STATE OF THE ART IN THE UNITED STATES OF CAD METHODOLOGIES FOR PRODUCT DEVELOPMENT

FINAL REPORT

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I. Introduction

This is the final report on ONR Contract Grant No N00014-94-1-0655 and Contract No N00014-93-C-0026 "State of the Art in Product Design Methodologies and CAD Applications in US Universities and Industry." This contract follows two previous contracts under which the author lived briefly in Japan in 1991 and in Europe in 1992 to report on these topics in those regions.[1] In all cases, the focus was electro-mechanical products such as cars, airplanes, cameras, ships, and so on. On the current project, the author visited the major US automobile manufacturers, the Naval Sea Systems Command, a researcher in design theory and methodology, plus several companies known for their advanced design and manufacturing practices: Hewlett-Packard, Lockheed, and Caterpillar. The auto industry visits are accompanied by a separate report that describes car design issues common to all the car companies, US and foreign. As an adjunct to the project, the author undertook to understand design issues in the field of VLSI because the degree of design integration achieved in that field greatly exceeds that in mechanical design. Separate reports have been written on each of these topics except for VLSI, which is included as a chapter in this final report.

In writing these reports, the author has relied not only on the hospitality of the host companies, universities, and agencies, but has also drawn on his past experience visiting similar companies or working on various industrial and research problems in the past. He is grateful to his hosts for their time, cooperation, and oversight of the reports written about them. He also wishes to thank the Office of Naval Research and his project monitor Dr Ralph Wachter for their support and encouragement. Finally he would like to thank both the Charles Stark Draper Laboratory, Inc. and MIT for their support and assistance during this project.

All of the reports from these projects have been posted on the World Wide Web by Mr Chris Wanjek of MIT whose assistance is gratefully acknowledged. The reports may be accessed using the web address http://web.mit.edu/ctpid/www/Whitney/papers.html. This page contains pointers to all the reports.

The final report is organized as follows. First there is a summary of the findings from the US study. These items are listed briefly and some of them are discussed in the remainder of this report. The others are dealt with in the course of the reports on individual companies. Next is a discussion of long term developments in design and product development covering the growing trend of companies to design and produce in partnerships with each other, the growth of the complexity of the design process, and the state of CAD in response to these trends. Next is a discussion of important core competence issues in both product technologies and supporting design and manufacturing technologies, followed by

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[1] The Japan visit report is [Whitney 1992] and the Europe visit report is [Whitney 1993].

a comparison of practices observed in the US, Japan, and Europe. This is followed by a discussion of VLSI design and why in the author's opinion mechanical design will not likely be done in a similar way.

II. Summary Findings

The Technical Nature of Design

Mechanical design is a complex, multi-discipline activity that is currently glued together by people supported by single discipline CAD and CAE tools; however, CAE tools are being increasingly integrated with CAD geometry

Design in many domains is running ahead of CAD's capacity in terms of size and complexity of the design; leading edge applications are VLSI, aircraft, and ships, where typical products have millions or tens of millions of parts

VLSI design was once offered as a model for mechanical design because it was top-down, computerized, integrated, and synthesis-driven; this model is rapidly eroding as miniaturization forces designers to consider device physics and the interactions of geometry, fields, wave propagation, thermodynamics, and even quantum mechanics; it is therefore becoming more like typical mechanical design while efforts to make mechanical design more like VLSI are not making much progress

Use of CAD for process, tooling, and factory design lags far behind its use for product design; this may reflect the kind of people or companies managing and doing the former kinds of work rather than a lack of design tools

The range of issues that designers must address is growing while less time and supporting tools are available to accomplish the design; these issues include

- refinement - more performance from less material and fewer parts
- density - more items or actions in less space
- flexibility - less committment to one set of decisions (design, production method, final product configuration)
- anticipation - more thought to the life cycle or to conditions and actors beyond the designers' control or ability to model
- interaction - more technologies, materials, and phenomena operating together
- substitution - electronics for mechanisms, composites for homogeneous materials, multi-purpose items for single purpose
- cooperation - more partners to work with, more requirements to balance

The Organizational Nature of Design

Companies are continuing to search for the right way to organize for better product development; at most of the visit sites, the current product development process was in place for less than two years, and some of the attached visit reports are already out of date by one or more generations of organizational change even though the visits happened less than 18 months ago

Products are becoming more complex and, at the same time, companies are trying to downsize and become "lean;" this is forcing companies to go outside for important skills, product elements, and design and production tools; this adds greatly to the complexity of reorganizing the development process

As design and manufacturing become increasingly dispersed over layered networks of suppliers, cooperation, communication, and coordination problems are arising

Dispersal of design and manufacturing is focusing attention on the structure of the design process, forcing participants together in new combinations to share new kinds of information and make decisions earlier in the process; this trend exposes gaps in process skills, design tools, engineering knowledge, and the ability to predict cost, performance, or production consequences, especially because it requires designers to understand the cultures and capabilities not only of others in their own companies but also those in other companies

Management of key interfaces is becoming more important as design and manufacturing get dispersed, but interface specification as a process lacks tools and management attention and is often left to low level employees

In many companies, the people who understand problems of interfaces and integration are at the end of the development process (asssembly tooling, pilot plant, product launch) rather than at the beginning (concept, styling, advanced engineering); the former inherit the problems created by the latter and must solve them anyway; this often means that efforts to improve the development process are reactive rather than proactive

Japanese companies appear more aware of the need for integration of design tools with design process organization than other companies and have been developing it longer

In the US there is growing awareness of the need for seamless tool integration and considerable progress in achieving this integration, but there is less awareness of the influence of process organization on tool integration

In the absence of a clear trend in design process organization, the primary paradigm for tools and process organization is to maximize common access to a central product data store

There is increased use of networks within and between companies to tie distant designers together, link suppliers and customers, and exchange design data and information

Implications for Companies

As design and manufacturing get dispersed, companies are trying to decide what capabilities they need to retain, not only regarding their products but also regarding manufacturing infrastructure (CAD, CAE, production technology); none of the available choices is totally comfortable

Some years or decades ago, centralized or vertically integrated was "good;" now decentralized or vertically non-integrated is "good"

Although the current trend is toward non-integrated companies networked into "agile partnerships," it is possible that only very large integrated companies or very specialized boutiques will survive in domains where the product integrates a number of complex technologies, where technology is advancing rapidly, or where product performance is tightly linked with production technology

Companies still do not know what is the right way to organize product development; among the methods being tried are

- matrix organizations with a strong project manager and more or less full time participation by people with specific functional skills
- partnerships of companies that each contribute physical elements of the product or process, or provide design services
- permanent platform teams that establish a base design and then elaborate it over several generations
- temporary "launch" teams with multidisciplinary composition
- overlapping design of successive versions of the same product that share portions of their designs

Japanese companies are approaching these issues quite differently from European and US companies

Implications for Computerized Design Support

Design is still primarily accomplished by people, whose methods are not well understood: at the individual level, it is not known how people create new concepts or how they integrate diverse information; at the group level, it is not known what makes people cooperate, negotiate productively, share information, and come to decisions quickly

Attempts to expand computer use in design are revealing gaps in engineering understanding: single application CAE tools are not enough because more refined design demands that interactions between phenomena be considered

Artificial intelligence appears helpful in avoiding major mistakes and guiding an inexperienced person through a standardized procedure for repeating a well-understood design process, but it has not shown an ability to aid creativity by jumping out of established paradigms

Solid modeling is becoming economical; companies are starting to use it to reveal geometric incompatibilities in assemblies, a vital capability that was totally unavailable before without massive human intervention; in some companies and industries, notably circraft, the improvement is so dramatic that they are unaware of variation as a contributor to assembly problems

In other companies and industries, notably autos, a correct nominal design is largely an accomplished fact, and attention has turned to the next frontier, namely understanding and managing variation

Computer displays and rendering are becoming so realistic that some people confuse this capability with real design support; this is especially true in problems involving assembly

The role of geometry as the core of design is diminishing and being replaced by information flow structuring, interface management, data management, and networking; in fact, many companies regard design as fundamentally a problem of data management and only secondarily as one of creating geometry, resulting in a totally different view of CAD and its relation to the design process

As design becomes more complex and interdisciplinary, considers more phases of the life cycle, and gets more dispersed, the nature of product data is expanding beyond the traditional geometry to include hooks to tools or methods for supporting

- variation prediction and management in a variety of geometric and non-geometric domains
- geometric interactions like assembly
- non-geometric or quasi-geometric interactions like NVH, corrosion, fatigue, radiation
- multi- or cross- discipline analyses
- production issues like modular assembly, flexibility, and customization
- design of product families
- interfaces between elements procured from dispersed sources, including production equipment and tooling
- support for design process management: finding information, finding knowledge, coordinating activities, managing engineering changes, assessing impacts

Traditional CAD companies have so far been unable to supply all the needed tools to support the emerging nature of design; their skills have been concentrated in geometric modeling, while the demands of data management have either been met by the user companies themselves or by companies in the data management sector, an entirely different industry with little experience in design and manufacturing

The STEP/PDES standard may falter for any of the following reasons:

- it focuses on describing and exchanging finished designs rather than on supporting designs in progress
- the nature of design is changing too fast
- no one has a clear idea of what a product data model should contain

III. Long Term Observations and Trends

A. Dispersal of Design and Manufacturing

One of the most important trends driving product development today is the dispersal of design and manufacturing. This dispersal takes several forms. It can include outsourcing under contract to traditional suppliers, or it can comprise a revenue sharing partnership. Both domestic and foreign companies may be involved. Items procured in such arrangements include parts and subassemblies, design services, temporary labor to operate CAD terminals, design and production of fabrication and assembly equipment, and so on.

Observers of this and other trends at Lehigh University have included it under the heading of "Agility."[2] Agility has been expressed as having four underlying principles [Goldman, Nagel, and Preiss]

- delivering value to the customer
- being ready for change
- valuing human knowledge and skills
- forming virtual partnerships

Of these, the first three can be found within the operating philosophies of companies generally thought to be "lean" as described in [Womack, Jones, and Roos]. The fourth principle is different. In fact, Agile and Lean take quite different attitudes toward partnerships, and here is where an important research and practical challenge may lie. Companies like Toyota stress <u>how long it takes</u> to develop effective partnerships for procurement of complex automotive assemblies. Relationships of 20+ years are typical. In the world of agility, where such partnerships are predicted to be of dramatically shorter duration, extra attention will have to be paid to launching and maintaining supplier relations.

Customer-supplier partnerships dominate the landscape of organizational forms for product realization of complex manufactured items. Companies seek partners because the product's complexity generally precludes any one company having all the marketing, design, or manufacturing skills to make them. Partnerships are not new, but increasing competition has put new pressures on them. Also, some striking apparent organizational successes (e.g., Chrysler Corporation) that rely heavily on supplier-partners have influenced some to believe that vertical disintegration provides a path to greater corporate profitability. While such partnership networks offer significant advantages, they are quite complex and present severe challenges in terms of managing time, cost, risk, and quality.

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[2] The following text, plus Figures 1 and 2, are taken from [Whitney et al, 1995].

Customer-supplier relationships have surprisingly many layers: suppliers of main assemblies have suppliers for subassemblies who have suppliers for parts, and all of these have suppliers for fabrication machines, plus suppliers of tools and fixtures to help make and assemble the parts, subassemblies and final assemblies. We have given the name "web" to this set of companies and their relationships.[3] A generic map of a web devoted to designing and delivering complex mechanical assemblies is shown in Figure 1, while a specific one describing some automotive parts is shown in Figure 2.

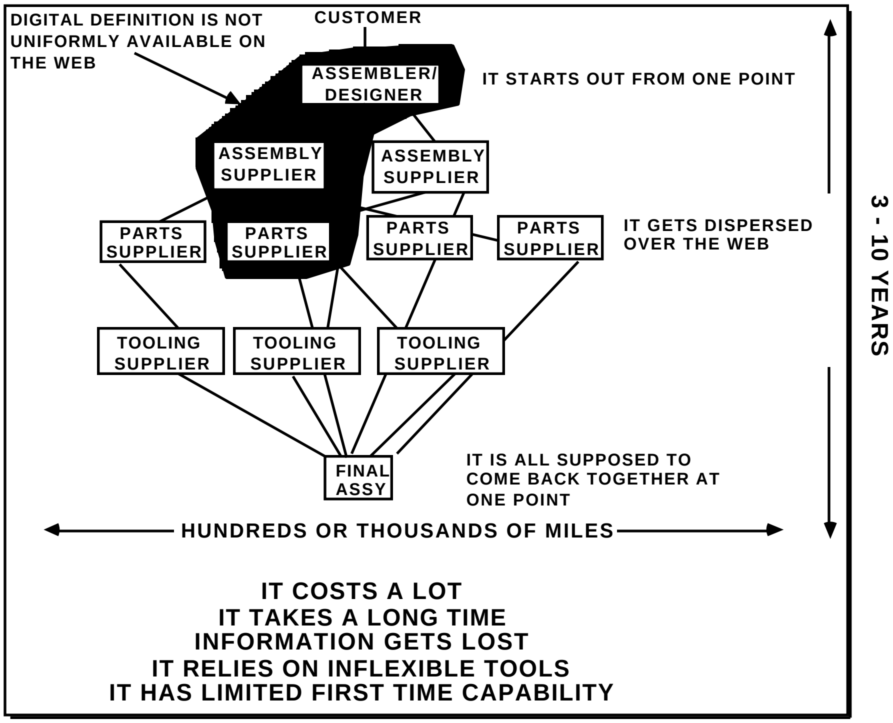

Figure 1. Schematic of the Web Environment for the Case of Complex Mechanical Assemblies. An assembly is designed or partially designed at the top to meet a set of customer requirements expressed as fitup specifications. The design is dispersed geographically and over time, during which new design activities occur, members are added to the chain, and information is lost. Only at the end can the original designer determine if the parts fit, that is, if the original customer requirement has been met. Usually an intense period of corrective action ensues. In the car industry, this period is called "launch" and it lasts several months prior to regular production. In the aircraft industry this period has, in the past, often lasted as long as the product was in production. Time and money are not devoted to a separate period during which problems are identified and solved.

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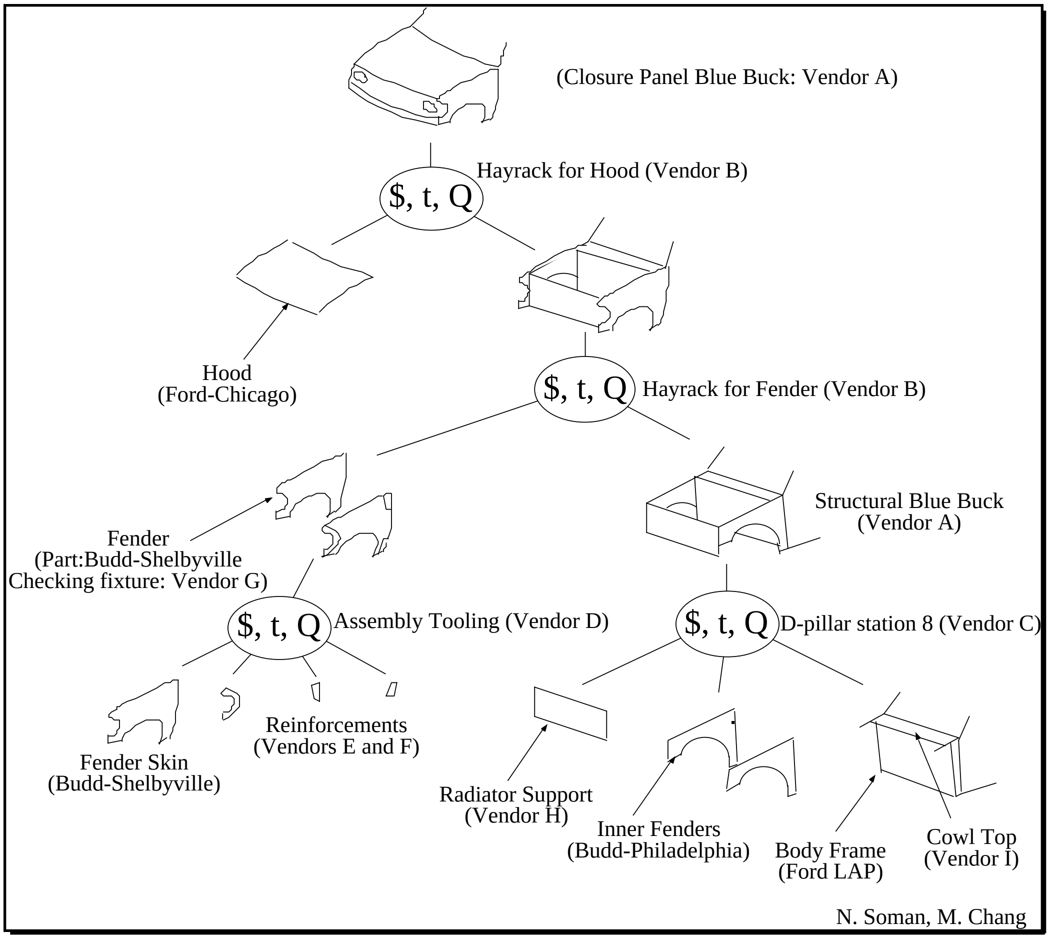
[3] We were introduced to the idea of web mapping by Dr. I. S. Fan and Dr. G. Williams of Cranfield University, UK, who in June, 1994 showed us their research on documenting the "extended development chain" for the A340 wing by British Aerospace and dozens of suppliers. Cranfield's term corresponding to "web" is "Extended Enterprise." [Cooper, et al]



N. Soman, M. Chang

Figure 2. The Supply Web for the Front End of A Car. This map shows the parts, fixtures, and their respective vendors and indicates that even for a small number of parts and fixtures there can be a large number of vendors. The bubbles with "$, t, Q" inside indicate major points where money and time are spent to obtain quality. Note that there is nearly one source for every part, fixture, and piece of tooling in this product, indicating that its procurement has been dispersed almost to the maximum degree possible. Participants in the design of these items have said repeatedly that maps like this (and others that show the organizations by name along with the kinds of information or objects they exchange) are unlike any information they have had before and add greatly to their understanding of the process in which tye are engaged.

At the moment, the design processes and design tools commonly available to companies take little or no notice of this web phenomenon. In fact, as noted below in this section, CAD generally has only recently begun to respond to the fact that products have many parts and are designed by many people, much less that these parts and people are associated with different companies. Recent recognition of these facts can be seen not only in increased efforts to standardize CAD data for translation purposes but also in efforts, mostly undertaken by large users of CAD such as Boeing:

- to enhance the ability of CAD systems to manage data, especially to increase the ability of designers to find each other as well as all the other parts associated with their own work

- to enable designers to assemble many parts associated with an assembly and determine if there are gross errors in the nominal design

- to combine CAD and CAE in a seamless fashion

- to permit designers in far distant countries to work together almost in real time

Behind these efforts, however, there is still a large gap in capabilities compared to requirements. Explicit methods for defining interfaces between parts and assemblies are missing as are ways of mapping the technical and organizational relationships similar to those shown in Figure 2. That is, the problem has been approached so far as a primarily technical one, with the managerial and organizational dynamics not taken explicitly into account.

B. Growth of Design Complexity and the Expanding Responsibilities on the Design Process

Products have become almost unbelievably complex. A Polaroid camera has hundreds of parts packed together so tightly that when the camera is folded up there is practically no air inside. A car has at least 10,000 parts, not counting the internal parts in most of the major subassemblies and purchased items like seats, engines, and radios. A passenger airplane has either 100,000, or 1,000,000, or 3,000,000 parts depending on whom one asks. Combat ships have on the oreer of 10,000,000 parts, not counting internal parts in purchased systems like missiles and radars. Microprocessors have 3,000,000 parts (counted as individual transistors) today and are expected to have 100,000,000 in five years. CAD systems and their accompanying data management systems can hardly keep up with the individual part files, much less manage bills of materials, collate test data, interface with simulations, and so on.

At the same time, companies are reducing the size of design teams and, as said above, dispersing design and manufacturing over time and space. The response so far has been to throw more and more computer power at the problem, but cracks are showing up more and more frequently. The most common solution currently in use is to put all product data in one common store and permit everyone to access it. But this store has become so big that finding and relating items has become costly, time consuming, and error-prone.

While everyone says that they are involving suppliers earlier, taking account of manufacturability and assembleability, and so on, there are few computer tools to support such activities. The advances in CAD capability that are discussed in the visit reports, such as enhanced solid modeling and associativity, enable individual designers to do geometric modeling and capture technical design intent at the level of individual parts. In this sense, they enhance the traditional roles and capabilities of CAD. In areas such as data management, it is users like Chryser and Boeing that are making the necessary advances, in cooperation with the CAD vendors.

In the area of CAE, the traditional CAD vendors are opening their systems so that third party vendors of CAE can integrate their products or exchange data with CAD geometry. As such tools grow in capability, user companies are starting to abandon their own software in these areas in favor of purchased software. CAE is strongest in traditional engineering performance areas like stress analysis and fluid flow. There are strong needs in variation prediction and prevention, such as tolerance analysis and allocation in both rigid and sheet metal parts.

In the area of CAM, several CAD companies offer products of varying capability and range. In most large user companies, existing CAM software is still felt to be superior. This is especially true in the area of sheet metal stamping process design for cars (GM and Ford) and in machining (Caterpillar).

An important area that illustrates the need for broader design tools is coordination of sheet metal and structural design for cars and airplanes. In the car industry, such parts are made as stampings that are welded together with the aid of fixtures and clamps. In order to have any chance of making these parts fit, the designers have utilized common reference points to the extent possible. But CAD tools do an incomplete job of supporting separate data items for this purpose.

Ford has recently modified its internal sheet metal design CAD system to permit such points to be defined and kept persistent throughout the design process. Ford uses these points to tie the supplier web together. Howsever, these kinds of data are not associative and must be updated individually following design changes. Chrysler has added similar points to its CATIA system.

In the aircraft industry the record is even less consistent. This problem is made worse by the tendency of manufacturers to buy most of the fixtures and, in the case of some car companies, to buy the sheet metal parts from chains of suppliers each of which make only one or two parts.

The fact is that not only are design tools missing, but the underlying data to support the tools have not been defined. These gaps go back to the underlying problem that the design process itself is in flux, with new actors entering at new times with new information and requirements, and new technical requirements being introduced as a result of technical advances, regulations, and international sourcing and selling. The most effective way to attack the problem is to be process-driven. This entails defining a process as a series of questions or sorties in search of information, the results of which launch new sorties, all with the ultimate result that a design data package is produced. Each of these sorties requires access to either data or algorithms, and the algorithms in turn need data.

So the sequence is

process definition -> algorithms and tools -> data models and structures

As long as the process itself is being defined, the need for algorithms and their specifications will be a moving target, which will in turn make it difficult to define what a product data model should contain or how it should be structured for efficient populating and access. Throughout my visits over all three projects, I have seen this issue addressed repeatedly: people try to invent data models without having a clear picture of the process that the models are intended to support.

A solid way to tie the design process together has not yet emerged. In past reports I have suggested assembly as a forum in which to create such integration. Assembly is inherently integrative, bringing together not only parts and tooling but also the people, organizations, and companies that make them. Recent research [Whitney et al 1995] indicates that companies are unaware of the complexity of the assembly-dsriven supply chains they have spawned during design of complex products. Those most aware are the people charged with performing the physical integration themselves, namely people in final assembly, quality assurance, pilot plant operation, dimensional control, assembly tooling acquisition, etc. These people defensively try to taker a greater role in the earlier design phases and often are welcomed when they do. But a pro-active effort to reach out to them is slower in emerging.

When I suggest to people from the back end of the design process that "assembly glues the process together," they agree. They often say "our company designs parts, not assemblies." This is a consequence of two factors. First, as reported elsewhere, CAD has in the past been unable to support views of several parts at once. Second, company organizations have failed to recognize that integration should happen early in the design process rather than late. The process should not mirror the sequence in which production is done but should invert that order: assembly first, then parts. So far it has not happened.

C. Core Competence Issues[4]

Throughout my visits, I encountered companies that were uncertain about what skills they should retain and which they should fill by buying objects or services from others. This is commony referred to as the core competence issue. It has been forced on companies by the growing complexity of products and the size of world markets that many companies are in now or want to enter.

Most companies design and make only a portion of what makes up their products, buying the rest from a complex multi-link chain of suppliers. A breakthrough in our understanding of automotive supply chains was achieved

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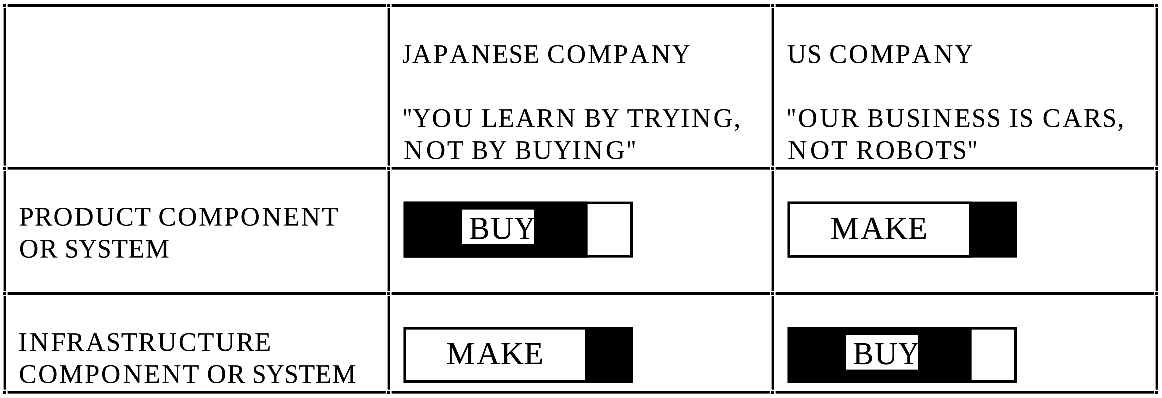
[4] Portions of this section are taken from [Whitney 1995b].

when it was found that the most successful Japanese car companies design and make as little as 30% of the items that go into their cars. [Clark and Fujimoto] For US car companies, the corresponding percentage ranges from 30% at Chrysler (which is severely short of engineers) to 70% at GM.

But there is another and less well understood supply chain, namely the one that provides the manufacturing infrastructure: hardware (machine tools, robots, and complete fabrication and assembly systems) as well as software (CAD, CAM, CAE for design as well as scheduling, logistics, and database programs for operations). An equally important and recently appreciated point is that Japanese manufacturing companies are firmly involved in the infrastructure supply chain. They make a surprisingly large fraction of their own key manufacturing equipment and write much of their design software. [Whitney 1992, 1993] In US companies, almost exactly the opposite pattern is observed: manufacturing equipment and much of the design software is purchased from other companies. Figure 3 illustrates the pattern.

Japanese automobile firms strongly support in-house CAD development as well as that of key manufacturing equipment. Such equipment may include robots, machines that cut stamping dies, sensors used in manufacturing, and assembly equipment. Firms in consumer electronics have moved even more strongly than car firms into assembly robots and now can assemble impressively complex mechanisms very rapidly and dexterously. One example is Sony, whose robot systems assemble delicate and precise products such as video cameras. Another example is Matsushita, which developed essential technology for attaching electronic components to printed circuit boards. Both firms now sell this technology and are either the only source or one of only a few that can deliver their level of flexibility, programmability, speed, and precision.



	JAPANESE COMPANY "YOU LEARN BY TRYING, NOT BY BUYING"	US COMPANY "OUR BUSINESS IS CARS, NOT ROBOTS"
PRODUCT COMPONENT OR SYSTEM	BUY	MAKE
INFRASTRUCTURE COMPONENT OR SYSTEM	MAKE	BUY

Figure 3. Japanese companies buy much of their product components but make much of their infrastructure components. US companies tend to do the opposite. Japanese companies that fit this trend include Toyota, Nissan, IBM Japan, Sony, Hitachi, Matsushita, Mitsubishi, Nippondenso, Epson, and Ricoh.[5]

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[5] A Japanese engineer told me that "You learn by trying, not by buying." Implicit in this statement is the idea that learning itself has very high value. [Whitney, 1992]

The pattern in Figure 3 applies to semiconductor manufacturers as well. Most major Japanese firms in this industry make or at least develop some advanced processing equipment, while most US firms buy all of theirs, usually from Japanese suppliers.[6]

In Europe, we find a hybrid of the US and Japanese patterns in which companies are comfortable making a considerable fraction of their manufacturing hardware or at least adapting it significantly to their needs. However, they tend, like US firms, to buy software. [Whitney 1993]

Why do these differences exist? The quotes in Figure 3 are part of the story: internal attitudes within the companies are quite different and have been for several decades. US companies want to concentrate on what they feel they do well and tend to value the product most highly. Japanese companies tend to view manufacturing in a holistic way. They know it is difficult to learn how to do well and they want to maintain control of as much of the process design and production chain as possible.[7]

Japanese companies operate in a different national context and historical background which may help explain why they operate this way. A quote from [Friedman and Samuels] puts it well: "Japan, we believe, values industries differently than does America. . . . [and believes] that industries have importance beyond the goods they produce. Acting on this belief, the Japanese are driven to procure or develop skills and knowledge that they may lack for their domestic economy so that non-production benefits--especially learning and diffusion--can be realized at home. Industrial policy in Japan is guided by the effort to maintain the nation's knowledge and technology base rather than to produce a specific product to which a domestic firm might affix a nameplate." "The U.S., in contrast, does not value industries in this way. . . . leading to wholesale capacity losses, or even domestic skill displacement from the American economy that Japan would never tolerate. ... As we have seen in the aircraft industry, Japan is willing to pay (and pay dearly) for the same technical knowledge that the U.S. is willing to transfer abroad because it values the ancillary industrial results of that knowledge as much, or more than, the ability to make specific goods."

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[6] In the case of semiconductor equipment, an interesting state of mutual dependency has emerged between the US and Japan. The Japanese have chosen to focus on DRAM design and production, a choice that exploits their skill in precision clean manufacturing. DRAMS require totally new processes and equipment at each new generation. The US has chosen to focus on microprocessor design and production, a choice that reflects its skill in software systems and logic design. Microprocessors up to now have been able to utilize the previous generation of manufacturing technology developed for DRAMS. As a result, microprocessor manufacturers focus their skills on developing aids to the design of their logically and physically complex products, and basically wait for the next generation of manufacturing equipment to fall in their laps. This permits them to create the next generation of processors which can address more memory, which creates new classes of computer systems that need better, faster, and more capacious memory.

[7] I have also been told by Japanese in charge of in-house manufacturing equipment development that Japanese companies are naturally secretive and fear releasing valuable technology to suppliers.

What advantages for individual companies are there to one strategy or the other? The product is what customers buy, not the underlying processes, so concentration on the product is not misplaced. But manufacturing skill shows up in many areas that customers notice in one way or another: quality of fit and finish, the rate at which new models come out, the time it takes for their car to be built and delivered, and its durability and reliability. The attitude that product and process excellence cannot be separated is reflected in Figure 4.

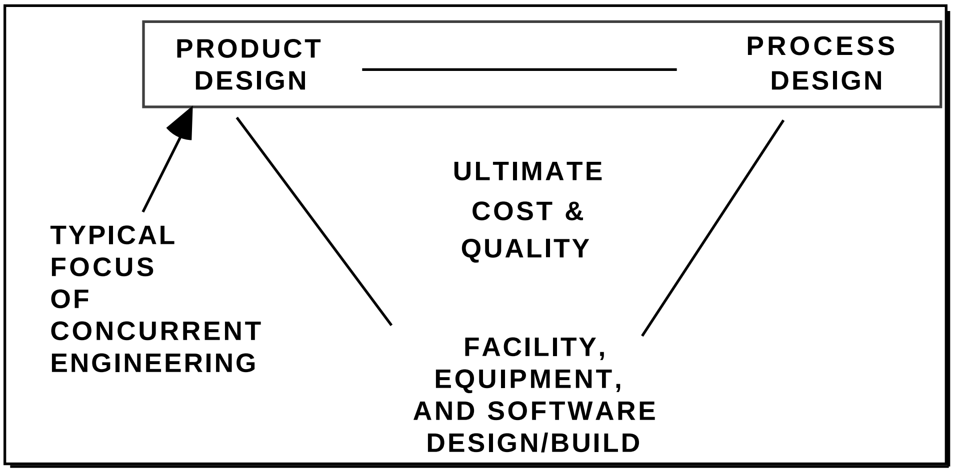

Figure 4. "Ultimate Cost and Quality." This figure was drawn for me by Sony engineers to emphasize the difference between typical concurrent engineering and the Sony approach. Until you have control over all three legs of the stool, you do not have ultimate cost and quality. The same point of view is expressed by Honda, which refers to a "triad" comprising product, process, and equipment. In both companies, an essential feature of the triad is in-house use of the equipment. This ensures rapid diffusion of the capability and rapid feedback to equipment designers concerning what capabilities will be needed by new product designs and what features of the equipment will best serve the factory. Example features include easy maintenance, small size, and ability to switch from one product model to another.

Beyond these general statements, even the companies themselves are hard pressed to say quantitatively and in sharp detail just what the pros and cons are. However, a few clues have emerged from visits to companies and a series of student internship case studies:

- Companies that design and build manufacturing equipment know what that equipment can do. They can use this knowledge to keep their designs within those limits, or they can ask for extensions to the limits when they know their new designs demand such extensions. Since they understand the equipment, they know what extensions are reasonable to request and can explain them lucidly enough to guarantee obtaining them.

- If the design and the equipment match, then operating the factory becomes much easier because many unnecessary startup and operating problems will not occur. "All the complexity is handled during design," one US manufacturing manager said of Toyota, "and the operations people can concentrate on making the factory more efficient."

• Companies that build manufacturing equipment can describe in detail what they want manufacturing systems to do and can more easily instruct suppliers when they choose to buy. They also can tell if the vendors are competent and are asking a reasonable price.

• Companies that build their own equipment understand how to maintain it and can obtain better uptime.

• Companies with in-house equipment builders can involve them from the first day of product design and can obtain long leadtime or unique equipment that is specifically tailored to the product's needs. [Whitney 1993b contains examples from Nippondenso.]

• Similarly, companies that produce their own design software can tailor it to their company culture and carefully nurtured design procedures.[8] An efficient design procedure links the right people at the right times, makes critical information available as soon as it is ready, and asks the right questions in the right sequence. A tailored software system for design combines extensive data sharing with a family of design tools that can access, modify, check, and distribute that information. Japanese companies regularly stress this point.[9] In the US, Boeing has been a leader in adapting commercial design software to its internal procedures. In 1991 Toyota had 350 in-house programmers working on CAD/CAM plus 250 more contract employees from Nihon Unisys. [Whitney 1992]. Today the same total number of programmers are on the job but only 100 are regular Toyota employees. Cost pressures have forced this shift. Toyota retains the final 100 in order to retain enough in-house skill to understand the problem and evaluate Nihon Unisys' work.[10]

Among the problems we have observed at companies that buy manufacturing equipment or software include the following:

• When products are assembled from parts made at different companies, using fixtures and jigs made at still other companies, something happens to the dimensions and tolerances that chain all these parts, jigs, fixtures, and companies together. The result is that the parts may fail to fit properly. These events may come as total surprises to the participating companies. Even when experience has prepared the participants for a certain number of these events, even to the extent

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[8] A Japanese director of CAD development at a car company said in 1991: "We used to buy CAD software and adapt our working style to suit. Now we are developing our next generation working style and will write or buy software to suit." [Whitney 1992]

[9] Recently the CAD/CAM director for a large European car company told me of visiting Japanese car firms early in 1994 and observing their astonishment when he said his company felt comfortable using commercial CAD.

[10] Prof F. Kimura, Tokyo University, personal communication, March, 1995.

that they budget time and cost for finding and fixing them, the exact problems found may still be a surprise and often there is insufficient information to permit a systematic hunt for the root cause.

We have observed this so many times in so many different industries that there must be a common set of reasons, though we have no clear culprits at the moment. Candidates include poor communication, the lack of specific CAD tools that deal with assemblies and tolerances, the opacity of the ANSI dimensioning and tolerancing standards, inadequate education and training of the people who do critical tolerancing work and design of tolerance-preserving fixtures, and the fact that these designers are very often nomadic temporary employees who lack university engineering degrees.[11]

An important area where issues of core competence are currently being played out is in CAD/CAM. Should a company develop its own CAD/CAM capability or seek a supplier? Is the procurement based on extending capacity or plugging a knowledge gap? In these terms, CAD/CAM is a fascinating and crucial case because design capability is so important to so many companies.

There is little doubt that most US companies outsource CAD/CAM due to lack of knowledge. The main knowledge being sought is the ability to represent complete and correct geometric models, especially of complex shapes such as aircraft wings or car fenders, and to do so efficiently. This knowledge is the hallmark of the CAD/CAM vendor community.

A cursory look at design can fool an observer into thinking that design is identical with creation of geometry. On this basis, design infrastructure is a commodity and thus one can feel comfortable outsourcing it from any of a number of CAD/CAM vendors. This is how it appears on the surface. However, a closer look at the design process shows that the main required skills lie well beyond creation of geometry and instead, as described above, involve systematic creation of decomposable subsystems and careful description of their requirements. The issue then becomes coordinating the different organizations and companies whose job is to deliver those requirements. Geometry is merely one of those requirements.

As a result, a focus on geometry as the centerpiece of the design process leads to a distortion of the process and neglect of more important management and engineering skills.[12] No current commercial CAD system provides system engineering capabilities, and the ability of current systems to manage the huge

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[11] See Appendix on the CAD/CAM Survey at the end of this report.

[12] It may also lead to an over-emphasis on standardizing CAD data as the cure to a variety of supplier relations problems. If design did indeed consist entirely of geometry, then indeed transmitting the geometry correctly and quickly would solve the majority of procurement problems between customers and suppliers. The fact that it does not lends credence to the idea that design is much more than geometry. The non-geometric elements that need to be communicated and shared are much harder to represent in explicit computer models than is the geometry.

amounts of data that comprise just the geometric part of product descriptions is one of their weakest elements. Managers who think that computer-based design systems can be purchased whole therefore are missing the point.

Yet, to repeat the obvious, most manufacturing companies can no longer write their own geometric modeling software. The solution many have adopted (except the Japanese) is to obtain the most open and standardized geometric modeler they can find and exploit the openness to add a variety of company-specific (i.e. nondecomposable) tools, databases, data management capabilities, and so on that have been specified and tailored to that company's products and design culture. This may make the best of the situation. The error in CAD/CAM would be to outsource the specific tools that permit the core geometric modeler to be coupled closely to the rest of the design process or the product's core technologies.

III. General Comparison of Japan, Europe, and the US

This project has taken nearly four years to complete. During that time many changes have occurred, most notably the end of the bubble economy in Japan and a sharp increase in the value of the Yen relative to the dollar. The comparisons reported here are therefore of limited validity and thus are brief. They are interesting to the extent that the character of regional approaches remains roughly the same.

A. Design Process Developments

At the beginning of this project it was clear that the Japanese were ahead in developing efficient design processes for complex products and supporting those processes with homegrown CAD tools. The intervening three years have seen US companies move quickly to reorganize and seek new ways to compete in design speed and effectiveness. It is unclear to what extent these changes will be successful in the long run. The Japanese appear ready to change again every five years or so as conditions change whereas large US companies appear to wish that the current reorganization will be the last. European companies appear to move the most slowly, with one firm reporting to me in 1992 that their shift from a functional to a process-oriented organization had taken ten years.

US firms' reorganizations have taken place in an atmosphere of downsizing. The impetus has been mostly to reduce the number of older workers, but a serious downside has been a loss of corporate memory and design skills. Japanese firms do a better job in two ways: First they seem to document corporate knowledge on paper to a greater degree. Second, the lifetime employment system forces them to keep employees on the payroll, preserving the knowledge. Since employees and the company know exactly when each person will leave, it is likely that they have set up a mechanism for passing knowledge on. US firms are still in the process of discovering how much knowledge they have lost in recent downsizings; many have called back retired workers as temporary employees or consultants.

The most striking development in design process organization in the US has been the adoption of platform teams at Chrysler. This method mirrors Japanese methods in use for years, although it has its own special character at Chrysler. It was accomplished in something of a crisis atmosphere and was accompanied by the abandonment of in-house CAD and adoption of a totally new system. The fact that Chrysler pulled both processes off successfully is remarkable. However, Chrysler has discovered some of the disadvantages of this approach and it is not clear if they have been overcome. The company relies on quite small teams by US standards and outsources more of its parts and manufacturing systems than any other US car firm.

Another striking development has been the rapid adoption of electronic commerce, electronic data exchange, close involvement of suppliers in early design and other aspects of "agile manufacturing." Japanese observers are asking "What is agile manufacturing?" just as they asked me in 1991 "What is concurrent engineering?" It turns out that both are names and relatively careful descriptions of things that the Japanese and other innovators have been doing intuitively for some time. It often takes an outsider to define such sets of activities and discern their structure, much to the amazement of the originators. The same thing happened when Chirillo analyzed Japanese modular shipbuilding methods in the 1970s [Chirillo]. He gave specific names to steps in the process as well as to different kinds of modules, distinctions that the Japanese practitioners had never found the need to make.

Many other companies have reorganized not only their design processes but the entire company. Most trends are in the direction of multi-function teams, early supplier involvement, and reduced cycle times. Since product development times in some of these industries exceed the duration of the most recent changes, it is too early to tell if they are effective. In the meantime, evidence is mounting that companies like Toyota and Volvo have already modified the organization structures observed in the late 1980s. The heavyweight project manager has been found too autocratic or too prone to re-invent the wheel. Programs are now more likely to be coordinated by higher level authority. Similarly, ecomonic pressures are forcing Japanese car companies to curtail product variety and lengthen design cycle times.

B. Deployment of Tools

In many ways, US firms are ahead in updating their CAD systems and integrating CAD, CAM, and CAE. They have moved faster to abandon mainframe systems and embrace client-server architectures, PCs, and workstations. They have forced CAD vendors to open their software and remove its hardware dependency. It is now easier to integrate third party design software to CAD models. Innovative design software incorporating constraints, associativity, and NURBS models are now available commercially in both UNIX and Windows environments. Such tools are, of course, available to all companies and it is clear that Japanese firms are paying close attention. They may in fact face a severe challenge since their exiting CAD/CAM is tightly integrated and depends on mainframes and has a closed architecture. They would prefer to go on developing their own CAD systems but may lack the money to do so. Next in desirability would be to adopt commercial geometric modeling but retain their in-house CAE and CAM. It is not clear if this is practical.

As noted above, the US is the first to deeply explore and exploit the opportunities of networking between companies, but this should be a easy technical jump for the Japanese, whose telecommunications infrastructure is very strong. However, it may be a more dificult cultural jump since Japanese depend heavily on face to face discussions in their design and business practices.

US innovation in design tools can also be seen in a rise in the use of knowledge-based systems for supporting routine design. Examples of such products are ICAD and Wisdom (recently purchased by ICAD). Interestingly, when ICAD was founded it was hoped that these methods would be useful for non-routine design. This in spite of the fact that the impetus for ICAD's founding was an unfinished contract to write a bidding package for design and pricing of tube and sheet heat exchangers, a routine design if there ever was one.

ICAD-like applications have been reported by several companies. Both these companies and ICAD itself acknowledge that these are software-intensive efforts requiring detailed process modeling first if any improvement is to be achieved. In one case, the company reports that typical models require 250 MB of disk swap space to operate properly. However, the company regards the applications as successes. Another company reports, however, that the resulting system is rigid and it takes effort and time to update it if engineers come up with a better method. This criticism is applicable to almost any significant software design tool, so it is not clear what the finding means about the capabilities of knowledge-based systems or the support organizations required to keep them effective.

Finally, there is the question of PDES/STEP. Recent demonstrations have shown that this is a viable method for exchanging design data between certain CAD systems. The EXPRESS language has shown itself to be useful in describing complex data objects related to design. But STEP has focused its energy on geometry while design technology has rushed ahead with features and constraints. More developments can be expected. The consulting firm D H Brown Associates, long a supporter of STEP, says "continuing strategic and aggressive participation of leading edge users, government, and vendors will be required over many years to support the successful evolution of an Open CAx environment. ... full adoption of STEP ... does not necessarily have to sweep the market for STEP to be considered as a successful effort. ... Users do not care whether standards arrive from a *de jure* or a *de facto* effort. In this perspective, STEP succeeds simply as a social and research phenomenon accelerating the development and adoption of Open CAx." [D H Brown]

IV. Electronic and Mechanical Design

In recent years there has been considerable discussion about the degree to which VLSI design has outstripped mechanical design. By any of several metrics, this appears to be true: number of parts in a typical product, number of engineers needed to create a product, general "complexity" of the product, coverage of the design process by CAD tools, degree of integration of these tools, the systematic top-down nature of the VLSI design process, and so on. Occasionally, people have wondered why mechanical design cannot emulate VLSI design, adopt or adapt its methods, and achieve its efficiencies and determinism.

I believe there are fundamental reasons why VLSI design is different from, and substantially easier than, mechanical design, and the differences will most likely persist. My conclusions are summarized in Table 1 and the reasoning is sketched below. An essential feature of the argument is to distinguish carefully between parts or components on the one hand and products or systems on the other. Table 1 displays this distinction.

ISSUE	**VLSI**	**Mechanical Systems**
Component Design and Verification	Model-driven design, single function components; design based on rules once huge effort to verify single elements is done; few component types needed	Multi-function design with weak or single-function models; components verified individually, repeatedly, exhaustively; many component types needed
Component Behavior	The same in systems as in isolation; dominated by logic, described by mathematics; design errors do not destroy the system	Different in systems than in isolation; dominated by power, approximated by mathematics, subject to system- and life-threatening side effects
System Design and Verification	Follows rules of logic, can be proven correct; system design separable from component design; simulations cover all significant behaviors; main system functions accomplished by standard elements; building block approach exploited and probably unavoidable	Logic captures a tiny fraction of behavior; system design inseparable from component design; cannot be proven correct; large design effort devoted to side effects; component behavior changes when hooked into systems; building block design approach unavailable, wasteful
System Behavior	Described by logical union of component behaviors; main function dominates	No top level description exists; union of component behaviors irrelevant; off-nominal behaviors may dominate

Table 1. Summary of Differences Between VLSI and Mechanical Design

It is important to recognize that VLSI design occurs generally in three very distinct prpduct environments: memory, microprocessors, and ASICs (application-specific integrated circuits). Memories are by far the most demanding in terms of both design and production. Microprocessors benefit from memory developments but still are very complex, with millions of transistors and very narow line widths. ASICs are very simple by comparison and can often be designed by the cookbook methods described below. People often think of these cookbook methods when they compare VLSI with mechanical design.

In fact, however, the most challenging design domains require most of the same kinds of efforts and pose the same generic kinds of design challenge as mechanical design does. As recently as the late 1980s, even microprocessors could be designed by the cookbook method but no longer. It is possible that the period from 1980 to 1990 was a golden age in VLSI design when top-down methods worked for most important classes of products. Today's microprocessors have 3 million transistors and a typical designer using today's best electronic CAD tools can design about 1000 gates per week. The next generation of microprocessors will likely have 10 million transistors. So the problem is growing faster than CAD can keep up.

The argument for saying that VLSI design is (or recently was) fundamentally different from mechanical design is as follows:

1. Mechanical systems carry significant power, from kilowatts to gigawatts. A characteristic of all engineering systems is that the main functions are accompanied by side effects or off-nominal behaviors. In VLSI, the main function consists of switching between 0 and 5 (or 3 or 2.4) volts, and side effects include capacitance, heat, wave reflections, and crosstalk. In mechanical systems typical side effects include imbalance of rotating elements, crack growth, fatigue, vibration, friction, wear, heat, and corrosion. The most dangerous of mechanical systems' side effects occur at power levels comparable to the power in the main function. In general there is no way to "design out" these side effects. A VLSI system will interpret anything between 0 and 0.5 volts as 0, or between 4.5 and 5 volts as 5. There is no mechanical system of interest that operates with 10% tolerances. A jet engine rotor must be balanced to within 10^{-2}% or better or else it will simply explode. