THE EXPEDITION OF EXPERTISE:
DESIGNING AN EXPERT SYSTEM FOR DESIGN

by

SAMUEL ISENSTADT

Bachelor of Arts
Washington University
St. Louis, Missouri
1979

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE DEGREE
MASTER OF ARCHITECTURE AT THE
MASSACHUSETTS INSTITUE OF TECHNOLOGY

JUNE, 1985

Signature of the author _____

Samuel Isenstadt
Department of Architecture
May 10, 1985

Certified by _____

Ranko Bon
Assistant Professor of Economics in Architecture
Thesis Supervisor

Accepted by _____

Julie Moir Messervy
Chairperson
Departmental Committee on Graduate Students

by Samuel Isenstadt

Submitted to the Department of Architecture on May 10, 1985, in partial fulfillment of the requirements for the Degree of Master of Architecture.

ABSTRACT

Principal assumptions are made during the early stage of the design process, fixing 70% to 80% of total building costs and most of a building's architectural and environmental qualities. The demands of any one constraint impose a whole set of assumptions that often result in a design that is satisfactory along only a few dimensions. Ruling out many alternatives at a stroke, such assumptions relieve the architect from exhaustively reviewing variations by removing opportunities from consideration. Both the power and crudenesss of assumptions increase as constraints multiply and conflict. Having the ability to quickly and thoroughly evaluate assumptions and their consequences would allow architects to intelligently challenge and reform those assumptions and, as a result, to explore a broader range of possibilities for any particular design.

This is particularly important in complex projects where the architect's primary role may be to orchestrate experts. This role is not insignificant, for the experts' recommendations will necessarily be bounded by their own concerns and will often conflict. The architect must assign values to design consequences and must provide the assumptions that the experts will base their recommendations on. The architect, then, focuses on making assumptions and interpreting evaluations. But assumptions are often outside analysis; rules of thumb, based on experience, generally prevail.

Knowledge-based computer expert systems are a promising path of research for the support of concious and explicit assumption-making. The crucial question for this technology and the central topic of this thesis is how to structure knowledge for use in such a system. My primary goal is to offer a representation of the knowledge involved in window design (a simpler and somewhat isolable subset of building design), a representation comprehensive enough to be useful, but also flexible enough to support differing design processes and decision sequences.

Keywords: Window Design, Expert System, Heuristics, Assumptions, Constraints, Knowledge.

Thesis supervisor: Ranko Bon

Title: Assistant Professor of Economics in Architecture

CONTENTS

INTRODUCTION

It is always interesting to try to reconstruct one of our complex activities, one of those complete actions which demand a specialization at once mental, sensuous, and motor, supposing that in order to accomplish this act we were obliged to understand and organize all the functions that we know play their part in it. Even if this attempt, at once imaginative and analytical, is clumsy, it will always teach us something.

Paul Valery 1939

Poetry and Abstract Thought

INTRODUCTION

Design expertise and design judgements are dependent on the scarce resource of knowledge. As evaluated by comparison with objectives, the difference between better or worse in design, is often a matter of the knowledge brought to bear on the task by the designer. This thesis is about structuring design knowledge for eventual implementation in a knowledge-based expert system.

I attempt this task by following two threads. One is window design, a significant and fairly well-understood task in many architecture offices. My premise is that window design attempts to satisfy functional requirements, subject to a prioritized list of constraints, by proposing a particular configuration of elements. Varying functions, constraints, and elements allows for a combinatorially huge number of satisfactory proposals. Attention from several different experts is often required. Architects make assumptions to simplify this situation and to provide the basis for input and for interpretation of expert opinions. This practice of assumption-making is not often analyzed. Experience leads to a reliance on common procedures and conventions. Most often, rules of thumb prevail. These heuristics are an important and effective tool which allows designers to reduce the number of possibilities and make decisions.

The other thread of my research is the development of expert systems. Expert system development is an area of artificial intelligence that concerns itself with programs that operate in a specialized domain at the level of an expert. Already implemented to various degrees in well-researched fields such as medicine and chemical spectroscopy, expert systems are able to evaluate situations within a narrow knowledge area with the accuracy of a human expert. The expert system, based on a simple information processing scheme, requires only two capabilities beyond the input and output features.

First, it must be able to draw inferences. This is actually off-the-shelf technology today. Second, it needs a large body of knowledge to make inferences about. "Knowledge engineering," the structuring of knowledge for use in a computer, is the foremost challenge to the development of expert systems and to their application to architectural design.

The difficulty in the knowledge engineering of design problems is that they are generically different from those in other, more deterministic domains. Rather than examining a given situation with a finite number of possible solutions, the designer refers to a situation that is not yet in existence. The difference is between analysis and synthesis. The former is fairly well understood, the latter is still a frontier. Much design knowledge is best quantified, such as energy loss through glass, but much is personal and subject to change over time.

The ability to alter is crucial, for any tool must leave open the design process. Any system which prejudiced the sequence of decisions, should be regarded as a failure. For example, the decision to consider daylighting factors before energy conservation may depend on the client, costs, climate or other constraints. This will vary from project to project and from office to office because the knowledge involved will necessarily be adapted for the project and the sensibilities at hand.

My research has followed these two disparate concerns, window design and expert systems, with the hope of discovering where they converge. Their common ground is a reliance on knowledge. Design in general and window design in particular are complex and rely on knowledge. Expert systems deal with complexity and strive to make knowledge explicit. An amateur and an expert reason equally well. The difference is experience, which boils down to knowledge. Tough constraints and variable attributes leads to a reliance on standard assumptions. The designer deals with this fact by

considering only a few possibilities. By tracing the economic, enviromental, and formal effects of assumptions between domains more comprehensively than the architect has time, resources, or patience for, a knowledge-based computer expert system would allow the consideration of a far greater number of alternatives and thus provide more complete information for design decision making. Rather than replace an understanding of analysis, it would make that understanding more explicit. Although much architectural thought is subjective, it is, nevertheless, amenable to rational understanding.

This thesis, then, is an exploration of the ways that an expert system may support the window design process and, by extension, the building design process. Windows are a good problem for expert system development because they require attention from several defined fields of expertise. Further, it is a domain small enough to be precise about, yet large enough to be interesting. Expert systems are promising for a design support system because architects typically use heuristics to manage conflicts and to choose among a large number of feasible solutions. Throughout this thesis, the greatest problem and the greatest source of intellectual excitement has been the exploration of an uncharted territory by attempting to provide a framework for building an expert system for window design.

Life itself goes on only in a framework of terribly narrow conditions, and it is only its most superficial manifestations that seem free and capricious. This flower is formed of a certain number of petals. My hand has five fingers, which I might consider to be an arbitrary number: it is for me to find some freedom in the exercise of this hand with five fingers, and the most agile and adroit actions that I shall obtain from it will be due only to the conciousness of that limitaion and to the efforts I shall make to supplement by art and exercise the small group of given means.

Paul Valery 1936

Fountains of Memory

WINDOW DEFINITION

A window is an opening in the exterior wall of a building, providing daylight, ventilation or sensory contact with the outside. It is also the construction installed in the opening. The opening is spanned by units of glass which are supported and fixed to the opening perimeter by a frame. These window parts, joined in some manner, determine the opening's degree of transparency to nature's proclivities.

Windows are, without doubt, an important part of any building's envelope. They are the most sensitive point of exchange between the interior and exterior environments. People spend most of their days indoors; windows, ranging in size from peepholes to entire buildings, provide the primary link to the outside. They are central to the physical and psychological well-being of inhabitants. "Windows, then, have a vital and multiple job to do: they are the eyes and ears of a building and also the lungs" (Pilkington Bros. 1969). From the outside they are also often the most expressive part of a facade, providing a human scale and a hint of vulnerability. In fact, tremendous effort is required to mollify the brutality of a windowless facade. They are sensitive in other ways; windows and doors (their logical counterpart) were the site of 25% of the durability faults in one study, (Harrison) and energy losses are always notably greater at windows.[1] Hence, the window has found a place in the language to denote any breach in a barrier, or pause in a boundary, connoted by both opportunity and fragility.

---

[1] "Although it is estimated that about one-fourth of the total energy used for heating and cooling buildings in the United States each year is lost through windows, a recent study at the National Bureau of Standards (Ruegg and Chapman, "Economic Evaluation of Windows in Buildings") has shown that it is possible to alter considerably the impact of windows on energy consumption and total lifetime building costs. Depending upon critical design and use decisions, it was shown that windows can increase, decrease, or have little impact on energy and building costs.

The entire window assembly is generally named by its operation. It can pivot, slide or fold or remain fixed in place. Some common window types are vertical and horizontal sliding, casement, awning, and louvre. The parts of a window include the frame, units of glass, joints, weatherstripping, storm windows, screens or shutters on the outside; arguably, blinds and curtains are also part of the window on the inside. Following is a list of window elements and some of the parameters:

Window Elements

FRAME: materials (softwood, hardwood, steel, aluminum, bronze, all with a variety of finishes, all with relative costs and many other properties) number of sashes, size of sashes, corner connection

GLASS: clear polished plate, tinted plate, rough plate, float, sheet, wired, rolled, patterned, insulating, heat-strengthened, tempered, laminated, safety, reflective, ceramic-colored (Koppes 1968)

JOINTS: frame/opening, glass/frame, frame/frame, sealants: mortar, putty, mastics, polysulphide rubber, butyl compounds, partially cured butyl compounds, cured butyl rubber, rubber, neoprene and other elastomers, silicone rubber, polyurethane (Rostron 1964)

HARDWARE: fittings, handles, hinges, latches, locks

SHADING DEVICES: interior, exterior, integral to the window, landscaping, etc.

Many aspects of any window are not exactly parts but are, nevertheless, critical. These are referred to as window attributes:

Window Attributes

>is in a space
>has area
>has a geometry
>has a position in a wall
>has dimensions
>has strength
>has sill height above floor
>has means of operation
>has overall R-value
>has a cost
>has a lifetime
>must be installed at a particular stage of construction
>is available only in certain quantities

Likewise, any particular window component, such as a frame or pane of glass, has an expected lifetime, an R-value, dimensions, etc.

Besides having physical attributes, the window also has multiple functions to perform. These are related to the senses and have as their basis the preservation of human comfort from a fluctuating environment. The window is a dynamic boundary controlling the transmission of daylight, air, sound, moisture, and radiation between the outside and a desired stable interior. Of all the forces acting on the window, including the human ones, only gravity is constant. As part of the overall building design, a window will be expected to make an aesthetic contribution, and will often need to provide some degree of security and privacy for the building's occupants. The following is a list of functions a window is called upon to perform (Koppes 1968, Bradshaw 1985, Jarmul 1980):

Function/Task

Daylighting: sunlight, view

Ventilation

Weatherproofing: rain, air infiltration

Energy Conservation: heat gain, heat loss, condensation

Sound Insulation

Appearance/Aesthetics

Different points of view would include the same tasks, only the grouping and relative importance of functions would alter.[1]

---

[1] For example: Bradshaw 1985, claims the four purposes of fenestration are: 1-Illumination, 2-View, 3-Solar Heat Gain and, 4-Natural Ventilation. Hillier would have window functions fall into the purposes he establishes for buildings, that is, to modify climate, behaviour, resources, and culture.

The performance of some functions can be evaluated by measurements. A test can determine, with a sufficient degree of accuracy, the R-value of an assembly. "Look good." a common requirement, is, however, notably hard to measure. To some extent, quantifiable aspects contribute to the satisfaction of a qualitative requirement. Fuzzy but frequent higher order functions like "It should feel comfortable." or "It should save money" are partly dependent on measurable thermal performance. Numbers have their place in the evaluation of functional performance, but the architect often relies on intuitions and experience, rather than thorough analysis. Footcandles alone are not enough to determine the quality of light in a room. "Building fenestration ... lays at the intersection of so many quantitative issues and, at the same time, is paramount as an element in the qualitative architectural vocabulary" (Widder 1985). Windows are called upon to enliven a facade as often as they are asked to admit no more than 625 Btus per hour on a warm spring afternoon.

For this reason, it is important to the success of any window design support system that it recognize the interdependencies of quantitative and qualitative functions. A light and airy space, partly a result of many window attributes, can justify measurably higher rents. Six inch high window sills on the upper floors of hospitals can aid patient recovery by allowing visual contact with the ground (Pilkington Bros. 1969). The cost of moving HVAC vents to the windows can be estimated, unlike the value of preventing cold downdraughts. The architect must somehow balance these complexly related functions in window design.

