CRITIQUING FREEHAND SKETCHING

A Computational Tool for Design Evaluation

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Abstract. Design Evaluator is a computational tool to support design reasoning. In this paper we discuss how architects reason about spatial relations, functional concerns and 3D space with drawings. Design Evaluator is a freehand sketching environment that offers critiquing of circulation paths and arrangement of functions in a floor plan diagram. The critiques are presented in the forms of text, diagrammatic annotation and 3D model.

1. Introduction

1. 1 ROLE OF SKETCH DRAWING: REFLECTIONS AND RESTRUCTURING

Design studies researchers have identified the role of freehand design drawings (i.e. sketches and diagrams) as material that stimulates reflection in the early stage of design. Schön, for example, describes designing as 'reflection-in-action': designers go through the actions of generating a design solution, evaluating it, reflecting on and changing it. He argues that drawing is essential as a tool in this reflecting process (Schön, 1985). Designers use drawings to externalize design ideas and then to develop their designs further. Through examining and interacting with the drawings, designers develop and modify their design ideas. Designers must see the visual image on the drawing (Goldschmidt, 1991) to make a decision, to add a new design idea, or to modify the design (Laseau, 1980). Schön argues that designers perform 'seeing-moving-seeing cycles' in designing. In this cycle, 'seeing' is the interpretation of a drawing that is composed of graphical symbols; it induces the designers to have a conversation with themselves about the design ideas that they have recorded in the drawing (Schön and

Wiggins, 1992). In 'seeing' their drawings, they might discover alternative interpretations from what they originally drew. Cognitive researchers have described this process as 'restructuring' and alternative interpretations as 'emergence'. (Verstijnen, et.al., 2001) This feedback initiates an action, resulting in adding, moving, or removing design symbols in the drawing. Experiments show that people cannot remember all design information and reason about design alternatives without using external representations (Tversky, 1999). These representations (drawings) help people offload the burden of keeping all relevant information in short-term memory.

1.2 STUDIO CRITIQUES AND REASONING

Architectural design has a unique and traditional education method, the studio. Architectural educators are familiar to giving frequent critiques at the students' desks, so-called 'desk crits'. The example of design review in Schon's research shows how design critiques can support the reasoning, especially visually (Schön, 1985). This example shows an example of discussion between the reviewer and the student. The reviewer sees graphical elements, properties, and relationships from the students' drawings. They try apply their different levels of knowledge to the student's designing and reframe the student's problem depending on what they see in the drawing. The student absorbs the reviewer's critiques, transfers them into his understanding (Goldschmidt, 2003) and restructures his knowledge. Critiques of such kinds cause the student to refocus or change attention on the current design problem (Hayes-Roth, B and Hayes-Roth, F., 1979). During a desk crit, they perform a continual evaluation as they experiment with design variations. They 'move' the graphical elements and reason about the design within their design constraints. Therefore, critiques can reframe the design problem and find reasons to guide further moves.

1.3 DESIGN EVALUATOR

Following this observation, we built the Design Evaluator, a design environment that offers critiquing annotations on drawings to facilitate design reflections. Design Evaluator encourages designers to think about alternative possibilities of design through critical feedback. This feedback can be the impetus to move spatial elements. The current Design Evaluator supports architectural plans that specify configurations of spatial elements. In the early design stage, architects draw a bubble diagram in the early design stage, and then manipulate shapes, functions and relationships of graphical elements. Three visual reasoning processes facilitates design development (Goldschmidt, 2001).

Design Evaluator offers critiques about functional issues and concerns about circulation path, adjacency requirements, as well as an interactive 3D visualization. Design Evaluator supports the designers with critiques until they arrive at a configuration that all requirements are satisfied.

The rest of this paper is organized as follows. Section 2 describes related work. Section 3 is a scenario that illustrates how architects reason with their drawings. Section 4 describes Design Evaluator and Section 5 concludes with a summary and discussion.

2. Related Work

Our project is based on two related premises. First, sketching is important in the creative design process. Second, freehand drawing system therefore is an appropriate tool to access design reasoning systems.

Computationally enhanced design tools can offer support for reasoning. In order to build an environment supporting architectural design reasoning, especially, we examined architectural concept sketches and observed they mainly employ three kinds of reasoning: spatial reasoning, functional reasoning and 3D visualization. Our Design Evaluator is therefore concerned about these three kinds of reasoning. Below we briefly review related work in these areas.

