Design context and intentions

To understand more about the role of drawing in design, one needs to look also at sketches made in the design process, not only at diagrams. From the previous study, we have identified several drawing conventions with respect to specific design context and intentions. For example, attention to lighting is often indicated by arrows, attention to functional arrangements with bubble diagrams. However, this previous study only deals with diagrams drawn to illustrate given design concerns, not those drawn in the context of a real design task. This raises an obvious next question: do designers use the same drawing conventions when thinking about design concerns when they design? In order to answer this question, we conducted protocol studies in which participants were asked to perform design tasks while attending to different design concerns [20].

3.2.1. Design drawing experiment setups, and tasks

Two architectural instructors and two senior design students participated in this experiment. Each of them was given a design brief for an architect's office and a sequence of four tasks, where each task asked the participant to focus on a particular issue. The experiment was set up to obtain the designers' drawings made in response to each individual task. Video recording was introduced to record actions taken in design, and the relations to the verbal descriptions of design intentions. Participants were asked to 'think aloud' describing what they were thinking when they design. The design program was to design an office for an architecture firm in a 70 ft by 25 ft one-story warehouse, providing workspace for 3 architects, 3 CAD operators, 2 contract draftsmen, a secretary and 1–2 student interns.
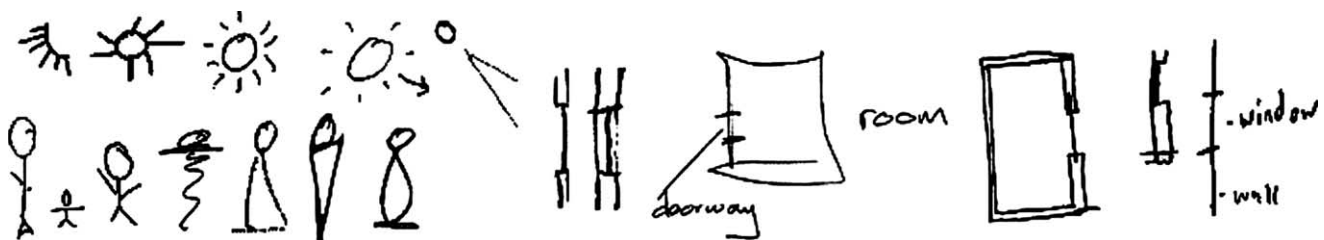

Fig. 5. Graphic symbols for sun, people, walls and windows.

Table 3
Number of plan and section diagrams drawn in task 1

#		Summary of text	Plan	(%)	Section	(%)	Other	(%)
1	P1	Map room location	58	94	0	0	4	6
2	P2	Natural lighting create glare	3	5	52	84	7	11
3	P3	Fun children's section	45	73	14	23	3	5
4	R1	Thick walls to reduce noise	40	65	8	8	14	23
5	R2	Visual contact to children's area	25	40	31	50	6	10
6	R3	Glass windows for lighting	7	11	52	84	3	5

#, Sub-task number, P1, problem 1, R1, response 1, total participants=62 (100%).
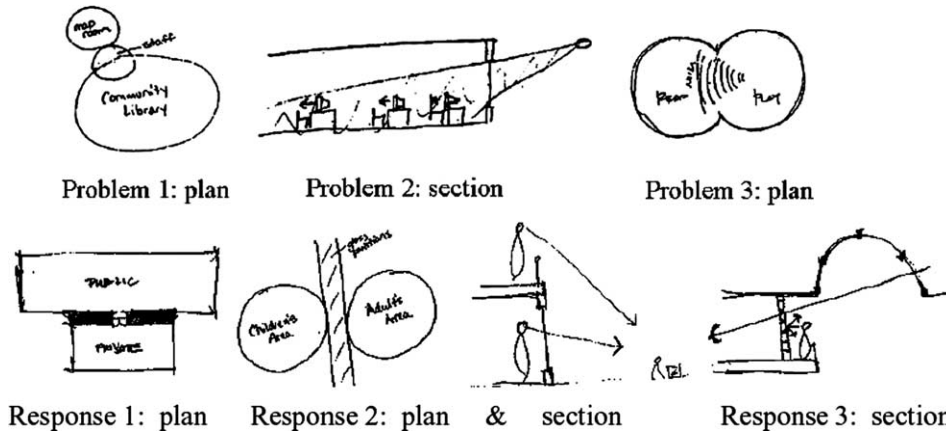
Fig. 6. Diagram examples showing view preference for descriptions, problem 1—plan representations, problem 2—sectional diagrams and problem 3—plan diagrams. Response 1—plan view, response 2—both plan and section and response 3—sectional representation.

The office was to be designed to have space for work groups, a meeting room, a small kitchenette, a bathroom, and a chief architect's private office, a general affairs section, storage space, printing and plotting area.

After reading the design program, designers were to start with a new sheet of paper (or tracing paper) for each task and to focus on four different concerns in conceptual, schematic design. The tasks include (1) spatial arrangement, (2) lighting, (3) visibility and privacy, and (4) fitting a special piece of furniture into the design.

Task 1 was to make a conceptual, schematic design for the above program and pay particular attention on zoning arrangements. The instruction sheet included suggestions to consider where to put the lobby, chief architect's office, meeting room, and the different work group spaces. Task 2 asked the designer to pay particular attention to lighting issues with the suggestions of considering the window location on the wall and introduce skylight into the office if plausible. Task 3 focused on the visibility and privacy concerns between different spaces. For example, one could

consider making each work group space to command a fine view to the exterior, or an easy access to the meeting area. Task 4 asked the designer to make sure the meeting room is large enough to accommodate the chief architect's favorite meeting table (4 ft×10 ft), as well as making sure the designers' work space would have at least 800 ft^2. Similar to the previous study, a pre-experiment questionnaire was included in the instruction sheets to collect basic background information such as their design experience, and the use of freehand drawing in communication or design process. A post-experiment questionnaire was given to solicit suggestions and evaluations of the task difficulties and their personalized symbols or short hands for design. Participants were asked to complete the first tasks in 10, and 5 min for each successive one. The two students followed the instructions and performed the experiment within 30 min. However, the two instructors simply ignored the time constraints and spent about half an hour each to perform the first task. Therefore, the time spent by participants for the entire design experiment ranged from
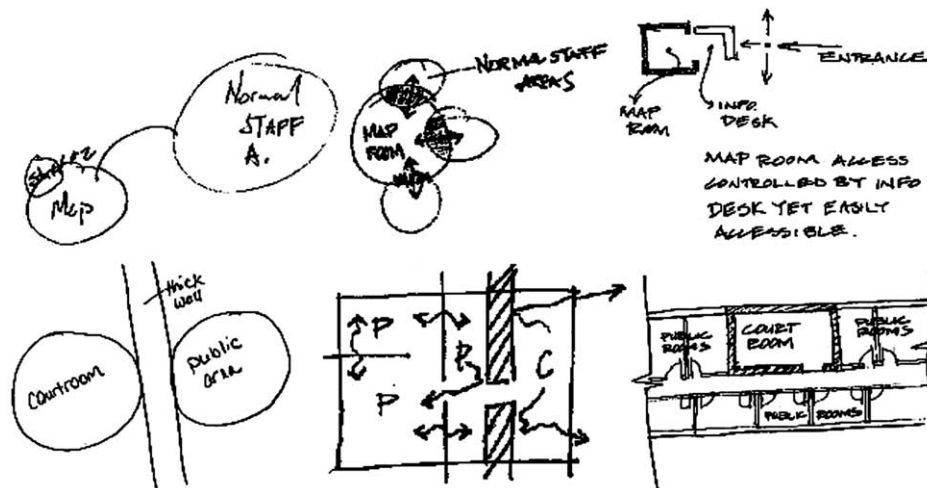

Fig. 7. Example of diagrams using keyword given in the text to label a space. Top: 'map' in map room location problem. Bottom: 'P' and 'C' or 'public' and 'court' for architectural response to reduce noise between courtrooms and public areas.

Fig. 8. Top: primitives (drawing elements) used in drawing included arrows, lines, hatches and simple geometric shapes. Bottom: symbols (architectural objects) such as walls, windows, and stairs are formed by combination of primitives.

30 min to 1½ h. All of the participants told the observer that they enjoyed the design experiment. The two participating instructors even commented that they were ready to make detailed design and physical models after they completed the design experiment.

3.2.2. Findings from design sessions

The four designers all have at least 3 years of design studio education in college with some experience working at architecture firms. A detail description of the profile of participating designers, detail analysis of the design sessions and the sample transcripts of the protocol can be found in [21]. Below we briefly describe the experiment results.

3.2.2.1. Designers share drawing conventions: symbols and their configurations.
The conclusion from the experiment sessions and the post-experiment questionnaires is that designers use drawing symbols in their design in a consistent fashion. Participating designers chose primitives from a limited universe of geometric shapes and symbols in their drawings, and composed them in highly conventional ways, just as the results of the previous study. Fig. 8 shows that primitives such as ovals and rectangles were drawn with varying size and aspect ratios, and combined together as symbols to represent architectural objects. For example, a symbol for direction North was composed with an arrow and a letter N; lines were composed to indicate walls and windows; and circle with lines or a blob was drawn to indicate a person.

3.2.2.2. Designers draw furniture in space and to put themselves in context.
Another finding of the experiment is that designers draw simple shapes representing furniture in order to put themselves in the right context to think about design. The construction of a space includes architectural elements such as walls and windows. However, additional symbols of furniture often are arranged in a configuration to represent how the space will look and feel. For example, top row of Fig. 9 shows variations of a conference table for the conference room in task 4 and bottom row shows different furniture placed in space for a lobby and office space. Designers used these symbols as a scale indicator and to see and test if the size and dimension of the space is appropriate.