WINDOW DESIGN

Design, in theory or practice, is not reducible to a single simple scheme and grows more complex due to increasingly sophisticated clients and consumers, stricter codes, new materials, and changing construction methods. Further, no design solution is unique. Different interpretations of occupant needs, budgets, climate and building uses result in different designs. Design evaluation is likewise dependent on viewpoint.

The situation is, however, far from hopeless, for design does have some generally recognizable structures. Markus 1973, names two:

> The first is characterized by a chronological sequence advancing from the abstract and general to the concrete and particular and is here referred to as the *design process*. The second is a decision process characterized by stages which proceed from analysis through synthesis and appraisal to communication (there are as many varieties of and descriptions of this cycle as there are authors) and is referred to here as the *decision sequence*.

The sequence of decisions depends not on time but on the designer's priorities. Thus, decisions about windows can be made and examined at any point in the design process. Priorities are set during an early stage of information gathering from clients, users, context, codes, etc. Analysis reveals relevant requirements and constraints. Design is action oriented; it seeks the purposeful change of an object or environment in order to generate desired behavior. Constraints, whether economic, technical or legal, make demands on the fulfillment of those purposes. Alternatively, any goal -- provide adequate daylight -- can be expressed as a constraint -- provide no less than 100 footcandles on a 2.5' working plane 5' from the window. (Markus 1973, Elder 1974, Best 1973)

Constraints

The first step in window design, then, is to set functional performance requirements and identify the constraints. Constraints are the significant bounds to any design process, for the action of a design is the prescription of physical characteristics that will achieve certain qualities. Any artifact is adapted to meet the designer's goals, and constraints ensure that the design will adequately perform its required functions.

Constraints come from many sources: clients, the architect, engineers, consultants, utilities, banks, government agencies, climate, etc.[1] They also tend to develop as the design develops. An important design skill is to understand the degree to which constraints can change. Finally, a constraint's influence on a design will vary: that is to say, a required thickness of glass will have less formative impact on a design than will a tight budget. Such constraints are not part of a window, but they are a significant and essential part of window design.

Constraints:

Construction Technology Available: parts, labor, equipment.

Functional: insulation value, etc.

Architectural: consistency with architectural ideas or theme.

Legal: Fire codes, easements, daylight regulations, etc.

Design Resources: time, expertise, money, computing power

Site: micro-macro climate, physical context, zoning, services, access, geography

---

[1] Simon (1975) distinguishes between constraints and criteria in optimization problems, but, the use of heuristic techniques for satisficing allows the designer to combine these into a large set of constraints, treating equally those constraints from the client, climate, designer, etc.

Programmatic: building use, duration of use, adaptibility, insurance requirements, construction budget, security needs, etc.

In the window design process, previous decisions will further constrain the problem. Design may, in fact, be characterized as a process of setting constraints; fewer and fewer alternatives will be able to satisfy an increasing number of constraints. In this sense, constraints are to be exploited, rather than bemoaned. "Each added condition in the problem statement is one more item that can be exploited in finding the solution, hence in increasing the power" (Newell 1969). Any particular element or space may have a variety of forms of constraints: functional, qualitative, locational, quantitative, or technical (Swinburne 1980). The architect's task is to sort out constraints and inevitable conflicts, and attend to the most important.[1]

Costs

Of all constraints, costs emerge as the most significant. As something desirable that can be bought or sold, the window is a commodity and is subject to the laws of economics. "Decisions on the kinds of windows that are to be used in a building have to be made at an early stage in the design and it is often necessary to balance conflicting requirements against one another in order to arrive at the best overall solutions ... costs have a special significance because they provide the basis on which the windows proposed for any building must ultimately be judged" (Beckett 1974). The need for a basis is imperative: "Without a single criterion alternative solutions for parts of the design can never be combined nor the best overall solution be found. It

---

[1] "In the case of aeroplanes the demand for windows is directly opposed to the rational provision of safety: a continuous unbroken hull is safer than one with holes in it, besides being more economical. But it is unlikely that men would fly across the world in sealed cabins" (Pilkington Bros. 1969).

is meaningless to ask, 'Which is better, a good lift service or freedom from glare?' But it is quite meaningful to ask which of two lift designs is better or which of two lighting installations produces less glare" (Markus 1973). Expert opinions are delivered in terms of shortened construction time or daylight factors; costs are thus the common denominator for diverse activities such as delivery, site storage, insurance, installation, maintenance, and for the various functions, including, aesthetics.

Satisfying cost constraints is not, however, a simple matter, for the costs of components, running costs, costs of the activity being housed, including advertising and worker productivity, must be measured against the value of acheiving objectives. All of these have hidden costs that are not fully appreciated. Expensive window units may very well save fuel costs, but they may also be too costly to insure and breakage could even delay a project. Also, many of these costs occur in time and are inherently unpredictable. It would be a major accomplishment for building research to discover cost relations with changes in assumptions made about the future (Markus 1973).

Assumptions

Design would be considerably simpler if all the concerned parties would agree on a set of explicit and prioritized constraints. Unfortunately, this is quite impossible. Constraints evolve along with the design. Designers consider the inherent uncertainties of predicting the future and simply must make assumptions. It is not only practical but necessary to make assumptions when approaching problems of forecasting (Ahuja 1983).[1] Assumptions are introduced so that their hypothetical consequences can be explored. In design, assumptions take the form of tentative decisions.

---

[1] "Since the consequences of design lie in the future, it would seem that forecasting

Designers press on in the face of conflict and complexity by making assumptions. The assumption is best seen as a strategic first move and becomes a commitment only gradually. The consequences of an assumption are explored in a variety of ways: in sketches, in estimates, in discussions with design staff and clients, by computer analysis, or by the familiar but poorly understood act of squinting.

These are all forms of evaluation. The designer pauses and looks back at the decisions that have been made, often using inexact but effective personal yardsticks. An emerging design is be ill-defined, so few evaluative standards are widely recognized.[1] General rules, gained from experience and tacitly understood, allow the architect to rank alternatives according to their potential for satisfying design objectives. Because any objective can be applied as a basis for appraisal, an expert system must be transparent regarding the underlying values. Transparency ensures the accessibility and mutability of the objectives underlying an evaluation and allows different alternatives to be judged on an equal basis. The current factual and declarative language of evaluation could thus be adapted to the alternative-seeking needs of design problems. The assumptions that give rise to evaluative yardsticks could be altered, changed, or left for another iteration. An inductive power and permanance accrues to long standing assumptions.

The field of tentative reasoning, or contingency decision-making, awaits exploration and classification.[2] Certainly included would be an assessment of the quality of data, a

---

is an unavoidable part of every design process" (Simon 1984).

[1] " ... the importance of testing one's hypothesis is of the essence. What is needed is the development of rigorous and systematic methods for testing and evaluating hypotheses -- i.e. designs ... this need may well be more important than the development of methods which try to systematize the generation of designs" (Rapoport 1973).

corresponding degree of uncertainty and, consequently, an assumption's capacity for change. One useful distinction would be between assumptions that directly affect a particular design, such as a frame material, and those that affect the process, such as the relative priority of constraints or the determination of constants and variables. Another distinction is between normative and descriptive assumptions. This distinction is based on the notion that the design task is to determine how an artifact should behave and then to predict how the current state of a design would behave. The artifact is the interface between designer and the world, thus, assumptions will center around it (Simon 1984). Further, a particular constraint, such as life-cycle study period, is itself an assumption. Some assumptions are widespread and conventional, like using a uniform sky when evaluating daylight levels. Other, more idiosyncratic, assumptions need to be supported and justified.

Justification is needed because assumptions have different consequences, with different cost implications.[1] For example, assuming window sealants need to be replaced every four years (rather than every six) may actually lower maintenance costs if replacement coincides with the repainting schedule. Capital costs could be lowered by the specification of a cheaper window seal. Whether the design is constrained by capital costs or running costs will depend largely on the assumptions about the method of appraising the building as an investment.

Thus the ability to quickly manipulate assumptions and learn about potential consequences is crucial. Different experts will base their recommendations on the assumptions made by the architect. Further, the architect must base his or her

---

[1] The values attached to different assumptions are also subject to change. This is apparent in higher risk projects where the assumed project life can have critical and far-reaching effects. "The client's projected life for the building will influence the choice of materials and finishes and the degree of adaptability" (Elder 1974).

interpretation of evaluations and expert recommendations on assumptions. For example, the same thermal performance evaluation will be judged differently depending on whether the investment time frame is five years or fifteen. Later decisions alter the assumptions that earlier decisions were based on. Depicting design this way makes it appear laborious, but, what takes many pages here often occurs within moments in the designers mind. Because the fixing of dynamic functions is an arbitrary, albeit useful, way of dealing with many-dimensional problems, a window design expert system should be able to treat decisions as tentative and lend some sense to the rich interpretations of design decisions. The goal is a system that could link an unpleasant view, small windows, increased artificial lighting, and building user satisfaction.

KNOWLEDGE

I think, my dear, you have a mania for exactitude and an impatience with partial knowledge which is ... well, unfair to knowledge itself. How can it be anything but imperfect?

Lawrence Durrell 1960

Clea

KNOWLEDGE

Knowledge Definition

Knowledge is basically an acquired familiarity with facts or relations. It is a term well-understood in daily speech that grows recalcitrant only when removed from discourse and scrutinized. As a resource, it is perishable, scarce, vague, inconsistent and difficult to accumulate. Significant cultural advances are made when a society finds ways to preserve, reproduce, formulate, systematize and stimulate the growth of knowledge. Perpetual reinvention is the fate of the culture that cares not for its knowledge.

Forms of Knowledge

There are many discernable forms of knowledge, though boundaries are vigorously disrespected. Descriptions of facts, empirical associations, theories, operations in some domain, heuristic methods for dealing with uncertain data or error, concepts, constraints, models, and beliefs are all forms of knowledge. "In short, knowledge consists of [1] the symbolic descriptions that characterize the definitional and empirical relationships in a domain and [2] the procedures for manipulating those descriptions" (Hayes-Roth 1983).

Three levels of knowledge are fairly well-recognized in artificial intelligence: facts, heuristics and meta-knowledge. Facts are assertions about the world that can be concrete or abstract, but they are always more or less observable.

Heuristics

Heuristics are a means of dealing with problems complex or not easily formalized. They are a distillation of knowledge into a highly usable form, a crowning

acheivement of the abstractive faculties. They are broad strokes that lop off whole sets of possibilities, effectively reducing the variety of options and relieving the decison-maker from reviewing all alternatives.

They are a rather private knowledge, resembling common sense and consisting mostly of rules of thumb that enable educated guesses based on incomplete information. "An expert's knowledge helps spot useful data early, suggests promising ways to exploit them, and helps avoid low-payoff efforts by pruning blind alleys as early as possible ... Elucidating and reproducing such knowledge is the central task in building expert systems" (Hayes-Roth 1983). As a new topic of study, there is equivocation over a precise definition of heuristics. In a symposium on heuristics in honor of George Polya, Groner writes: "What are heuristics, the methods and rules guiding discovery and problem solving in a variety of different fields? ... the final discussion [at this symposium] revealed that there is no agreement in the definition of heuristics, not even whether such a definition is possible." Heuristics, then, is an emerging concept with a broad reach across human endeavours and bearing on logic, philosophy and psychology. We can, however, indicate a spectrum ranging from "a method or trick whereby the number of plausible solutions can be reduced" to Polya's claim "that the goal of heuristics is to develop methods of discovery and invention" (Pushkin 1972).[1] It is the science which studies the design of new actions in new situations and the art of bringing complex problems down to the scale of human energy. Although heuristics are not guaranteed, observations of problem-solving techniques reveal that people use them. They promise a savings in effort in a universe that is largely redundant.

---

[1] Some of Polya's heuristics on solving mathematical problems: Working backwards from a solution, decomposing a problem, dealing with subproblems in order of difficulty, trying to solve simpler parallel problems first, using models as a guide.

The fact that heuristics are so evolved obscures their structure and the rationality they are based upon. I can presently distinguish two major categories of heuristics, procedural and substantive. Procedural heuristics suggest strategies, a path such as "Try x first, then y, then..." An expert can often simply know which is a more promising path, despite unavoidable unknowns. Such heuristics rely on the common sense approach of turning frequent and repeated decisions into routines. Substantive heuristics deal more with the "what" of the decision, not the "how." This is easily seen in the form of trade-offs. Most choices are between alternatives, whether present or future, at a micro or macro level, singly or in groups (Grant 1964). The trade-off heuristic says something like; "All else being equal, choose the window alternative with better daylighting qualities because that will do the most to improve the environmental quality." In a view of design as the movement between an existing state and a desired state, procedural and substantive heuristics correspond respectively to states and the movement between them.