Sketching systems that support spatial reasoning have been developed for design. Electronic Cocktail Napkin (Gross, 1996, Gross and Do, 2000) recognizes and interprets users' sketches to activate often a simulation or an image retrieval. For example, if the user draws a stack of boxes, the system would recognize the diagram of Wright's Guggenheim museum for the CBL.

The sKEA (Sketching Knowledge Entry Associate) system interprets sketches and the spatial relations in them to retrieve relevant information (Forbus and Usher, 2002). For example in a sketch, sKEA can match a rounded body of a cat to the rounded human torso. This matching capability can suggest possible placement locations for the limbs of a cat, close to the Design Evaluator project we present here.

Critiquing systems have also been built support design. KID (Knowing-in-Design) (Nakakoji, 1993) and CRACK (A Critiquing Approach to Cooperative Kitchen Design) (Fisher and Morch, 1988) support kitchen floor plan design with critiquing messages for problematic aspects such as a poorly placed appliance or an incorrectly sized work triangle. The systems also offer successful kitchen layout examples for identified design tasks.

Several design systems provide critiques about functional behavior of recognized diagram symbols. For example, Critter (Kelly 1984) is a system for critiquing digital circuit designs. It provides critiques about behaviors such as unsatisfactory operating speed or power consumption. SketchIT

(Stahovich, 1996) is a system for conceptual design of mechanical devices such as hook and pushrod. SketchIT identifies the parts and simulates the system's behavior to provide design feedback about function.

Several systems provide 3D visualization from 2D sketches. Teddy (Igarashi, 2000) enables a designer to quickly generate a three dimensional model from a sketch. Teddy generates three dimensional curved objects with a polygonal mesh representation that is useful, for example, for the early design stages of character animation (i.e. modeling a Teddy bear). VR Sketchpad (Do, 2001) enables quick creation of three dimensional space in VRML from a floor plan drawing. The project provides designers with a visualization tool to understand the relationships between the 2D plan view and its corresponding 3D space.

3. Reasoning with Sketches

3.1 VISUAL SYMBOLS: SPACES AND TEXT LABELS

Architects use visual symbols to represent their design ideas. For example, lines represent walls and a shape enclosed by lines defines an architectural space. Labels often appear inside these enclosed shapes to denote functional assignments. These symbolic representations in drawings help designers to keep in mind the spatial arrangement is and what each space represents. Upon careful examination, one can identify designer's reasoning process in a design drawing. Drawings expose designers' reasoning, because they record their ideas and concerns. For example, Graves describes that he sketches to record his observations and discoveries. He keeps his shorthand notes and sketches to be combined with other version of sketches. He also explained that represented symbols are a kind of language to communicate with himself or others (Graves, 1977).

Architect Steven Holl usually makes many water color drawings on 4*5 pads in the early design stages. His sketchpad is a mixture of words, sentences, and sketches. It includes everything from concept ideas to details. In his interview (Yukio Futagawa, 1996), he explained that he records his rough ideas in his sketchpad and his ideas are articulated with words, images, thoughts of space, spatial propositions and even materials. Moreover, he argued that his drawings help his design decisions. For instance, in the Museum of Contemporary Art in Helsinki, he said as follows (El Croquis, 2002): *"We made the watercolor concept drawings and perspectives, then we found the tectonics of the curved steel truss"*. The 'then' suggests, we sense that he reasoned about his design using drawings. The words and sketches in his sketchpad are the articulated design ideas and the

reasons for design decisions. Therefore we can understand and trace architects' ideas and reasoning from their sketches.

Figure 1 is an early design drawing by Steven Holl for the University of Iowa's Art and Art History Building. In this drawing he used lines and arrows to represent walls and visual access. He also wrote labels such as 'office', 'painting', 'history', 'class', 'court', and 'sculpture' to label these functional spaces. He wrote "main horizontal passages = meeting places" with a yellow box as a legend, and drew the pedestrian circulation passage in yellow. Several double-headed arrows indicate visual access between the passage and the classrooms, because a call-out arrow from the path is linked to the text of "see ongoing work along passage in court". These graphic symbols and text annotations indicate that the designer is concerned about the passageway between the court and the other classrooms (Figure 1).

