Invited Keynote address: "Representation of Design Processes", Conference on Design Thinking, MIT April 23-25, 1999.

REPRESENTATION OF DESIGN PROCESSES

Charles M. Eastman

Design Computing, Edutech Institute,
Georgia Institute of Technology

Email: chuck.eastman@arch.gatech.edu

Abstract. An important representation issue in design is of processes The need for study and improved representations of design processes is presented.

Keywords. design representation, design process research, design thinking

1. An Observation

External representations are one of the hallmarks of humanity. Only mankind has such a rich range of drawings, language or mathematics. Representations serve many cognitive purposes. Some are external, formal and well specified, others are personal and maybe exist for only a few moments in time. Thus it is difficult to count representations. At the same time, it is fairly obvious that the external representations available to any individual has grown slowly up until very recently. The development of spoken languages, various forms of writing and record keeping, the development of graphical representations, and mathematical systems were all rare and difficult social inventions. They are rare because they involve complex syntactic constructs in their design, corresponding to modeled conditions in the world. They also are rare because they must become known to at least a few people if they are to communicate using the representation. Representations are also limited because of the media available to develop them. Carvings, paintings, writing, drawings, are all static representations. With the telegraph and Morse code and later radio, movies and television, we gained dynamic representations, but these were available to only a few people.

Recently, digital media and the computer offer a rare opportunity to invent new external representations. These new representations are based on the unique qualities of the new media. Some of those unique qualities are:

- individual and low-cost production of dynamic representations,
- the development of hyperlinks between presentations,
- representations with built-in processing, that can move or process information
- the ability to quickly -- often instantaneously -- convert information between one representation and another,
- the ability to transmit 3-D images, optionally with dynamic capabilities, offering four dimensions of variation,
- the ability for anyone to use these representations and to "publish" them to a world audience, at almost no cost.

None of these capabilities have been widely available until recently. Thanks to computation, they are available to anyone with a computer and a modem and ISP. This makes the current time an extremely exciting one for cognitive science, because new ways of structuring and presenting information can easily lead to new ways to think about information and material. I think it is apparent that we are in *the age of representation*.

2. Representation of Processes in Industry

The role of processes in most intellectual activities has changed dramatically over the last century. Prior to the nineteenth century, the study of human processes was extremely rare. One may read the history of the guilds, for example Unwin (1904) early studies of German and Swiss watchmakers (Landes, 1983) or the building of the cathedrals (xxx. 1946) and one finds only the barest descriptions of processes and no representations of them. There are even few process descriptions in words written during these times. Only slowly has the consciousness of processes emerged in the 20th century. Around 1900 Frederick Taylor, the early developer and promoter of industrial management, decomposed and organized work activities and gave rise to what is now known as Taylorism (1911). Taylorism arose from the explicit study of processes. This explicitness had many effects, including making processes more explicit and self-conscious. In so doing, they also became more controlled, leading for example to the first factory assembly lines. The idea in Taylorism was to identify each action within a larger job and to partition work into these actions and to sequence them in an efficient manner.