Heuristics play a role in window design. From experience, an architect knows that some things are more likely to work than others. For example, "Reducing window area reduces heat losses and in the majority of dwellings has no detrimental effect upon the quality of living" (MHC 1979). The architect can reduce the window area without further consideration of other alternatives. This assumes that there is something fundamentally correct about this heuristic. It is certainly efficient with a constraint such as "Design it by tomorrow." The decision to lower heat loss by reducing window area is good enough. The missed opportunity for passive solar gain was simply outside the constraints of the problem. Even with unlimited time, it makes great sense to consider the strongest or most determining influences rather than those with less impact.

This simple example actually relies on quite a bit of knowledge on the architect's part. Required is knowledge of objectives, assumptions, constraints, about "the majority of dwellings," and "the quality of living," and about the speed of path exploration, all within the framework of a subjunctive building. A major goal of expert system development must be to offer some structure for this compact form of knowledge, to identify a common structure for heuristics. Culled from years of experience, how can heuristics be classified, indexed, cross-referenced, augmented, stored and retrieved and linked, as design knowledge so often is in our minds?

A third level of knowledge is "meta-level knowledge, or knowledge about knowledge. This takes several forms but can be summed up generally by saying that a program can 'know what it knows.' That is, not only can a program use its knowledge directly, but it may also be able to examine it, abstract it, reason about it, and direct its application" (Davis 1983).

Expertise

Problem-oriented facts and general problem-solving heuristics, as stated earlier, are not easily separated (Minsky 1968). The expert employs all levels when solving problems, explaining decisions, restructuring knowledge in light of new experience, breaking conventions, extending concepts, and knowing the limits of the domain of expertise. This leads to another observation about expert knowledge, that it is domain-specific. "Expertise consists of knowledge about a particular domain, understanding of domain problems, and skill at solving some of these problems" (Hayes-Roth 1983). Further, expert system development is critically reliant on digging out such knowledge. "The success of any reasoning program is strongly dependent on the amount of domain-specific knowledge it contains. This is now almost universally accepted in AI" (Buchanan 1977).

An interesting paper by D. Lenat in 1975 depicts knowledge as the interaction of experts with no knowledge outside of their narrowly defined domain. Along with several associates, he created a group of "experts" who write programs. They are expert only in their own field (being able to recognize the limits of their domain); they come with a body of facts and strategies, they can set up and alter structures and they can recognize their relevance to a question. About 100 experts with different responsibilities interacted within a question and answer paradigm.[1] These Beings, as Lenat called them, were slow, but valuable for the very explicit way their knowledge was organized in a field that requires a huge and complex mass of knowledge.

In choosing between alternatives, a human expert also relies on knowledge not necessarily endemic to the field of expertise. It is culled form daily experience, much of which is coincidental. The understanding that people are amenable to a broad range of standard arrangements could be called upon as a reason to accept one window design alternative over another. "Sitting in the sun is nice," and "Contact between copper and aluminum encourages corrosion" are both statements of general knowledge that might become significant in the process of designing a window. While there exist immediate and more distant neighbors to windows, it would be difficult to delimit any one domain to which these statements would belong. In an expert system, it would be useful for any bit of knowledge to be accessible from several directions. For example, "People prefer daylight" could be invoked as a rationale for decisions affecting windows, building massing, even elevator placement.[2]

---

[1] One of these experts recognizes the value of procrastination and tries to defer decisions whenever possible. Another expert is a kind of traffic cop who can send messengers to get more information or store and retrieve calcualtions from an earlier stage.

[2] In the design of Rockefeller Center's RCA building, the architects describe the form evolving from considerations of the distance between the windows and the

Knowledge is a commodity when experts are hired for their knowledge. This is the impetus to develop expert systems. The difficulty lays in transferring knowledge from expert to expert system. Judgement, intuition and experience, intimately and often mysteriously bound to knowledge, are notably hard to describe. The novice, in the early stages of knowledge assimilation, requires explicitness. The expert's knowledge, however, is often so thoroughly internalized as to seem subconcious and his or her comprehension of choices will not always be compatible with theory. Further, some traits of heuristics will be lost in the formalization of the knowledge of a domain. Tacit concepts can go unrecognized if they are not named. At the highest levels of intelligence many functions are both formal and non-formal, and it is doubtful whether the essence of knowledge can be characterized in wholly logical terms (Gurova 1972). The good news is that the effort to acquire knowledge for an expert system forces precise and thorough introspection in a domain. Medical doctors were surprised to learn that approximately 500 rules were sufficient to diagnose infectious diseases, a practice previously regarded as only part science. Expert system development promises expertise closer at hand more cheaply.

vertical circulation core. (Krinsky)

Knowledge Representation

If we are not directly manipulating or pointing to palpable things, then we are, to some degree, using representations. The need for representation is clear; reality is not readily altered. By transforming the variety of reality into the clarity of the artificial, representation becomes the mechanism of thought itself (Akin 1982, Eastman 1975, Best 1973).

Although the power of representation in shaping perceptions has only been recently broached in architectural thought, its role in architectural history is obvious. Changes in conceptions of space brought about by the invention of projective and analytic geometry, perspective or axonometric drawings certainly affected the practice of building design. Likewise, representations can be seen as a tool for conceptualization; witness the influence of tracing paper in the early twentieth century. Certainly, such refinements push the limits of viable representations and thus, architectural innovation.

A representation, in fact, is best characterized by its limits. A representational system, to modify Borges slightly, "is nothing more than the subordination of all aspects of the universe to any one such aspect." Information is organized to facilitate the study of whatever aspect is currently of interest. That it limits itself makes the representation both useful and, well, limited. It allows the selected manipulation of selected information.

The larger picture emerges with the overlaying of representations, a process that lends richness and understanding to our conceptions. The variety of building descriptions used by architects overcomes the limitations of any one description. Major alternatives will generally be modeled several ways before a decision is made since the more comprehensive description "depends not only on each partial representation but also on

interaction among representations" (Negoita 1981). Attempts to alter the decision problem frame is a good means to the test the robustness of any one model (Tversky and Kahneman 1974). Also, overlaying representations can help prevent any one model from producing its own meaning and superseding the reality it is meant to serve. Confusion arises from inconsistency, normative values hidden in purportedly descriptive statements,[1] and sometimes incompatibility between models.

Our representational mode forms our perception of a problem and anticipates our solution.[2] The reformulation of a problem into terms of another domain can generate solutions literally inconceivable in terms of the original problem domain. "Experience has shown that designing a good representation is often the key to turning hard problems into simple ones" (Winston 1979). The new model will direct further analysis and serve as the basis for further evaluation (Miroshkhina 1972). The moment of representing is full of potentialities and concealments and the solutions generated from the switching of representations often appear as flashes of insight, a window in an otherwise opaque wall. This explains why an insight is often paired with a sense of self-discovery; we learn about our conventions and viewpoint, as well as the specific problem. For example, when cross purposes are encountered, an architect will often stop and dwell on the conflict, sometimes forgetting the problem at hand while consulting other conflicts from other domains (Davis 1983). Indecision is here a sign of the need for more learning about the nature of the problem. This facility to probe

---

[1] Formulation effects can occur fortuitiously, without anyone being aware of the impact of the frame on the ultimate decision" (Tversky and Kahneman 1974).

[2] "Our inability to make precise statements about complex behaviours is a fact we have to accept and adjust to. Complexity is associated with descripton rather than being thought of as an intrinsic property of objects. Hence, we may well consider reducing the complexity of an object, not by changing that object, but by changing our views about it" (Negoita 1981).

into a consideration in terms of conflicts rather than in terms of the current problem is effectively contrasted with the computer's current means of numerical conflict resolution. An expert system that could change a representation when it recognized conflict, would become indispensable in a field literally riddled with such an activity.

Efforts in expert system development, have led to some general concensus on the appropriateness of a representation, whether it is iconic, symbolic, or analog. First is that our choice should in fact emphasize and make explicit that part of reality under consideration.[1]

"During the past ten years, the notion has gained acceptance that reasoning becomes simpler if *the structure of the representation reflects the structure of the reality being reasoned about*" (Szolovits 1983). Other criteria are that a representation should expose the domains natural constraints. It should also be concise, complete and transparent (Davis 1985).

Appropriateness of a representation depends on the purpose, whether it is to be evaluative, generative, or supportive. The purpose of a particular element's presence in some design is easier to rationalize than the purposes of designing. No theory has yet been able to adequately circumscribe design activity, only to describe some piece. The main goal of finding an appropriate representation is to ease the manipulation of knowledge. The concern is not for an efficient program as much as for comprehensibility of the schema to the user of a knowledge-based system. This is crucial in design where a number of issues are taken into account for "the ones which can be most

---

[1] Or in Simon's words: "Efforts to solve a problem must be preceded by efforts to understand it." (Simon 1984) The representation is so important that we often classify problems by the most fruitful means of solving them. In architectural design, this takes the form of calculation problems, perspective problems, section problems, etc.

clearly expressed carry the greatest weight and are best reflected in the form"
(Alexander 1967). The key to a good representation is that it expose the limiting
resources, or, the natural constraints. Furthermore, it should allow for modifications
and additions. This is due to the fact that knowledge changes with time and its
relevance changes with each project (Davis 1985).

Expert systems have typically represented knowledge with some combination of
procedures, production rules, frames or semantic nets. Production rules, if-then
statements, form the basis of most systems (Barr 1981). These representations are
understood to varying degrees. Frames appear to me to be promising for window
design knowledge representation.

Frames

A frame is a mental structure for representing data about a common situation. It
contains data about an event, space or object, along with information about how to
use the frame, expectations, and what to do if expectations are not met. Such
information is often in the form of a loosely attached default value. This is parallel
with human perception in routine situations where observation is accompanied and
often directed by preexisting beliefs. The "top levels" of a frame are fixed and always
true for the entity in question. The "lower levels" have many terminals or slots.
These are the specifications that make up instances. The slots can be filled with some
value, such as red, or anodized aluminum, or they can be filled with a subframe, such
as round or Palladian. Different frames in a frame system share the same terminals
so that information is coordinated and instances of the same entity or phenomenon
can be recognized from different viewpoints. With respect to windows, the concept of
frames will be developed in the next section (Winston 1979, Minsky 1974).

WINDOW DESIGN KNOWLEDGE REPRESENTATION

To the problem of knowledge: cognition is recognition, but it is necessary to have known in order to recognize, but cognition is recognition ... How can we evaluate this dialectic? Is it a legitimate instrument of investigation or only a bad habit?

Jorge Luis Borges 1956

Avatars of the Tortoise

WINDOW DESIGN KNOWLEDGE REPRESENTATION

In design the mere identification of the problem's structure is itself a problem. That design encompasses a very broad range of activities is confirmed by the fact that there is no unitary description of design available.

> Design problems are immense in terms of the number of variables that must be determined. The functional, logical or aesthetic relations that must be satisfied between the variables are dense. There is no one representation that allows detailed consideraton of such diverse concerns as spatial composition, structural performance, material selection and construction scheduling. The only means possible to represent such diverse relatons is the use of multiple representations. A variety is typically relied upon, developed and individually merged by the various design professionals, i.e., architect, specifications person, structural engineer, lighting specialist, etc. (Eastman 1982)

Existing Representations

The variety of representations currently employed is the first place to look at how experts represent their knowledge. My assumption is that there is a degree of wisdom embedded in conventional practice. In any case, those conventions can't be questioned if they can't be defined.

The external representations of architectural design, as opposed to mental representations, are either geometric: drawings or models, or verbal: specifications, programmatic statements or literary descriptions. Drawings are iconic representations and are opaque to those unused to the particular way that they cut up the world. An experienced architect, however, can foretell staining problems from a detail drawing or discern inadequate privacy from a floor plan. New materials and new construction methods have caused an increased reliance (explicit in legislation) on specifications which are more suitable than drawings for expressing quality, testing, installation procedures,

guarantees and required labor. There is in fact a whole science of specification writing and at least one school offers it as an academic concentration.

Because the purpose of a text is to communicate information and make it public property, texts are extremely useful for my purposes. They are already attempts to formalize, or at least to organize, window information. Whole texts on windows are few, but almost any book on building design will discuss fenestration. Writings about windows may be crudely broken down by the author's place in the building design process. Huntington's text "Building Construction" is a standard of the construction industry and treats the window as an assembly of parts. After briefly mentioning some factors affecting the selection of a window, he considers materials of the frame, illustrated with many sectional details. Common to both Huntington and Beckett's "Windows", a text oriented more towards design professionals, is a section on glazing which includes types of glass and methods of glazing. Beckett devotes half of his entire book to functions and performance, among which he includes: daylight and view, dimensions, durability, heat insulation and condensation, and windows as design elements. The second half is a discussion of design and installation of windows and includes chapters on: materials, shading devices, window selection, cleaning access and testing.

