Toward the Ideal Mechanical Engineering Design Support System[1]

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ABSTRACT

This paper details the progress toward the development of the ideal mechanical engineering design support system. It attempts to look at the gap between the needs of a mechanical engineer and what is currently available on CAD systems. Since the term "CAD" emphasizes that the computer as an aid to the human designer, this paper is designer-centric. It is based heavily on the activities performed by designers and the types of information developed by them.

Seventeen goals for the ideal mechanical design support system are listed. These are directed at the types of information developed during the design process and the activities used to develop them. For each of the seventeen, background information, the current "state-of-the-art", and opportunities for future development are itemized.

Key words: Mechanical Engineering Design, CAD, Support System.

1. INTRODUCTION

This paper summarizes the progress made toward the development of the ideal mechanical engineering design support system. For nearly 30 years, computer aided design (CAD) systems have been touted by their developers as systems that support engineering designers developing products. CAD systems have had a major impact on how design is accomplished in the workplace. This being said, there is amazingly little formal research on the effects of these systems on the designers and on the final products[2]. This paper presents a structure for discussing these effects. In doing so, it summarizes what is known and what needs to be studied. Finally, it discusses how CAD systems have evolved to support increasing portions of the activities that are used to develop products.

The term "CAD" emphasizes that the computer is an aid to the human designer, so this paper is designer-centric. It is based heavily on the activities performed by designers and the types of information developed by them. In many ways, this is an update of two earlier papers, "The Importance of Drawing in the Mechanical Design Process" [Ullman 90] and "Issues Critical to the Development of Design History, Design Rationale and Design Intent Systems [Ullman 94]. The 1994 paper developed thirteen outstanding issues that needed to be resolved to realize the capture and query of engineering design information as a potential for improving the design process and the reuse of design information.

[1] Autodesk funded this paper, however the opinions and conclusions stated represent those of the author and are based primarily on his work.
[2] A recent, and believed to be thorough, effort to locate all work on this topic only yielded eight studies, most of them focused on 2-D systems [Alder 89, Liker 92, Luczak 91, Manske 89, Robertson 92, Robertson 93, Salzman 89, Springer 90]. The author could find no published study on the effect of parametric systems.

The foundation for the 1990 paper was the study of the marks made on paper by five mechanical design engineers of varying backgrounds and experience. They were each given the initial specifications for one of two fairly simple, yet realistic, mechanical design problems taken from professional practice. The engineers were requested to think aloud as they solved the problems. Their verbal reports, drawings and gestures were video and audio taped for a period of 6-10 hours. The taped data were then transcribed to obtain a "protocol" of the design session. Each designer made numerous drawings during his/her solution of the problem. All of these were on paper. CAD systems were not used in the study because none of the designers used CAD in their daily practice, and its use would have added another variable to an already complex experiment.

From the more than 40 hours of data taken, 15 sections were selected that represented typical conceptual, layout, detail and selection design for each subject. The 15 sections of protocol data consisted of 174 minutes of data. The data were analyzed to explore the observations that drawings are used to:

1. Archive the geometric form of the design.
2. Communicate ideas between designers and between the designers and manufacturing personnel.
3. Act as an analysis tool. Often, missing dimensions and tolerances are calculated on the drawing as it is developed.
4. Simulate the design.
5. Serve as a completeness checker. As sketches or other drawings are being made, the details left to be designed become apparent to the designer. This, in effect, helps establish an agenda of design tasks left to accomplish.
6. Act as an extension of the designer's short-term memory. Designers often unconsciously make sketches to help them remember ideas that they might otherwise forget.

The 1990 paper refined and supported these observations. Additionally, although the subjects did not use CAD systems, the results suggested that:

1. CAD systems must allow for sketching input.
2. CAD systems must allow for a variety of interfaces for the designer. This does not mean more ways to define a circle, but an effort to match the interface and the image on the CAD system to that needed by the designer.
3. CAD systems must recognize domain-dependent features and treat them as entities.
4. CAD tools need to be able to manage constraints (even abstract and functional constraints) and ensure their satisfaction, as it is evident that human designers are cognitively limited in this ability.

Since that paper was written, CAD systems have matured and have addressed, at least to some degree, all four of the conclusions. However, even the most recent systems are a long way from the ideal mechanical engineering design support system. In this paper, the ideal system will be described and progress toward this ideal discussed.

2. A MODEL OF DESIGN PROBLEM SOLVING

It may someday be possible for a designer to put on a “thinking cap” that can take his/her thoughts and develop a hardware representation. Research on understanding cognitive processes, CAD and rapid prototyping is certainly moving that direction. This ideal implies that we can formulate concepts in our heads that are sufficiently well-formed to warrant hardware. It also assumes that CAD systems are sufficiently developed to take our thoughts and manage the evolution of parts and assemblies. CAD system development will require an understanding of the cognitive workings of designers so that the transition from thought to representation is possible.

To explore what is known about this link, consider the relationship between the human problem solver and the external environment shown in Figure 1.