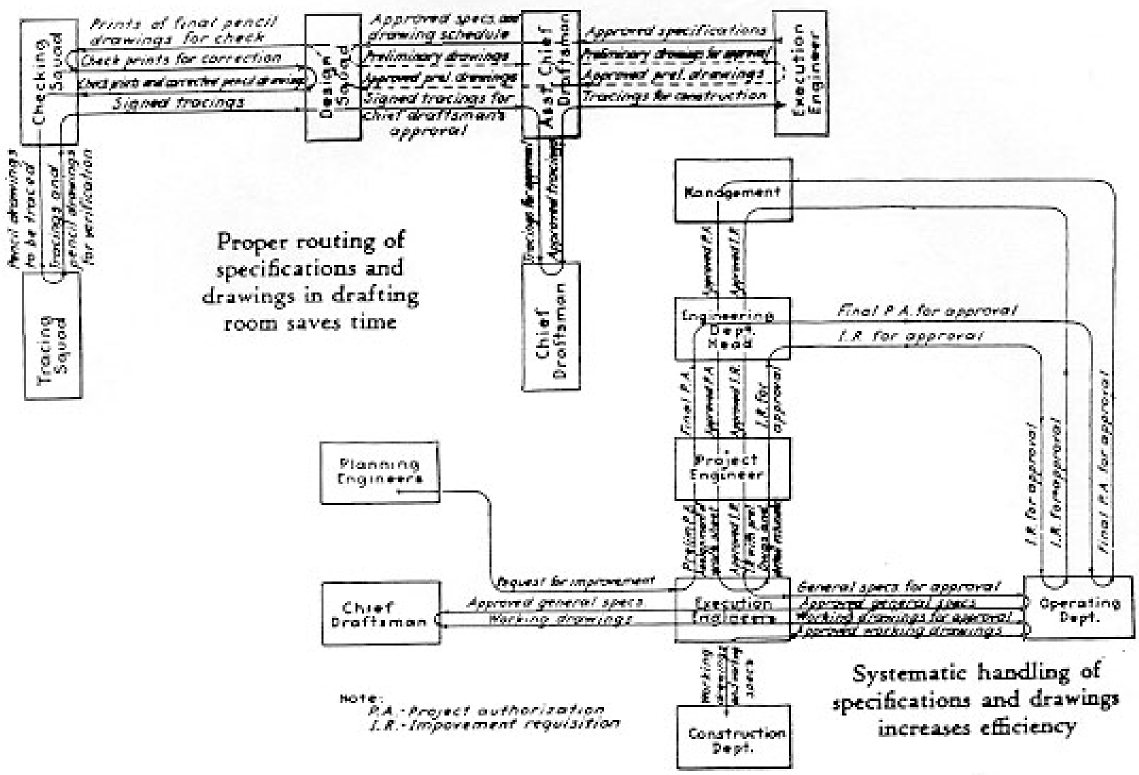

Figure One: An early production plan for design offices, circa 1930.

Later, these same ideas began to be applied to non-fabrication activities. Early work in large organizations applied the assembly line concept to design and engineering work. In the professional journals, engineers who designed were distinguished from the draftsmen that drew up designs. Bills of material were derived by another group. Drafting became further specialized with drafters, tracers and checkers; the last group verified the correctness and consistency of drawings. It was about 1930 that articles on drafting room practice refer to the solution of "serializing the process", determining a standard flow through which all work would pass from department to department (Morton, 1930). The flow sequence was based on control of manpower allocations, material requisitions and checking of designs, See Figure 1.

Another example of such fixed flow development is shown in Figure 2, from a 1932 paper presenting machine design management at Western Electric (Alden, 1932). Five different departments are involved, with twenty-four steps. At least three representations are involved: a cost estimate for drawing, then layout drawings, then assembly and detail drawings. Each representation is reviewed after it is developed and they are analyzed again all together at the end for cost.