Pilkington Bros. Environmental Advisory Board's "Windows and Environment," also directed to design professionals begins with some general thoughts on light followed by three sections: windows and light, windows and heat, windows and sound. These sections subsume many aspects often separate in other texts. For example, window and light includes a section on maintenance as it affects dirt build up and the transmission of light. Information on shading devices is contained in two different sections. The last section, "Windows in buildings," discusses window design by building type. Beneath

this chapter is the recognition that different types of buildings have different constraints and thus will have different design solutions.

Still other texts discuss windows as a part of some other investigation, for instance, the window's role in energy consumption or window design as a factor in life-cycle costs. These are especially instructive because of their need to be as concise as possible; they strive to be heuristic. These texts tend to concern themselves with only one or two aspects of the window, such as its cost, thermal performance, or commercial value. In the do-it-yourself style books, years of experience are boiled down to a crude, but relatively accurate statement. The following are several examples of window heuristics.

Tall windows sell space (Architectural Forum 1955).

As a building design becomes more energy efficient, the major targets of opportunity can shift. Typically, lighting energy strategies become more important (Misuriello 1982).

The choice of material for the window frames will be mainly on the basis of costs and appearance (Beckett 1974).

If installing new operable windows, the caement or awning variety should be the preferred choice as they maintain a better seal over time (Marshall 1980).

A long, low window will give a lengthy ellipse with poor penetration, while a very high window will give good penetration to the remoter parts of the room but not very much to the sides (Hopkinson 1963).[1]

---

[1] In Hopkinson's text, a number of statements such as this one are also depicted in an even more concise diagram.

A Natural Structure

There is general agreement among experts and that means there is hope for my task. Recognized experts imply recognizable fields of expertise, a structure shaped by the real world. Also, schools of architecture are in general agreement about what courses to teach. Architectural design is partly taught in classrooms and partly taught in the studio format, a relative of the apprentice system. If design is taught, it is to some degree formalizable. The domains of specialization that come to mind are lighting, energy, acoustics, detailing and cost estimation. Computer programs are now on the market that offer partial evaluations of daylighting, solar heat gain, and life-cycle costing for a design. On a small project, one person can directly perform these evaluations, but, for a project with a high degree of complexity or a high price or high risk, an architect will consult experts. Sometimes the architect's primary role may be to orchestrate experts. This is no insignificant task for the experts' recommendations will often conflict. Much of the architect's knowledge apparently centers around the interpretation and resolution of cross-purposes in the building design process, in short, the management of the design team.

Conflicts are actually a structural necessity. Each expert's knowledge is organized differently because of the different purposes involved. If the goal is energy efficiency at low first cost, a window will be seen as an expensive way to lose heat. If the goal is daylighting and low life-cycle cost, then windows will be viewed as opportunities. Each expert applies analytic techniques and personal experience to the project as defined by the architect. The architect must assign values to design consequences and must provide the assumptions the experts will base their recommendations on. It is finally up to the architect to interpret an expert's recommendation on the basis of the bias of the expert. The architect then, focuses on assumption-making and the

interpretation of evaluations. Lenat's paper on interacting experts is interesting to window design because there is presently no detailed representation of the relations between design professionals and other actors.

The range of possible organizations is limited to the possible purposes. Already mentioned were drawings and specifications when the purpose is communication. The choice of one over the other is dependent on the nature of the information and to whom it is being communicated. Much knowledge, however, will be common to all window designs. There is, for example, something common to all the varieties of windows, enabling us to call them by the same name. The ability to have the computer recognize what a window is in the first place would be a big step in the development of a window expert system. Perhaps there is a way to capture this important knowledge.

Prototype Windows

A prototypical window seems to be a convenient way of representing much of what is known of the window and its functions. Borrowing from Minsky's frame theory, a window can be seen as a complex of relatively fixed relations between variable elements. A prototype would have slots for the various window elements and attributes, and it would have a range of acceptable values for those slots. This parallels the expectations that people bring to any familiar concept. We expect the window to be able to resist the transfer of heat to some degree. We expect that it shall be glazed in a certain manner, that parts shall need replacement in time and that they will cost more in the future than they do today. Further, we expect the window to be stored on the site for some time, installed somehow, in a wall so thick, and so on. A prototype seems appropriate for use in an expert system because this way of representing knowledge allows the system to specify and make inferences. This is in

fact the ability to abstract. In all ways not made explicit, the window being designed inherits a description of its form or function from the prototype, given a minimum level or critical mass of information such as building uses or some performance criteria.

There could be many prototypical windows, each identified by its salient features. This would occur in the form of fixed top levels. A prototypical double hung window would have its "means of operation" slot already filled with a value of "double hung." A design could start with a prototype, and proceed along until completion, or, the prototype could be switched at the top levels only without loosing many later decisions that are still satisfactory. Window design is then seen as the filling in of this prototype with increasing specificity. The method of operating on a pattern or type of window in order to make it appropriate to the particualar context of a project is with transformations. An actual window has filled all the slots with the values of specific elements. The individual window is an instance of the prototype.[1] It is sobering to note the cumulative variety in this model. Considering only ten parts with three options each allows for 59,049 alternative configurations. The actual number of possible variations is certainly astronomical.

The greatest advantage to this notion is that it allows different organizations. All the parts with R-value less than x or certain whole configurations with R-value less than x could be examined. Configurations that involve particular manufacturing processes like crimping or extruding could be set apart. Any set of variables could be isolated and brought under consideration. It would be a pleasant surprise to discover that an

---

[1] This view of design conforms, coincidentally, with notions of typology currently in architectural theory. A type exists in a mental realm only and is manifested as a model or instance.

identifiable set of windows have R-value greater than x and first costs less than y. To me, this is enormously exciting because it suggests a way to use patterm recognition which seems fundamental to architect's working methods. Thus, an architect could attach values to certain configurations, store them and recall a set of patterns triggered by a particular order of constraints. For instance, if first costs are low, area is small and daylight is medium at rear wall, then the system might recognize promising patterns that include glass = clear, position-in-wall = high.

These classifications, sensibly based on the window attributes, are actually often secondary in architectural design to other categories based on formal properties. By expecting the window to exist in some relation to the wall, the protoype could recognize certain relations that, for formal or historical reasons, have already assumed the power of a type. The bay window is a window that extends beyond the plane of the wall. A ribbon window is a continuous horizontal band of glass and a clerestory is a horizontal band above eye level for the purpose of providing light but excluding view. A transom is a window above another opening in the wall and a sidelight is the same only to the side. The storefront is a kind of window that occurs along the commercial edge of a building. The curtain wall arose when the ratio of window to wall reached one. Distinct window configurations: circular, square, arched, pedimented or Palladian bring with them a range of architectural possibilities and ideologies. This kind of understanding is crucial for the architect and, thus, is crucial for the expert system. Also, forms and details from earlier projects could easily become top levels and define new prototypes. As an object, a window has endless properties -- endless because any property depends upon our ability to recognize it. The properties we can indicate are limited only by our imagination, the only requirement being relevance to our purpose.

EXPERT SYSTEM TRACE

He believed in an infinite series of times, in a growing, dizzying net of divergent, convergent and parallel times. This network of times which approached one another, forked, broke off, or were unaware of one another for centuries, embraces all possibilities of time ... Time forks perpetuallly toward innumerable futures.

Jorge Luis Borges 1941

The Garden of Forking Paths

DESIGN TRACE INTRODUCTION

The following scenario is a trace of the development of a window design. It is a close-up of a much larger building design. The depth of examination of a few decisions and their supporting knowledge will, it is hoped, compensate for the narrowness of the view. In order to be both relevant and clear, I try to strike a balance between a realistic design process and a schematic one. The kinds of questions a designer is likely to ask reveals, at least implicitly, the way he or she thinks of the problem and identifies and breaks up pertinent knowledge.

In this scenario, the window design is characterized as a change of states. Elements, any one of which is susceptible to change, are specified as a means of acheiving goals or satisfying certain constraints. The action of tranforming elements is what I am calling a change of state. The operations that can change a state are discussed in a following section as an emerging vocabulary of window design primitives. The setting of assumptions and constraints is the start of the window design process and the problem definition process. The first change, then, is from a verbal to a form state. Often referred to as the "first pass," this is the selection of a prototype. The various constraints, whether functional, financial, technical or temporal, help determine an appropriate prototype.[1] It would also be possible to start with a fully specified window and alter various aspects. In many cases, this would be more expedient.

---

[1] "Direct retrieval of possible courses of action as a result of recognizing familiar features of the problem situation provides a major (one might say the major) basis for professional performance in complex situations." Simon 1983 "On How To Decide What To Do"
This is, of course an assumption about the potentiality of a direction for developement.

At points, the evolving design is tested against various constraints. In this scenario, only daylight, net energy performance, and costs are considered.[1] The ability to measure the design against different criteria is crucial as the design will most often evolve in a breadth first manner with any decision contingent upon later decisions. States are altered, evaluated, altered again and so on until a design is satisfactory. The design is adjusted on the basis of feedback and is guided by the particular objectives. It is a simple matter to change the prototype frame while retaining many lower level decisions. This reflects the fact that designers often preserve the desirable aspects of some otherwise unsatisfactory scheme. The later iterations in the process will tend to deal much more with finer concerns such as hardware or joint drainage and will no longer question earlier, provisional decisions.

The final stage in window design is the matching of the design with an actual product. If the information in the system is accurate and the range of built-in options for any prototype parameter is within what is currently manufactured, then this stage will entail no significant alteration of the design. This is the final stage of specification.

The scenario follows three streams. Boldface type indicates the designer/system dialogue, the questions a designer might ask and useful responses from the system. The ascii typeface describes what the system is doing, the operations it is performing and the knowledge bases it is checking. Finally, the discussion in italics illustrates the specific bits of knowledge the system has found to be relevant and with which it has made some inference. With regards to the aspects of window design mentioned earlier

---

[1] See Appendix: Three Domains.

in this paper. constraints limit the region of possibilities. functions are goals within a domain. and the window parts are what is being configured to reach those goals.

DESIGN TRACE

SEQUENCE OF ACTIVITIES AND QUESTIONS

Set Initial Assumptions

Set Evaluation Path

Pick Prototype

Specify Attributes

Ask Glass Area Effects

Evaluate Current Design

Ask Ways to Reduce Heat Gain

Ask Best Heat Gain Option

Replace Glazing

Evaluate Glazing Change

Evaluate What If Investment Criteria --> L.C.C.

Ask Ways to Reduce Glare

Ask Glass Type Options

Compare Glass Type Options

Replace Glazing

Evaluate Glazing Change

Evaluate What If Payback Period --> 5 years

DESIGN PRIMITIVES

KNOWLEDGE BASES

ACTIVITY: Set Initial assumptions [Project Info. K.B.]

Project:

>Building Use: Office [firm] [1]

>Office Layout: Special Rooms

>Hours of Operation:

>Number of Occupants: 200 [medium]

>Height:

>Shape:

>Mechanical Systems:

>Square Footage:

>Glazing to Perimeter Ratio:

Financial:

>Investment Assessment: Payback period 3 years [medium]

>Capital Costs:

>Annual and Non-annual Recurring Costs: rate of increase, year, amounts

>Depreciation Method:

>Estimated Heating Fuel Costs: $6/million Btu [firm] rate of increase:

>Discount Rate: 12% [medium]

>Salvage Value, Year:

Window Context:

>Window Orientation:

>Room:

>>Dimensions:

---

[1] Firm or medium refer to the degree of conviction the designer has in the assignment of a particular value. Certainty factors could also be used.

Thermal Properties:

Surface Reflectivity:

Obstructions:

Wall System:

Site:

Climate: medium-cold 6000 degree days [firm]

Microclimate: urban [firm]

Window:

Shape:

Height, Width:

Height Above Floor:

Position in Wall:

Shading Devices:

Glazing Area: at least 10% of floor area[1]

R-Value: Frame: Glazing:

Transmissivity:

Glazing Percent of Aperture:

Performance Requirments:

Daylighting:

Heat Loss:

The system expects a variety of assumptions, in different catergories, to be made. Some may have been set earlier, some will be set later. The system queries the user for any further assumptions and provides

---

[1] *At least, greater than, less than* ... are relative, yet crucial, terms in design. They could be taken to represent a set of values or, alternatively, an inequality.

the opportunity for the user to set other factors that may be known at this time, but are not necessary for the operation of the system. Some values, such as hours of operation, may be set by default, others, such as building use, must be specified.

> Basic assumptions are necessary for any evaluation, computed or otherwise.