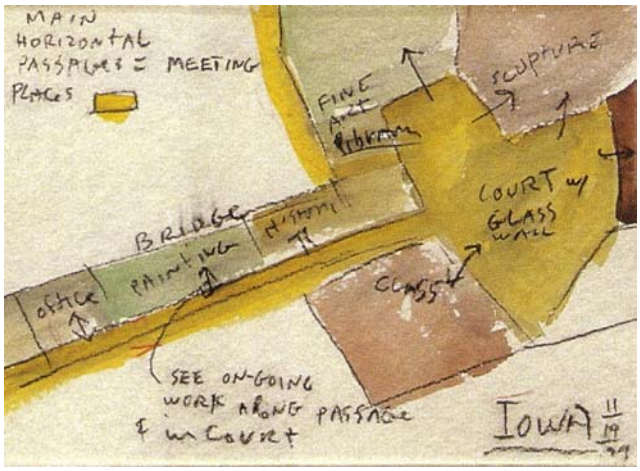


Figure 1. Visual symbols in Steven Holl's design drawings for the University of Iowa's Art and Art History Building include wall lines and text labeled spaces: The circulation path (passage way) is highlighted in yellow. Double-headed arrows indicate visual access. (Source: El Croquis, Holl, Steven, 2002)

3.2 SPATIAL CONCERNS

Architects see spatial relations such as connection and adjacency among spaces in their drawings. In the example (Figure 1), a 'court' (polygon space on the right) is connected with a sculpture room (top right) and a classroom (lower left). These spaces are clearly labeled 'sculpture' and 'class.' The architect has written, "w/ glass wall" below the functional label 'court' to note a material choice. Arrows from the court to sculpture room represent

concerns of visual access (i.e. the intent for people to can see the sculptures through the glass walls).

Architects also use drawings as a medium to contemplate spatial arrangements. For example, Figure 2 shows a concept sketch in which the different colored shapes represent functional spaces. Figure 2 shows the Y House concept sketch. He divided the house into two characteristic areas. He notes "NIGHT" and "DAY" in the bottom of sketch and colors the corresponding spaces light yellows and brown. He also decides the character of each space, such as 'sleep' and 'active'. His notes and coloring of spaces make the focus and concerns more visible on the paper and perhaps helps him to remember the idea or to communicate with others.

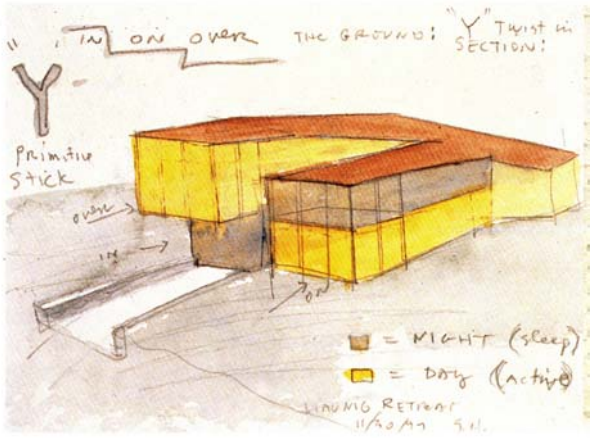


Figure 2. The different functional spaces are drawn in different colors in the concept sketch for the Y House (Source: El Croquis, Holl, 2002)

3.3 FUNCTIONAL CONCERNS

We can identify architects' concerns and decisions about functional arrangement of spaces and circulation from their design drawings. For example, in the plan for the Y house again (Figure 3, Holl wrote 'MBR', 'BR', 'DR/K' and 'LR' as functional labels. The connecting linear shapes in yellow (center of the drawing) represent a continuous ramp. We can see that he drew a call-out line to label this as a "Y" ramp. The rectangle symbol next to the ramp represents a staircase. We suppose that this is a design for a two storiey house, judging from symbols (stair and ramp) and text ("upper level" and "below"). In this drawing, the designer is concerned about the functional arrangements on the different floors. For example, on the top right, the architect wrote "BR below LR", a shorthand for the placement of a

bedroom placed below the living room (at this level). He places ‘BR’ in the ‘NIGHT’ area (lower level) and ‘LR’ in the ‘DAY’ area (upper level). Similar markings of ‘MBR (master bedroom)’ and ‘BR (bedroom)’ also appear on the lower part of the sketch. Adjacent to the rooms is an arrow with the text DR/K (Dining room /Kitchen). He places ‘MBR’ and ‘BR’ in the ‘NIGHT’ area and ‘DR/K’ in the ‘DAY’ area. Holl also circled his annotation of “2BR upper level” (lower left). This drawing shows that the designer was concerned about arrangements of functional spaces and spatial relationships such as horizontal or vertical adjacency between rooms.

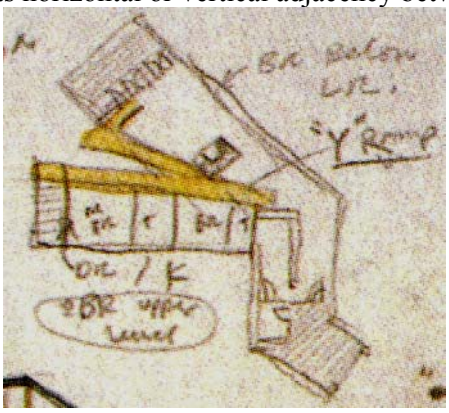


Figure 3. Text labels in the concept sketch for Y House indicate concerns about spatial arrangements of functional spaces. (Source: El Croquis, Holl, 2002)

We can understand Holl’s sequential actions in terms of Shank and Abelson’s ‘scripts’. These interconnected activities of zoning and room placement are causally linked (Schank and Abelson, 1977). He considers the previously decided characters of spaces in the room placements: for example, the rooms such as living room, kitchen, and dinning room that have ‘active’ character are placed in the ‘DAY’ area. ‘BR’ and ‘MBR’ are placed in ‘NIGHT’ and ‘SLEEP’ zone. If ‘BR’ is placed in placed the previous determined ‘DAY’ and ‘ACTIVE’ zone, he should move ‘BR’ into the planned zone.

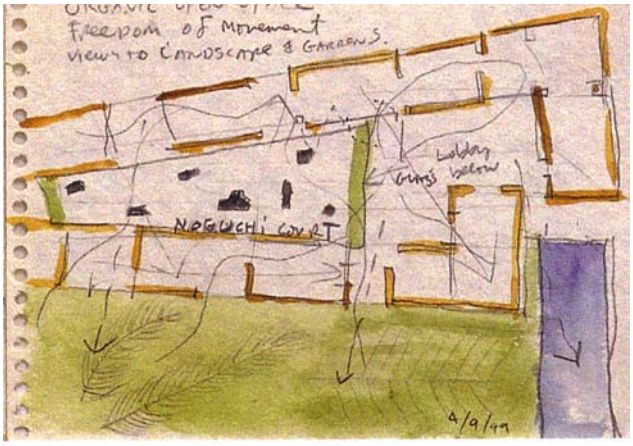
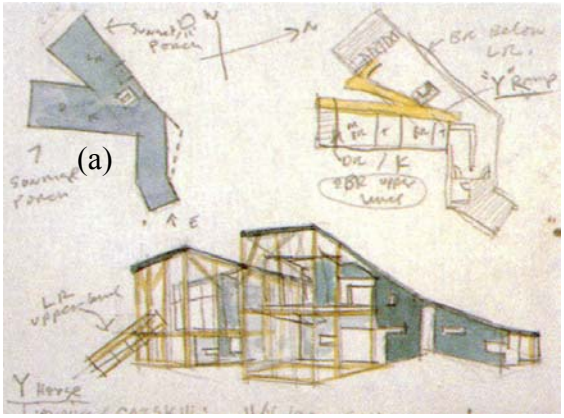


Figure 4. Circulation path concerns represented as curvy arrows in Holl's concept sketch of the Nelson Atkin Museum of Art Expansion (4/9/99) (Source: El Croquis, Holl, 2002)

Architects also consider the circulation paths in their design. In Figure 4, Holl's concepts are 'Freedom of Movement' and 'view to landscape & gardens' like reflecting his concepts, the drawing has entangled curvy arrows between lines. The lines represent wall partitions. The curvy arrows represent the circulation paths. In this design sketch, 'NOGUCHI COURT' is in the middle of the building. He reasons about whether the building users can move freely in other areas while seeing the gardens. His reasoning is embedded in the act of drawings of entangled curvy arrows.