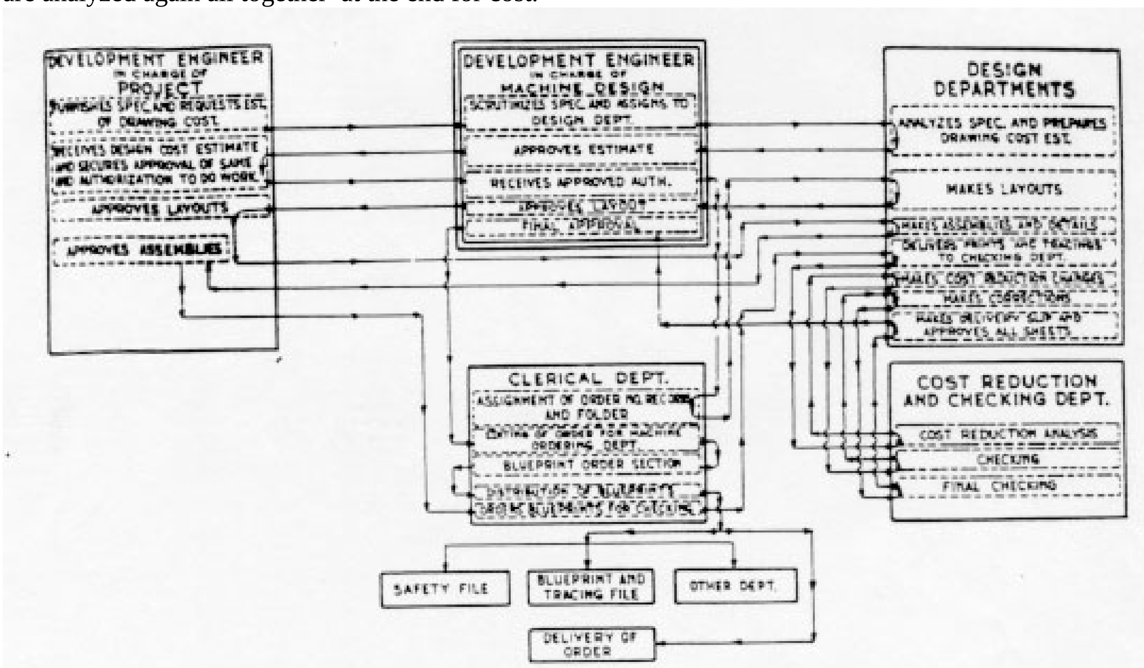

Figure Two: Another production plan for a design office, from Western Electric, circa 1932.

An early associate of Frederick Taylor was Henry Gantt, who first used and demonstrated the value of bonus incentive pay based on productivity. Later, in efforts to improve the productivity of munitions plants in the First World War, Gantt developed charts that mapped production tasks, laid out in rows, over the horizontal axis being time. Such a chart is now universally known as a Gantt Chart. An example is shown in Figure Three. As processes became articulated, the issues associated with processes emerged for study. One could, for example, "see" each task and use colors or other notation to indicate the machine or workstation involved. People were assigned to machines and the machines were what were typically allocated. To some degree a project could be tracked, determining whether it was ahead or behind the schedule (Goldfarb and Kaiser, 1964).

Gantt charts show the relations between tasks implicitly, with successor activities starting at the completion date of the predecessor activity. Some variations of Gantt charts explicitly connected the termination of predecessor activities and the start of successor activities.

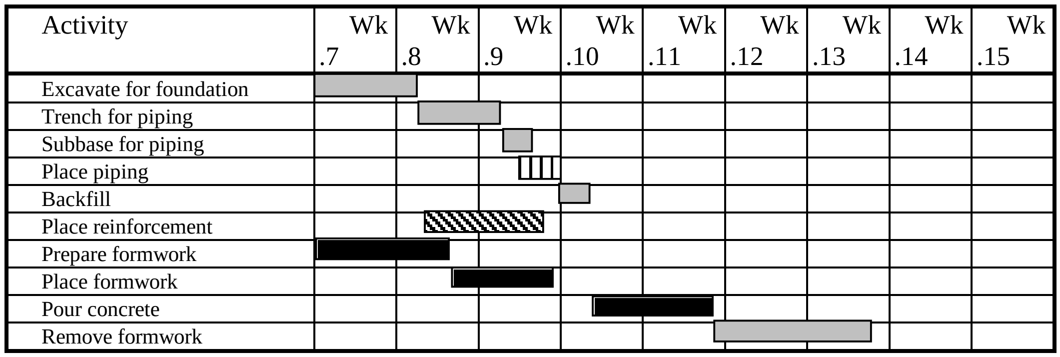

Figure Three: A typical Gantt Chart.