ACTIVITY: Set Evaluation Path

Set Path of Evaluation: 1-costs, 2-energy, 3-daylight

The system is checking a set of rules within the procedural knowledge base. It looks at the rule predicates, tests their truth by checking the assumptions, follows a chain of inferences and recommends a path through evaluative filters or a design strategy. The system finds and fires a rule like:

If Financial:

Payback period < 5 years

Discount Rate > 10%

Then Evaluate First:

Costs

Generally speaking, a short payback period means that the effects of time will not be considered. Payback period equals the first cost divided by the annual net savings (Jarmul 1980). The benefits of daylighting or energy strategies do not enter the equation. Because of the nature of the assumption, first costs are the most significant constraint. Likewise, a high discount rate reduces the present value of future costs.

Mechanical systems are generally specified by their capacity to handle peak demand. Thus energy performance, as it affects HVAC, will have a greater impact on first costs than daylighting.

ACTIVITY: Pick Prototype

Pick Prototype --> Fixed Window:

Filled Slots: operation = fixed

Effects: ventilation (HVAC) /weatherseal durability (longer)/ Heat loss (less) window first costs (less)/ HVAC first costs (more)/other expectations.....

Similar to the previous decision concerning a design strategy, a series of rules has led the system to recommend a fixed window, as the most promising place from which to start the window design exploration. The rule would be similar, though more comprehensive, to the following:

If Project:

not dwelling

If Site:

Urban

If Investment Assessment:

Simple Payback Period

Then Prototype --> Fixed Window

The primary effects of a prototype's salient features are listed as a check. Presumably, some of these are the very reasons the prototype was chosen.

Other knowledge the system would be checking for: Is the building to be air conditioned? If not, can provision be made for ventilation, apart from the windows? Will the windows be in very exposed positions? Will there be easy access to the outsides of the windows for cleaning? Fixed windows should be used if the answers to these questions are yes. (Beckett)

Will the absence of openable windows be a complication in relation to fire-fighting and escape from fire? Will the use of fixed windows involve additional indirect costs likely far to outweigh any saving on the fixed windows in comparison with openable ones? Fixed windows should not be used if the answers to these questions are yes (Beckett 1974).

With regards to costs: Fixed windows are much cheaper than openable windows and in a building where opening lights might normally occupy say two fifths of the total window area it might be possible to save up to 40 per cent of the first costs fo the windows by using only fixed windows. In terms of total costs reckoned over the life of the building the situation may, however, be very different. In relation to ordinary maintenance the balance of costs is likely to favour the fixed windows because of the elimination of moving parts and fittings liable to wear. Consider also costs related to cleaning access and alternative means of fire escape (Beckett 1974).

Knowledge of effects could easily be a subframe of the larger prototype frame.

ACTIVITY: Specify Attributes

frame material --> ?

glass area --> ?

glass type --> clear

weatherseal --> ?

Throughout the design process, the system, as well as the designer, will seek design resolution by specifiying components. The system will be clever in the sense that it will ask questions at relevant times. For example, when receiving a specification about the frame material, the system could ask about the desired finish or color. This must be answered sooner or later and it is clearly related to the current concern.

The prototype has slots that it expects to be filled. It can ask questions about slots in subframes, for example, "window frame" is itself a frame with terminal slots expecting certain values.

Although it should be flexible, the underlying order of attribute specification would be based upon some generally accepted notions:

1) Decide performance requirements for external wall.

2) Take basic decisions on positions, shapes, and sizes of openings.

3) Take basic decisons on characteristics of windows.

4) Take decions on details of windows: joints, weatherseal, drainage ...

(Elder 1974)

QUESTION: Glass Area Effects

Glazing Area effects: Heat Loss (increase on the north side, increase at night), Heat Gain (increase on the south side), Capital Costs (increased), Fuel Costs (increased need for heating during cold season, potential solar gain), Maintenance Costs (increased), Daylighting (increased)

Default is approximately 25% glazing to wall proportion: assuming 8' floor to ceiling height, 2.5' working plane height, Simple Payback Period = 3 years.

The system has the ability to respond to questions. For example, with regards to glazing area, the designer may wish to ask about the relative costs of differing proportions of glazing. The system could respond by simply saying that more glazing means higher initial costs, greater heat loss and greater potential for daylighting and for greater heat gain. Alternatively, it could present a table:

Proportion of Glazing	0%	6.25%	25%	56.25%	75%	90%
Initial Costs	114	127	166	244	268	319
Annual Costs	19	21	27	40	42	49

Note These are relative values only. (Beckett 1974)

"Glass and window frames are usually considerably dearer than the equivalent area of solid cladding. Running cost is high in terms of maintenance and thermal loss" (Elder 1974).

ACTIVITY: Evaluate the Design

First Costs --> low

Running Costs:

Fuel Costs (lower with an effective daylighting strategy)

Operating Costs: higher

Energy:

Heat Gain --> high in summer

Daylight:

D.F. --> ?

Glare --> potential

Problem: Heat Gain too high due to large glass area on south wall.

When the project file does not contain enough data to run a full evaluation, the system checks a heuristic knowledge base that contains rules about trade-offs. These are necessarily relative values. A question from the user would be answered by the last rule fired that gave a particular value. Further questions would travel down the reasoning chain. Given the constraints, the system searches for any problem that seems both imminent and germane. Heat gain was chosen for its effect, not on running costs, but, on its effect on the size of an air conditioning plant.

With regards to Costs: Because the cost of the air conditioning plant in amodern building is likely to be at least a quarter of the whole cost fo the building and because up to a quarter fo the plant may be needed to handle the solar heat gain through poorly designed windows, considerable savings in captial expenditures are possible with careful window design. (Turner 1977)

Fixed windows are much cheaper than openable windows and in a building where opening lights might normally occupy say two fifths of the total window area it might be possible to save up to 40 per cent of the first costs of the windows by using only fixed windows. In terms of total costs reckoned over the life of the building the situation may, however, be very different. In relation to ordinary maintenance the balance of costs is likely to favour the fixed windows because of the elimination of moving parts and fittings liable to wear. Consider also costs related to cleaning access and alternative means of fire escape. (Beckett 1974)

With regards to energy: Total heat gain is a result of solar gain (time of day and magnitude), heat gain from people, machinery, electric lights, outdoor temperature build-up... In this case, although direct solar gain through teh window is less in summer than in the spring, the combination of latent heat from the morning sun, no shading devices, and outdoor temperature build-up on pavement, have triggered a potential heat gain problem. (Turner 1977)

With regards to Daylight: The system is unable to say whether the window will be large enough to admit adequate daylight without some data on interior dimensions. Glare, because it is dependent on activities and lines of sight, is always a potential problem.

QUESTION: Ways to Reduce Heat Gain ?

User Question: What are the options for reducing heat gain?

There are two means of environmental control: 1) energy and 2) physical devices which are generally more expensive initially but have much cheaper life-cycle costs (Elder 1974).

Methods of preventing or reducing heat gains due to solar radiation (Rostron 1964, Jarmul 1980, Turner 1977, Hastings 1978): [1]

1. By correct orientation.

2. By ventilation.

3. By glazing modification.

4. By physical barriers or shading devices.

Interior:

Shades, draperies: easy operation, privacy but least effective shading, can absorb sound, can be thermal insulation.

Blinds: easy operation, privacy but least effective shading, allows light redistribution.

Exterior:

Operable shading devices: most effective shading but difficult to maintain, subject ot more rapid deterioration.

---

[1] Alternatively, a broader viewpoint might be advisable at this point:
To improve overall energy performance:
        Site Design: windbreaks,...
        Exterior Appendages: awnings,...
        Window Frame: tilted,...
        Glazing: increase R-value,...
        Interior Accessories: shades,...
        Building Interior: thermal mass, reflectance,...
        Building Management: maintenance schedule,...

Elements: Fins, overhangs, projections, roofs, porches, balconies, upper floors...

5. By limiting the area of exposed glass on southerly walls.
6. By design of microclimate. (Vegetation, Sitework)

The system has knowledge of the range of control options for any function. Ideally, the system would present only those options relevant to the current situation. It is, however, a sensitive point whether the system or the architect decides relevance to a particular problem. Furthermore, the user could ask for greater detail.

A response to a question about the relative effect of blinds on solar heat gain might look like this:

LOCATION	COLOR	CORRECTION FACTOR
Inside	White	.58
Inside	Aluminum	.47
Inside	Medium	.65
Inside	Dark	.78
Outside, slats at 45	White	.21
Outside, fully over window	White	.15
Outside, 2/3 over window	White	.43

A response to a question about the relative effects of glazing variations on costs, heat loss, durability, etc. might look like this: (Selkowitz 1978)

GLAZING OPTION	RELATIVE COST	U-VALUE	DURABILITY
Single Glazing	0	1.14	high
Exposed Heat Mirror	+2.00	.65	uncertain
Sealed Heat Mirror	+3.25	.35	moderate
Double Glazing	+2.50	.56	high
Storm Windows	+2.25	.55	high
Triple Glazing	+4.50	.36	high
Quad Glazing	+5.50	.27	high

QUESTION: Best Heat Gain Reduction Option ?

With respect to: Simple Payback Period = 3 years:

1-Reduce window area

2-Consider shading devices

The system checks the relative effects of various options against the prominent constraints.

The most effective way to reduce the solar heat gain through fenestration is to intercept the direct radiation from the sun before it reaches and penetrates the glass. A fully shaded window can receive up to 80% less solar heat gain. When the primary objective is minimizing heat transmission through the envelope, window areas should be reduced as far as the psychological need for visual contact with the outdoors will allow (Bradshaw 1985).

The simplest and most rational way to reduce summer heat gain is to use the smallest acceptable windows, especially on the south, south-west and west facades. Unless large windows are required for daylight or for vision their use may pose thermal problems out of all proportion to their mythical attractions. The first step in reducing solar heat gain is, therefore, to limit glass areas to the smallest compatible with other functional requriements. Only when this has been done should recourse be had to shading devices and special glass (Rostron 1964).

The energy savings options you will want to consider are those which provide rapid return on investment, simple payback (New York State 1980).

ACTIVITY: Change glazing [K.B.: Changes/Operations/Prototype]

    single glaze --> double glaze

effects: appearance (thicker sash needed)/ window capital costs (more)/ running costs (less)/HVAC capital costs (less)/Durability (same)/ *Important* Non-quanitifiable: benefits from reduction of cold downdraughts, radiation and condensation. (Elder 1974, Beckett 1974)

Note If first costs are an overriding consideration, then go for standard windows and forget about refinements such as double glazing. (Beckett 1974)

The system checks this change against what it knows and points out conflicts. It can keep a step ahead of the user by identifying rules with perhaps only one predicate unfired and ask relevant questions. For example: Is the building to be air conditioned? Is there likely to be a serious condensation problem in the building, as a result of exposed wet processes? Is double glazing desired as an amenity, and is someone prepared to pay? If the answer to these questions is yes, then there will be stronger rationale for using double glazing (Beckett 1974).

As long as the designer is willing to entertain such questions, the system would continue: Will the double glazing be set in a single or double frame? "Why?" from the user would be answered with, "A double frame will reduce sound transmission, increase overall frame dimensions (appearance of heaviness), and require access to the cavity for cleaning."

At the same time, the system would indicate a relative increase in the window cost per square foot due to the perimeter to area ratio of the aperture (Rostron 1964).

Because of the new need for increased quality of the edge seal. Most failures of double glazing units are caused by failure of the edge seal (Rostron 1964).

Double glazing makes a considerable reduction to the heat losses but is expensive to install and results in some reduction in the light penetration. Clearly, the greater the difference between internal and external temperatures and the longer the hours the building is used, the greater the likelihood that double glazing will be economically worthwhile (Stone 1980).

It must be acepted that to double glaze throughout has a high captial cost compared with other forms of additional insulation which can produce similar energy savings. The greatest value is double glazing selected rooms (Williams 1977).

Code Requirement: Window and Door Minimum R-value 1.54 Accepted Practice: double glazing, single glazing with storm sash, or other with R = 1.54 (Illustrated Guide to Mass. Energy Code 1979).

ACTIVITY: Evaluate (From Earlier Path Setting: 1-life-cycle costs, 2-energy, 3-daylight)

System Questions: What is the inside design temperature? What is the number of occupants?

Unsatisfactory for Payback period = 3 years. Double glazing with greater effect over time.

The system asks the questions because it has found some relevant rules, but is lacking enough data to fire them. It is possible that the system would be able to offer an evaluation based on heuristics about the preceding change only. At this point, I am uncertain how a system would be able to recognize the value of deferring a decision.

The most pertinent reasons are given for the results of an evaluation.

