Sketches and Their Functions in Early Design: A Retrospective Analysis of Two Houses

Neiman, B. Do, E. and M. Gross

Proceedings Design Thinking Research Symposium, Cambridge MA

1999

design machine group
University of Washington
Seattle WA USA 98195-5720
http://depts.washington.edu/dmachine

Sketches and Their Functions in Early Design – A Retrospective Analysis of a Pavilion House

Bennett Neiman, Mark D. Gross, and Ellen Yi-Luen Do

Sundance Lab, University of Colorado, Boulder, CO 80309-0314

Email: {neimanb, mdg, ellendo}@colorado.edu

Abstract. We performed a case study of the design of a house to investigate the underlying reference systems of design transformation. In the collection of sketches we examined we found that the type of drawing could often be identified by a combination of drawing style, projection type, and key elements found in the drawing. Our study presents the collection of design drawings made by the architect, and an analysis of the relationships among the drawings.

Keywords. design drawing, design thinking, non-sequential analysis, coding schemes of drawing intentions, operations, transformations of design objects

1. Introduction

During conceptual design an architect engages in various tasks: concept formation, form-making, testing functional capacity, and exploring structural and construction possibilities. The architect moves among these activities while producing sketches, drawings, and sometimes models. From the collection of sketches and design drawings for an architectural project we can trace the designer's attention to a set of different concerns.

In this pilot study we examined sketches and drawings made by one of us (Neiman) for the design of a residence. We tried retrospectively to understand the purpose of each drawing, and constructed a conceptual framework to account for connections among the drawings and thus among the various activities of the design process.

1.1. The Pavilion House – architectural program & antecedents

Neiman's design for the Pavilion house is a personal design journey carried out continuously over the period of 15 years. Neiman's Pavilion house project was inspired by Le Corbusier's thematic elements, by an exercise of John Hejduk (Neiman's teacher at Yale) and by 'speculative sketches' Neiman made in his sketchbook. Hejduk's influence on Neiman's design process is evident (among other things) through the use of crayon sketches and primary colors in the drawings.

The program is for a single residence situated on a hilltop, approximately 90' x 130' running north south. The building area is about 3000 square feet. The project incorporates Le Corbusier's five thematic elements of architecture.

Here is the description of the project in the architect's own words:

"Architecture concerns the variegated application of systemic spatial ordering principles derived from materials, function and site. This project begins with Le Corbusier's five points of architecture: piloti, free-plan, free-facade, ribbon window, and rooftop garden. This project also investigates the idea of place within a place. The site is unknown, but probably on the edge of a slope.

The design is seen as a singular volume suspended somewhere between the sky and ground (House in a Box). A thickened wall serves as both lateral structure and threshold plane (House on a Wall). Entry to the structure is via a bridge from the north. The entry facade is presented as mysterious masked plane of projections and voids that partially hide the view beyond. The verticality of the house offers numerous indoor and outdoor framed views beyond to the south. The sequence culminates with a rooftop garden. The entry level has the living, dining, and kitchen activities. The single volume is sub-divided in one primary double height volume (as living) and two secondary volumes; one as dining/kitchen, the second as sleeping quarters (upper portion of the singular volume)."

1.2. Examination of the design drawings

This case study of the Pavilion House design is an attempt to identify relationships between drawings as a way of understanding a design process. It started as thought experiment and ended with a repertoire of plausible interpretations to account for what might have actually happened in the design process. The interpretations were done through several iterations of sorting, classification and coding. The results were later compared with the designer's retrospective examination.

We first approached the data – Neiman's collected drawings – as a puzzle solving activity in which all the pieces put together would reveal the whole picture. However, in analyzing the drawings we found our original goal of 'putting everything together' was not feasible. As we looked at all the drawings at the same time, and found ways to link different drawings by either spatial or visual relationships, we found the design project to be more a puzzle making process. As Archea suggests (Archea 1987), designers do not clarify their goals like problem-solvers do; instead, they "treat design as a search for the most appropriate effects that can be attained in a unique context." Therefore, the architect's mode of action "is best described as puzzle-making." He further argues that designers must have a "logical and appropriate relation" to the achievement and are concerned about "the rule systems (they) superimpose (design pieces) on a given context." He describes the three key elements of puzzle-making design as: (1) sets of combination rules of appropriate domains that fit between (2) tangible or intangible kits of parts and (3) the formal, symbolic or experiential effects that emerge when the specific relations among the parts are realized at a given point in space and time.