3.2.2.3. Lighting concerns are portrayed in sectional view with light rays.
The result of the experiment suggests that different design concerns tend to be correlated with either sectional or plan representations. The experiment asked the designers to focus on separate issues such as zoning, lighting, visibility and dimensioning. As in our previous study of diagram making, participating designers seem to share a preference for using plan or section to illustrate certain architectural concepts. For example, participants used conventional symbols for the sun, light rays, windows and walls; some drawings also included symbols for persons and computers. Fig. 10 shows lighting included in a sectional view, with light from the sun passing through the building envelope. The changed direction arrows
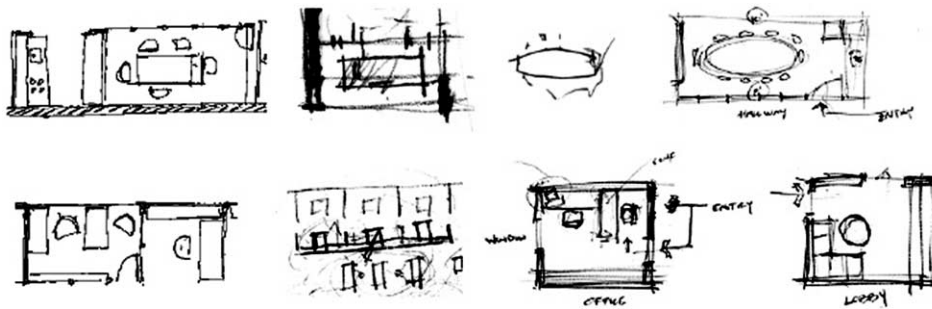

Fig. 9. Symbols give clues for context. Top row: symbols for the conference space including tables and chairs. Bottom row: furniture drawn for office space arrangement.
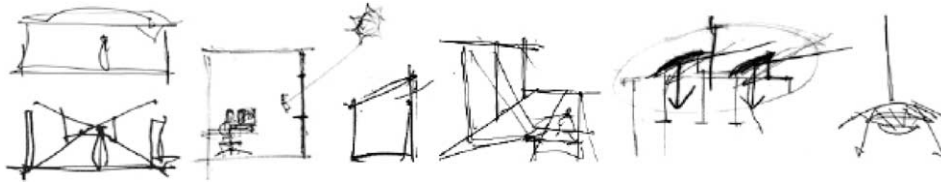
Fig. 10. Drawings illustrate lighting by using light lines that penetrate building envelope from windows and roof.
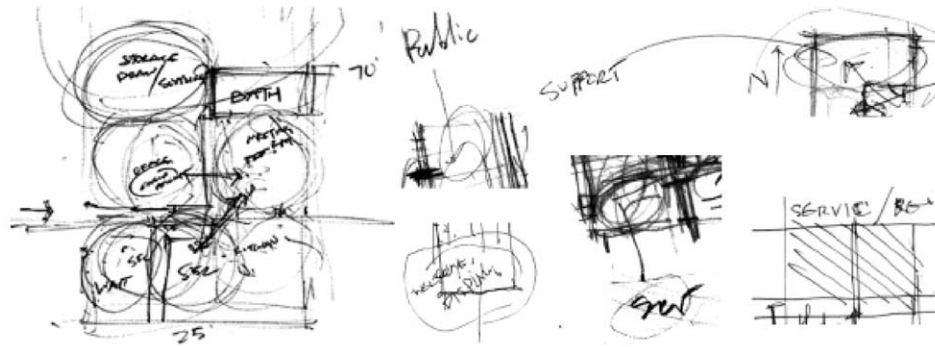

Fig. 11. Diagrams for layout and zoning included overtracing (circle) to select a space, labels inside the shapes, or lines drew out to indicate space use, and putting emphasis through hatching.

indicate reflecting light from a roof skylight (second to right) and in an interior lighting fixture design (right).

3.2.2.4. Attention and focus can be identified through labels and overtracing. The design drawings from the experiment exhibited that plan drawings have more text labels than sections. The data also revealed that participants frequently included key words from the design concepts as labels in their drawings. Designers wrote text to label the functions or names of the space. Fig. 11 shows examples of the labels for functional spaces written inside a containing shape (oval, blob, or rectangle), or occasionally put beside the shape with an arrow or line from the label pointing to the shape it identified. The video protocols of the empirical studies showed that designers constantly engaged in overtracing, repeated outlining a particular shape or area of the drawing. This overtracing, or redrawing, serves as an act of selection, that draws attention to an element, refines a shape, adds detail to the drawing, or explain something. Designers also used hatching to distinguish a particular space from others.

3.2.2.5. Designers perform dimensional reasoning through figure calculations. When thinking about allocating objects or spaces within required dimensions, designers wrote down numbers besides the drawing to reason about scale and calculate sizes. For example, a participating designer drew dimensional marks with $10'$ intervals along the length of the site (three $10's$ and a $7'$). Then he checked to see if the table could fit into the conference room (20×10). First he wrote down the dimension of the table (4×10), calculated and wrote down the answer 40, and doubled it (80) for buffer space. Designer wrote down a sequence of numbers to label dimensions, to calculate the square footage requirement, and to reason about what the width and length of a space should be. Fig. 12 shows the drawing and annotations of the reasoning process derived from the verbal protocol.

The results from this experiment verified the hypothesis that graphic conventions also appear in a design process. In both empirical studies, we found that novice and experienced designers consistently using diagrams and symbol configurations in their drawing to help them thinking about the design context. For example, when thinking about
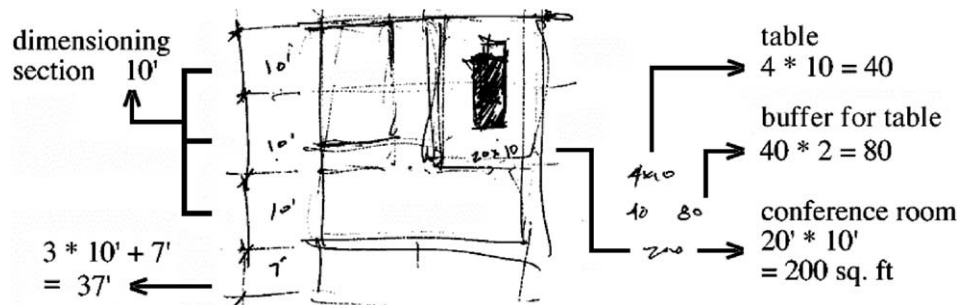

Fig. 12. Dimensional reasoning for spatial arrangement according to program square footage requirements (numbers, markers and calculations).
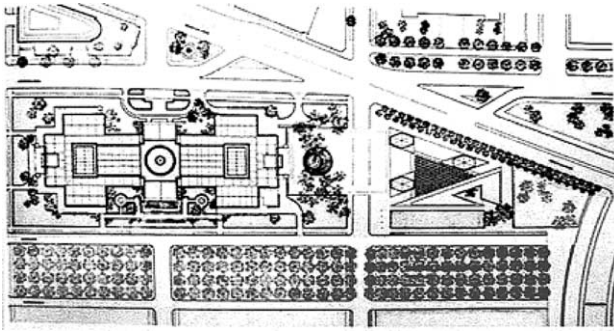
Fig. 13. Site plan for the east building, National Gallery of Art (drawn after ([26])).

spatial arrangements of functional spaces, designer would draw bubble diagrams to represent the rooms and their connections. They also drew graphic symbols for furniture objects to put themselves in the context of the design problems. When thinking about lighting concerns, a designer would draw a configuration consisting of an arrow penetrating a vertical wall with window, representing a light ray in a sectional view.

4. Case studies of design drawings

In the field of architecture and industrial design the notion of design being the integration of form and function is widely accepted and followed [22]. Architect Louis Sullivan introduced the dictum 'Form follows Function' [23] in 1896 to explain that his building design follows natural law. Later Frank Lloyd Wright further argued that "form and function are one"[42]. Many modernist architects and designers share this notion. There are often debates about whether form precedes function or vice versa [24,25]. However, it's in the common training and education of

architects that successful building should incorporate form and function together.

4.1. The case of Pei's National Gallery of Art

The east building of National Gallery of Art designed by I. M. Pei is a good example of how conceptual drawing evolves to account for the form and functional arrangements of the building. The east building was designed to extend space for programming and to act as complement to the west building. It was a design task to provide not only organization and functional needs, but also to fit in a none-regular (trapezoidal) site with strict restrictions of setback lines from the surrounding streets and aesthetic principles (symmetry, axis, etc). Fig. 13 shows the spatial relationships of the National Gallery of Art's original west building and the east building on site.

The early design concepts kept in Pei's notebook or diary shows concerns about the axis of the west building (Fig. 14, left), and extending it to divide the trapezoidal lot into several triangles, as shown in Fig. 14 (right). This could be interpreted as design reasoning concerning only the form factors.

Examining Pei's design drawings from a formal perspective reveals that the shapes or the form are tightly connected to the function of the spaces. At first glance, the drawings in Fig. 15 share similar shapes and structure. They all have triangle components. The three drawings on the right are actually from facing pages of the notebook. It appeared that these explorations of geometrical formal arrangements were not just useful construct to respond to symmetry and site constraints, these shapes also served as tokens representing functional concerns that can be manipulated and moved. Functions were embedded in the graphic symbols of these drawings.

The first sketch on the left is a very simple diagram showing two triangles, one isosceles and one right triangle.
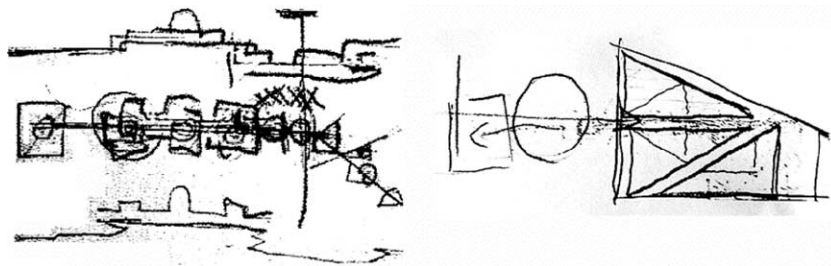

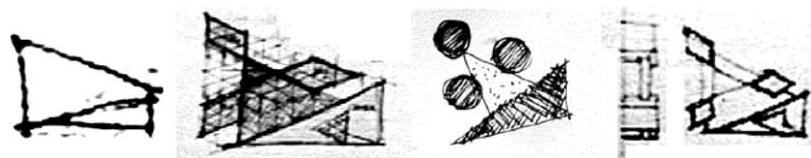Fig. 14. Concept sketch, site analysis, and spatial arrangement (drawn after pei [26]).

Fig. 15. Design drawings from the design notebook (after pei [26]).