The system knows that the relative first costs of an equivalent level of insulation will increase as the difference between interior and exterior temperatures increase. It also knows that the value of any insulation will decrease as the internal heat gain increases. Internal heat gain changes with the level of heat from artificial lighting, number of occupants, activities, etc (Elder 1974).

ACTIVITY: Evaluate What If Investment Assessment --> Life-Cycle Costs

Problems --> Potential glare.

"What If" is a function that allows an evaluation or other operation under some temporary assumption. As such, it allows the creation of momentary subjunctive situations.

If the major constraint is the reduction of running costs, then the means of lighting will be very important (Rosen 1982). It is necessary to calculate the extent of daylight useful for task lighting and the amount of supplementary artificial lighting. First step is to calculate the daylight factor at various points on working plane (Turner 1977). The concern for daylight will tend to increase the window area. With increased window area there is increased potential for glare and increased need for protection from glare. Glare is not a totally quantifiable phenomenon and thus must be studied in several ways. Glare is related to sky luminance seen through window, direction of view, line of sight, room activities, contrast, window height.

The system could also offer a summary of the alternative investment assessments:

SIMPLE PAYBACK PERIOD:

Advantages:

-- Easy to understand and to communicate.

-- Effective filter for higher-risk proposals.

-- Good assessment of the liquidity of a measure.

Disadvantages:

-- Does not account for time value of money (interest rate), or for escalating energy costs.

-- No provision for credits or savings after the payback period.

Life-Cycle Costing:

Advantages:

-- Considers time value of money.

-- Accounts for longer term interests.

-- Especially useful when comparing an alternative with high initial costs and good efficiency to one which may cost less but with poor efficiency.

Disadvantages:

-- More difficult to calculate.

-- Difficulty of assessing non-economic factors

(Bradshaw 1985, Sizemore 1979)

QUESTION: How to reduce glare?

By means of an operation:

Site: Courtyards, arbors...

Room:

Include window in adjacent wall, or (less desirably) in opposite wall (Elder 1974)

Increase room surface reflectivity to acheive a gradual change of brightness.

Wall:

Orientation of Openings:

Depth of reveal: Contrast grading, reveal should reflect 60-90% of light.

Position of Window: Height depends on room activites; Place near light colored partitions; Place away from bright views.

Reveal Treatment: Splay, widen, deepen, lighten color

Shape: Tall windows admit light further but increase glare.

Frame:

Sash: size, color; Avoid heavy, dark frames

Glass:

Reduce Area:

Glass Type: tinted, diffusing

By means of an Addition:

Interior: Flexible control; lets in solar gain

Blinds:

Curtains:

Baffles, Louvres:

Exterior: More uniform illumination through room

Screens:

Shelves: Deeper penetration, increased uniformity, shades glazing

Overhangs:

Fixed: Preferable on a south or north elevation (Pilkington Bros.)

Moveable: Adjustable devices are more efficient on east or west walls

Canopies

Louvres: Increased diffusion

The system, keeping track of previous inquiries, would be able to offer comments such as:

If heat gain is to be minimized, then put the glare barrier on the outside.

As a rule of thumb for avoiding glare problems and for proper daylight penetration and distribution in a room, the height from the top of the window to the floor should equal about one-half the depth of the room, and whenever possible, additional daylight should be introduced at the back of the room.

Also, as in the previous operation, the system could make recommendations with respect to constraints such as: How to reduce glare with the least change in costs, or performance, or internal appearance.

Glare is a subjective phenomenon and as such it is an expression of a visual sensation which can not be directly measured. In lighting terms glare is taken to be the expresssion of the undesirable visual effects which result from the presence within the visual field of areas of

excessively high brightness. The degree of glare discomfort has been shown to be a funciton of:

(i) The luminance of the sky as seen through the window,

(ii) the apparent size of the visible patch of sky,

(iii) the position of the patch of sky relative to the direction fo view, and

(iv) the adaptation conditions in the room, luminance of room surfaces.

(Hopkinson 1966)

For the average office a rule of thumb is that complaints of glare will arise if sunlight strikes an unshaded vertical window at angles of incidence less than 45 degrees. (Pilkington Bros. 1969)

QUESTION: Glass Type Options?

Transparent:

Tinted Float

Wired

Patterned

Translucent:

Wired

Patterned

Solar Control:

Tinted

Patterned:

Metallic Film

Reflective, Heat mirror, Color, Thickness, Surface Applied to.

Glass Type change affects:

Intra domain: glare, penetration, color of light

Inter domain: costs, thermal performance, condensation, acoustic, fire rating strength/stiffness, appearance.

More detailed information about, say, relative merits of glass types on the reduction of heat gain:

TYPE OF GLASS	SUNLIT	NOT SUNLIT
Single glass	100	33
Double glazing	73	22
Heat-absorbing glass	68	24
Double-glazed heat absorbing glass	51	17
Sunscreen on single glass	35	17
Sunscreen on double glazing	26	12
Sunscreen on heat-absorbing glass	24	12
Sunscreen on double-glazed heat-absorbing glass	18	9

(Huntington 1975)

ACTIVTIY: Compare options: clear glass, low-transmission glass

Clear Glass:

Heat Gain: higher

Heat Loss: same

First Cost: lower

Running Costs: higher

Glare: higher

Low-Transmission Glass:

Heat Gain: lower

Heat Loss: same

First Cost: higher

Running Costs: lower

Glare: lower

The system assumes a condition of *ceterus paribus* and considers very general, relative merits of the alternatives.

Considering the relative merits of two alternatives is common in many decision making processes. Much of the above information could have been put into more absolute terms such as: per cent visible transmission, per cent total solar transmission, R-Value, actual recent prices, etc. Also, much information could be presented graphically. For instance, one chart could have information on the relative degree of satisfaction of various objectives, including the fuzzier sort. It is likely that recognizable patterns would develop in such a dense representation.

ACTIVITY: Change Glazing [K.B.: Changes/Operations/Prototype]

double glaze --> single glaze with heat mirror treatment

effects: appearance (thinner sash needed)/ window capital costs (less)/ running costs (more)/HVAC capital costs (more)/Durability (less)/ Non-quanitifiable: reduced benefits from reduction of condensation downdraughts and cold radiation (Elder 1974, Selkowitz 1978).

The system knows about general relations between the acceptable values for any parameter.

ACTIVITY: Evaluate 1-First costs

For: medium cold climate, fuel costs = $6/million Btu, Payback period = 3 years

$1.40/square foot maximum allowable installed cost

An extremely useful feature would be a series of charts depicting the behaviour of the many parameters two or three at a time. The system could look up the curves generated by specified parameters. In this instance, estimated fuel costs are plotted against maximum allowable installed cost of a window.

The abiltiy to quickly review the sensitivity to change of aspects of a design with respect to any particular constraint could save considerable time and effort in decision making.

ACTIVITY: Evaluate What If: Payback period --> 5 years for 1-First Costs

For: medium cold climate, fuel costs = $6/million Btu, Payback period = 5 years

$1.75/square foot maximum allowable installed cost

The system would have some knowledge in the form of charts, graphs or tables. It would search for the relevant constraints and look up values on a chart (Selkowitz 1978).

Longer useful life favors higher first cost. (Ahuja 1983)

EXPERT SYSTEM DESIGN PRIMITIVES

The level of a primitive is clearly dependent on the purposes involved. If the concern is movement on the street, then "walking" would be satisfactory. If the concern is walking, then primitives would describe muscular movement. Following is an emerging vocabulary of window design primitives:

Towards Clarity of Form

TRANSFORMATION	PARAMETER
Increase	an attribute, an element
Add_to	an element
Remove	an element
Replace	an element
Posit/Instantiate	an organization, set of relations
Assemble	several elements
Choose, decide	between elements, organizations
Specify	elements, attributes

Towards Clarity of Project/Possibilities

INFORMATION SOUGHT	PARAMETER
Decompose	an organization
Compare/Trade-off	two or more organizations, tansformations
Prioritize	constraints
Set Assumptions	constraints
Evaluate	organizations
Options Possible	for a transformation or strategy
Effects	relative effects of a transformation
Problems	with an organization
Current State	of an organization
Next Step	promising transformations

Primitive transformations are likely to have general implications. For example, increasing south-facing window area will more than likely increase heat loss at night, increase daylight, increae noise, increase cost of window operation, icrease glare, and increase heat gain. Such statements would be the core of an heuristic knowledge base.

KNOWLEDGE BASES

The window design expert system trace is illustrative of the sorts of questions an architect might be asking through the process of designing, evaluating, and selecting a window. This section discusses the knowledge bases desirable for such a system. For the sake of a complete picture, possibly more distinctions than is necessary have been made. The intended functions of these knowledge bases is the capture of several kinds of knowledge: facts (how things are now), normative (how things should be), explanatory (why things are the way they are), and instrumental (how to amke things the way they should be). (Rittel 1970)

List of Expert System Modules:

Operating Systems

Expert Evaluators

Knowledge Bases:

1) Project File

2) Procedural Knowledge

3) Window Prototypes

4) Inter-Domain Heuristics

5) Facts/Tables

6) Regulatory Knowledge

7) Window Details

8) Manufacturer's Catalog

OPERATING SYSTEM: All the very essential functions, that are outside the concern of this paper, are lumped into this category.

EXPERT EVALUATORS: These are the three existing evaluative programs discussed earlier in this paper. They need only be adapted for integration into the expert system.

KNOWLEDGE BASES:

PROJECT FILE: This contains the information relevant to this project, such as the site, program, financial information, procedural and substantive constraints, the wall that waits for its window, etc. Obviously, much of this information will not be available at the start of the design. Actually, quite a bit will be determined as the window design evolves. These then are the project's assumptions. They could be attached to this knowledge base more or less firmly by some indication of conviction. For instance, if this is an office building for Pittsburgh Plate Glass then the conviction regarding "curtain wall" will be "1". Otherwise, that aspect could be left open till later in the process. Strength of conviction numbers recognize the fact that some assumptions are more susceptible to change than others. Precisely which assumptions are open to change will be set by the specifics of the client, site, project, etc. This knowledge-base is constantly used and altered throughout the design process. It is a record of the current state of the project, as well as a history of the project, including promising paths not followed. Necessary assumption clusters are: financial, site, functional, window context (wall, ceiling, floor)...

PROCEDURAL KNOWLEDGE: This knowledge base exploits procedural heuristics. It reviews assumptions and suggests a path through the evaluative filters, selects a window prototype or else it can suggest a design strategy. Example of path:

"If operating costs must be minimized, then, start with daylighting."(Because the greatest effect windows can have in offsetting operating costs is by lowering lighting costs and lighting heat load.(Rosen)) Example of strategy: "If context allows, consider microclimate as energy saving strategy: windbreaks, deciduous trees as shading devices..." Example of prototype selection: "If payback period is less than three years, then consider a fixed window." Questions the user may have about a recommendation at this stage would be answered with the relevant assumptions that triggered the procedural rule.

PROTOTYPE KNOWLEDGE BASE: Prototype windows, discussed earlier, would be contained in this knowledge base. They could be indexed by formal arrangements, special features, operation, or some other category an office felt was useful. Associated with each prototype, or under its own menu listing, would be typical sections or patterns. For example, "lightshelf," could be illustrated along with a summary of benefits and potential costs. Something like an on-line pattern book would actually support the architect's common habit of perusing references.

INTER-DOMAIN HEURISTICS: These are the trade-offs between alternatives. This knowledge base removes the need to run every change in the design through an evaluation. Knowing that reducing the window area in a dwelling by less than some percent will reduce heat loss without significantly reducing daylighting, is good enough for the designer's purposes. This kind of thinking parallels that of the expert's, who knows simply that heat loss can be reduced without much trouble and it is a decision best deferred.

FACTS/TABLES: The various subsystems will often need to look up tabular information. It may be that such information is best attached directly to the program requiring it.

REGULATORY KNOWLEDGE: This knowledge base is similar to the knowledge base in Kim 1984. It contains not only facts about the letter of the applicable codes but about the spirit of such legislation and precedents for negotiations. Besides setting some constraints, this knowledge would also be used for explanations to the user about certain recommendations.

WINDOW DETAILS: This is knowledge that is frequently consulted in offices. Often it is in the form of details from previous projects and books of standard construction. An on-line body of window detail information, cross-referenced by compatibility with window type, material durability or just office standards, would be a useful tool for a necessary step in window design.

MANUFACTURER'S CATALOG: This is basically Sweet's on-line. It is a catalog of what's available, how much it costs, how flexible the manufacturer is with respect to delivery, sizes, finishes, etc.

AFTERWORD

Informed somewhat by a desired destination, I have tried to look at windows in a way that would expedite the embodiment of expertise in a design support system.