3.4 3D VISUALIZATION



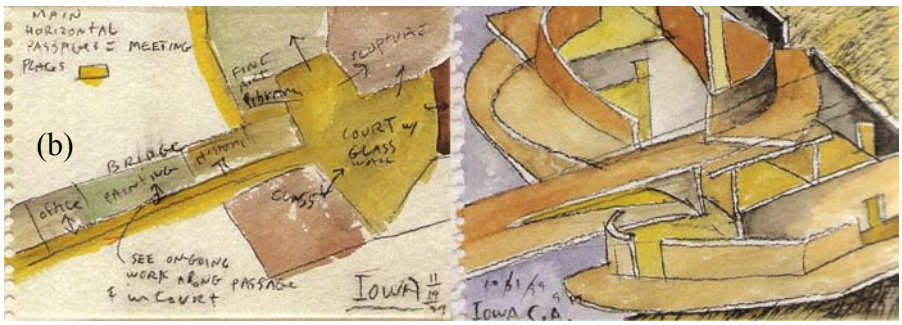


Figure 5. (a) Concept Sketch, Y House: (b) Concept Sketch, University of Iowa's Art and Art History Building (Source: El Croquis, Holl, 2002)

Architects use 3D perspective or isometric drawings during designing to reason about form and functional arrangements. Often these plan and 3D drawings appear on the same piece of tracing paper or on pages in the same sketchbook. Figure 5-(a) shows a 3D drawing that appears directly below the plan drawings of the Y House on the same page. This figure illustrates that the designer was concerned about the look and feel of the 3D form when he represented his design ideas in 2D drawings. Figure 5-(b) shows a bird's eye view (left). The relations of rooms are illustrated clearly in this drawing by simply extruding the wall lines from the plan diagram. The circulation path here is also colored in yellow like the plan diagrams (Figure 5-(b) and Figure 1).

4. Computational Tool for Reasoning with Design Critiques

In the previous section, we saw how one architect recorded his concerns about spatial, functional relation and 3D visualizations in drawings. Our observations are as follows. Holl uses the visual symbols and shorthand notes for recording his design ideas and concerns. He reasons about the relations among neighboring rooms (Figure 1) as well as the whole arrangement with dividing larger functional spaces (Figure 2 and 3). Figures 4-5 show that he is concerned about functional relationship and circulation path. Using his drawing, he reasons about horizontal or vertical adjacency. For reasoning about the form and relationship of spaces, he used 3D perspective drawings.

To support architects' reasoning activities about spatial and functional relationships and 3D spaces in their design drawings, we built the Design Evaluator as a proof-of-concept system. The Design Evaluator supports designer's reasoning process by providing design critiques.

In architectural design, one of the most complicated tasks is hospital design. In this section we show Design Evaluator at work using examples from hospital designs. In Figure 2, designer starts to sketch the large functional spaces (In Design Evaluator, we call this large functional space a zone). A hospital typically has three zones: Clinical zone, Nursing zone, and Support zone. The architect first specifies and draws the extent of these zones, then plans and draws several rooms for specific functional activities such as ER, ICU, and ward. For this kind of work, Design Evaluator provides a Zone checker. Zone checker verifies that the ER and ICU are in the clinical zone and ward is in the nursing zone.

Arranging the rooms, the architect is concerned with circulation path and functional issues. As in Figure 3 and 4, the designer considers adjacencies and circulation path. For example, ER and ICU should be adjacent, or a path must follow a specific sequence. To support this kind of reasoning, Design Evaluator provides a Path checker. The Path checker gives some design feedback.

From critiques, a designer can discover another reason to seek alternative design. If the system gives the text critiques with visual annotation and 3D VRML models, the designer might be stimulated by what is displayed, the visual annotation and critiques. Given a text message of "ER AND ICU SHOULD BE ADJACENT, TOO FAR IN CURRENT DESIGN", he imagines the arrangement of only two rooms. Visual annotation (path from ICU and ER) and the path in texture-mapped models gives the visual suggestion of how to apply the provided design knowledge to his design solution or how to revise his design. Like graphical maps, visual marks (annotations) on the drawing deliver knowledge in a compact way and they can generate new design ideas in problem-solving process. (Tversky, 2001)

4.1. KNOWLEDGE CAPTURE FROM FREEHAND DIAGRAMS

Design Evaluator is a sketch drawing environment. The designer uses a stylus with a digitizing tablet to make freehand diagrams that represent spatial arrangement of rooms in a floor plan. Designers enter two types of data into their drawings: spatial diagrams and text labels. Spatial diagrams of drawn shapes are recognized as functional zones and rooms and their connections. Design Evaluator allows a designer to draw two kinds of bubbles: zone and room. The designer uses a type-in box to input a text label for each room.

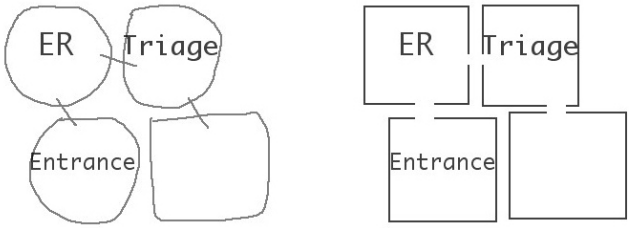


Figure 6. Sketched Diagrams: Design Evaluator provides two modes of drawing; sketched and rectified diagrams. In sketch mode, lines represent doors and in rectified mode, white space indicates doors.

The system also has two modes of display: sketch mode and rectified mode. The designer draws bubble diagrams to represent functional spaces such as entrance and triage (Figure 6 - left) and draws lines to connect bubbles to represent connections between functional spaces. The system can also display the space in a 'rectified' mode. In this mode, a freehand bubble will be converted to a rectangle shaped room and doorways are shown as open areas along the wall lines of the room (Figure 6 - right).

The Design Evaluator system captures information from the designer's sketches. Recognized symbols (zones, rooms, and doors), text and spatial relationships are compared with stored *a-priori* design knowledge to generate critiques. Design Evaluator recognizes the spatial relationships in the diagram and generates a network representation of all the rooms and doors, and also generates the set of all possible paths through the floor plan.

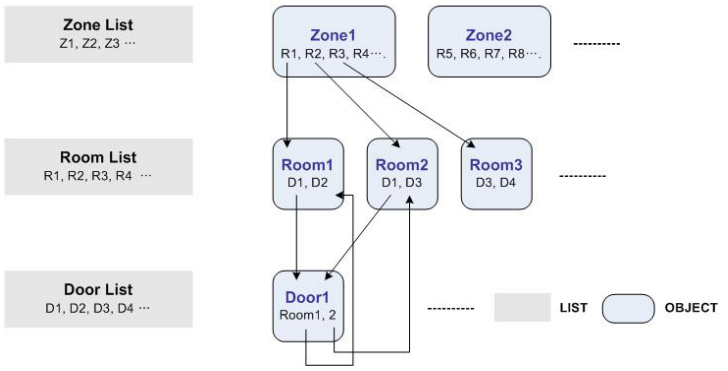


Figure 8. Relations of the Sketched Objects: Each zone has a list of its rooms and each room has a list of its doors. Each door knows which rooms it connects.

These sketched symbols are connected with each other in the database. Each zone object stores all rooms that are drawn in the zone likewise, each

room object stores the object describing the zone it is in. In this way, the system represents zoning information from the diagram (Figure 8).

4.2. CRITIQUING

Design Evaluator works with two kinds of information: captured information from the drawing and design criteria as built-in rules. Design Evaluator has two checkers: a Path Checker and a Zone Checker. The Path Checker operates with two kinds of rules: 1) path sequence rules, and 2) room adjacency rules. The Zone Checker currently only has one kind of rule dealing with room placements in the appropriate zones.

The design criteria are categorized as *Zone Rules* and *Path Rules*. These rules are previously proposed by the designer to the DE system for determining that the proper placement of rooms and proper sequence of circulation for the rooms.

(1) Room Sequence Rule in the Path Checker
The Path Checker takes the form of an expression of:
(<Requirement> <room1> <room2> [<room3>])

This expression indicates that path sequence should follow room1– room2 – room3. For example, the following expression represents a required circulation sequence in a hospital design:

(MUST-PASS-THROUGH ENTRANCE TRIAGE ER)

The path from entrance to the ER must pass through the Triage area. This rule represents that the placements of functional spaces of ENTRANCE, TRIAGE AND EMERGENCY ROOM (ER) should follow a particular sequence of ENTRANCE – TRIAGE – ER. This requirement ensures that once patients are received from the entrance, they should be directed to Triage for treatment decisions before being sent to the ER.

(2) Adjacency Requirement in Path Checker
The Path Checker takes the form of an expression of:
(<Requirement> <room1> <room2>)

For example, the following expression represents a required adjacency of two rooms in a hospital design.

(SHOULD-BE-ADJACENT ER ICU)

This requirement means Emergency room and Intensive care unit should be adjacent. If the patient is delivered to the ER seriously ill, he should be directly moved into the ICU.

(3) Proper Room Placements in the Appropriate Zone in Zone Checker
The zone checker takes the form of an expression of:
(<Requirement> <Zone> (<Room> <Room> <Room> <Room> ……))

This expression indicates that all the Rooms should be in the given Zone. For example, the following expression represents a typical room placement requirement in hospital design:

(MUST-BE-IN CLINICAL-ZONE (ER TRIAGE CLINIC-FOR-OUTPATIENT DAYWARD…)).

Certain rooms that we used for direct patient care should be placed in the clinical zone.

Each rule is compared with the zone and room in the designer's sketch, and the paths that the system has derived. The checkers compare the spatial arrangement of zones, rooms and paths with the rules. First, the Zone checker helps to identify improper room placement in a zone. Although these seem simple to decide, in a design for a complicated building like a hospital, it is not uncommon to find poor placement of rooms. If the Zone checker discovers conflicts against rules, it suggests the proper zone.

Secondly, the Path checker supports functional reasoning with two issues: to identify improper arrangement of path sequence between rooms and adjacency requirements. If the captured paths from sketched diagrams violate these path rules, the Path checker lets the designer know.

4.3 DISPLAYING CRITIQUES

Design Evaluator uses three methods to display the generated critiques: text messages, annotated drawings, and color coded 3D visualization. Critiquing is an effective way to stimulate designer's reflection, because it provides feedback for designers to improve their design, yet minimizes the increase in the designer's cognitive load. This section describes how the system gives critical feedback to the designer.

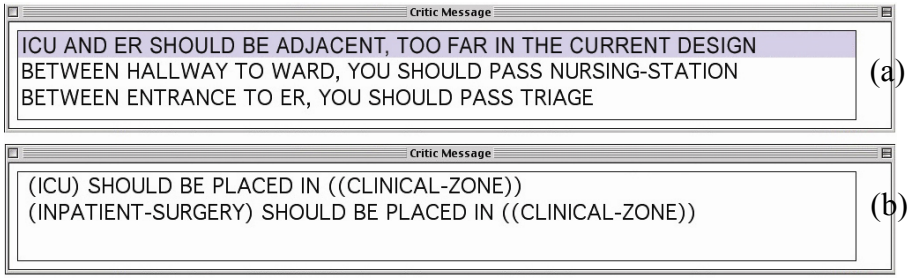


Figure 8. Textual Critiques: (a) Path Checker critique messages display adjacency requirement (1st message) and proper sequence of rooms (2nd and 3rd messages), (b) Zone Checker critique messages signal problems with room placement.

4.3.1 Textual Feedback

The system generates text messages in a special critique window, when the checkers find problems in the proposed design. Figure 8 shows an example of textual critiques. The first message in Figure 8-(a) shows that "ICU AND ER SHOULD BE ADJACENT, TOO FAR IN THE CURRENT DESIGN". The messages in Figure 8-(b) are about zoning requirements.

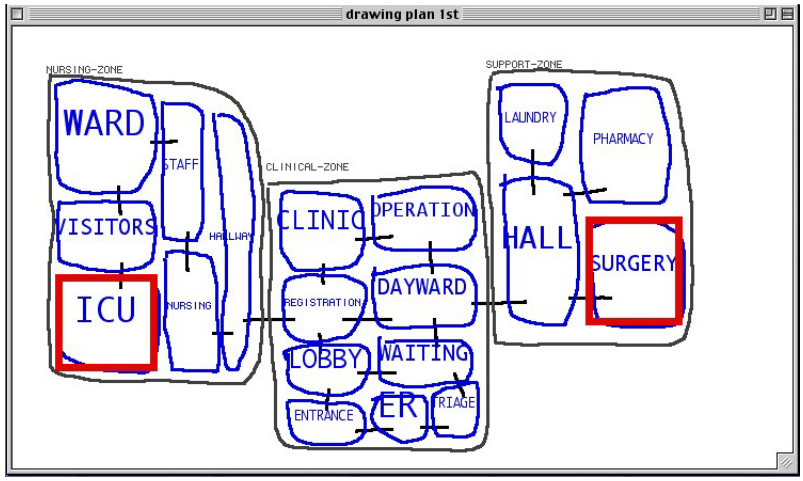


Figure 9. Zone Checker: Annotated drawing of zone rules conflicts: This annotation draws designer's attention to the placements of ICU and Inpatient-Surgery. (top- sketched input with critique annotation; bottom- rectified display mode with critique annotation)

4.3.2 Visual Feedback

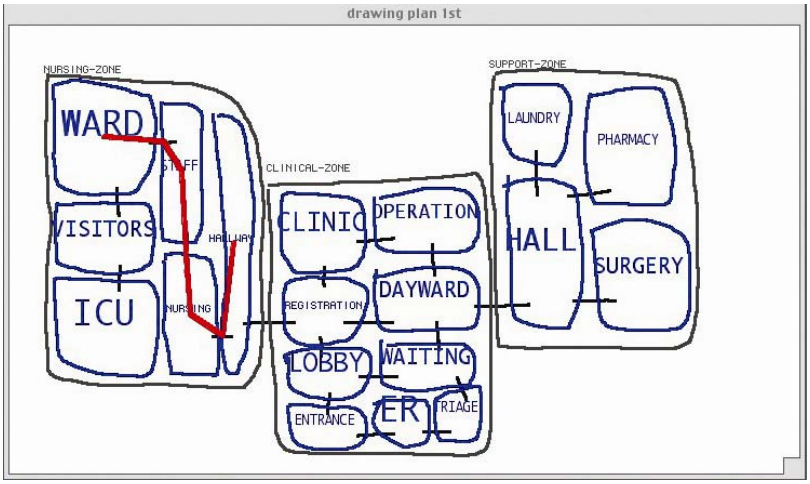


Figure 10. Path Checker: Annotated Drawing of conflicts against path rules

Each generated textual critique message is connected with a drawing annotation. By drawing annotation we mean symbols added to the design drawing. For example, when a problem space is identified, the system will highlight that room boundary with thick wall lines (ICU and Inpatient-surgery in Figure 9). The Zone checker shows the designer the wrongly placed rooms by with highlighted thicker lines and also gives a text suggestion to move the rooms to the appropriate zone (Figure 9). The textual and visual critiques are connected: if the user clicks on the first message in Figure 8, the Path checker shows the path from Ward to Hallway (Figure 10).

4.3.3 3D Visualization for 2D floor plan

The third method for providing design critiques is a 3D visualization of the space with VRML (Virtual Reality Modeling Language). Figure 11 shows the texture-mapped VRML model in the web browser, with highlighting path. Texture-mapped models give the designer a realistic simulation of the designed space. A 3D model enables the designers to easily visualize the spatial relations in 3D and be able to "walk" inside the simulated space to further evaluate the spatial quality of the design.

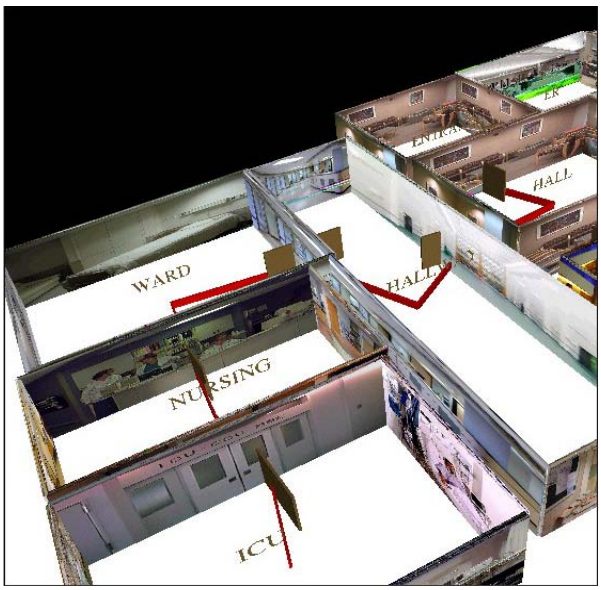


Figure 11. Texture-mapped VRML model: Each room label is appears in the middle of room and path between ICU and ER is displayed

5. Discussion

Architects reason when they are making design drawings. As discussed above, architect Steven Holl drew graphical symbols to represent his design solutions. These symbols include lines and enclosures to represent functional spaces and text labeling for the rooms. Holl included semantic information such as notations of design rationale on drawings apparently to remind himself of that information or to communicate it to others. We observed that architects reason about spatial relations, functional concerns and 3D space with their design drawings. We explored the potential of supporting these three categories of reasoning by implementing Design Evaluator, a sketch-based design critiquing system.

When the sketched diagrams violate previously stated rules, Design Evaluator generates and annotated critiques. Knowledge is represented in the system as predefined rules that concern spatial relation, functional concerns and 3D space. Design Evaluator provides designers with textual and visual design critiques. Through visual critiques, designers may recognize potential problems. The designer might then try to solve those problems by moving rooms based on the provided critiques. In other words, Design Evaluator reminds designers of missing design information visually as well as in other ways; these visual critiques might trigger new design alternatives. The

critiquing helps the designer to reason with his drawings about any issues he might have overlooked.

Acknowledgement

This research was supported in part by the National Science Foundation under Grant CCLI-0127579. 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.

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