Much later, in the 1960s, these ideas were picked up by Dupont de Nemours and Univac who worked together to improve the planning and scheduling of construction projects using a computer. The Dupont and Univac team made explicit the dependencies between tasks. They also recognized that within a set of parallel activities some activity sequences determined the overall length of a project but that other sequences did not. It was the longest sequence among parallel sub-sequences that determined the overall project time. In large projects, these were not easy to identify. Computational methods to search all sequences and to identify those that determined total project time were developed and called Critical Path Method (CPM). An example is shown at the bottom of Figure Four. The critical path sequence of tasks is shown in dark gray. About the same time, the US Navy developed the Program Evaluation and Review Technique (PERT) for planning the Polaris submarine construction. It focused on the stochastic aspect of scheduling (marks and Taylor, 1966). CPM and PERT are the main methods for planning and managing construction processes used today. However, they have not been heavily used to plan creative work such as design or planning.

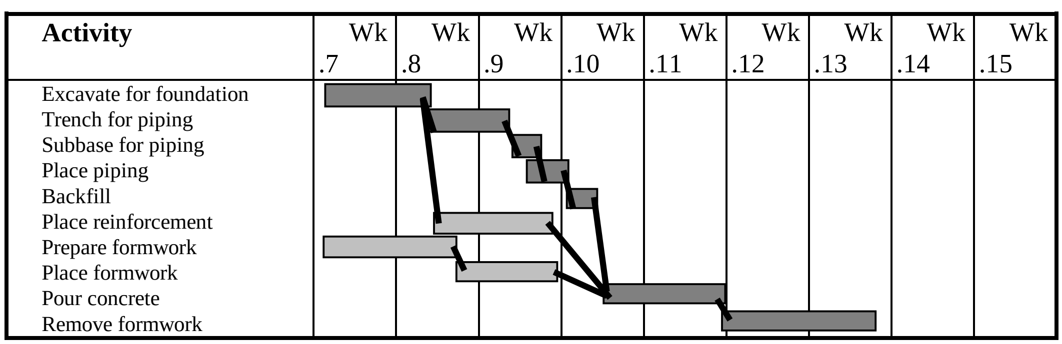

Figure Four: A typical CPM or PERT chart, with explicit dependencies and processing times.

CPM Charts show parallel activities and the precedence relations usually indicate the flow of a product or work from one activity to another. However, the issue of communicating between concurrent tasks is considered implicitly. It was only with the development of electronic computation that issues of parallelism were studied deeply. For example, an early problem given in artificial intelligence courses was how to organize a line of soldiers so that they might fire their muskets simultaneously, but their communication was limited to only talking to the person directly next to them. See Figure Six. Each soldier has memory and processor. Can you figure out the answer?

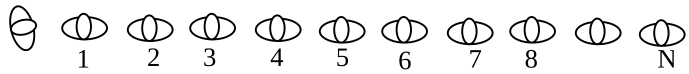

Figure Five: The firing squad synchronization problem. Each soldier can speak to the person on both sides. They are to be given instructions by the person at the left so they may all fire at the same time. What are the instructions?

The distribution of processor and data storage was studied for many years before adequate multiprocessor architectures were developed. Database research has dealt with concurrency problems ever since it was found out that two schedules of activities that were not properly synchronized could either generate nonsense results, or could deadlock the machine. Transaction management involves how a data store may be managed while receiving concurrent updates without being corrupted.

3. Human Processes and Workflow

With the development of computer science, psychology gained an electronic model that could be interpreted as "thinking". While the original developers of computers thought of them as mathematical engines, another group recognized that they were more general and could be viewed as symbol or information manipulation machines. Out of this recognition came the field of artificial intelligence. Computers could address such issues as vision, speech recognition, expert systems—all areas initiated as AI problems.

With the computer, psychology also gained a paradigm for the elusive notion called "thinking", opening the possibility for the parallel development of cognitive psychology. The Miller, Galenter and Pibram book, *Plans and the Structure of Behavior* (1960), was one of the earliest influential books in the new field of cognitive psychology. It's TOTE units were an early application of process models (flow charts) developed for computation and then applied to human behavior. This line of work expanded quickly into a range of process studies, including protocol studies of different kinds of design and problem solving behavior, cognitive models of learning of skills and ideas, the distinction between short term and long term memory, chunking and other concepts.

While the brain is undoubtedly a parallel processing system, almost all of the work in cognition has focussed on central attention activities involving serial processing. Problem solving has been one focus and sensory processing—especially vision and sound—have been the main foci. Many local debates within cognition have emerged. Is the brain a symbol processing system, like traditional computers, and are concepts carried in the brain in symbol-like structures? As word-based grammars, semantic nets or frames? Or is the brain's processing closer to the various sensory modalities that humans have—visual processing, sound and tactile processing? Does the brain operate similar to current computers, with a single conscious region where most information is processed serially, and to what degree is there reliable parallel processing outside of our attention and self-conscious information region? These are just a few of many issues being addresses in cognitive science.

The combination of cognitive science, high speed digital connection of many parts of the world, and the growing support of human activities on computers and the World Wide Web, has led to a tremendous emphasis on processes in almost all industries. US industry has gone through a generation where businesses were re-engineered, based on process analysis and re-design. Work originally done within a firm is outsourced to other organizations that can do the work more effectively (Wheelwright and Clark, 1992).The basic idea is that any group within an organization, if not fully utilized, should be made separate so that its capabilities have a chance to be fully utilized all the time. This raises an interesting question: "if communication anywhere in the world is free, allowing anyone to access or locate anyone else at little cost, and the structure of communication improves through better specialized languages, for example, then is there a need for business organizations? Couldn't any architectural firm hire on the spot any group of draftsmen anywhere in the world to do some project? Hire a structural or mechanical engineer and communicate through the Web? Couldn't a contractor do the same for some project, hiring workers off the Web and procuring parts by specifying them on the Web for procurement? Couldn't any automobile company outsource all the components of a car design for fabrication and delivery, as they are doing for some parts currently? These possibilities raise several interesting questions. What are the essential capabilities of an organization, over a group of individuals? To what degree can human communication be perfected to enhance the now implicit communication that now is associated with the culture of an organization?

Another type of example of work being transformed by communication and cognitive science is the health industry. It has moved from a paradigm where each doctor developed their own knowledge model of illnesses, based on their own experience and reading, to one where explicit diagnosis decision trees are taught as the structure of knowledge in various health fields. A branch in a tree is associated with a set of symptoms. A node defines the most discriminating test that can distinguish the cause of the symptoms. The leaves of the tree identify medical responses. The decision trees identify what tests to give for what symptoms, what the possible results of a test mean percentage-wise, and what other tests or information will refine the diagnosis. Research in medicine is directed toward refining these decision trees. Can a more discriminating test be developed? Are there other causes for the same set of symptoms? Medicine, like most areas of society, are become very process conscious (p.c. 1995).

Many organizations are adopting work flow management systems and these are attracting attention in engineering design firms and a few architectural firms (Doherty, 1997, Chapter 11). Workflow management is based on modeling the process flows within a business and supporting the smooth execution and management of those flows. Most recent workflow management have a fixed flow that cannot be adapted by the users and follows rigid information flows. The flows generated look a lot like the diagrams I showed earlier from the 1920s and 30s. Design operations are different from these systems and some work has articulated these differences.

4. Design Processes

Against this background, the application of process issues in design has only slowly emerged from a kind of knowledge that was previously completely *tacit*. Design was learned by watching and working with an expert. Even today, many of the issues of procedure in design education are dealt with implicitly, through assignment due dates and by example. In design studio education, how to design is tied up intimately with the final product. During my education at Berkeley, we learned different design process from different faculty. Only later did some of us figure out that each faculty member had their own process of design and that at the upper levels we were expected to slowly synthesize our own design process. We are still slowly moving from the notion of Christopher Alexander's of a partially unself-conscious design to self-conscious and explicit design processes (1964).

I predict that the next decade or so will be marked by a radical focus on process in design, making procedures of design much more explicit and self-conscious. The terminology and issues of process will become as commonplace as the issues of product and form. It will be recognized that process and product are highly synergistic-- that the are complementary aspects of a single result. The self-consciousness will apply to both practice and to education. Already, the terms of "problem formulation", "problem space" and "search" are used increasingly frequently to identify different types of information processing in design. The basis for this prediction is partly the historical trend, outlined above. The same growth in self-consciousness is happening in all fields. It is also necessity. As we develop the tools of communication, of distance coordination and collaboration, it will be necessary that we communicate our desired processes-- to each other and to computers.

Why is better knowledge of design processes needed? Why will it be demanded? I offer four reasons:

1. *to better manage complexity* - The number of technical issues in architectural design are growing quickly. Green buildings, energy conservation, improved safety from accidents, improved performance in response to earthquakes, floods and storms, new systems for communication and intelligent buildings are all influences that will be pushed onto the responsibility of future building designers. Designers will have to learn how to integrate these various issues. In the US, people may come to wonder why they have greater environmental comfort in their car than they do in their house or office and may demand greater environmental comfort in their architecture.

2. *to improve collaboration among the specialists in design teams* - Each of the issues above involve additional types of expertise. Design teams will grow in size and complexity. There are at least two ways that large design teams can effectively operate: (a) by following rigid cultural conventions that specify each team member's role; (b) by explicit design, definition and agreement of the process to be followed. All of our collective knowledge would support that innovative and responsive design is best supported by the second way. If the architect's role in design is only as a tram member for exterior decoration, it will be because architects have not developed and captured the knowledge needed to coordinate diverse design teams.

3. *to improve the tool support for design* - Most design tools provide an ineffective fit between what one wants to do and how it must be accomplished within the tool. I must emphasize that this is a two-way fit and that designers trained to work with paper and pencil got what they deserved when they voted in the marketplace for CAD drafting. Both sides must adapt. But to do so, we must have greatly improved understanding of design processes, form generation processes, evaluation processes, coordination processes.

4. *To improve design education* - There are many strengths in current design education. But we fail with many students not because they are not smart, but because they are not adept at culture-based learning. I do not advocate a purely prescriptive and explicit design education, nor a completely intuitive one. We need to search for a mix of learning experiences that include explicit skills based on self-awareness and knowledge of process.

There are probably more reasons why better knowledge of design processes is strongly needed.

5. Research on Design Processes

An expanded understanding of design processes will only be generated through a strong program of research. This research is not likely to be carried out by practitioners. Process research is an ideal focus for universities to engage.

Design studies have mostly been in the form of protocol studies and case studies. A protocol study involves deep analysis of information processing over a relatively short time period. It was originally developed for capturing problemsolving processes, in terms of such issues as operations, goals and solution strategies. These issues are directly relevant to design, and address some of the open issues involving design processes. Protocol studies also have been used to identify roles of individuals in certain types of teamwork situations, and high level planning strategies (Cross et al, 1996). They have allowed analysis of the general structure of small-scale design situations (Akin 1986).

Full design development may involve a large team and take several years to complete. Designing, like most intellectual tasks, does not start upon sitting down at ones workspace, but continues sometimes consciously and sometimes unconsciously. Important ideas may become clear while driving or in the shower. In a recent case study of a large architectural design project, the estimated total design effort for this large project was 100 man years for the complete design. This suggests that a protocol (of maximum size of ten person-hours) covers about 1/20,000 of the overall scope of a large scale design. Because it typically takes 10 hours of protocol analysis for every one hour of collected protocol, it is clear that we will never collect even one large scale design protocol (Eastman, Potts and Hsi, 1998).

Other types of design studies are needed. Like other large information spaces that cannot be exhaustively searched, studying design processes inevitably involves sampling strategies. Random sampling of information flows, processing strategies, communication are needed if architecture and design are to proceed in their development and not become a couturier art. The HCI area (Grudin, 1992) and the social sciences have developed good practices for collecting case studies (Lincoln and Gruha, 1985). There are a very small number of carefully collected case studies of design, focusing on information processing. We need more broad-based case studies that document information flows, decision-making, throughout the design phase of a building (Krauss and Myer, 1971).

Below, I outline one beginning set of practical issues about design processes and why we need to understand them. Some apply to design practice while other apply to education:

(A) *improve design coordination over distance and across cultures and professions:* Increasingly, large design projects involve international clients, locations and consultants. One need only consider the recent set of projects in Shanghai and in Berlin. Coordination among design teams involves trust and professionalism and also cultural assumptions. Often these break down in international projects and they operate in perpetual crisis mode. By studying these types of projects, procedures and possibly new representations that help to explicitly define coordination processes and roles could be developed.

(B) *how consultants solve design problems and how they utilize information and tools in developing responses:* A designer come to the consultant with design issues. These issues are sometimes general, say, about building orientation or causes of energy consumption or poor acoustics. Such questions are specific, such as "how to reduce the summer heat gain through a window wall", "how to deaden the echoes in a lobby", "how to air condition one zone of a building 24 hours a day, when all the others are conditioned ten hours". Consultants use analysis tools heavily. The issue of effective analysis tool use is NOT that there is an interface from some CAD tool. Rather it is the ease in which the consultant can combine information from various sources and possibly use multiple analysis tools to run some experiments, out of which the answer to some question is answered. Today, no interface between design tools and analysis tools come close to supporting this kind of experiment setting and trial and error analysis process I have described. We don’t know enough about the processes involved to design one. How consultants use tools is needed to improve analysis tool front ends, to provide better coordination linkages between consultants and designers and to better educate future designers and consultants.

(C) *better integration of design and construction planning:* The potential efficiencies of design/build construction methods offer both improved economy, but also the potential of more innovative design (in some ways, Frank Gehry's projects can be viewed as a particular kind of design/build). While most other industries have gone through a generation of coordinating design with construction -- what is called concurrent engineering -- the traditional roles and relations of architects and contractors do not fit this new process model. By studying the process of design/build construction improved methods and explicit coordination procedures and practices could be developed, making this a construction method available for much wider use.

(D) *conceptual structures in design:* Most good designers set up his own formulation of context and problem structure. This may be a form vocabulary; it may be a process to be followed; it may be a set of issues that are used as the initial basis for form generation. But how are the contextual issues identified and structured? Is this simply discountable as a "stylistic issue"? My design friends tell me of much more interesting searches for form and structure that solve multiple dimensions of concern. How can design tools support the range of contextual issues that an architect is trained to deal with? Some contextual issues are external, dealing with site, idiosyncrasies of the use or user of spaces. In other cases, the context is internal -- set up by the designer -- for example articulating some aspect of the structure of the design or applying some preconceived rule. Design tools do well at applying external and fixed rules. We see multiple tools supporting adjacency matrices and bubble diagrams. However, there are no tools at present that support application of the designer's own rules. A possible exception is the potential of shape grammars to allow user definition and application of rules. Another is the application of symmetry operations that have been developed in some research systems. In general, most design tools that attempt to support "intelligent design" provide an internally rigid capability that does not support adaptation to context. We must know more about these design processes if better tools are to be forthcoming.

(E) *design detailing and how a detail is adapted to local conditions:* Most building product suppliers provide standard details for their building elements, such as doors, windows, mechanical equipment, interior or exterior paneling and so forth. These details are studied and then adapted to a very large number of local conditions by hand by designers. Litigation arises from whether the intent of a standard detail has been followed or not, when that detail fails. Some have a goal of automating the detail adaptation process, with all conditions and their solution built into an intelligent program. Another direction being discussed is to set up the detail as a parametric model that can be adapted by the designer. Process studies of detailing do not exist that suggest how to make standard details easier to adapt, or how they might have more rules or guidelines built into them.

(F) *how to teach students to integrate different kinds of design knowledge:* While it is clear that the designs of Renzo Piano and other technologically driven designs are based on the integration of combinations of knowledge that most other designers don't have, we at universities don't have very good ideas how to produce students that can integrate well these skills. The current solution is to find someone who has this knowledge AND can design this way and hopefully they will teach it to students. That is, we are not able to articulate how this knowledge is integrated, how it is applied and how unique solutions come form it. If we could identify the process, surely we could enable students to learn these ideas more easily.