The second sketch is much more elaborate. The motif of triangles has become patterns covering several areas. The final building uses the triangle pattern for the space frame above the concourse that connects exhibition space and the Center for Advanced Study. The lower triangle shows a courtyard arrangement. The form of triangle serves the purpose of functional support for the frame. The third sketch is diagrammatic. Each circle represents an independent museum as noted in the notebook [26], and connected to the bottom right triangle with another triangle. The last sketch shows the symmetric feature of the west building. Each gallery has a prism shape and is connected by bars to the other two galleries. These bars seemed to represent container for circulation traffic or corridor. The opening courtyard in the lower triangle seemed to be a simplified representation of the second sketch.

This series of diagrams explain the development of the east building from preliminary concept stage to the final building realization. This formal arrangement solves the problem of the site; at the same time it provides functional space for two programming requirements. The isosceles triangle is used for exhibition galleries, and the right triangle is the Center for Advanced Study and other scholarly and administrative functions. These two functional spaces are connected by a triangle concourse, an atrium with skylights. The three corners of the isosceles triangle became gallery towers connected by bridges.

Stories of how these drawings account for the design, and the solving of aesthetic and engineering decisions are abundant [26,27]. The descriptions of form and function in design development are usually inter-connected. Besides the evolution of architectural drawings in the design process, some other drawings also shed light on what actions designer take when thinking about design. One example is the move or projection from two-dimensional floor plan drawing to three-dimensional isometric drawing. Fig. 16 shows a 3D isometric drawing derived from the 2D plan.

Pei's sketches also showed the development of the design involved trying out alternatives such as changing the arrangements and locations of the design components. Fig. 17 shows a pair of the east building design with similar shapes but different details. An architectural component, the opening courtyard for the Center of Advanced Study

Fig. 17. The location of the opening or courtyard for the Center of Advanced Study (occupying the right triangle at the bottom) are different in these two design sketches. The opening on the left scheme is on the south side, while the drawing on the right has the opening from the slope of the triangle. (after pei [26]).

appeared in different locations in the two drawings. This is not surprising. Designers often move, rotate, and transform design elements in their drawing to make formal arrangements. It is worth noting that in this case, the transformation of the drawing elements involves functional arrangements as well. Any move of functional space would result a change of circulation pattern and spatial relations, and hence induce a sequence of design moves and reasoning.

4.2. Architect's design sketches

Our retrospective analysis and story telling of Pei's design process with drawing may be compelling. However, was his use of sketching in functional and formal reasoning a personal style? Is there a convention of operation for design drawing that designers follow? Below we looked at several famous architects' drawings to investigate how different drawings are used in design.

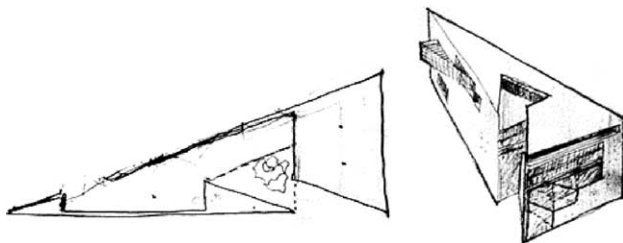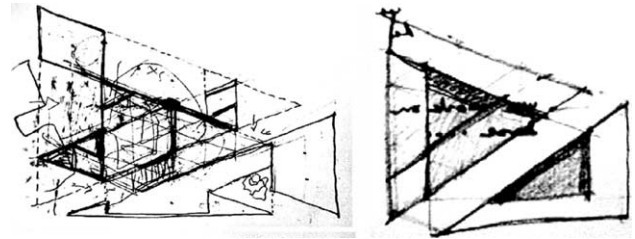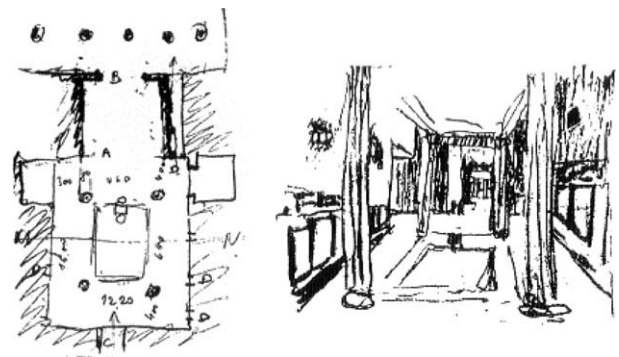Fig. 18. Sketch (plan and 3D) of the house of the Silver Wedding, Pompeii, 1911 (after Le Corbusier [36]).

Fig. 16. (1) Design of the Center for Advanced Study with courtyard. (3) Isometric drawing of the volume for the Center for Advanced Study (after pei [26]).
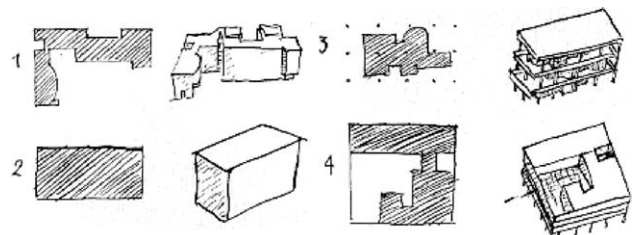

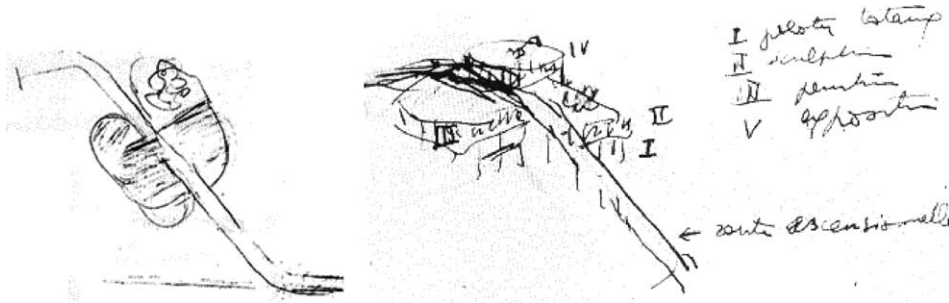Fig. 19. Variations on the House Forms (after Le Corbusier [37]).

Fig. 20. Concept sketches of the Carpenter Center (pencil and colored pencil on trace, after Le Corbusier [38].

Let's first look at study drawings. Fig. 18 shows the sketch of the Silver Wedding space Le Corbusier's had made in his Pompeii trip. A plan sketch was composed of lines and circles representing level change, walls and columns. Short line marks with regular intervals seemed to indicate dimensional spacing. A 3D perspective sketch accompanied the plan diagram to show spatial relations among these architectural elements.

While practicing as an architect, Le Corbusier also wrote numerous articles on his theories of architecture. His ideas for the house forms includes diagrams of both plan figures as well as 3D isometric drawings. As show in Fig. 19, the 3D massing drawings appeared to be simple extrusions from the plan diagrams.

Corresponding plans and 3D views also frequented appeared in Le Corbusiner's design sketches. For example, Fig. 20 shows the concept sketches for the design of the Carpenter Center for the visual arts. Le Corbusier in the early design process did not only draw plan diagram, he also drew 3D isometric views. It appeared that it's a common habit of the architect to think about 3D from 2D and vice versa.

This convention of drawing 3D views that derived from the plan diagram is a common practice among designers. Fig. 21 shows that architect Peter Eisenman's sketches for the house of cards used simple extrusion from the floor plan drawing to form 3D view. Symbols of architecture elements such as columns, walls, doors, and windows also appeared in the drawing. Short hand representations for the sink and toilet were included to represent the bathroom. These graphic symbols are a medium for designers to represent different concerns and to put themselves in the context for thinking about spatial arrangement.

Drawing conventions such as dimensional marking and calculation for functional considerations can also be found from architect's drawings. Fig. 22 shows representation of dimensional reasoning in Eisenman's (left) and Mies van der Rohe's drawings of Ulrich house (right).

4.3. Design moves and transformation

We also conducted a retrospective analysis study on an architect's drawings of a pavilion house design.

The architect had been engaged in formal manipulations of the design for a residence over the course of 15 years and archived all the drawing into six CD-ROMs. The architect shared with us his drawings to explore the possibility of a diagram or object based indexing and retrieval (instead of having to input descriptive text for every single drawing). We looked at 110 drawings selected by the architect and developed a coding scheme to classify these drawings into different categories. This study resulted a conceptual framework to account for connections among the drawings (reported in detail in [28]. Our study attempts to identify relationships between drawings in order to understand the role of formal reasoning in a design process. What began as a thought experiment resulted in a range of plausible interpretations to account for what might have actually happened in the design process. The interpretations were made through several iterations of sorting, classification and coding. The results were later compared with the designer's retrospective examination of the drawings.

Many of the drawings are composed of more than one drawing and consist a composition of plan, sectional, or isometric views of the floor plan, or study variations of a façade. The drawing types ranged from plan collage, concept sketch, to section and 3D isometric sketch. We divided the composite drawings into individual drawings and coded them with unique identifiers and drawing properties. Fig. 23 shows the common architectural elements and their codes (in parenthesis). For example, E1
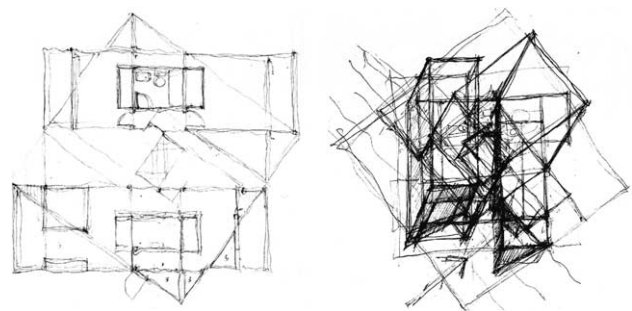

Fig. 21. Study sketches: plan layout (left) and 3D volume extrusion from plan (right) (after Eisenman [39]).
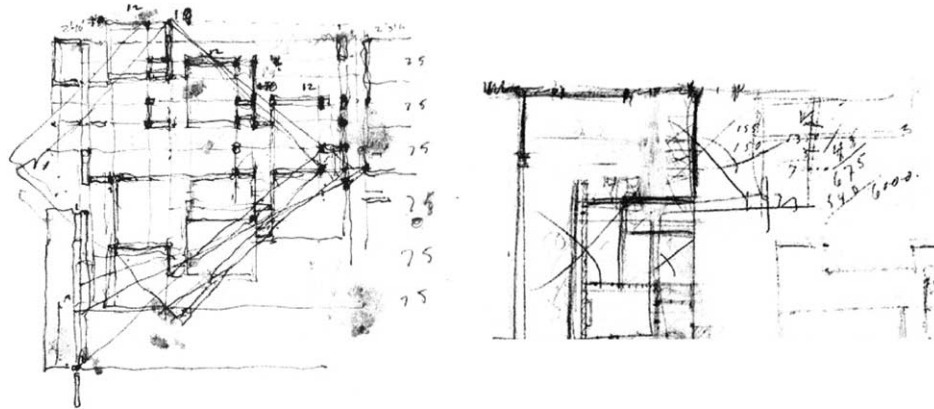
Fig. 22. Plan sketches showing dimensional reasoning. Left: House V (after Eisenman [39]). Right: Ulrich Lange house, (after Mies van der Rohe [40]).

represents a column, E2 represent a wall, and E12 represents a vertical window.