We selected for examination drawings from Neiman's personal archive of scanned images stored on 6 CD-ROMs. These drawings do not have date or time stamps to show when the drawing was made and therefore, we could not make a sequential examination of the work.

1.3. Non-sequential analysis of relationships

Our analysis of the design drawings therefore does not account for sequence. Rather, we consider all drawings at the same time. This is a different approach than traditional protocol analysis. We found our approach valuable for several reasons: First, the drawings we examined came from a real design project that span a long period of time (years), whereas protocol studies usually cover a short experiment time span (hours). Second, this design project focuses more on form manipulation than on functional problem solving activities that are often the focus of design protocols. Third, the fact that the drawings do not have sequential information freed us from analyzing the sequence of events following one particular concern or operations that might not be directly relevant to the design task (e.g., pen up, pen down event). Fourth, by examining all the drawings at once, we investigated how patterns of design operations and manipulations emerge from the drawings.

As Lloyd, Lawson, and Scott pointed out, the method of protocol analysis can interfere with the act of designing (Lloyd, Lawson and Scott 1995). Real design is usually "considered"; designers would not normally work out a design in the artificially short period set up by a protocol analysis section. A real design process would be in a real setting (e.g., in a studio, using a drafting table, with pencil and tracing paper) instead of in the isolation of a laboratory. There are also concerns about how the verbal protocols might interfere with visual reasoning. Schooler and Engstler-Schooler's experiments show that verbal reasoning interferes with visual reasoning in visual memory tests (Schooler and Engstler-Schooler 1990). Similarly, Wilson shows that people often misstate what they are thinking about in talk-aloud protocol studies (Wilson 1994). These studies present arguments that verbal protocol studies can obstruct reasoning and give an inaccurate account of the design process.

1.4. Related work

Design researchers and cognitive scientists have studied design drawing. Several studies view design as problem solving and information processing (Newell and Simon 1963; Newell and Simon 1972). For example, Eastman (Eastman 1968) and Akin (Akin 1978; Akin 1986) use protocol analysis to study design as a process of problem formulation and solution generation. They use a Problem Behavior Graph (PBG) to represent the transformations (links) of different states (nodes). Chan (Chan 1990) further suggests using schemata (Rumelhart and Ortony 1977; Rumelhart 1980) to represent domain-specific knowledge such as design constraints and associated rules in memory.

Propositional models of design thinking based on analysis of design protocols view design reasoning as information processing. Moran (Moran 1970) proposes that design has components of memory, representation conventions, interpreted problem, and design strategy. He argues that the many representations designer use can be viewed as different kinds of languages to express the state of the problem. These representations, in turn, may affect the designer's ability to find design solutions. Schön describes design as an act of 'reflection-in-action' (Schön 1983) in which designers develop rules to guide their own thinking (Schön 1988). He argues that designers 'see' and then 'move' design objects (Schön and Wiggins 1992). Goldschmidt's 'interactive imagery' argument (Goldschmidt 1991) further suggests that designers interact with a drawing using 'seeing as' and 'seeing that' reasoning modalities (Goldschmidt 1989; Goldschmidt 1991). The act of sketching is a systematic dialectic with oscillating arguments that gradually transform design images. Oxman and Oxman extend Eastman's and Akin's information processing description to include refinement and adaptation (Oxman and Oxman 1992).

Dorst and Cross's review paper (Dorst and Cross 1995) argues that although think-aloud protocol is a powerful and well used technique for analyzing design activities, it has the disadvantage that concurrent verbalization and behavior could cause side effects or account for incomplete activities. Other studies use introspective, retrospective, or speculative knowledge instead of 'think-aloud' protocols. For example, Galle and Kovács (Galle and Kovács 1992) argue that an introspective record allows a designer (Galle, also the first author of the article) ample time for reflection. They do not need to rely on either an 'information processing model' or other type of assumption (e.g., theories of human cognition, knowledge representation) for analysis. They argue that although introspection may fail to collect some important information (e.g., voice annotations in a design session), it is a useful supplement to either protocol or interview studies conducted over a short period of time. The record is more compact than a protocol transcript, but more detailed than answers collected in an interview. They present their record of the design sketches and the 'train of thought' for a housing layout design.

In another alternative to protocol analysis, Suwa and Tversky applied retrospective reports of design sessions (Suwa and Tversky 1996) to study designers' perceptual processes. They videotaped designers doing a museum design, and later when watching the tape reporting what they were thinking when they sketched. Porter and Schön carried out a speculative account of design process as a "thought-experiment" (Porter 1988) to account for the underlying logic of designing. Porter claims that although 'replication' is a fictional design process (not necessarily matching the actual design experience), it is a form of inquiry appropriate to teaching design and exploring the implications of computer tools. He presents two cases, an existing plaza and a building design, showing their present state, and a plausible chain of reasoning about how the design might have evolved from the beginning.

Architectural historians echo this notion of the relationships between design and its drawing. For example, Hewitt argues that architectural historians and theorists should look at the history of architectural drawing "as a medium of thought" (Hewitt 1985). He argues that an 'idea sketch' consists of "personal and intuitive, or may be based on clearly defined methodologies or programs of instruction." This 'conception' of design is "a triad of interrelated operations–thinking, seeing, and drawing." A recent study by Akin and Lin echoes this argument (Akin and Lin 1995), concluding that novel design decisions usually occurred when the designer was in a "triple mode period" of drawing, thinking and examining.

2. Analysis of the Project Drawings

Below we briefly describe the process of our analysis and the coding schemes we used to analyze Neiman's Pavilion House. Ming-Hung Wang in his Ph.D. thesis "Ways of Arrangement" presented a similar coding scheme (Wang 1987) with a focus on the spatial relationships between objects (e.g., abut, adjacent). Our scheme on the other hand, focuses on the transformations of objects (design elements or drawings) among different states (e.g., staircase moved from east to west, wall height reduced).

We performed several iterations of analysis. Neiman first presented the project images (referred to later as P1 for Pavilion House presentation 1, Figure 1-left) with brief explanations. We questioned Neiman about the relationships between drawings. For example, we asked which drawings represent the conceptual ideas, references, and which drawings were developed later in the process. Neiman organized his presentation of 44 images into six categories: (1) multiple viewpoints/ideas, (2) plan variations, (3) section, (4) frontal projection/obliques, (5) isometric, and (6) related project/ideas. Later Neiman presented a "Small House" project (S1, with 10 images) of computer drawings, a more developed alternative to which the ideas and elements in the Pavilion House could lead. He also presented the Pavilion House a second time (P2, Figure 1-right) with a different organization, in which one category, "design itinerary," accounted for 33 images. However, in this one category, the drawings were grouped and sequenced together according to the drawing types – 1) reference sketch, 2) variations of object arrangements, 3) variations of dimensions and grids, 4) bathroom studies, 5) floor plans, 6) project summary.

Both presentations presented concept sketches in the beginning and the end, but each was organized with a different emphasis. Presentation P1 was organized according to different drawing types (e.g., plan, section, isometric). In contrast, presentation P2 rearranged the sequence according to design intentions (variations of object arrangements, dimension studies, etc.). The links in Figure 1 show the relationships between the positions of the drawings (22 images) in the two presentations. The second presentation had fewer images (33 instead of 44) and in a clearer sequence.

It became apparent that two drawings may be related in several ways: They may belong to the same projection type (plan, section, isometric), the same medium (crayon, pencil and pen), or design intentions (variations of object arrangements, grids and dimensions). They may describe the same elements (bridge, columns, stripe windows). They may share the same view angle (north, southwest, wall side, bridge side, corner). Or, one drawing may be a blow-up singled out from a composition of multiple drawings. The graphs in Figure 1 show the presentation sequence as appeared in different categories. For example, the images in the P1 category of "related project/ideas" (37-44) can be sorted to four subcategories: articulation study, color inverted 3D drawing, concept sketch, and planes. Likewise, the P2 category of "object arrangements" can be divided into two types, a single view drawing, or a composite of several drawings in one slide. The network lines show how the designer restructured the presentation by moving around the slides, regrouping them according to different classification scheme. We later found that Neiman performs similar manipulations (i.e., move, rotate, turn to different sides) of design elements in the design process.