I could go on. There are many more issues than these six, which just skim a few of the obvious areas where there is needed study of design processes.

6. Discussion

There is a number of ways to represent processes and some of these are helpful for representing design:

Gantt and CPM type schedules, flowcharts and state diagrams, Petri-nets and predicate logic. For a survey, see Eastman (1999, Chapter 10). It is important to identify functionally what a representation is to depict and to select or design a representation accordingly. We will see more representations of design processes as they are studied more.

We should be aware of why there is reluctance to try to make design processes explicit. Because processes and product are highly intermixed, making explicit ones process gives away some of their design secrets. Others may be able to replicate their designs by replicating their process. Or even more critically, the process may be analyzed and criticized.

To some the discussion of design process removes some of the mysticism and the art of design. But quite the opposite, discussions of process will inevitably lead to the refinement of processes and allow attention to be given to the creative modification and enhancement of processes, for both social and for individual and creative ends.

References

Omer.Akin, (1986) *The Psychology of Architectural Design*, Pion Press, London.

C. Alexander, (1964) *Notes on the Synthesis of Form*, Harvard U. Press, Cambridge, MA.

J.L. Alden, (1932) "Machine Design Management", *Proc. Society of Mechanical Engineers*, SMP-54-9, pp. 105-118.

N. Cross, H. Christiaans and K. Dorst, (1996) *Analysing Design Activity*, edited by John Wiley & Sons Ltd, Chichester UK

P. Doherty, (1997) <u>Cyberplaces: Internet Guide for Architects, Engineers and Contractors</u>, R S. Means, Kingston, MA.

C.M Eastman,. (1999) *Building Product Models:Computer Environments Supporting Design and Construction*, CRC Press, Boca Raton FL.

C M Eastman, D S,Parker T S Jeng, (1997) "Managing the Integrity of Design Data Generated by Multiple Applications: The Principle of Patching" *Research in Engineering Design* **9** pp. 125-145.

C.M Eastman, I. Hsi, and C. Potts, (1998) "A Study of a Large Shanghai Architectural Project", GVU Report, College of Computing, Georgia Institute of Technology, Atlanta, March,.

N Goldfarb and W Kaiser, (1964) Chapter 1, in *Gantt Charts and Statistical Quality Control* Goldfarb N, Kaiser W Eds, Hofstra University Yearbook of Business 1:1, (March, 1964),

J. Grudin, (1992) “Why CSCW applications fail: Problems in the design and evaluation of organizational interfaces”, in D. Marca and G. Bock (Eds.), *Groupware: Software for computer-supported cooperative work*, IEEE Press, Los Alamitos: CA, pp. 552-560.

R. Krauss, and J.H. Myer, (1971) "Design: A Case History, in *Emerging Methods in Environmental Design and Planning*, G. Moore (ed.), MIT Press, , pp. 11-20.

David S. Landes, (1983) *Revolution in Time*, Belknap Press and Harvard University Press, Cambridge MA.

Lincoln, Y. and Guba, E. (1985) *Naturalistic Inquiry*, Sage Publications, Newbury Park: CA.

N. Marks and H.L. Taylor, (1966) *CPM/PERT: a Diagrammatic Scheduling Procedure*, Bureau of Business Research, Graduate School of Business, U. of Texas, Chapter One.

G.A. Miller, E. Galenter and K. Pibram, (1960) *Plans and the Structure of Behavior*, Holt Rinehart and Winston, NY.

W.B. Morton, (1930) "Proper procedure expedites design work", *Electrical World*, 96:2 (Dec. 13,), pp. 1082-1083

Personal communication, Frank Alder, School of Medicine, UCLA.

Frederick Taylor, (1911) *The Principles of Scientific Management* Harper Bros., New York

George Unwin, (1904) *Industrial Organization in the Sixteenth and Seventeenth Centuries*, Oxford Press, London .

S.C. Wheelwright and K.B. Clark, (1992) *Revolutionizing Product Development*, Free Press, NY.