The scheme codes properties of the drawings such as the elements depicted as well as projection types and view angles of the building. The elements of the design drawings includes architectural general elements such as wall, column and balcony, as well as more specific artifacts for the pavilion house design including light monitor, chimney box, and bridge. Each element is identified with a name and a coding annotation. Several drawing types (e.g. plan, section, isometric) and viewing directions (e.g. north, south, northwest) and the medium used for the drawings (pencil, pen, maker, CAD) are also identified. Table 4 shows categories of classifications with four drawings and their codes.

To identify the transformation among drawings, the coding scheme accounts for the transformations of the design elements such as geometric translations of shapes, locations and color. The letter codes E, L, T, and C correspond, respectively to element identifiers, location identifiers, transformation types, and the use of a color. Element location can be specified as placement on a 3×3 location grid. For example L1 represents the top left grid, L5 in the center, and L9, bottom right corner. Location change, rotation, and scaling of the element can be represented as different type of transformation. Object transformation of moving to the right is coded as T1, 90° clockwise rotation, T5. The colors of the drawing such as yellow, light blue, and red are coded as C1, C2, and C4, respectively. Table 5 shows codes for element types, transformation, location and medium used.

With the coding scheme, we can then formulate a description among any two drawings. Fig. 24 shows three design drawings, the 3×3 location grid, and the expressions of transformations of the staircase between them. For example, the transformation between the first two drawings (I and II) can be represented as the expression

$$E16@L4 \rightarrow (T4 + T1 + T17) \rightarrow @L9$$

This expression indicates that the design element #16 (staircase) at location #4 (middle left) moves down (transformation #4), moves right (transformation #1) and rotates 180° (transformation #17) to location #9 (lower right).

The location of the staircase (E16) is identical between two drawings (Fig. 24, II and III). There is no transformation (T17) of the location (L9: lower right) of element #16 between two drawings. Therefore, it would be coded as

$$E16@L9 \rightarrow (T16) \rightarrow @L9$$

The codes and expressions enable easier comparison and sorting of the element types and operations. The number of types and fields associated with each drawing can then be extracted and represented as manipulations of symbolic operations.

Our coding scheme is quite low-level, dealing with the specific characteristics and relationships of drawings. However, this exploratory study broadened our understanding of the role design drawings play in design. A designer manipulates design objects (elements) through transforming shapes and locations, and changing viewpoints and drawing types and media to explore design alternatives. Previous designs are used to generate design alternatives, and are also to predict the outcomes of new proposals (by applying transformations to various design objects). The designer manipulates the visualized representations to evaluate the consequences of design moves. The manipulations are simple,
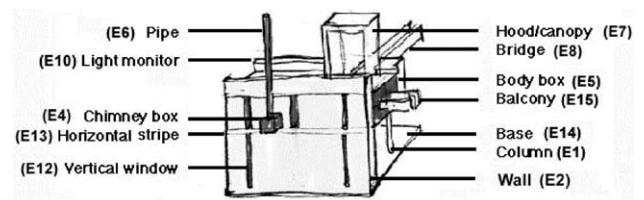

Fig. 23. Principal architectural elements for the pavilion house (with coding for element types).

Table 4
Example drawings in coded table of different classifications

ID #	Drawing	Elements	Location	Drawing Type	View angle	Medium
P1-9a (P2-16)		E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E12, E12, E12, E12, E13, E14, E15		3D Frontal Isometrics (D3 + D4)		pencil (M1) yellow, red, blue markers (M4)
P1-7g (P2-14)		E1, E2, E3, E4, E5, E5, E5, E6, E7, E8, E9, E10		Section (D3)		pencil (M1)
P1-9f (P2-15f)		E1, E2, E3, E4, E5, E6, E9, E10, E14		Section (D3)		pencil (M1)
P1-5a		E2, E2, E3, E5, E7, E8 E16		Plan (D1)		pen (M2)

but in combination the process became complex. Once a design object is placed (designed) in an appropriate position, elaboration and reformulation of both the object and the context (other objects) are conducted.

We found the designer 'plays games' by defining rules, selecting strategies and design moves between self-imposed rules, and discovering and evaluating the outcome. We found each of the design elements transformed throughout the design process: i.e. through change of dimensions, orientation and placement.

5. Computational sketching tools

The findings from the empirical studies validates the hypothesis that designers draw symbols and arrange their configurations differently when thinking about different design concerns. The case studies of architect's drawings further provide evidence that designers use drawing symbols in design thinking and dimensional reasoning, use 3D drawing to visualize the spatial form, and manipulate object transformations of architectural elements. The

Table 5
Codes for elements, transformations, locations, and color

Elements	Transformation	Location (in plan)	Color
E1: column	T1: move right	L1: top left	C1: yellow
E2: wall	T2: move left	L2: top center	C2: light blue
E3: thickened wall	T3: move up	L3: top right	C3: dark blue
E4: chimney box	T4: move down	L4: middle left	C4: red
E5: body box	T5: rotate 90 CW	L5: middle center	C5: black frame only
E6: pipe	T6: rotate 90 CW	L6: middle right	C6: black
E7: hood/canopy	T7: enlarge length	L7: bottom left	C7: white
E8: bridge	T8: reduce length	L8: bottom center	C8: light gray
E9: small box	T9: enlarge width	L9: bottom right	C9: dark gray
E10: light monitor	T10: reduce width		C10: green
E11: horizontal window	T11: enlarge height		C11: orange
E12: vertical window	T12: reduce height		C12: other
E13: horizontal strip	T13: shape change		
E14: base	T14: removed		
E15: balcony	T15: added		
E16: stair case	T16: no transformation		
E17: other	T17: rotate 180		
	T18: other		

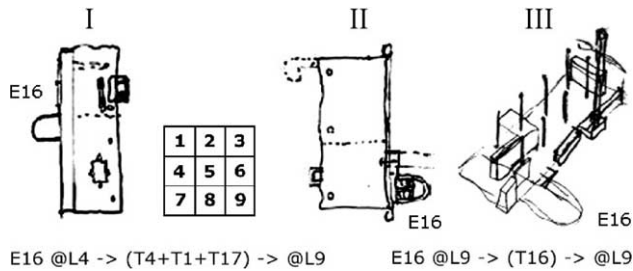| 1	2	3
4	5	6
7	8	9

Fig. 24. Staircase (E16) in drawing I (left) is moved (T4: down, T1: right, and T17: rotate 180) to a different location (from L4 to L9) in drawing II (middle). The location of the staircase is identical between drawing II (middle) and drawing III (right) and coded as transformation T16 (no transformation).

conclusions from above studies suggest that one can describe the relationships between drawing symbols and designers' intention in different design contexts. For example, when thinking about lighting concerns, designers draw section diagrams of a sun and light ray that penetrate a window. If this is true, then an intelligent assistant (be it human or computer) could offer the right tool for the task at hand. For example, a layout bubble diagram can activate design cases with similar configurations. View lines drawn on a floor plan can bring up a visual analysis tool.

Recognizing that it is possible to associate symbols and spatial arrangements in a drawing with the designer's intention, or task context, we have designed a right-tool-right-time framework with implemented computational tools to use freehand sketching as an interface to intelligent systems for design. These design tools include using diagrams for knowledge and image retrieval, building performance simulation, and three-dimensional model making for early stages of design [21,29]. Below we describe the implementation of right-tool-right-time software architecture and several application modules involving knowledge-based design tools.

5.1. The right tool at the right time architecture

The right-tool-right-time system described here is to demonstrate that it is possible for a computer program to recognize drawing symbols and, based on those symbols, activate different design tools. The system is based on several assumptions. First, in order to be useful, knowledge-based design tools must be available at the right time. Second, different design activities need different kinds of supporting tools. Third, drawing conventions such as symbols and diagrams can serve as clues to activate the right design tools at the right time. The system building efforts and the studies of design drawings were carried out at the same time. Both work reinforced each other: the empirical work provided the basis of the system-building and the system-building provided questions and hypothesis for further investigation. Therefore, right-tool-right-time is not a system based strictly on empirical studies to support

design drawing intentions. Rather, it was built to explore the possibility of recognizing design drawings and intentions with the current implementations.

The right-tool-right-time system basically activates different design assistants based on inferences made from a design drawing, as the designer engages in a design process. The conceptual diagram of the right-tool-right-time control structure has a process flow of (1) drawings, (2) contexts, (3) intentions, and (4) design tools. As show in Fig. 25, the top row of the diagram shows an example array of different drawing fragments—symbols and configurations. Here we show five examples: a bubble diagram of a spatial arrangement, a diagram of a building façade, a viewshed analysis drawing of a person with view lines in a plan view, a numeric calculation, and a 3D solid mass study. Then a design intention recognizer (represented here as a rounded box) attempts to infer design intentions from given drawing symbols and configurations within a recognized context. The identified intentions (represented as boxes)—spatial arrangement, image query, view analysis, number calculation, and mass study are then issue commands to design assistants through an inter-application communicator (rounded box). The design assistants, or knowledge-based design systems, are portrayed here as cylinders on the bottom row of the diagram. These systems include: the Archie case library, the Great Buildings Collection, the Isovist visual analysis program, a calculator, and a three-dimensional modeling program. The inter-application communicator sends commands using a standard event protocol to other programs on the same platform. For example, a command could query a database or activate a simulation program to support the task at hand.

5.2. Symbol and configuration recognizer

At the most basic level of symbolic processing, our systems capture stroke data from the tablet and use the pen path and stroke features (speed, corner, aspect ratio, etc) to identify symbols drawn by the designers [30,31,35]. A symbol could be a single-stroke glyph, or consisted of multi-strokes glyphs. A low-level recognizer starts the processing and display recognition upon a pen-up action. Drawing primitives such as circles, arrows and boxes, which may consist of one stroke or multiple strokes can be recognized. Configuration recognizer automatically considers the spatial relationships between all drawn elements after the systems detects inaction (duration preference is adjustable). It identifies any configuration in the drawing that matches a previously defined one, groups its components into a compound symbol and displays the name of the identified configuration. For example, a 'window' is identified when a group of a symbols in a specific configuration (a vertical line directly connected to two long rectangles, one above, and one below) is found. Likewise, a wiggly line drawn directly below a horizontal line is identified as a symbol for the 'ground'.
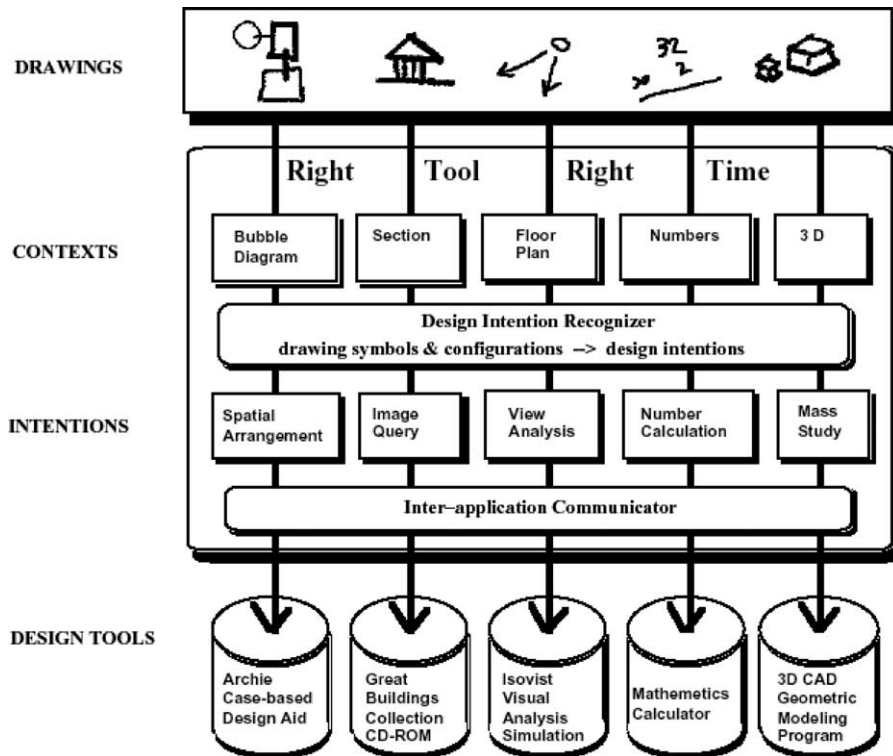
Fig. 25. The conceptual model of the right-tool-right-time drawing environment. Top: different drawing symbols and configurations. Middle: (1) context identification, (2) intention recognizer, (3) inter-application communicator. Bottom: different design tools that would be activated based on detected intentions through drawing symbols and configurations.

Designers can also turn off the recognition display, or ask the background processor not to resolve ambiguous symbol until further information is given that helps the program identify the context. Resolving ambiguous intentions is necessary because the same drawing symbol could mean different things in different context [31,35]. For example, a circle on a floor plan could mean a column while a circle outside and above a building section with a line penetrating the building envelope would be the sun and light ray. Similarly, a circle with alphabet neighbors is likely to be an alphabet O while a circle next to a number is likely to be the number zero. A higher-level recognizer deals with analysis of spatial relations among drawing symbols and the combination thereof. For example, a big circle surrounded by small squares on a floor plan could mean a dining table set.

5.3. Context and intention recognizer

After recognition of symbols and configurations, the system attempts to identify the context of a drawing. The context recognition function will set the variable 'context' to be the identified context and add it to the list of the current contexts (a variable named 'current-context-chain'). It then executes any necessary mappings and attempts to recognize all configurations in the current context. When the designer starts drawing, the initial context is 'shapes'. When the designer stops drawing for two seconds, the program activates the background recognizers. The recognizer looks first in the current context for templates to identify the symbols in the drawing. If no match is found, the system searches symbol templates in the other contexts. For each symbol in the drawing, a list of the possible matches with the symbol templates is returned. If the most likely match is in a context other than the current one, then that context is returned as a candidate for 'current context'. If a symbol is unique to this found context, then the system sets the current context.

The right-tool-right-time identifies context based on existence of special symbol or configuration to trigger an intention recognizer. For example, A 'gound' symbol is unique to a 'section' context. Therefore, after recognizing the 'ground' context (horizontal line directly above wiggly line), the system sets the current context to be 'section'. Fig. 26 shows a recognized 'window' configuration in the 'shapes' context (on the left), when a wiggly-line placed directly below an horizontal line is being recognized as a symbol for the 'ground' the current context is changed to be 'section' (right).

An 'intention configuration' is recognized by the existence and interrelationships of one or more special configurations in the current context. For example, an intention about 'computer monitor glare' is named as an intention configuration called 'monitor_glare' and identified through the co-existence in a drawing of (1) a sectional drawing context, (2) lighting symbols (e.g. sun and light
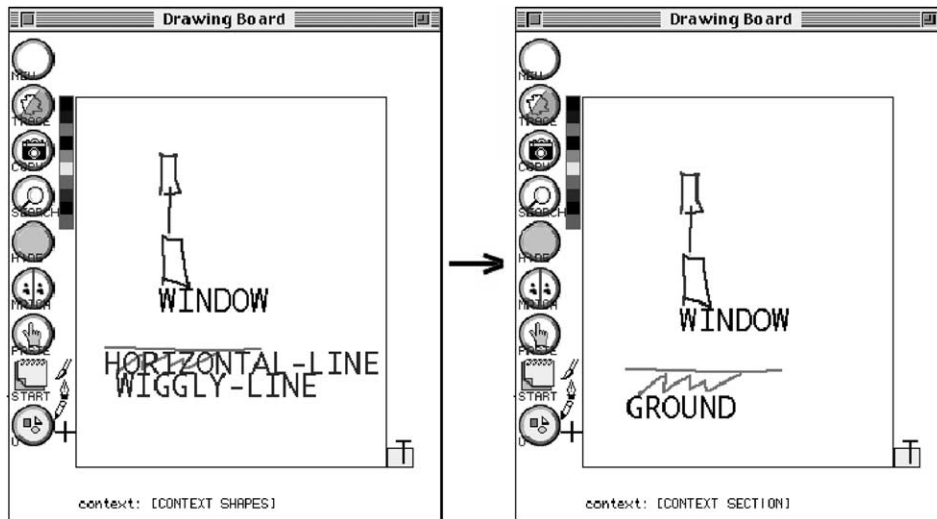
Fig. 26. A 'ground' symbol is composed of a horizontal line and a wiggly-line (left). The names of the elements are replaced by the new name of the configuration (and sets the context to 'section').

ray), and (3) a computer monitor symbols. Once design intention is recognized in the drawing, the system would automatically activate the appropriate tools for the task at hand.

For example, the intention and context information derived from the drawing would activate keyword search on a web search engine or a database. Fig. 27 shows that an intention of 'monitor glare' is recognized by seeing the configuration of a computer (monitor and hard drive) and a sun ray (sun symbol with arrow indicates light direction). This intention activates the browser to launch a keyword search using a web site. The same interaction can be applied to other knowledge-based systems, a slide library, or a case library like Archie.

Another example translates drawing symbols as input to a simulation program. This involves first the identification of the inferred intentions (based on symbol configurations, the intention-application-mapping table, and the current context), activation of the tool, and also interpretation and translation of the designer's drawing into the appropriate data formats. The translation of drawing to the tool-specific format enables designers to use the tool without having to follow complicated inputting procedures. For example, when a 'view' (visual perception) intention is recognized, right-tool-right-time translates all the lines in the 'floorplan' context as 'wall lines' and passes them to the visual analysis simulation program called Isovist [32]. The 'view' symbol is also passed on to the program so that the designer can then
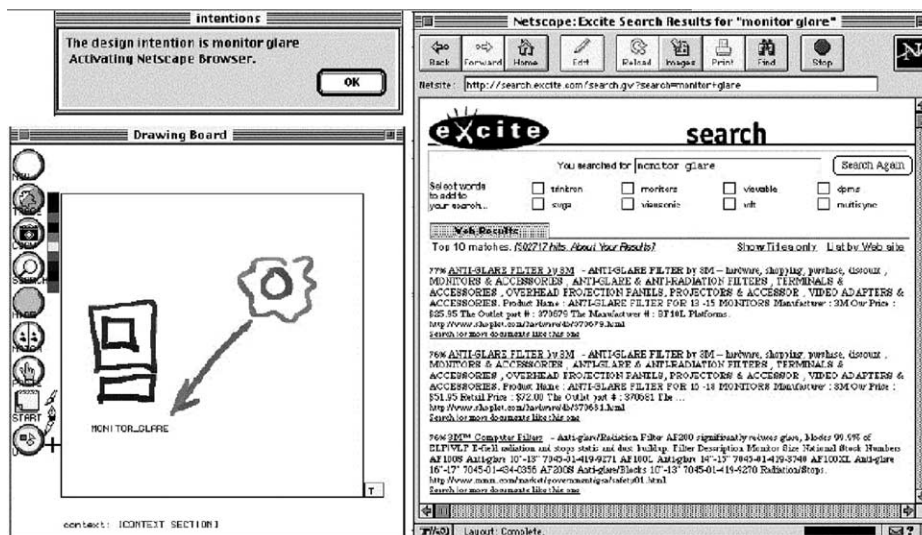

Fig. 27. When a 'monitor_glare' intention is recognized, (bottom left) a message prompts the user (top left) and it activates a web browser (right), requests a keyword search and the search returns a list of relevant information.
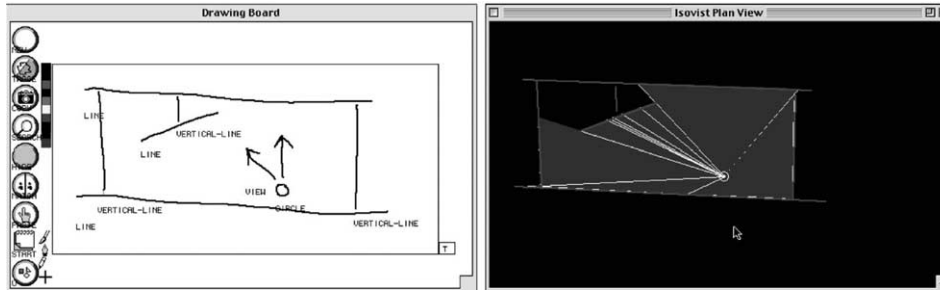
Fig. 28. A 'view' intention recognized in a 'plan' context results in the translation of wall lines (lines) and a view point (arrows and circle) sent to the Isovist visual simulation program.

freely move the view point and receive immediate feedback (plots and calculations of the visible area). Fig. 28 shows that once the system recognizes the intention of 'view,' the symbols of viewpoint and lines from the drawing are translated into the program for simulation.