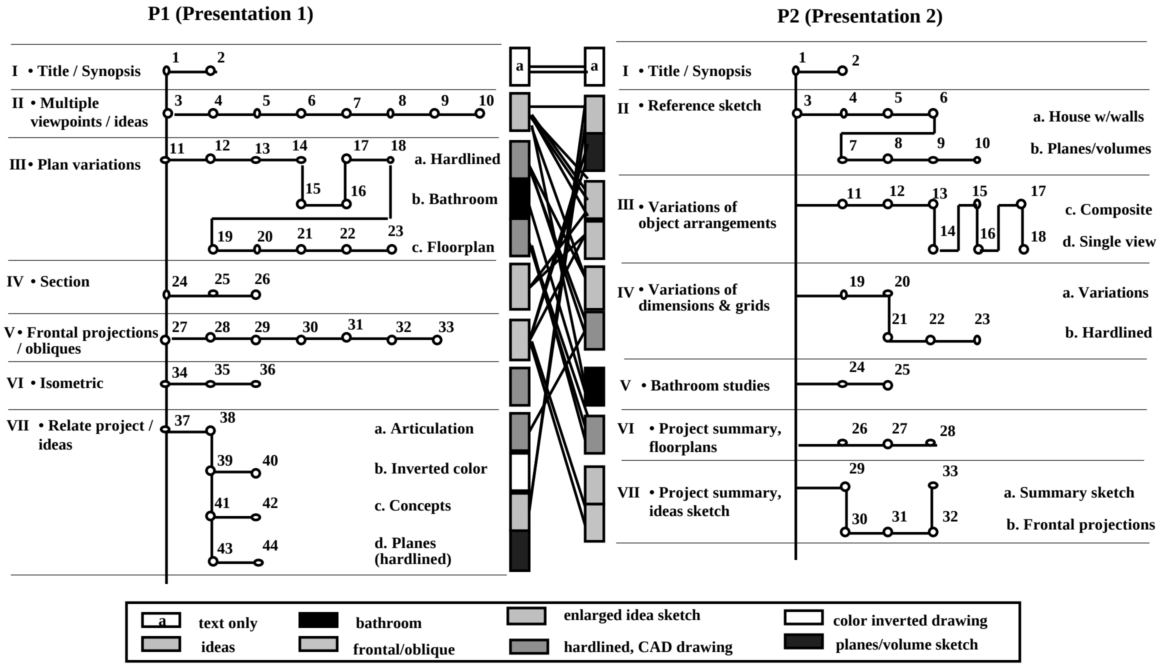


Figure 1. Graphs showing drawing/slides in sequence as in different categories, and the relations between the location sequence as appeared in two different presentations.

We arranged all the drawings on the table to make a map in which drawings are positioned by their similarity to one another (Figure 2). We identified the main elements in the design and color coded them. They are: thick wall (orange), bridge/entry (pink), pipe/chimney (yellow), structure grid (blue), light monitor (green), stair case/balcony (light blue), columns (red), infills (fixed e.g., bathroom and storage, and free infills, e.g., furniture).

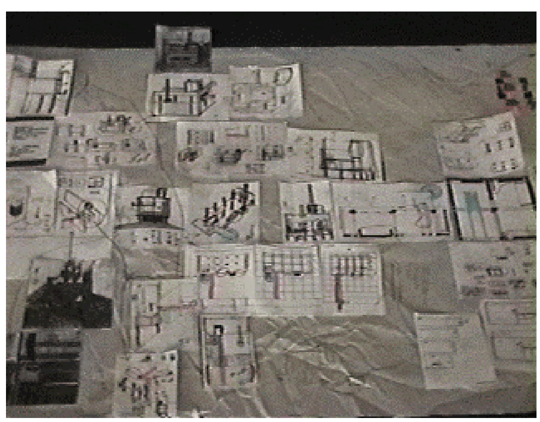


Figure 2. The collage of all drawings appeared on a relation map.