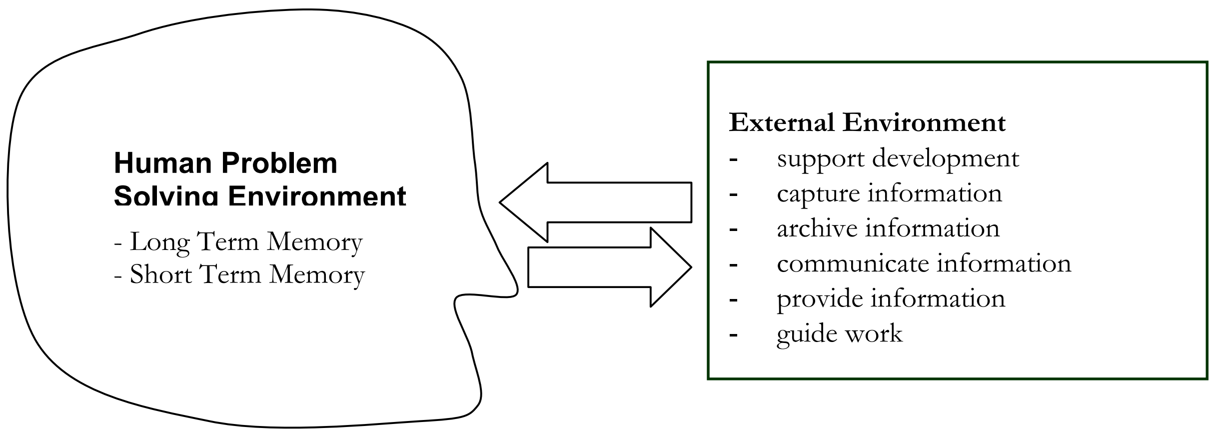

Figure 1. The Problem Solving Environments

This figure is based on the model developed by Newell and Simon [Newell 72] and is called the Information Processing System (IPS). The figure is a simple “map” of where information about the design is developed and stored. The figure shows an internal, human problem-solving environment (inside the mind of the designer) and an external environment (outside the mind of the designer). Within the designer, two locations correspond to the two different kinds of memory: short-term memory (STM) and long-term memory (LTM). External to the designer, there are many “design storage locations” including graphical representation media such as pieces of paper and CAD tools, as well as other media such as textual notes, handbooks and colleagues. Each “location” has certain properties that affect how it can be used in design.

Detail on the characteristics of the STM and the LTM is based on Newell and Simon’s model [Newell 72]. Extensions have been made to it for visual imagery [Kosslyn 83, Kosslyn 85, Kosslyn 94] and efforts have been made to codify it [Anderson 83]. It must be realized that the contents of the model given here are not fully agreed to in the cognitive psychology community, but they are certainly secure enough to provide a basis for discussing the role of CAD in mechanical design.

2.1 THE SHORT TERM MEMORY

Short-term memory is very fast and powerful. The contents of the STM are the information we are aware of, our conscious mind. All design operations (e.g. visual perception and drawing creation) are based on information in short-term memory. Unfortunately, the STM has limited capacity. Studies show that it is limited to approximately seven cognitive units or “chunks” of information. During design, these chunks are visual images of forms, information about function, mental models of fit, steps to represent an idea in a CAD system or other discrete pieces of information. Although limited in capacity, the STM is a fast processor with processing times on the order of 100 msec [Card 83].

2.2 THE LONG TERM MEMORY

The long-term memory, on the other hand, has essentially infinite capacity, but access is slow. Access to long-term memory is also not direct. Memories must be triggered by some cue or retrieval strategy based on information in short-term memory. During design, parts of the design are stored in long-term memory. These are relatively easy to cue because, at any time, currently important parts of the design are in short-term memory and can act as pointers for the knowledge in the long-term-memory.

2.3 EXTERNAL ENVIRONMENT

In the experiments run in 1990 [Ullman 90], it was clear that many drawing actions were not to document the results of the design activity but were part of the design process itself. If the subjects could have performed these activities in their heads they would have done so without making the sketches, notes and calculations on paper. Thus, it is concluded that the external environment is often used as an extension of the STM and LTM. It is critical that the media used in this environment support the designer’s cognition. Itemizing the match or mismatch between the media and human cognition is one of the objectives of this paper.

The approach taken in this paper is to first describe the types of information managed (Section 3) and then discuss the activities performed by the external environment supporting the designer (Section 4). The types of information and activities are developed in terms of the capabilities of an ideal system. Each sub-section begins with statements about what the ideal engineering design support system should do. Supporting information follows these statements. Next, there is a description of how paper-and-pencil, 2-D CAD systems, solid-modeling systems, parametric systems and other support tools meet the ideal. Each subsection concludes with the opportunities for improvement.

3. INFORMATION MANAGED BY AN IDEAL MECHANICAL ENGINEERING DESIGN SUPPORT SYSTEM

Mechanical engineers manage a broad range of information. In this section, the various types of information will be itemized beginning with the most basic and progressing to the most demanding.

3.1 FORM, FIT AND FUNCTION

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:

1. *Allow designers to work from desired function to the other types of information.*
2. *Allow designers to flexibly work on the architecture, shape, fit and function of parts and assemblies.*

The mechanical design community has traditionally thought in terms of form, fit and function. Figure 2 shows the interplay among these basic types of information that describe the product being designed. Generally, the reason for the object being designed is to fulfill some desired functions. The form of the parts and assemblies, and the fit between them, depend on the desired function of the product. Thus, the ideal system should allow the designer to work from function to form and fit.

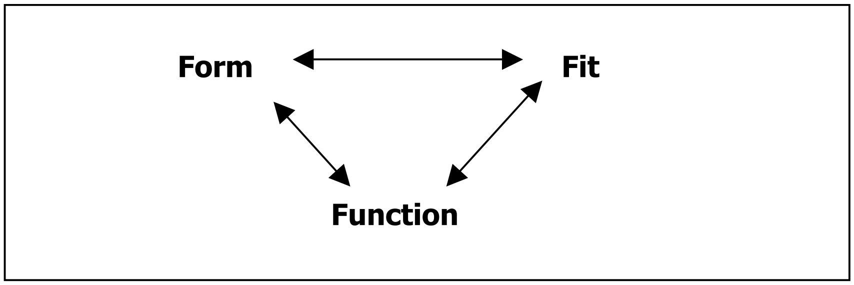

Figure 2. The Basic Types of Mechanical Design Information

The term “form” actually implies both the architecture and the shape of parts and assemblies (Figure 3). The term “architecture” has come to mean the skeletal structure that maps the function to the form. Architecture is the “stick figure” that can be easily manipulated and changed before the shape is refined. Shape implies the geometry that adds body and detail to the architecture. Often designers first develop the general architecture of the object being designed, then add details about shape and fit.