5.4. Finding visual references

The right-tool-right-time system provides several modules to retrieval of visual references. A diagram with an identified intention can act as an input to querying databases of design information. For example, a design diagram with a 'spatial arrangement' intention will activate a search to the Archie database to find the closest match diagram index and retrieves the associated design information. Fig. 29 shows a story of library's Adult and Children's sections concerns retrieved by a diagram of spatial arrangement.

Designer often searches visual references to find inspiration. For example, a designer might browse through magazine pictures to find ideas and make sketches to record them. A designer working with a circular floor plan might collect pictures of round shaped buildings, textiles with circle patterns, and even still life paintings of fruit baskets with apples, oranges and watermelon. Later the designer might incorporate those pictures into design drawings to produce a lobby hall with a dome roof, patterns for a rose window and floor tiles, and even perhaps a color scheme inspired by fruit.

We argue that different database items indexed and retrieved by a similar diagram could help designers access more visual references for creative designing. Fig. 30 shows that a spiral diagram brings up images of natural and man made environment from a variety of databases. These visual references could range from the geometry construction of logarithmic spiral of the Golden Section, to the pattern of human's fingerprint, to images of galaxy and the shell of a chambered nautilus, to architecture elements such as a column of ionic order, a staircase, or a floor plan.

5.5. Graphics interpreter of design actions

With the coding scheme developed for the pavilion house analysis, a module of a Graphics Interpreter of Design Action—attempts to manage drawing comparison and sorting of the diagrams. This module enables a user to diagram over a picture underlay of design drawing and to generate an analysis of the drawing itself and its relationships with other drawings. For example, a diagram's topological and geometric relations among parts of the drawing can be recorded and used in comparison to another diagram traced from a different design drawing to reveal the spatial transformations among the elements. Fig. 31 shows a pair of design drawings traced from the pavilion house façade study. The system lays out a 3×3 grid over the
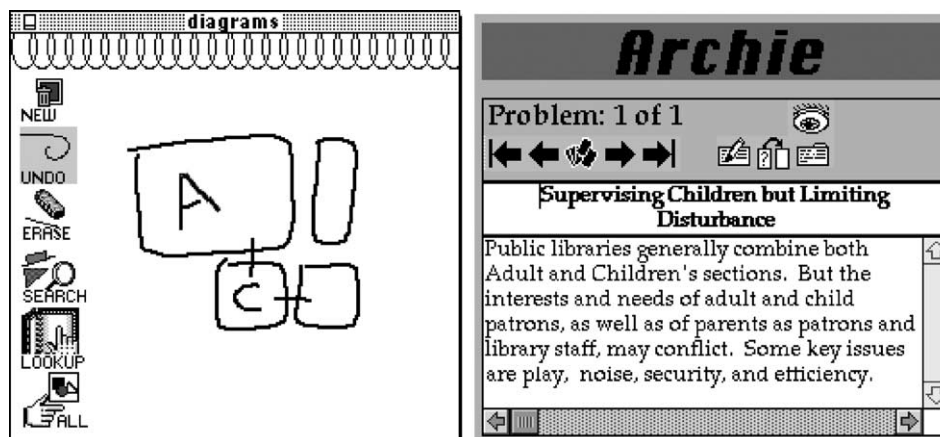

Fig. 29. Spatial arrangements diagram retrieves a case about the arrangement of adult (A) and children's (C) sections in library from Archie database.
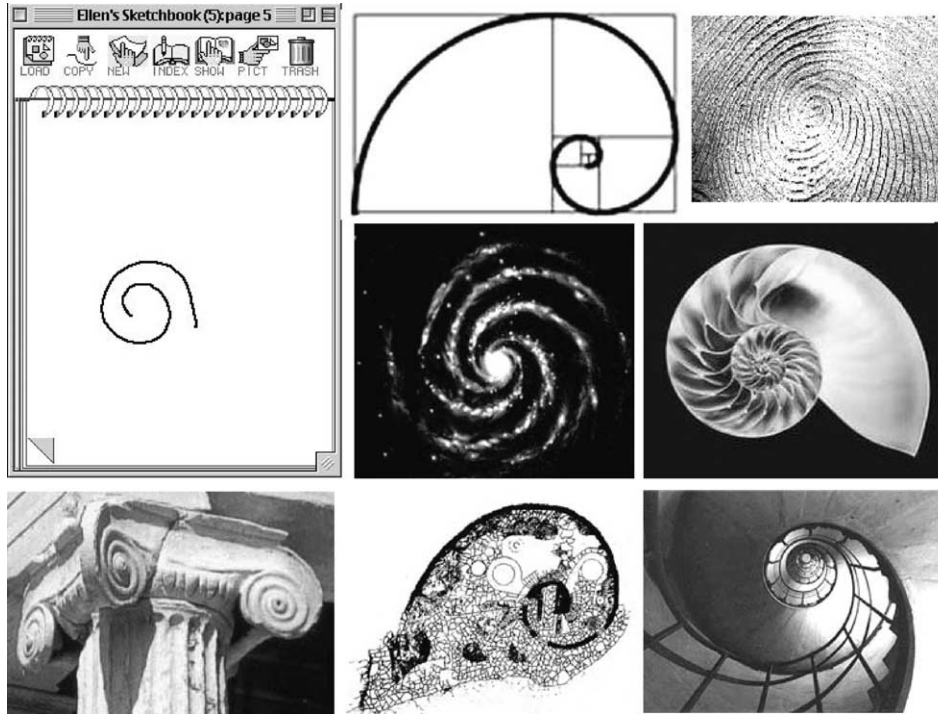
Fig. 30. A spiral diagram (top left) retrieves images of: (1) a construction drawing of golden spiral, (2) portion of a finger print, (3) a spiral galaxy, (4) cut section of nautilus shell, (5) capital of an ionic order column, (6) floor plan of Bavinger house (after Goff, in [41]), and (7) a photograph of a spiral staircase.

drawing and generates a list of occupied cell numbers for each object.

Table 6 shows the list of elements for each drawing and their corresponding cell sequence generated from the comparison. In this example, drawing #1 has nine elements: thick wall (large box), chimney box (small box connected with), chimney pipe (short line), vertical windows (2 long lines and 1 short), hood (top right), and horizontal strips (horizontal lines). Drawing #2 has eight elements: thick wall, chimney box and chimney pipe, vertical window (1 on the right), and horizontal strips (4 parallel lines). Each element has a position in the global coordinate system and a list of the local grid cell sequence. For example, the location of V-window 1 has the location value of (6 9) in drawing #1, and the value of (3 6 9) in drawing #2. The Horizontal Strip 1 appeared approximately
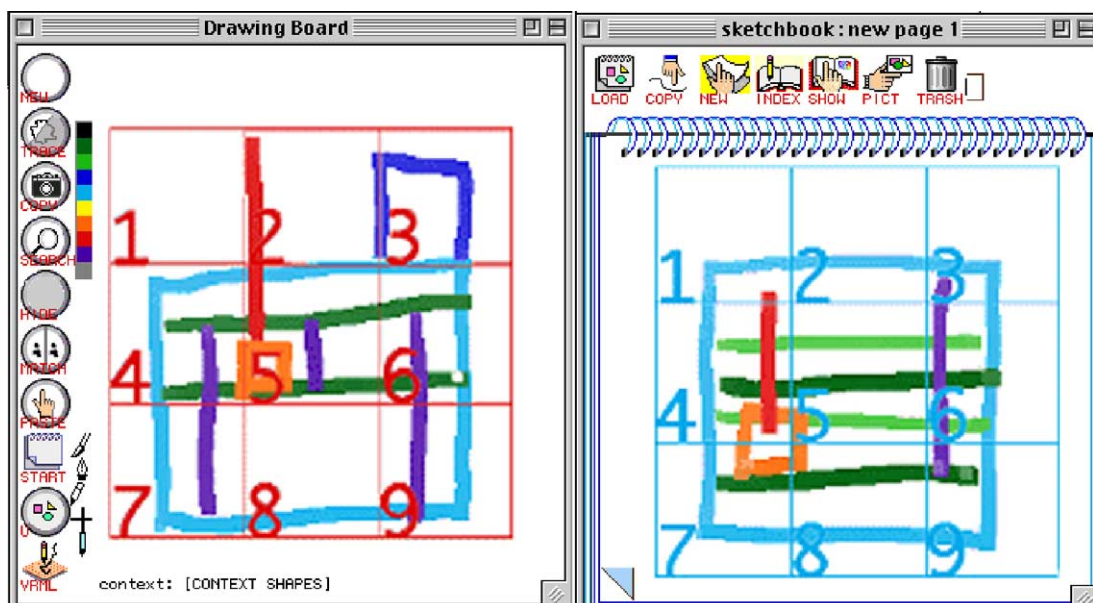

Fig. 31. Location identifier (3×3 grid) over two design drawings.

Table 6
State of drawing elements represented as list of cell sequence

Element	Drawing #1	Drawing #2
Thick Wall	(7 4 5 6 9 8 7)	(7 4 1 2 3 6 9 8 7)
Chimney box	(4 5 4)	(7 4 5 8 7)
Chimney pipe	(1 4)	(1 4)
V-window 1	(6 9)	(3 6 9)
V-window 2	(5 1)	
V-window 2	(4 7)	
Hood	(6 3 2)	
H-strip 1	(4 5 6)	(4 5 6)
H-strip 2	(4 5 6)	(4 5 6)
H-strip 3		(4 5 6)
H-strip 4		(7 8 9)

in the same location (4 5 6) among the two drawings. Though the system has the capability to find elements of similar size among two drawings to perform automatic identical label assignments. Currently, the labeling of the element names are done by hand for accuracy.

Transformations between drawings can be inferred by comparing the lists of the same elements from different drawings. For example, the cell sequence list of V-window 1 was changed from (6 9) to (3 6 9). The bounding box sizes of the element in the two different drawings are very close. This describes the shifting-up transformation for this element from first drawing to the second one (addition of grid cell 3). The table shows that the Hood element in drawing #1 is removed from drawing #2. Likewise, the transformation of the chimney box is a moving down from (4 5 4) to (7 4 5 8 7).

5.6. Calculation and dimensional reasoning

The right-tool-right-time project and its application modules demonstrate that a pen-based, or calligraphic interface can be used in a variety of domains in design process. Designers can use freehand sketches and diagrams to index and retrieve databases or to activate knowledge-based information systems and simulation programs. It is also a framework of knowledge capture. One can use the graphic recognition of the system and add to the framework more modules and functionality to support design.

A common task in design is dimensional reasoning and calculation of area footage. Drawing symbols of dimensional markers and numeric operators can be recognized as a context of 'calculation' and thus activate a calculator for designer. Fig. 32 shows such interaction.

5.7. VR Sketchpad—symbol processing and visualization

Examples from architects' drawings show that designer often make 3D sketch to accompany depiction of the space in 2D floor plan. In VR Sketchpad [33] we developed a simple mapping and translation system that inferred three-dimensional models from two-dimensional sketches. The idea is to use drawing to construct virtual built spaces to serve as a visualization aid to designers. Our current prototype system enables a designer to draw a floor plan with walls, columns, and furniture elements and the program produces a 3D model in VRML (virtual reality modeling language) format. The model can be read by any standard CAD software or posted on the web for viewing and sharing with collaborators. The basic level of the 3D translation is simple extrusion of architectural elements: circles as columns, and lines as walls. Fig. 33 shows that any freehand sketch can be converted and extruded as columns and wall partitions.

The recognition engine of the system interprets drawing symbols (e.g. circles and lines) with designer intended object representations (columns, walls) and diagram configurations (e.g. dining table and chairs). A designer can also draw arrows to indicate locations of interests and therefore define a viewing path into the 3D world (encoded as viewpoints into a VRML world and appeared in the browser navigation panel). A designer can also define a configuration of symbols to represent furniture objects as shown in Fig. 34. By sketching the furniture layout in diagrammatic form with arrows indicating specific
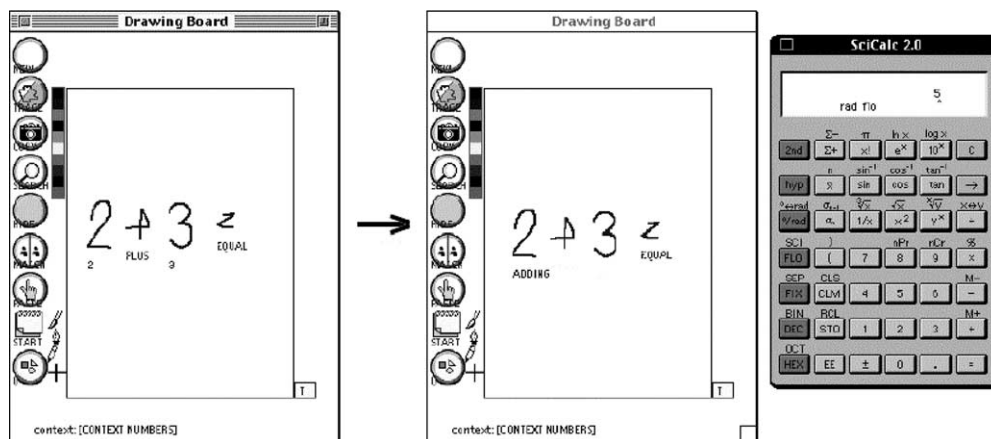

Fig. 32. A configuration of numbers and arithmetic marks (left) is recognized as an 'adding' intention (middle) and RTRT activates a calculator (right).
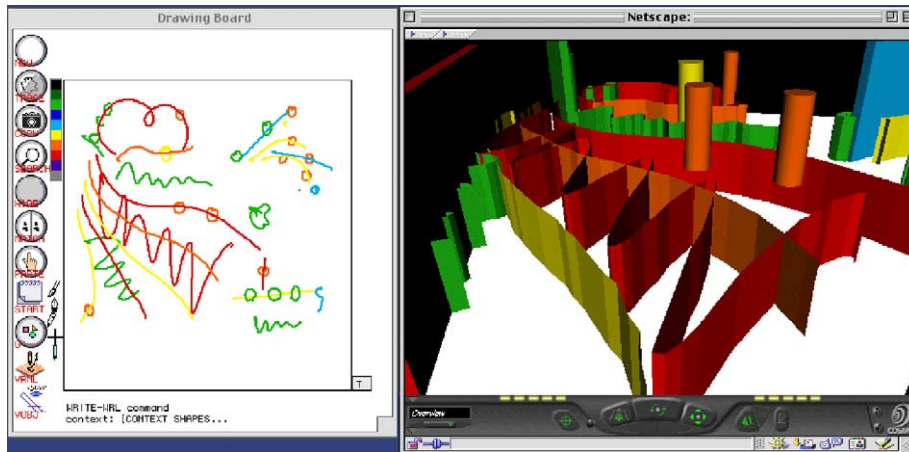
Fig. 33. Curve shapes and lines (left) are extruded to make partitions in a VRML world (right).
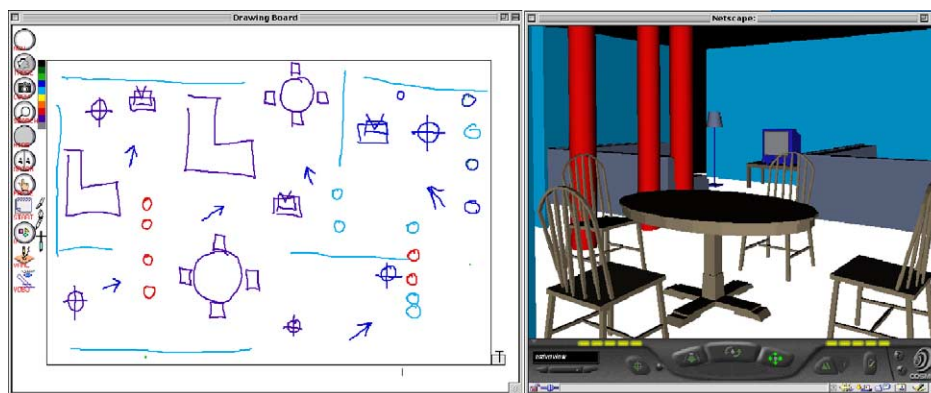

Fig. 34. Furniture layout sketch (TV, couch, dinning table set, columns, and walls) creates 3D VRML scene (right) with objects.

viewpoints and view angles, designer can produce a 3D scene in an instant and the visitors can follow the guided path to explore the virtual space as designed. Fig. 34 shows the furniture layout sketch including symbols of lamp, television, couch, dinning table set, columns and walls are recognized and translated as object placements in a 3D VRML world.

6. Summary

This paper attempts to discuss design sketches from several distinct perspectives. We include here empirical studies and case studies of architects' drawings to investigate drawing conventions and design intentions. We present our implementation of computational environments for using drawings as an interface to knowledge-based design systems. The framework of the right-tool-right-time architecture demonstrates that design tools with sketching interface might provide appropriate help for various tasks at hand in the design process. These are all part of a larger research agenda on the role of drawing for design support. Many issues are worth further exploration. The empirical

studies examined intentions in and relations among design drawings. Our prototype systems demonstrate how freehand drawing interfaces can support analysis and design.

Sketching plays an important role in the early, conceptual stages of architectural design. Drawing is a knowledge-based, knowledge-rich activity. The act of drawing is a form of design reasoning. An architectural design involves both functional and formal reasoning with embedded design intentions. We argue that a computational sketching tool might bring knowledge-based information to the conceptual design stages when such information would be most useful.

The studies of design students on the concept diagramming exercise and the protocol analysis of architecture design reveals promising results for computational tools to support sketching. We found the designers draw different symbols and configurations when thinking about different functional design concerns. For example, design drawings use lines and geometric shapes to represent natural or man made artifact such as building components and plants, phenomena such as sound and light, human behavior such as sight and circulation, as well as boundaries of spaces. The study also reveals drawing type preferences as they are

associated with design tasks (e.g. plan view for functional layouts and section for lighting concerns). It shows the importance of drawing type and context in interpreting symbols and configurations to infer design intention. It takes a crack at how these might be embedded computationally. Because the drawing marks are conventional and not idiosyncratic, they can be recognized and interpreted by a program and used to govern and guide human-computer interaction. In a computer system to support architectural design, for example, identifying the designer's working intention enables the system to offer task-relevant advice, whether prompting the designer actively or making the advice available on demand.

Case studies of famous architect's drawings demonstrated that these conventions of drawing also appeared in real practice. The series of design drawings of the east building by Pei reveal that designer move back and forth from functional to formal concerns fluently. The geometric shapes are manipulated first for formal arrangements such as symmetry and establishing axial lines. Then these shapes are read as symbol arrangements for functional spaces. The ingenious part of the design is that all problems, be they functional or formal, are all solved and evolved through these architectural sketches.

Design sketches are made of geometric shapes. Not surprisingly, aesthetic principles and formal expressions also influence how a designer works. Our exploratory study of the pavilion house broadened our understanding of the formal role that drawings play in design. From the study we found that a designer manipulates design objects through transforming shapes and locations, changing viewpoints, drawing types, and media to explore design alternatives. When functional concerns are easy to solve, these form manipulations involve the search of implicit graphical law or convention. For example, the balance of the configuration, its symmetrical or axial considerations, aspect ratio of the object and proportion, all serve as criteria for design manipulation, or moves. Transformations are also applied to previous designs to generate alternatives and to predict the outcomes of new design proposal. The designer manipulates the visualized representations to evaluate the consequences of design moves. These manipulations are simply geometric transformations but in combination the process becomes complex. We found that designers play mental games with themselves. They play by defining rules, selecting strategies, making design moves from the rules, and evaluating and discovering the outcome. These design moves change the shape, dimensions, orientations, and placements of the design elements.

The right-tool-right-time system illustrates an architecture for accessing design tools through design drawing. Several application modules were presented to demonstrate the use and feasibility of computational tools for various design tasks of formal reasoning such as finding visual references and concerning spatial arrangements, or functional reasoning such as dimensional reasoning,

analysis and simulation. This work shows that it is possible for a human or a computer to make intelligent guesses about the designer's intent by observing the drawing marks the designer is making. Right-tool-right-time demonstrates that an intention inferring system can be built based on recognizing design drawing configurations. Furthermore, the right-tool-right-time system could encourage designers to use different design tools by providing access to different knowledge-based design systems and a search engine on the web.

In summary, we report that we can view the act of drawing as manipulations of symbols that represent internal functional and formal knowledge. Understanding architectural sketches are not an easy test. Laboratory studies can isolate studies of different problems separately. However, in a real life setting, these issues mingle and are dealt with at the same time. To make computational tools really support sketching activities in design, we would need to study more how designers move between different modes in a real design task. Observing and analyzing design protocols could probably help identifying how designer operates. Maybe the transitions among various states, the sequence of drawing, are the external controls of the environment representing the mental image. It is clear that the activity of drawing can not be detached from seeing, and thinking about the subject being represented. We can not draw an object or a scene unless we see it before us whether in real physical world, or in mind's eye. Many times, the drawings are created from adopting and adapting objects from memory or imagination. Therefore, using drawing to accessing databases or knowledge repository is definitely an important issue.

Analyzing and understanding what sketches represent is important. There are many future research directions that could extend the scope of this work. For example, one could look into the dynamic character of a design drawing process. The speed, pressure and sequence of drawing may reflect the thinking involved during the design activities. One direction of future research could look at relationships between different types of objects, different levels of hierarchies and compositions. One could also investigate the function of verbal expression in a design process. We need to continue to explore in order to understand more in depth how sketches are made, and why are they made, to support what activities. On the computation front, one could explore how sub-contexts and sub-intentions can influence the determination of an intention. Future research could investigate other ways to represent design intentions, instead of the current scheme of using a 'high level recognizer' for defining both design symbol configurations and intention recognizers. This scheme is simple and it works because the symbols and configurations found from the empirical studies are mostly combinations of design elements with specific spatial relations. There could also be more ways to use drawing as an programmable interface to access different kinds of knowledge-based systems. Furthermore,

the right-tool-right-time system could go beyond just mere activation of design tools. Instead of just activating tools from recognition of the design drawing, the system could also bring feedback from the design tools back to the drawing environment. This integration of the drawing environment with different knowledge-based design tools that can inform and provide feedback to the drawing board could be useful and is worth investigating in future work. The study of design sketches and implementation of sketch tools to support design remain as topics worth further exploration.

Acknowledgements

References

[1] B. Edwards, Drawing on the Right Side of the Brain: A Course in Enhancing Creativity and Artistic Confidence, J.P. Tarcher, Los Angles, 1979.
[2] W.J. McGuinness, B. Stein, J.S. Reynolds, Mechanical and Electrical Equipment for Buildings, Wiley, New York, 1980.
[3] R.H. McKim, Experiences in Visual Thinking, Brooks/Cole Pub. Co., Monterey, Calif, 1972.
[4] Fish, JC, How Sketches Work—A Cognitive Theory for Improved System Design, PhD, Loughborough University of Technology, 1996.
[5] V. Goel, Sketches of Thought, MIT Press, Cambridge, MA, 1995.
[6] M.M. Mezughi, The Integral Role of Drawing in Architectural Conception, PhD, Glasgow School of Art, Mackintosh School of Architecture, University of Glasgow, 1996.
[7] D.A. Schön, G. Wiggins, Kinds of Seeing and their functions in designing, Design Studies 13 (#2) (1992) 135–156.
[8] G. Goldschmidt, The dialectics of sketching, Creativity Research Journal 2 (2) (1991) 123–143.
[9] M. Suwa, B. Tversky, What Architects and Students See in Architectural Design Sketches: A Protocol Analysis, First International Symposium on Descriptive Models of Design, Istanbul, Turkey 1996.
[10] M.A. Hearst, M.D. Gross, J.A. Landay, T.F. Stahovich, Sketching intelligent systems, IEEE Intelligent Systems 13 (3) (1996) 10–19.
[11] J.A. Landay, B.A. Myers, Sketching interfaces: toward more human interface design, IEEE Computer3(2001) 56–64.
[12] K.D. Forbus, RW Ferguson and JM Usher: towards a computational model of sketching, Intelligent User Interfaces (2001) 77–83.
[13] E. Ferguson, Engineering and the Mind's Eye, MIT Press, Cambridge, MA, 1992.
[14] E.Y.-L. Do, M.D. Gross, Thinking with diagrams in architectural design, in: A. Blackwell (Ed.), Artificial Intelligence Review, Academic Publishers, Dordrecht, The Netherlands, 2001, pp. 135–146.
[15] D.M. Herbert, Architectural Study Drawings, Van Nostrand Reinhold, New York, 1993.
[16] E. Domeshek, J. Kolodner, A case-based design aid for architecture, in: J.S. Gero (Ed.), Artificial Intelligence in Design'92, Kluwer Academic Publishers, Dordrecht, Netherlands, 1992.
[17] J.L. Kolodner, Improving human decision-making through case-based decision aiding, AI Magazine 12 (2) (1991) 52–68.
[18] C. Zimring, E.Y.-L. Do, E. Domeshek, J. Kolodner, in: J.P. Mohsen (Ed.), Supporting Case-Study Use in Design Education: A Computational Case-Based Design Aid for Architecture Computing in Civil Engineering, A/E/C Systems'95 vol. II, American Society of Civil Engineers, Atlanta, GA, 1995, pp. 1635–1642.
[19] E.Y.-L. Do, What's in a diagram that a computer should understand, in: M. Tan, R. Teh (Eds.), CAAD Futures'95: The Global Design Studio, Sixth International Conference on Computer Aided Architectural Design Futures, National University of Singapore, Singapore, 1995, pp. 469–482.
[20] E.Y.-L. Do, Computability of design diagrams—an empirical study of diagram conventions in design, in: R. Junge (Ed.), CAAD Futures 97, Kluwer, Munich, 1997, pp. 171–176.
[21] E.Y.-L. Do, The Right Tool at the Right Time-Investigation of Freehand Drawing as an Interface to Knowledge Based Design Tools, PhD Georgia Institute of Technology, Atlanta, 1998.
[22] J.L. Meikle, Twentieth Century Limited: Industrial Design in America, 1925–1939, Temple University Press, Philadelphia, 1979.
[23] R.C. Twombly, Louis Sullivan: His Life and Work, Viking, New York, 1986.
[24] S. Anderson, The fiction of function, Assamblage 2 (1987) 18–31.
[25] H.W. Janson, Form follows function—or does It? Modernist Design Theory and the History of Art, Maarsen, The Netherlands, 1982.
[26] Galleries, AD: 1978, I.M. Pei & Partners, Drawings for the East Building, National Gallery of Art. Its Evolution in Sketches, Rendering, and Models 1968-1978, Exhibit Catalog, Washington, D.C.
[27] C. Wiseman, I.M. Pei: A Profile in American Architecture, H.N. Abrams, New York, 1990.
[28] Neiman, B, EY-L Do and MD Gross: 1999, Sketches and Their Functions in Early Design: A Retrospective Analysis of Two Houses, Design Thinking Research Symposium '99. W. Porter and G. Goldschmidt.
[29] M.D. Gross, E.Y.-L. Do, in: J.A. Jorge, E. Glinert (Eds.), Drawing on the Back of an Envelope, Computers and Graphics, Calligraphy Interface vol. 24, Pergamon Press, New York, 2000, pp. 835–849.
[30] M.D. Gross, The electronic cocktail napkin—working with diagrams, Design Studies 17 (1) (1996) 53–69.
[31] M.D. Gross, E.Y.-L. Do, Ambiguous intentions Proceedings, ACM Symposium on User Interface Software and Technology (UIST'96) 1996 pp. 183–192.
[32] E.Y.-L. Do, M.D. Gross, Tools for visual and spatial analysis of CAD models—implementing computer tools as a means to thinking about architecture, in: R. Junge (Ed.), CAAD Futures 97, Kluwer, Munich, 1997, pp. 189–202.
[33] E.Y.-L. Do, Graphics interpreter of design actions: the GIDA system of diagram sorting and analysis, in: B.d. Vries, J.P.v. Leeuwen, H.H. Achten (Eds.), CAAD Futures, Kluwer Academic Publishers, Eindhoven, 2001, pp. 271–284.
[35] Gross, MD, EY-L Do: 1996, Demonstrating the Electronic Cocktail Napkin: a paper-like interface for early design, CHI 96, Conference on Human Factors in Computing Systems, ACM, Vancouver, British Columbia, Canada, Conference Companion: 5-6.

[36] Le Corbusier, Vers une architecture, Towards a new architecture, John Rodker Publisher, London, 1927.

[37] Le Corbusier, W. Boesiger, P. Jeanneret: 1937-1970, Le Corbusier: Oeuvre Complete 1934-1938, Zurich, Switzerland, Les Editions d'Architecture Erlenbach, Zurich.

[38] Le Corbusier, Creation is a Patient Search, Frederick A. Praeger, New York, 1960.

[39] P. Eisenman, Peter Eisenman House of Cards, Oxford University Press, New York, 1987.

[40] F. Schulze, G Danforth and L. Mies van der Rohe, Mies Van Der Rohe Archive, Garland, New York, 1986.

[41] J. Hale, The Old Way of Seeing, Houghton Mifflin Company, Boston, New York, 1994.

[42] F.L. Wright, Genius and Mobocracy, Duell, Sloan and Pearce, New York, 1949.