Making the collage map helped us recognize that many images (P1, category II, multiple views/ideas) were composed of several drawings made on the same sheet of tracing paper. Some represent alternatives, or variations of one theme, i.e., facade studies (Figure 3a). Some are different types of drawings exploring the same idea (plan, section and 3D, Figure 3b). Some explore different concerns (structure grids, dimensions, volume capacity, Figure 3c). We decided to divide these composite images to compare at the level of a single drawing. For example, we divided Figure 3a (P1-9 or P2-15) into six drawings (P1-9a ~ 9f, or P2-15a ~ 15f).

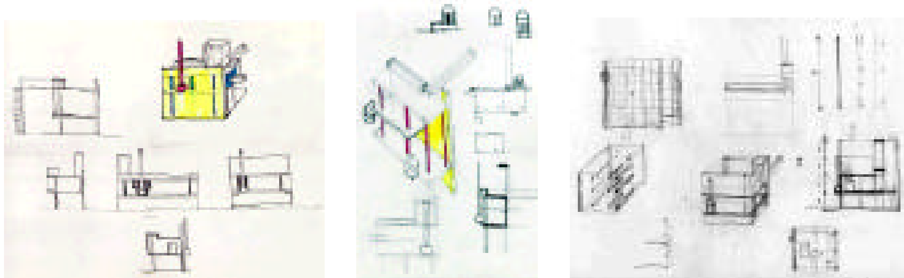
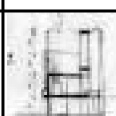
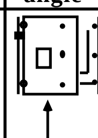
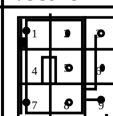
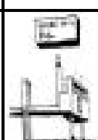
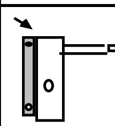
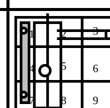
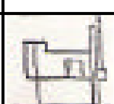
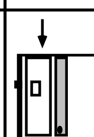
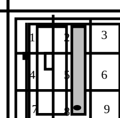
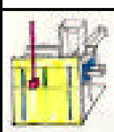
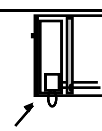
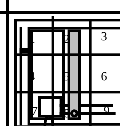


Figure 3. Examples of slides showing composition of multiple drawings: (a) facade variations (P1-9), (b) different drawing types, plan, section and 3D (P1-6), (c) different concerns, structure & dimension (P1-7)

We broke apart the composite sheets into individual drawings and assigned unique identifiers to each drawing, pasted them up on a large sheet of paper to examine them simultaneously and in detail. We then developed a coding scheme to classify these 110 drawings. The coding scheme includes the lowest level of detail such as element types and higher level, such as drawing view angles. Table 1 shows the categories of classifications with four drawings and their codes.

Table 1. Drawings in coded table according to different classifications.

ID #	Drawing	Title	Intention Annotation	Drawing Type	View angle	Elements	Location /scale	Medium
P1-7g (P1-26) P2-13g (P2-14)		Section: vertical cadence	Dimension Object relations	Section (D2)		E1, E2, E3, E4, E5, E5, E5, E6, E7, E8, E9, E10		pencil (M1)
P1-41a P2-4a		house on a rail	concept diagram	3D section (D4+D2)		E1, E1, E1, E1, E3, E5, E7, E8, E9, E10, E11, E12		pen (M2)
P1-9f P2-15f		thickened wall and projection	variation of sectional space	section (D2)		E1, E2, E3, E4, E5, E6, E9, E10, E14		pencil (M1)
P1-30 (P1-9a) P2-16 (P2-15)		wall & projected volumes (variations on the theme)	isometric front • slots in wall • marking internal grid system on the facade	3D Frontal Isometric (D3+D4)		E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E12, E12, E12, E12, E12, E13, E14, E15		pencil (M1) yellow, blue, red markers (M4)

2.1.Principal architectural elements

We identified key elements from the collection of drawings. We also selected four single drawings—a plan collage, a concept isometric sketch, a section, and a 3D isometric sketch—that best represent the essence of the design. Figure 4 shows these drawings annotated with their elements. The codes for element types and locations in the design are shown in Table 2.

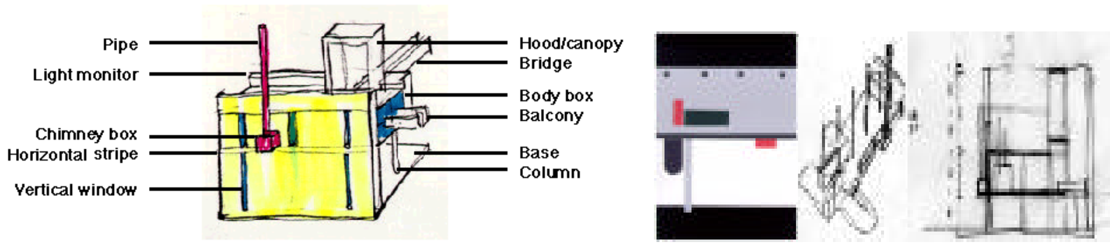


Figure 4. (a) Principal architectural elements. (b) plan collage, (c) 3D sketch and (d) a section.

Table 2. 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 CCW	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	1 2 3	C12: other
E13: horizontal strip	T13: shape change		
E14: base	T14: removed	4 5 6	
E15: balcony	T15: added	7 8 9	
E16: stair case	T16: no transformation		
E17: other	T17: rotate 180		
	T18: other		

2.2. Types of drawings

We easily identified 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). We identified drawing intentions from the titles, texts and annotations Neiman provided in the presentation slides. Table 3 shows our coding legends.

Table 3. Coding legends for a design drawing

Drawing Type	View Direction	Medium	Intention
D1: plan D2: section D3: elevation D4: isometric D5: frontal projection D6: perspective D7: other	V1: North V2: East V3: South V4: West V5: NE V6: SE V7: SW V8: NW	M1: pencil sketch M2: pen sketch M3: crayon M4: marker M5: hardline M6: measured softline M7: CAD M8: inverted color M9: hybrid M10: other	I1: variations I2: dimension I3: grid I4: volume I5: wall attachment I6: reference I7: sequence I8: entry I9: service I10: concept I11: other

2.3. Coding relationships among drawings

The relationships between any two drawings can be coded as a list of transformations applied to each design element in the drawing. For example, the expression below indicates that design element #16 (staircase) at the location #4 (middle left) is moved down (T4) and rotated 180 degrees (T17) to the location #9 (lower right).

E16 @ L4 → (T4 + T17) → @ L9

The examples that follow are selected from the pair of drawings illustrated in Table 4.

At the drawing level, the transformation between drawings P1-7g and P1-9a (see Table 1) is a change of viewpoints from section (D2) to a frontal isometric projection (D3 + D4). We code it as:

D2 → (D3+D4).

At the object level, the transformation of design elements such as chimney box and pipe, and horizontal stripe (E4, E6, E13) in two drawings can be coded in similar form. For example, a chimney pipe (E6) moved up from drawing #1 (P1-7g) to drawing #2 (P1-9a) can be described as (E6 → T3) and thickened wall (E3) with a height reduction is (E3 → T12).

With the codes we can sort drawings according to the transformations between them as well as the transformation of their individual design elements. Each element in a drawing will have one form of representation in relation to another drawing. For example, a bridge in P1-7g (at the right side of the plan, occupies grids 9, 6, and 3) was rotated 90 degrees clockwise and moved to the bottom right of drawing P1-9 would be represented as

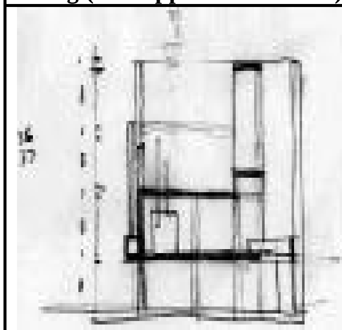
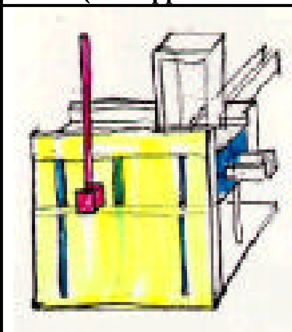
E8 @ L9-6-3 → T5 → @ L8-9.

A thickened wall with a height reduction, and redrawn in a different color would be represented as

E3 C5 → (T12 + T18) → C1.

The codes enable easier comparison and sorting of the element types and operations. However, the amount of data, and the number of types and fields associated with each drawing increases the amount of data by several times. Furthermore, it is hard to keep track of the sorted design elements and their source drawings.

Table 4. Operations and relationships among two design drawings

P1-7g (also appears as P2-15e)	**Transformations**	**P1-9a (also appears as P 2-15a)**
 Drawing Type: Section View direction: South Medium: Pencil Intention: Variation, dimension (vertical cadence) (also appears as P1-26, P2-14)	D2 → (D3 + D4) V3 → V7 M1 → (M1 + M4) (I1 + I2) → (I1 + I5 + I10) E1 @ L2-5-8 → T16 E2 @ L3-6-9 → T14 (bridge) E3 @ L1-4-7 → T12 (front) E3 C5 → T18 → C1 E4 @ L1 → T3 (chimney) E5 @ L1-2-4-5-7-8 → T3 E6 @ L1 → T3 (chimney) E7 @ L8 → T2 → L7 E8 @ L9-6-3→ T5 → L8-9 E9 @ L4-5 → T14 (inside) E6 @ L4-5 → T14 (inside) E6 @ L4-5 → T14 (inside) E10 @ L2-5-8 → T16 E12 C5 → C2 E14 → T16 E15 → T15 @ L8	 Drawing Type: Elevation, 3D View direction: SW Medium: Pen, markers Intention: Variation, concept wall attachment, elements in space thickened wall and projections) (also appears as P1-30, P2-16)

3. Discussion: What can we infer from this analysis of project drawings?

Neiman used drawings and fragments of drawings from previous designs as studies for the Pavilion House. Thus, one kind of drawing that appears in the process is a 'memory sketch' (Graves' "referential sketch" (Graves 1977)) that recalls elements and organizations from previous work. Other 'functional arrangement' sketches, made in plan and section, explore layouts of building uses: a service core, access, and stairs. A 'structure sketch' examines layouts of a structural grid, and the spatial and dimensional implications of the locations of columns, beams, and walls. Isometric 'form making sketches' examine the three dimensional geometry of the building, exploring alternative arrangements of the primary architectural elements, volumes, and voids.

Our coding scheme is quite low-level, dealing with the specific characteristics and relationships of drawings. A higher-level coding scheme, built on top of our low-level scheme might be able to account for operations that we believe can be found in Neiman's design process. For example:

- 'direct quoting' in which a piece of a previous design is used without modification,
- 'reference' in which a previous design is modified before inclusion,
- 'division' in which an area or volume is subdivided,
- 'addition' in which a pattern is allowed to extend an existing arrangement of material and space,
- 'geometric transformation' in which elements are reversed, rotated, or otherwise permuted,
- 'capacity testing' that compares physical elements and space against space needs of specific functions.

Our 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, 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. Recalling previous designs seems also to play an important role. Previous designs suggest possible solutions, frameworks and design strategies. Constraints are imposed by the designer's preference of visual aesthetics such as proportion and balance. 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.

We assigned categories to the drawings, the tasks that they were made for, the operations that they reflect, and the resulting changes to the design. The subjective nature of retrospective analysis makes it impossible to argue for the truth of interpretation, plausible as it may be. Our analysis of Neiman’s design does, however illustrate a style of projection and exploration that we believe can be found in architectural design processes more generally, one in which specific tasks, operations, and results can be identified at each step in a design history.

In future work, we plan to ask different designers to sort the project drawings, to establish inter-rater reliability in identifying drawing types and operations. We would also like to study different types of design projects that have a different focus than form manipulation, such as a site planning problem or the design of a highly functional building like a hospital. Our study also suggested computational tools we might build to help analyzing and sorting the drawings. For example, we could have used a ‘diagram spreadsheet’ to sort drawings according to the number of objects, the types of objects, or the drawing and projection types. We could also have used a program that would track drawing intentions and arguments along with sequence of moves with linked documents.

Acknowledgments

This research was supported in part by the National Science Foundation under Grant No. IIS-98-19856. The views and findings contained in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors also acknowledge support from the Chancellor’s office at the University of Colorado at Denver.

References

Akin, O. (1978). How Do Architects Design. Artificial Intelligence and Pattern Recognition in Computer Aided Design, IFIP. E. J.-C. Latombe. New York, North-Holland Publishing: 65-104.

Akin, O. (1986). Psychology of Architectural Design. London, Pion.

Akin, O. and C. Lin (1995). “Design Protocol data and novel design decisions.” Design Studies 16 (#2, April): 211-236.

Archea, J. (1987). Puzzle Making: What Architects Do When No One is Looking. Computability of Design. Y. Kalay. New York, Wiley Interscience.

Chan, C.-S. (1990). “Cognitive Processes in Architectural Design Problem Solving.” Design Studies 11(2): 60-80.

Dorst, K. and N. Cross (1995). “Protocol Analysis as a Research Technique for Analysing Design Activity.” Design Engineering Technical Conferences 2(DE-83): 563-570.

Eastman, C. M. (1968). On the Analysis of Intuitive Design. Emerging Methods in Environmental Design and Planning. G. T. Moore. Cambridge, MIT Press: 21-37.

Galle, P. and L. B. Kovács (1992). "Introspective observations of sketch design." Design Studies 13(3): 229-272.

Goldschmidt, G. (1989). Architectural sketching, seeing as and seeing that, Unpublished manuscript submitted to the National Science Foundation.

Goldschmidt, G. (1991). "The Dialectics of Sketching." *Creativity Research Journal* v.4(# 2): 123-143.

Goldschmidt, G. (1991). Visual Clues: Tacit Information Processing via Sketching. *3rd Symposium on Systems Research, Information and Cybernetics*, Baden-Baden.

Graves, M. (1977). "The necessity for drawing: tangible speculation." Architectural Design 6(77): 384-394.

Hewitt, M. (1985). "Representational Forms and Modes of Conception: An Approach to the History of Architectural Drawing." JAE 39(2): 2-9.

Lloyd, P., B. Lawson and P. Scott (1995). "Can concurrent verbalization reveal design cognition?" Design Studies 16(#2, April): 237-259.

Moran, T. P. (1970). A Model of a Multilingual Designer. Emerging Methods in Environmental Design and Planning. G. T. Moore. Cambridge, MIT Press: 69-78.

Newell, A. and H. A. Simon (1963). GPS: a program that simulates human thought. Computers and Thought. E. A. Feigenbaum and J. Feldman: 279-296.

Newell, A. and H. A. Simon (1972). Human Problem Solving. Englewood Cliffs, NJ, Prentice Hall.

Oxman, R. and R. Oxman (1992). "Refinement and adaptation in design cognition." Design Studies April 01 v 13(2): 117-134.

Porter, W. (1988). "Notes on the inner logic of designing: Two thought-experiments." Design Studies 9(3 July): 169-180.

Rumelhart, D. E. (1980). "Schemata": the building blocks of cognition. Theoretical Issues in Reading Comprehension. R. J. Spiro, B. C. Bruce and W. F. Brewer. Hillsdale, NJ, Lawrence Erlbaum.

Rumelhart, D. E. and A. Ortony (1977). The Representation of Knowledge in Memory. Schooling and the Acquisition of Knowledge. R. C. Anderson, R. J. Spiro and W. E. Montague. Hillsdale, NJ, Lawrence Erlbaum.

Schön, D. A. (1983). The reflective practitioner : how professionals think in action. New York, Basic Books.

Schön, D. A. (1988). "Designing: Rules, Types and Worlds." *Design Studies* 9(#3, July): 181-190.

Schön, D. A. and G. Wiggins (1992). "Kinds of Seeing and their functions in designing." *Design Studies* 13(#2): 135-156.

Schooler, J. W. and T. Y. Engstler-Schooler (1990). "Verbal Overshadowing of Visual Memories: Some Things Are Better Left Unsaid." Cognitive Psychology 22: 36-71.

Suwa, M. and B. Tversky (1996). What Architects and Students See in Architectural Design Sketches: A Protocol Analysis. 1st International Symposium on Descriptive Models of Design, Istanbul, Turkey.

Wang, M. "Ways of Arrangement: The Basic Operations of Form-making." Ph.D dissertation., MIT, 1987.

Wilson, T. D. (1994). "The Proper Protocol: Validity and Completeness of Verbal Reports." Psychological Science: a journal of the American Psychological Society / APS. 5(5 (Sep 01)): 249-252.