Windows are complex and complexly considered by architects. But generalizations can be made regarding windows and thoughts about windows. Notions of a prototype window, multiple representations, and primitive design operations arose from frequent patterns percieved in window design. The expert system design trace looks at some of the questions an architect might ask and the kinds of answers that would be useful. Parallel with the design steps are discussions of how an expert system would find relevant knowledge and in what form that knowledge would be. Finally, and rather too briefly, the section on knowledge bases suggests ways to break up knowledge in order to exploit the advantages coincident with subsystems.

Although the structuring of window design heuristics and general knowledge is far from complete, some progress, I think, has been made. Further research on a taxonomy of heuristics should at least consider:

Procedural Heuristics: These determine the path through evaluative filters or through constraints.

Substantive Heuristics: These are the trade-offs:

Within functional domains.

Between functional domains

Between design transformations.

Between alternative assemblies.

Other window design heuristics classifications are imaginable. Heuristics can be related to building phases. Each phase has its principal actors and major concerns. In schematic design, a project developer and an architect would be more concerned with forming alternative concepts and discovering the priorities of constraints. Heuristics appropriate to this phase would, for example, deal with the orientation of a building, or with glass area and exposure. In the construction documents phase, an architect and contractors would rely on rules-of-thumb that were concerned with details, material selection, etc. Naturally, after construction, an architect or building management team would be concerned with maintenance and repair issues.

Another possibility would be the classification of heuristics according to specific architectural issues. For example, orientation decisions are informed by heuristics such as: To obtain the greatest benefit from the sun as a winter heat source, buildings located in northern latitudes should concentrate window areas on the south side and reduce window areas to the north. Other considerations, like controlling sunlight from south-facing windows are obviously important but subordinate to the more general goals of orientation. The point is that heuristics could be indexed by their relevance to orientation.

Important issues have been ignored or only momentarily mentioned in this thesis. Further work should deal with questions such as:

Visual knowledge, employing powerful operations like pattern recognition, is poorly understood but is perhaps the primary form of knowledge for designers. A design support system must recognize and reinforce this knowledge rather than require the designer to adjust to its own limitations.

How is the expert system tied to other systems in an office? Perhaps the construction of incrementally smarter CAAD systems is the best approach to expert system development.

What is lost with heuristics? What is foregone when no alternative over some amount of dollars will be considered?

Finally, how far could an expert system go towards design support? Where does it fall within the spectrum of man/machine relations: assistant, colleague, expert, master? For instance, our representations inform our perceptions; there is no observation without an observer, no fact without a theory, however vague. If the machine can create new representations by reorganizing knowledge, then it may be able to temporarily reorganize knowledge in terms of an entirely different domain. This powerful and generative ability is closely related to the human ability to create metaphors.

The balance I have sought in this thesis is between very big considerations, such as those in the above questions, and very minute considerations such as the relative durability, elongation, and adhesion of liquid sealants and preformed gaskets as glazing compounds. Minute concerns are unsatisfactory because, while they enable us to make precise statements, they are an uncommon way of thinking for designers. Adding bits of precise knowledge will not lead to general knowledge, at least not without the ability to abstract. Despite the fact that design is dependent on the perceived context or constraint network, designers usually make broad statements. But, generality brings crudeness, at least for an expert system. If this research is to proceed beyond the conceptual stage some position must be taken. Based on insights from earlier expert system development, beginning at a general level is advisable (Davis 1985). This offers

the chance to refine generalities and to have experts find faults with some schema and explain their doubts.

If there is no chance for an optimum, then we must look to experts and their standards. When the means to an end is obvious, then no problem is perceived. Design is about making choices and is not at all obvious. Experts are brought into a design process and coordinatied by the architect, who is no longer designing an artifact, but is designing a process that will design an artifact (Simon 1975).

This research has been brought up to a point. But, there remains a significant task ahead. The next logical step is the actual construction of a model system with expertise in window design as it relates to three, or perhaps, only one domain. By limiting the domain of performance, the project has a chance of success. A good choice would be the use of building economics as a measuring stick for evaluation. This choice seems appropriate for its predominance as a design constraint and due to architects' unfamiliarity with the subject.

The hardest part, however, is not writing the program, but deciding what to do. This job ultimately belongs to the designer. The professional practice of architectural design is still being designed. Like the pencil, like tracing paper, the computer will, to some extent, change the way architects design. The aim of this thesis has been to aid in the design of a new design tool.

APPENDIX -- THREE DOMAINS

For the sake of simplicity, only three domains of concern have been considered in the expert system trace. These were chosen for their predominance in most window designs and for the fact that evaluative computer programs exist for each of these domains. It is necessary only to give some idea of their structure and to list the primary inputs and outputs.

DAYLIGHT STRUCTURE

DAYLIGHT in a room can be adequately described by:

QUANTITY can be determined by:

LIGHT:

from the sky

reflected from external objects

reflected from internal objects

adjusted to account for obstacles at window, including dirt

QUALITY is determined by:

color of glass

GLARE is determined by:

window size

window position in wall

treatment of reveal

line of sight

luminance of sky seen through window

DISTRIBUTION is determined by

WINDOW:

shape

size

position

ROOM:

proportions

surfaces

DAYLIGHT PROGRAM INPUTS & OUTPUTS

INPUT

Glazing:

color

transmission

reflectance

dimensions

orientation

Room:

dimensions

wall thickness

surface reflectances

measurement height

Site:

sky

time of year, day

climate

latitude

ground reflectance

OUTPUT:

Footcandles on a surface

Artificial light Savings/Offset

ALTERNATIVE DAYLIGHT STRUCTURE

DAYLIGHT:

OBJECTIVES: To provide adequate daylight for a task for the higher order purposes of: human psycho-physical needs, increased worker performance, decreased energy costs.

GENERAL REQUIREMENTS FOR SATISFYING OBJECTIVES: The proposed window design should provide: sufficient quantity, good quality, and effective distribution of daylight.

RULES ENSURING ADEQUATE DAYLIGHT:

IF a sufficient quantity of daylight is received and

the quality is good and

the distribution is effective,

THEN daylight is adequate.

> IF the estimated daylight factor is not less than the recommended daylight factor for the assumed activity,
>
> THEN the quantity of daylight is sufficient.
>
> IF potential glare is controlled and color is within normal range and uniform,
>
> THEN the daylight quality is good.
>
> IF the room is less than x feet deep and
>
> the surface reflectance is greater than y per cent and
>
> the window is of area z and
>
> the window bottom is above so many feet,
>
> THEN the distribution is effective.

ENERGY USE STRUCTURE

ENERGY USE can determined by finding:

HEAT GAIN is determined by:

INTERNAL LOAD:

lights

people

equipment

EXTERNAL LOAD:

convection

conduction

radiation

infiltration

HEAT LOSS:

INTERNAL:

Air Conditioning

EXTERNAL:

convection

conduction

radiation

infiltration

ENERGY PROGRAM INPUTS AND OUTPUTS

INPUTS:

Similar to Daylighting only with information about R-values, thermal capacity and mass of materials, wind and exposure.

OUTPUT:

Heat Gain/Loss

Auxiliary Heat need over a reference building

Solar Savings Fraction

Savings in Btus.

LIFE-CYCLE COSTS STRUCTURE

LIFE-CYCLE COSTS depends on:

    CAPITAL COSTS depends on:

        Materials used, finishes

        Size

        Quantity ordered

        DESIGN COMPLEXITY depends on:

            Method of operation

            kind of hardware/fittings

            joint methods

RUNNING COSTS depends on:

    OPERATING COSTS depends on:

        Cleaning/Janitorial

        Repair

        Replacement

    ENERGY COSTS depends on:

        Heat Loss

        Heat Gain

        Desired Interior Temperature

        Hours of Building Use

BUILDING LIFE-CYCLE COSTS INPUTS & OUTPUTS

INPUT:

    LCC Analysis Assumptions

        Study Period

        Discount Rate

        Tax Rate

        Depreciation Method

        Replacement Costs, Salvage Value, Year of Replacement

        Annual and non-annual recurring costs

            rate of increase

            year

            amounts

        Energy Costs: rate of increase

OUTPUT:

    Comparative Life-Cycle Costs

BIBLIOGRAPHY

Books on Artificial Intelligence and General Issues

Amarel, S. 1968. "On representing problems of reasoning about actions" Machine Intelligence 3. pp. 131-77

Arbib, M.A. 1972 The Metaphorical Brain; an introduction to cybernetics as artificial intelligence and brain theory. New York: Wiley-Interscience

Barr, A. and Fiegenbaum, E.A. 1981 The Handbook of Artificial Intellignece. Los Altos, Ca.: Wm. Kaufmann

Baumol, W.J. and Quandt, R.E. March, 1964 "Rules of thumb and Optimally Imperfect Decisions" American Economic Review pp. 23-46

Bogoyavlenskaya, D.B. 1972 "On the Heuristic Function of the Model of the Problem Situation" in Pushkin 1972

Brachman, R.J. "On the Epistemological Status of Semantic Networks" in N. Finder, ed. Associative Networks: Representation and Use of Knowledge by Computers.

Buchanan, B.G. March 1977 "The DENDRAL Project: A Short Summary" Working Paper, Stanford University Buchanan, B.G. and Shortliffe, E.H. 1983. Rule-Based Expert Systems. Reading, Ma. Addison-Wesley

Business Week, "Artificial Intelligence is Here" July 9, 1984

Chien, R.T. et al May 1984 Applicability of AI Techniques fo the Checking of Architectural Building Designs. Urbana, Il.: Advanced Automation, Inc.

Clancey, W.J. and Shortliffe, E.H. eds. 1983 Readings in Medical Artificial Intelligence: The First Decade. Reading, Ma.: Addison-Wesley

Craik, K.J.W. 1943. The Nature of Explanation. Cambridge University Press.

Davis, R. 1982. "Expert Systems: Where are We?, and Where Do We Go From Here?" AI Memo No. 665, MIT AI Lab, MIT, Cambridge

_____, 1983 "Interactive Transfer of Expertise" in Buchanan 1983

_____, Spring, 1985 "Knowledge-Based Expert Systems in Management," lecture course at M.I.T Sloan School of Management.

Duda, R.O. et al, 1978 "Semantic Network Representations in Rule-Based Inference Systems" in Waterman and Hayes-Roth, Pattern-Directed Inference Systems. Academic Press

_____, September 1981 "Knowledge-Based Expert Systems Come of Age" Byte Magazine September 1981

Fahlman, S.E. 1979 Netl: A System for Representing and Using Real-World Knowledge. Cambridge, Ma.: MIT Press

Feigenbaum, E.A. et al "On Generality and Problem Solving: A Case Study using the DENDRAL Program" in Machine Intelligence 6, Meltzer and Michie, eds.

Feigenbaum, E.A. and McCorduck, P. 1983 The Fifth Generation: Artificial Intelligence and Japan's Computer Challenge to the World. Reading, Ma.: Addison-Wesley

Gero, J.S. and Coyne, R. April, 1984 "The Place of Expert Systems in Architecture" CAD Journal April 1984, J. Wexler, ed. United Kingdom: Butterworths

Gevarter, W.B. 1984 Artificial Intelligence, Expert Systems, Computer Vision and Natural Language Processing. Park Ridge, N.J.: Noyes Publications

Groner, R. et al 1983 Methods of Heuristics. New Jersey: Laurence Erlbaum

Gurova, L.L. 1972 "Heuristic Processes in the Solutions of Descriptive-Logical Problems" in Pushkin 1972

Hayes-Roth, F. and Lenat, D.B. eds., 1983. Building Expert Systems. Reading, Ma.: Addison-Wesley

Hofstadter, D. 1979 Godel, Escher, Bach. New York: Vintage Books

Kim, M.K. August, 1984 Appropriate Directions for the Application of Artificial Intelligence to building Design and Evaluation. Urbana, Il.: U.S. Army Construction Engineering Research Laboratory

Lenat, D. Sept. 1975 "BEINGS: Knowledge as Interacting Experts" International Joint Council on AI. Cambridge, Ma.: AI Lab Publication

March, J. 1978 "Bounded Rationality, Ambiguity, and the Engineering of Choice" Bell Journal of Economics vol. 9 No. 2 Autumn 1978

Minsky, M.L. Fall, 1967 "Why Programming is a Good Medium for Exploring Poorly Understood and Sloppily Formulated Ideas" Design Quaterly

_____, ed. 1968 Semantic Information Processing. Cambridge, Ma.: MIT Press

_____, 1974 A Framework for Representing Knowledge. AI memo No. 306 Cambridge, Ma.: MIT AI Laboratory

_____, 1975 Artificial Intelligence. videotape MIT Center for Advanced Engineering Study

Miroshkhina, E.A. 1972 "Heuristic Programming and the Psychology of Problem-Solving" in Pushkin 1972

Negoita, C.V. 1981 Fuzzy Systems. England: Abacus Press

Newell, A. and Simon, H.A. 1961 "The Simulation of Human Thought" Current Trends in Psychology Theory. Pittsburgh, Pa.: University of Pittsburgh Press

Newell, A. "Artificial Intelligence and the Concept of Mind" in Schank and Colby, Computer Models of Thought and Language.