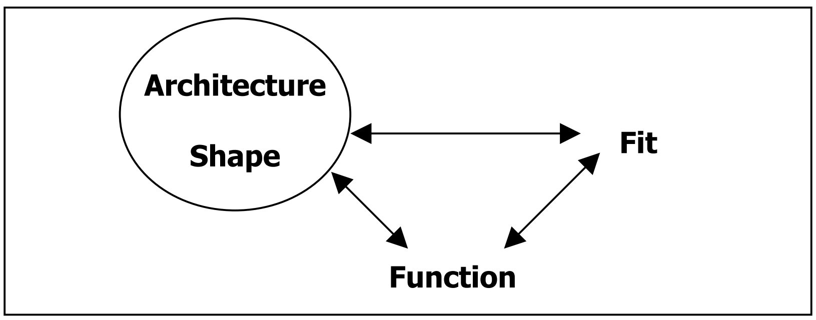

Figure 3. The Basic Types of Mechanical Design Information with Form Refined

WHERE WE ARE TODAY

Engineers generally work from the function of a system, to the architecture of an assembly, to the shape of parts. Function occurs primarily at the connections or fits between the parts in an assembly. In other words, function is developed in assemblies. This being said, CAD systems have primarily supported the form or geometry development of parts.

Paper-and-pencil allows easy sketching of architecture with stick figures and their evolution to components. Paper-and-pencil also supports limited function modeling through sketching actions that show motion or flow in assemblies [Herbert 87, Kuffner 91].

Both 2-D CAD systems and paper-and-pencil are limited to simple input of line segments to represent the edges of components. Solid modeling systems are still component-oriented even though they support the representation of edges, surfaces and solids. Parametric systems greatly improved the modeling of form with the limited ability to model fits and assemblies.

Future systems need to help the designer visualize function before geometry is fully defined. Computer systems are allowing better representation of function, e.g. kinematic, dynamic, fluid flow and virtual reality systems. With the continued development of computer support tools, the ability to work from function to form will continue to evolve.

CAD systems to date have been part-driven. Parts are developed and then fitted together to make an assembly. The contributions of the layout drawing have not been well-supported. Parametric systems have begun to move to a more natural flow, but parametric modeling requires the designer to plan ahead of time the geometric constraint relationships that define the part. Many parametric systems refer to the ordering of the constraints as the design intent. This methodology, while moving toward the ideal, does not well support the designer as the planning needed adds burden, and the ordering may not be known initially and may change during the development. Further, "design intent" as used in parametric systems is too limiting (see discussion of design intent below).

OPPORTUNITY

Extend CAD systems to allow the designer to develop the architecture of parts and assemblies to fulfill needed function. They must allow the designer to work from the architecture to the shape and fit of the components themselves. This will require work with abstractions of parts and assemblies and building the geometry of objects from their architecture and interfaces with other objects.

3.2 MATERIAL AND MANUFACTURING

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:

3. *Integrate the manufacturing and assembly practices and common material usage of the company or its vendors.*

One of the cornerstones of Concurrent Engineering is the integration of the development of the product and the processes that support the product. Key among these processes are those used to manufacture the parts and assemble them. These activities also depend on the selection or development of the best materials for the product. Thus, as shown in Figure 4, the basic form (architecture and shape), fit and function need to be tied to materials, manufacturing and assembly.

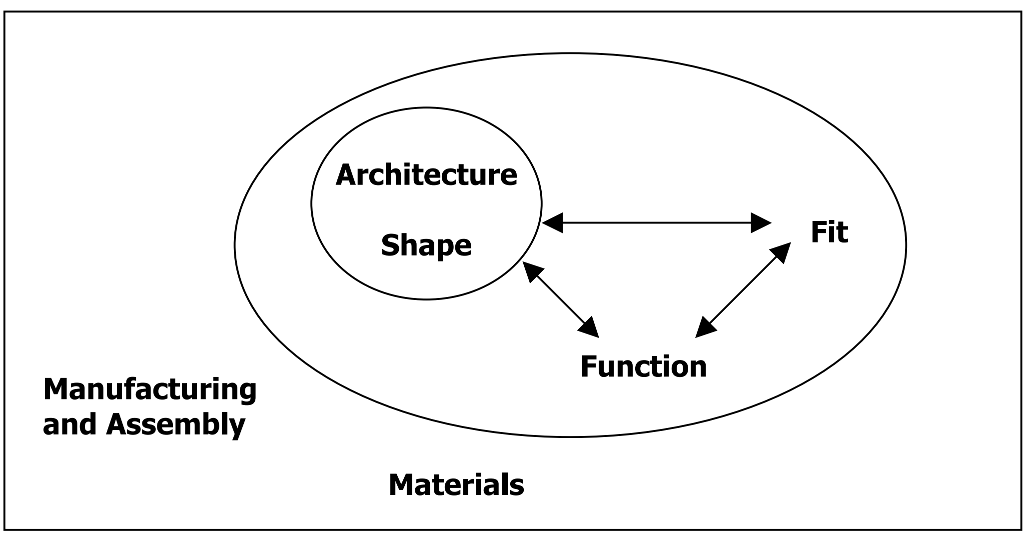

Figure 4. The Basic Types of Mechanical Design Information with Manufacturing, Assembly and Materials Added

WHERE WE ARE TODAY

Currently, there are systems that aid in development of injection molds and sheet metal parts. However, for most manufacturing and assembly methods, only text notes have supported this non-geometric information.

OPPORTUNITY

Extend CAD systems to provide the designer with information about anticipated material and manufacturing methods. This needs to be personalized as each company and vendor has certain materials and manufacturing and assembly methods that are standard and well-known. Knowledge about these should be easily available to the designer to aid in the development of parts and assemblies.

3.3 COST

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:

4. *Support the engineer so s/he is aware of the effect of each feature change on cost as it is generated.*

The cost to make the object being designed is not a part of its description, yet it is a major factor in all design considerations. It is shown in Figure 5, as closely tied to the material used and the manufacturing method and through these indirectly to the function and form. Often there is a disconnect during the design process between drawing a component and establishing a cost for it. In many companies, the engineer draws a component and sends it to another group for cost estimation. The time lag in this process does not match what is needed for efficient design.

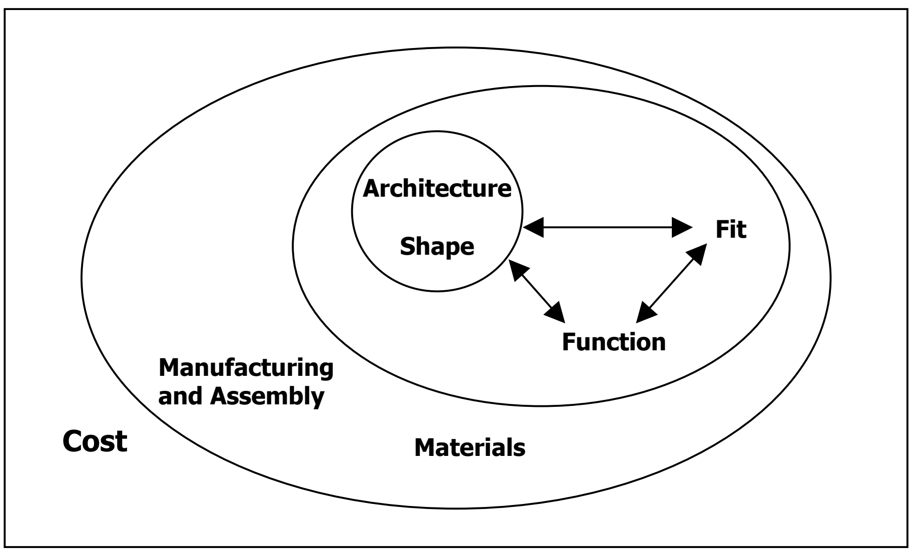

Figure 5. The Basic Types of Design Information Plus Cost

WHERE WE ARE TODAY

Cost estimation has not been well-supported by any type of system. Some DFA (Design for Assembly) systems can estimate for cost, but these are not integrated with part representation in a CAD system.

The cost of a component is based on: the major dimensions of the component, the architecture of the component, the tolerances and surface finish needed, the number to be made, the material used, the machines used in the manufacturing process and labor and machine rates[3]. The first three items can be directly developed from the geometry and other notation commonly put on a drawing. The number to be made can be input by the designer. Since every organization has a palette of materials and manufacturing processes that are used for most products, these should be integrated with the geometry through a database. Then, the material properties, material costs, machine costs and labor rates for the organization could be linked with the geometry. With this information a cost estimate within 10% of the actual can be developed and updated with changes made in the geometry or other variable.

OPPORTUNITY

CAD systems need to generate a running update of costs as parts and assemblies are changed – in real time.

3.4 REQUIREMENTS

The ideal engineering design support system should:
5. Support the relationship between the requirements and the development of the product.

The requirements (here the term is used synonymously with constraints, specifications or goals) for a part or assembly are a type of information that does not describe what is being designed, but the limitations and targets on it. As such, it is critical information. At shown in Figure 6, there are requirements on all the other types of information previously discussed. Traditionally, engineers have done a poor job at developing requirements for products.

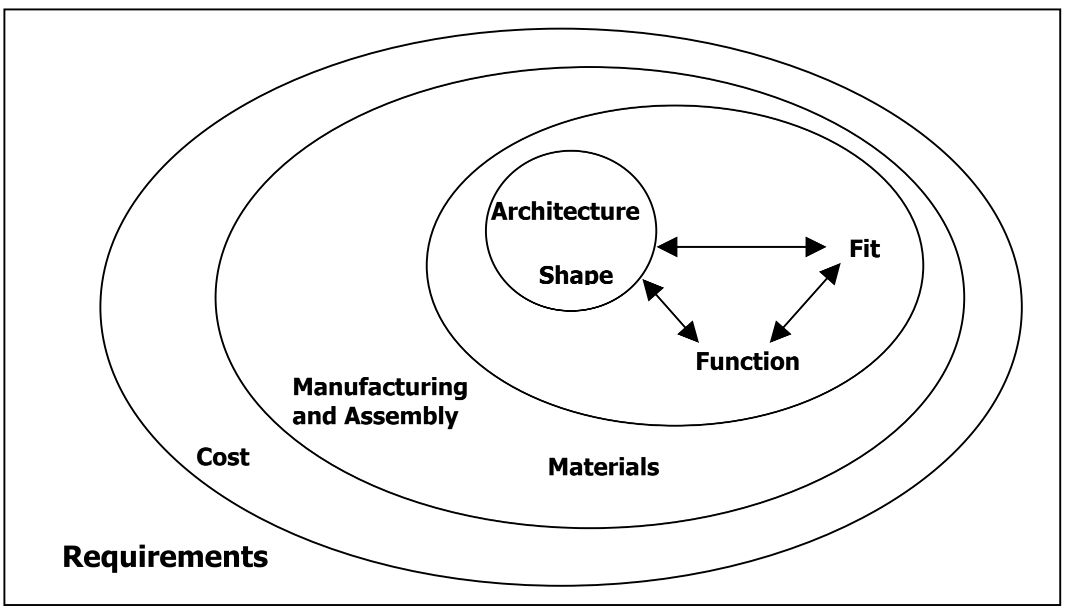

Figure 6. Requirements on the Basic Types of Design Information

WHERE WE ARE TODAY

One of the best practices currently used to develop requirements in industry is Quality Function Deployment (QFD) [Clausing 94, Ullman 97]. Many companies use the results of this method to directly

[3] Basic cost estimation for designers is discussed in *The Mechanical Design Process* [Ullman 97]. Simple rule-based systems to estimate the cost of plastic injection molded, machined and forged parts have been developed and checked versus actual cost by the author. These systems have shown that estimating cost at sufficient detail to guide the designer is readily possible.

feed requirements to the development of components and assemblies. Admittedly, many of the requirements developed with the QFD are for function; however, there are always many constraints on both function and geometry that drive the development of parts and assemblies. To date, this is not well integrated with CAD systems.

Stauffer [Stauffer 87] showed that as the design process moves from conceptual through layout to detail design, the source of constraints moves from those imposed from outside the control of the designer to those based on previous design decisions. This implies that not only should requirements like those developed using QFD-type methods be integrated, but also the reasoning behind earlier decisions needs to be supported. This will be further discussed in the section on design intent.

OPPORTUNITY

CAD systems need to integrate requirements and constraints into the development of parts and assemblies.

3.5 ISSUES AND PLANS

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:

5. *Support the development, following and updating of plans.*
6. *Support the management of issues not planned for.*

Where all the types of information described so far represent the artifacts being designed and the requirements on them, the following types of information represent the process through which the artifacts are developed. The importance of the process has been a concern in industry since the early 1980s and an area of research since the mid 1980s. The tie between product and process is a major part of concurrent engineering. In the late 1990s, this concern has been brought into prominence with the development of interest in Integrated Product and Process Development (IPPD) the successor to concurrent engineering.

Traditionally, the product design community addresses the design process in terms of the tasks to be completed to develop a new product. These tasks are focused on specific design issues that can be planned for in the development of the product. However, many issues arise during the design of a product that can not be planned for. This is especially true during the development of new products or during the use of new technologies. Figure 7 shows that issues and plans address all types of requirements and product information.

Issues or tasks in product design require the designer to develop new information. One of the first experiments aimed at understanding human information processing during design tasks [Stauffer 91] showed that over two-thirds of the strategies used by the design engineers during the development of new products were searches through design space. Searches imply that there is a range of potential solutions to every issue and that the designer must look at several of these alternative solutions to develop one that is satisfactory. Search strategies are well studied by the Artificial Intelligence community. Three types of strategies defined by computer scientists and identified in the cognitive study were “generate and test”, “generate and improve” and “means ends analysis”. In each search type, the designer develops and refines the alternatives and compares them to the requirements until some satisfactory choice had been made in the time available. Based on these findings, in order to support designers, systems must not only track the completion of planned work, but must also support the development and management of multiple alternatives for all issues addressed.

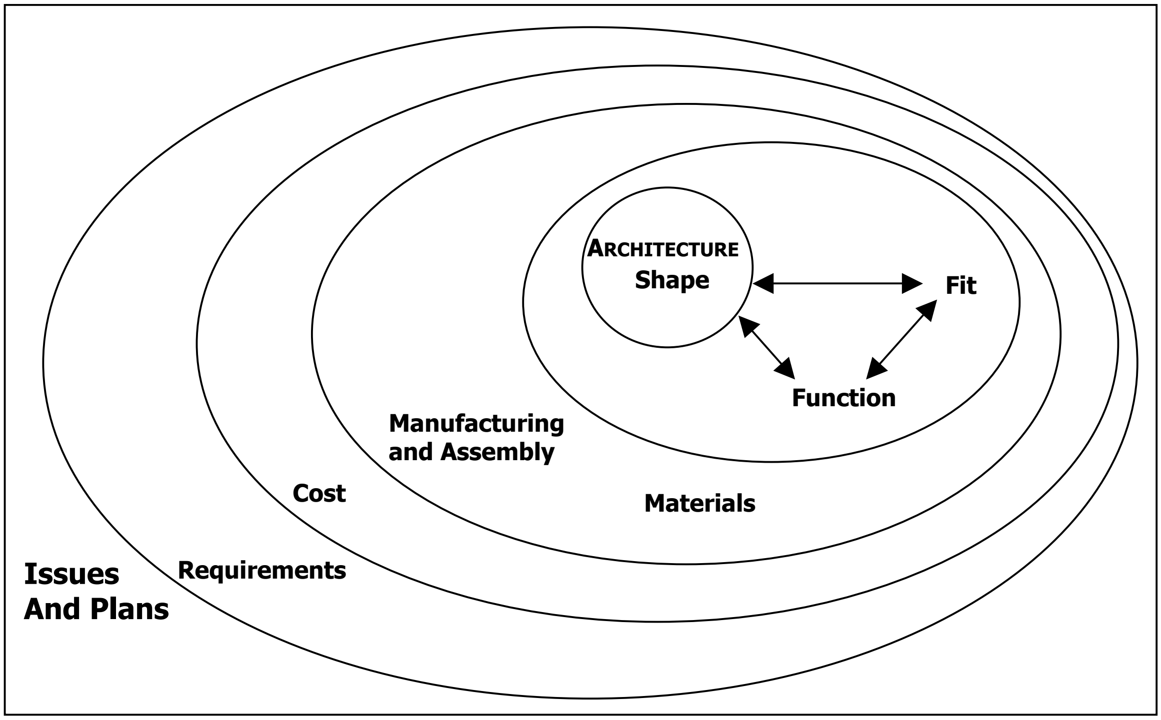

Figure 7. Issues and Plans for Design Information Development

WHERE WE ARE TODAY

Project planning and change management has always been a large part of engineering management. Product Data Management (PDM) systems have made large strides toward integrating the actual design work with what was planned. These systems are still maturing.

OPPORTUNITY

Computer support tools need to continue evolution to assist the engineer in developing the product and the process in an integrated fashion.

3.6 INTENT

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD MANAGE ALL THE PREVIOUSLY DEFINED TYPES OF INFORMATION IN A DATABASE PLUS:

7. *Support information about problems or issues addressed (e.g. business issues, planning issues and artifact design issues).*
8. *Support information about arguments for or against alternatives (e.g. qualitative discussion, quantitative analysis, rules and standards) based on requirements.*
9. *Support information about the decisions reached.*

A number of authors have explored the concept of recording a design history. Nearly fifteen years ago, Mostow stated that there was a growing consensus in the artificial intelligence community that "An idealized design history is a useful abstraction of the design process" [Mostow 85]. In the late 1980s, this author and his colleagues built an object-oriented database that organized information about the design of a simple mechanical system [Ullman 91a, Chen 90, 91]. This database could be queried about the evolution of constraints and the effect of decisions on the artifacts being developed.

Since Mostow, the artificial intelligence community has been active in developing design rationale systems. A workshop held in 1992 [Lee 92] defined the term “rationale” as “an explanation that answers a question about why an artifact is designed as it is.” Baxter [Baxter 90], in his thesis, refines the definition: “Design rationale: An information structure that justifies how the implementation (consequences of the design selections) satisfies its specification.” This definition emphasizes the structure of the design information and tracking the relation of decisions back to the specifications.

Another community, which is organized around development of the STEP IV standard, uses the term design intent. Their use of design intent refers to the cause and effect relationships among product data. In an unpublished document, a STEP IV researcher states: “Generally, the term intent means the purpose or plan for performing activities. During product design, these activities transform a set of requirements to the final specifications for production. In a basic sense, the intent is the blueprint for the evolution of the requirements into the production specifications. This blueprint not only has information about the development of the geometry, but also on the evolution of the product function and behavior, the rationale underlying design decisions and the influence of business activities.”

In the CAD community, the term “intent” is used to describe the ordering of geometric constraint equations in a parametric system. This ordering defines the geometric dependency needed by the system in order to make changes and is not necessarily the cognitive ordering that was followed by the designer in the development or refinement of the part or assembly.

Finally, in some business literature, the term corporate memory is used to emphasize the feeling that the information managed is beyond that associated with the traditional artifact as it includes business information as well. In the results of the first CERC Workshop on Enabling Technologies [Nichols 92], the discussion on corporate memory was in terms of design histories and rationales.

Supporting full design intent information may even be more complex than storing what has been generated during design. Gruber [Gruber 93] claims that it is not sufficient just to capture, store and retrieve the same information. He observes: “Rationales (intents) are constructed and inferred from stored information rather than as complete answers.” In other words, design intent systems may have to answer questions that require information different than that captured. The questions that arise during query may not be answerable with only the information of the original design. This implies that the data must be structured during capture or storage so that answers can be developed to needed questions.

Design intent systems must record and manage information that shows why and how a decision was made about each issue addressed. As shown in Figure 8, a design intent system needs to support all the types of information previously developed and store this information in an easily indexable database.

WHERE WE ARE TODAY

To capture, store and allow query of the design information is a challenging research area [Ullman 94]. To a limited degree, PDM systems are beginning to manage some of the needed information. However, these systems tend to be oriented toward information that is well-refined and not evolutionary information. Further, these systems do not have a formal mechanism for managing information about argumentation leading to decisions.

Parametric and variational systems allow for design reuse. Thus, it is easy to find the answer to queries about the effect of form changes and sensitivities. In this manner, these systems have captured some of the intent behind the information modeled. One limitation of these systems is that they can only be used with geometric decisions and decisions about behavior that can be geometrically modeled. Additionally, these systems do not model the actual decision structure. They only record the order initially anticipated to give the system necessary geometric reasoning. If the value of a parameter (i.e. the length of a part) is queried, parametric systems will give information on this length's dependency on other dimensions of the part. However, it does not give the rationale for the relations or the arguments for the current value.

A number of CAD companies have begun to offer design notebooks that allow the designer to put notes about the evolving products. These notebooks are the first step in supporting needed activities and information. However, it is believed that additional structure and indexing will be necessary to achieve useful design rationale support systems.

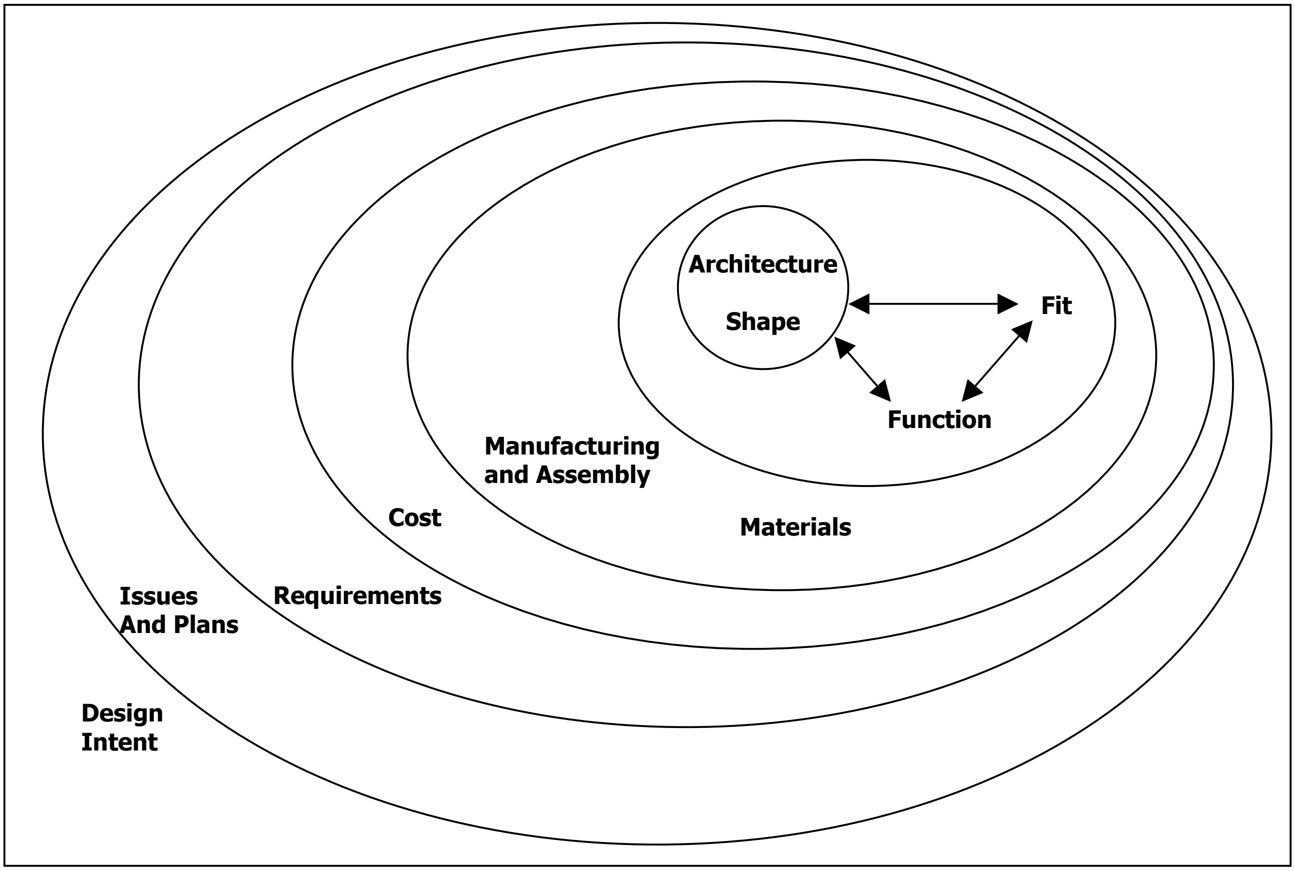

Figure 8. Design Intent

OPPORTUNITY

There is great potential in this area for improving the design process and the reuse of information. CAD systems have begun to capture and manage the needed information.

4. IDEAL MECHANICAL ENGINEERING DESIGN SUPPORT SYSTEM ACTIVITIES

There are seven activities that the external environment provides to the designer regardless of information managed and the media used. These activities serve as dimensions for measuring the external environment's ability to aid the designer. The activity discussion is based on that presented in "Issues Critical to the Development of Design History, Design Rationale and Design Intent Systems" [Ullman 94].

4.1 SUPPORT INFORMATION DEVELOPMENT

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD SUPPORT THE MANIPULATION OF THE DIFFERENT TYPES OF INFORMATION AND:

10. Match the speed of the Short Term Memory during information development
11. Add no cognitive burden while supporting information development.

Design is the evolution of information punctuated by decisions. The types of information that are developed during the design process represent both the product being designed, the process by which it is being designed and other processes in the life of the product such as manufacture, distribution and retirement. This information does not spring into being fully formed but evolves through a series of problem solving episodes. Based on cognitive studies, the average problem-solving episode is about one minute in duration [Ullman 88]. In a majority of these episodes, a micro problem is addressed that has as its goal the development or refinement of information [Stauffer 91]. In each of these, a number of alternatives are considered and judged relative to some criteria. The resulting decision can be one of many options: adopt a single alternative, develop new criteria, refine the evaluation, etc.

Support for information development is to act as an extension of the short-term memory. To accomplish this, the external memory must match the speed of the STM. Engineers are notorious for not being able to think without making "back-of-the-envelope" sketches of rough ideas. Sometimes these informal sketches serve to communicate a concept to a colleague, but more often they just help the idea take shape on paper by extending the STM. Dan Herbert in Study Drawings in Architectural Design: Applications for CAD Systems [Herbert 87] considers the use of sketches (study drawings to architects) in the solution of architectural design problems. He defines "study drawings" as "informal, private drawings that architectural designers use as a medium for graphic thinking in the exploratory stages of their work." Architects often make these study drawings in the borders of or adjacent to their formal drawings. In Herbert's theory, sketches are used because they provide an extended memory for the visual images in the mind of the designer. Since sketches can be made more rapidly than formal drawings, they allow for more facile manipulation of ideas. Furthermore, sketches allow the information to be represented in various forms such as differing views or levels of abstraction. Thus, he calls sketches graphic metaphors for both the real object and the formally drafted object under development. In fact, Herbert claims that sketches are a principal medium of external thinking. Thus, the external media must match the speed of the STM. It also should support the manipulation of the ideas.

Since humans are already cognitively limited by a STM that can only manage seven chunks of information, the media of the external memory must provide aid with minimal cognitive baggage. For each additional chunk required by the external media is one less for problem solving. For example, if it takes part of STM to draw a sketch for a new idea using a CAD system, then the idea represented will, by necessity, be less complicated [Springer 90].

WHERE WE ARE NOW

Springer compared an early version of AutoCAD (2.6) to work on a drafting board. The results showed that CAD took nearly twice as long to produce a comparable design because "a bottleneck in using the CAD-system forces the subjects to concentrate on the use of the CAD dialog and to neglect the design task." This result held regardless of increased CAD experience. Although this research is dated, the result is not. During the use of CAD systems, icon and menu selecting add unneeded steps to creating an image. A current best selling parametric system has menus up to 5 levels deep that are needed to do many operations. These steps add an extreme cognitive burden to both the novice and expert user.

One part of the cognitive research discussed in the introduction of this paper [Ullman 90] focused on the marks on paper designers make during the design process. In the protocol sections studied, the average length of time to make a mark on paper was 7.3 seconds with a standard deviation of 7.8 seconds. The 363 marks-on-paper studied were divided into "draw" marks and "support" marks. These are further refined into "sketch" and "draft" marks and "text", "dimension" and "calculate" marks respectively. Thus, there are five types of marks-on-paper:

- **Sketch:**
  Drawings of features made free hand. 48% of marks on paper. Sketching on paper is not the same as sketching on the computer using a CAD system.
- **Draft:**
  Drawings made with mechanical devices. 24%
- **Text:**
  Letters, words or numbers that are not part of a dimension on a drawing and not part of a calculation. 9%
- **Dimension:**
  Dimensions or dimension lines on a drawing (either a sketch or a draft). 14%.
- **Calculate:**
  Equations and answers to calculations. Combines constraints or design proposals to derive new information. 5%

There was some debate as to how to differentiate between sketch and draft. There are two measures to consider: (a) the use of instruments and (b) whether or not the drawing was to scale. Consistency with traditional college graphics texts suggests that the criteria should only be the use of instruments as defined above. All of the subjects had instruments at hand. However, some subjects chose to make their scale drawing free-hand. It would seem that they felt that it was easiest not to use the instruments. The differentiation between sketch and draft is made even clearer by considering when in the design process the drawing was made. When the subjects were trying to conceptualize the design, 100% of the drawings were sketches. Later in the design, during the layout and detail phases, this drops to 52% as some of the subjects used instruments to draw their refined design while others continued to sketch.

Over 67% of the drawings were sketches. Many of these sketches could have been made using drafting equipment or on a CAD system. But, with the average length of these sketching actions at less than 8 seconds, the use of instruments or CAD could have slowed the drawing action to the point that the cognitive problem solving would be impaired. Thus, even the use of simple drafting instruments added sufficient cognitive burden that they were not used during conceptual design.

OPPORTUNITY

A goal of CAD vendors should be to develop systems that work at the rate of cognition. Such systems would have virtually no menus. A research project with this goal was undertaken in 1989 [Hwang 90]. The resulting system could infer complex geometry solids from simple sketching motions. Although this may not be viable for a commercial system, five layers of menus are not viable for a system that matches human abilities.

4.2 CAPTURE, ARCHIVE AND QUERY INFORMATION

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:

12. *Capture all types of information with single entry.*
13. *Archive all the types of information so that design intent can be readily recovered.*

14. Support designer query about the design intent for all types of information.

The three activities necessary for a design history or design intent system are the capture, archiving and query of design information. Thus, these three are discussed together. Design information is captured in the external environment. This information may be discarded as with traditional paper layout drawings, white board drawings and many notes, or it may become part of the product archive. Typically, only information about the geometry of the final parts and assemblies are archived. Many engineers also capture information in design notebooks. This information is often only readable by the engineer who wrote it and is not indexed in any useful way. Captured information forms the basis for a design intent system.

The external environment also serves to store information about the product or the process. Typical types of information archived in the past are, for example: part and assembly drawings, plans, meeting notes, bills of materials and simulation and test results. These types of information generally give a snapshot of the final product with minimal information about the decisions that went into its development (the intent). To support the types of information described above will require an enhancement of the current types of information stored and a refinement of database technology.

Query is the activity of reviewing design documentation in an attempt to learn about past activities related to a product or a process followed. Designers currently working on a project, reviewing their own past work, or the past work of others often seek information about both the product's and the process' history. Often this is described as seeking the design rationale, intent or corporate history [Ullman 94]. Similar to designers, managers usually want to obtain information at a high level and then have the ability to burrow down to deeper information as desired. Further, they also want information about whom is responsible for a given issue on a project, who is working on a project and the inter-relationships between projects.

Kuffner [Kuffner 91] performed a small set of experiments to try to determine the value of design information during redesign. In this study, he gave engineers drawings for a simple product and asked them to make changes. He recorded their work and analyzed it. One of the conclusions of this study was "mechanical design engineers are interested in design information other than that which is contained in standard design documentation." Query is often directly related to the role. Typical roles he found were state (versions), proposal, requirement and example. Version information included changes that occurred earlier in the development than those captured by the traditional engineering change management system.

The designers also sought answers to process questions. These included questions about the issues faced, the alternatives developed to satisfy the issue, evaluations of the alternatives and decisions made.

WHERE WE ARE NOW

Current CAD systems capture primarily form information. Some systems are adding notebook features that allow notation and linking to other information. These additions are in their infancy and are still difficult to query.

OPPORTUNITY

This area is seen as one with the greatest potential for future design support. Engineers spend a great percentage of their time recreating prior work or looking for prior information. The ability to capture, archive and query the full range of design information will have extensive payback in terms of design efficiency and design quality.

4.3 COMMUNICATE INFORMATION

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:
15. Communicate information in the format, level of abstraction and level of detail needed.

Communicating information among design team members and managers is an essential part of engineering workflow support. Communication must be across time and location. Further, many types of information are used in the support of engineering design, i.e. text, CAD files, analysis results and the ability to actively run analyses at remote locations, experimental results and photographs.

Additionally, communication must support others who are in need of the information developed by the engineers. Manufacturing, product support, sales and other functions need the information from different viewpoints and at different levels of abstraction and detail.

WHERE WE ARE NOW

The Internet has greatly improved the ability to communicate graphical information among engineers. There are still some limitations due to difficulty converting data between systems. Various standards have helped but there is still need for more work on data conversion.

One measure of the efficiency of a system is to count how many times the same information needs to be entered on paper or in the computer. The ideal system will have a single entry. Thus, the best computer support system should allow a piece of information to be entered once and then be usable by all parties to support their function in the organization. CAD companies have been aware of this goal for many years and have been making progress toward it.

OPPORTUNITY

CAD vendors need to continue to work on file transfer, geometric and other standards and single entry of information.

4.4 GUIDE WORK

THE IDEAL ENGINEERING DESIGN SUPPORT SYSTEM SHOULD:
16. Guide the designer about what to do next.

During the design process, decision-makers repeatedly ask three questions [Ullman 98]:

- What is the best alternative"?
- Do we know enough to make a decision yet"?
- What do we need to do next to feel confident about our decision"?

This last question is a request for guidance. Should the designers [Ullman 00]:

- Develop more evaluation information?
- Further interpret and discuss evaluation information?
- Generate new potential solutions?
- Refine criteria features and targets?
- Negotiate changes in criteria features and targets and their importance?
- Decompose the issue into sub-issues?
- Reach conclusion and document result?

Currently, there is no methodology for guidance about what to do next. Often designers do whatever is easiest, not what will lead to a better decision. This is compounded in team situations. The guidance addressed here is not the same as planning. Planning can be done in advance whereas this is directed at work in progress.

WHERE WE ARE NOW

There has been very little work in this area. Twelve *Steps to Robust Decisions: Building Consensus in Product Development and Business* [Ullman 01], attempts to address these issues.

OPPORTUNITY

Every feature added to the design of an assembly or part requires many decisions. Much time is wasted making poor decisions. The opportunities here are great.

5.0 CONCLUSIONS

Mechanical design support systems have done much to change engineering design practice over the last twenty years. Yet computer based systems are weak in their ability to support many of the activities and types of information identified in this paper. Further, there is little experimental evidence on the effect of CAD on the designer. It could be argued that much in this paper is outside the expectations of what a CAD system is supposed to do and that PDM systems, planning software, notebooks, material selectors, etc. are designed to provide these missing functions. It could also be argued that evidence of CAD's ability to support the design process is evidenced by its wide use. These arguments depend on expectations. If a CAD system is designed to support drawing only, then that is all it will support. However, and this is a major point in this paper, design is more than making drawings. It is a complex human/computer undertaking and, to date, the computer has only filled a very small segment of its potential. Future CAD systems need to be mechanical design support systems and fill all the needs developed in this paper. This is now possible, as previously CAD systems were developed to meet the computer's capability. However, computer systems are now very powerful and well refined. Thus, future CAD development needs to be driven from the "D" and not from the "C" in "CAD" where the "D" is for design, or even more appropriately, "D" stands for designer. This will require focused studies of human designers and their interactions with mechanical design support systems.

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