_____, 1972 Human Problem Solving. Englewood Cliffs, N.J.: Prentice-Hall

Nilsson, N.J. 1980 Principles of Artificial Intelligence. Palo Alto, Ca.: Tioga Press

Pearl, J. 1984 Heuristics: Intelligent Search Strategies for Computer Problem Solving. Reading, Ma.: Addison-Wesley

Piaget, J. 1971 Biology and Knowledge. Chicago, Il.: University of Chicago Press

Pospelov, D.A. 1972 "Towards a definition of Heuristics" in Pushkin 1972

Prescott, E.C. 1978 "Papers in honor of Herbert A. Simon: an introduction" Bell Journal of Economics vol. 9 No. 2 August 1978

Pushkin, V.N. ed. 1972 Problems of Heuristics. Jerusalem: Israel Program for Scientific Translation

Simon, H.A. 1975 "Style in Design" in Eastman 1975

_____, 1983 Models of Bounded Rationality, vol. 2: Behavioral Economics and Business Organization. Cambridge, Ma.: MIT Press

_____, 1984 Sciences of the Artificial. Cambridge, Ma.: MIT Press

Stahl, F.I. Oct.1984 "Expert Systems" Progressive Architecture October 1984

Stefik, M. and Conway, L. Summer 1982 "Towards the Principled Engineering of Knowledge" AI Magazine

Szolovits, P. 1983 "Artificial Intelligence and Medicine" in Clancey

Tversky, A. and Kahneman, D. 1974 Judgement under Uncertainty: Heuristics and Biases. Science 185 pp. 1124-31

_____, April, 1984 "Choices, Values, and Frames" American Psychologist vol. 39 No. 4 pp. 341-349

Quillian, M.R. 1968 "Semantic Memory" in Minsky 1968

Wickelgren, W.A. 1974 How to Solve Problems: Elements of a Theory of Problems and Problem Solving. San Francisco: W.H. Freeman

Winston, P.H. ed. 1975 Psychology of Computer Vision. New York: McGraw-Hill

_____. 1976 Constraint Structures. videotape MIT Center for Advanced Engineering Study

_____. 1976 Exploiting Constraints. . videotape MIT Center for Advanced Engineering Study

_____. 1976 The General Problem Solver. videotape MIT Center for Advanced Engineering Study

_____. 1977 Learning by creating and justifying transfer frames. AI memo No. 414A MIT AI Laboratory

_____. 1979 Artificial Intelligence. Cambridge, Ma.: MIT Press

Books About Architecture, Window Design, and Related Topics

Abel, C. August,1969 "Ditching the Dinosaur Sanctuary" Architectural Design August 1969

_____. 1982 "The Case for Anarchy in Design Research" in Evans 1982

Ahuja, H.N. 1983 Successful Methods in Cost Engineering. Canada: John Wiley

Akin, O. 1982 Representation and Architecture. Silver Spring, Md.: Information Dynamics

Alexander, C. 1967 Notes on the Synthesis of Form. New York: McGraw-Hill

Architectural and Engineering News, Dec., 1969 "Broken Glass: Analysis of Failure"

Architectural Forum, 1955 "Building for Business", New York: Architectural Forum

ASHRAE. 1977 Handbook of Fundamntals. New York: ASHRAE

ASTM 1984 "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems" Philadelphia, Pa.: American Society for Testing and Materials

Baker, G. and Funaro, B. 1948 Windows in Modern Architceture. New York: Architectural Book Publishing

Beckett, H.E. and Godfrey, J.A. 1974 Windows. New York: Van Nostrand

Benson, J. et al 1980 The Housing Rehabilitation Book. London: Architectural Press

Best, G. 1973 "Method and Intention in Architectural Design" in Broadbent 1973

Bradshaw, V. 1985 Building Control Systems. USA: John Wiley

Broadbent, G.H. and Ward, A. 1973 Design in Architecture. London: Architectural Association

Brooks, A. 1983 Cladding of Buildings. England: Construction Press

Bross, I.D.J. 1965 Design for Decision. New York: Free Press

Byggforskningsradet, Swedish Council for Building Research 1984 Windows in Building Design and Maintenance. Stockholm

Clarkson, C.W. and Lilly, M.L. 1978 "Single and Multiple Glass Glazing Media in Passive Solar Energy Construction" in Passive Solar 1978

Cook, F. 1970 Talk of Windows. New York: A.S. Barnes

Dell'Isola, A.J. and Kirk, S.J. 1981 Life Cycle Costing for Design Professionals. New York: McGraw-Hill

Dogniaux, R. 1984 "Psychological and Physical Aspects of Windows in the Architectural Design" in Byggforskningsradet 1984

Eastman, C.M. 1982 "The Computer as aDesign Medium" in Akin 1982

_____, 1975 Spatial Synthesis in Computer-Aided Design. New York: John Wiley

Elder, A.J. 1974 AJ Handbook of Building Enclosure. London: Architectural Press
Evans, B. ed. 1982 Changing Design. England: John Wiley

Glegg, G.C. 1973 The Science of Design. England: Cambridge University Press

Grant, E.L. 1964 Principles of Engineering Economy. New York: Ronald Press

Gregory, S.A. 1966 The Design Method. London: Butterworth Griffin, C.W. Dec., 1982 "Life-cycle Costing Primer" Progressive Architecture, pp. 61-62

Habets, J. 1984 "The Integration of the Window as a Passive Solar Collector in the Architectural Design" in Byggforskningsradet 1984

Harrison, H.W. 1985 "Estimating Service Life" Building Research and Practice January 1985

Hastings, S.R. 1978 "A Comprehensive Approach to Window Design for Energy Conservation" in Passive Solar 1978

Hopkinson, R.G. 1963 Architctural Physics: Lighting. London: Her Majesty's Stationery Office

_____, 1966 Daylighting. London: Hinmann

_____, 1969 The Lighting of Buildings. London: Faber and Faber

_____, 1970 "The Ergonomics of Lighting", London: MacDonald Technical and Scientific

Huntington, W.C. 1975 Building Construction. New York: John Wiley

Jacques, R. 1982 "Changing assumptions about design problems" in Evans 1982

Jarmul, S. 1980 The Architect's Guide to Energy Conservation. New York: McGraw-Hill

Jones, J.C. 1963 "The State-of-the-art in Design Methods" Conference on Design Methods. England: Pergamon Press

Kaufman, J.E. ed. 1981 IES Lighting Handbook. New York: Illuminating Engineering Society

Kittler, R. 1984 "Changing Priorities in Window Design" in Byggforskningsradet 1984

Koppes, W. F. 1968 Metal Curtain Wall Specifications Manual. Chicago, Il.: National Association of Architectural Metal Manufacturers

Lam, W.M.C. 1977 Perception and Lighting as Formgivers for Architecture. New York: McGraw-Hill

Lawson, B. 1982 How Designers Think. New York: John Wiley

Lewis, J.R. 1975 Construction Specifications. New Jersey: Prentice-Hall

Liljefors, A. et al 1984 "Window Design and Perceived Interior Qualities in Dwellings" in Byggforskningsradet 1984

Lim, B.P. 1979 Environmental Factors in the Design of Building Fenestration. London: Applied Science Publishers

Lynes, J.A. 1968 Principles of Natural Lighting. New York: Elesvier Publishing Co.

_____, ed. 1978 Developments in Lighting. London: Appllied Science Publishers

Markus, T.A. 1960 Daylight with Insulation. England: Pilkington Bros. Ltd.

_____, 1967 "The Function of Windows" Building Science vol. 2. Pergamon Press

_____, 1973 "The role of building performance measurement and appraisl in design method" in Broadbent 1973

Marshall, H.E. and Ruegg, R.T. 1980 "Simplified Energy Design Economics" Washington, D.C.: National Bureau of Standards

Massachusetts State Building Code Commission, 1979 "An Illustrated Guide to the Massachusetts Energy Code". Boston

Matteoli, L. and Bricarello, G. 1984 "Windows as Elements of Architecture" in Byggforskningsradet 1984

Maxwell, M. 1984 "Informing Design Decisions: An Approach to Corporate Building Design" M.Arch thesis, MIT

McKinley, R. 1981 "Design of Glazing Systems", Design of Building Cladding. BSCE/ASfCE Structural Group Lecture Series, MIT

Means "Building Systems Cost Guide" 1981 Massachusetts

Midlands Housing Consortium (MHC) 1979 Designing to Save Heat. Coventry, England: Midlands Housing Consortium

Milne, M.A. et al 1966 Computer-aided Design. Oregon: University of Oregon Press

Mitchell, W.J. 1977 Computer-aided Architectural Design. New York: Petrocelli/Charter

Misuriello, H. et al June, 1982 "Energy Design of Office Buildings" Progressive Architecture

Moore, G.T. ed. 1968 Emerging Methods in Environmental Design and Planning: Proceedings fo the Design Methods group First International Conference. Cambridge, Ma.: MIT Press

National Association of Home Builders, 1974 "The Builder's Guide to Energy Conservation" Washington, D.C.

National Bureau of Standards Feb., 1976 "Design and Evaluation Criteria for Energy Conservation" Washington, D.C.

Negroponte, N. 1970 The Architecture Machine. Cambridge, Ma.: MIT Press

Neubauer, 1977 "Effect of Window Areas on Energy Use" ASAE paper No. 77-4546 Michigan

New York State Energy Office, 1980 "An Energy Management Program for Multi-Story Office Buildings"

Park, W.R. et al 1984 Cost Engineering Analysis: A Guide to Economic Evaluation. New York: John Wiley

Passive Solar State of the Art: Proceedings of the Second National Passive Solar Conference. March, 1968

Pilkington Bros. Environmental Advisory Service, 1969 Windows and Environment. London: Architectural Press

Pye, D. 1978 The Nature and Aesthetics of Design. New York: Van Nostrand

W.H. Ransom, W.H. 1981 Building Failures. London: E & FN Spon, Ltd.

Rapoport, A. 1973 "Facts and Models" in Broadbent 1973

Rittel, H.W.J. 1966 Universe of Design. Berkeley, Ca.: University of California Press

Rittel, H.W.J. and Kunz, W. July, 1970 "Issues as Elements of Information Systems" Working paper No. 131 University of California, Berekeley

Rizzi, E. 1980 Design and Estimating for Heating, Ventilating, and Air Conditioning. New York: Van Nostrand

H.J. Rosen, H.J. 1972 Window and Wall Testing, ASTM STP 552. Philadlphia, Pa.

Rosen, J. 1982 Natural Daylighting and Energy Conservation. MIT thesis, supervised by H. Bryan

Rostron, M. 1964 Light Cladding of Buildings. London: Architectural Press

Rybnikar, O. 1985 "Computer-Aided Architectural Design" Building Research and Practice January 1985

Selkowitz, S. "Transparent Heat Mirrors for Passive Solar Heating Applications" in Berlad, A.L. et al 1978

_____, August 1980 "Windows for Energy Efficient Buildings" Berkeley, Ca.: Lawrence Berkeley Laboratory

Sizemore, M.M. 1979 Energy Planning for Buildings. American Inst. of Architects

Stone, P.A. 1980 Building Design Evaluation: Costs-In-Use. London: E. & F. Spon

_____, 1983 Building Economy; Design, Production, and Organisation. Great Britain: Pergamon Press

Swinburne, H. 1980 Design Cost Analysis. New York: McGraw-Hill

Turner, D.P. 1977 window Glass Design Guide. London: Architectural Press

Vonier, T. Aug., 1984 "Next Window, Please" Architectural Record, p.104

Wagner, W.F. ed. 1980 Energy Efficient Buldings. New York: McGraw-Hill

Walsh, J. 1961 The Science of Daylight. New York: Pitman Publishing

Watson, D. ed. 1979 Energy Conservation Through Building Design. New York: McGraw Hill

Widder, J. 1984 "The Window in the Wall", Case Study in Building Economics

Williams, B. 1977 Remodeler's Handbook. Calif.: Craftsman Book Co.

Yellott, J.I. "Fenestration and Heat Flow Through Windows" in Watson, ed. 1979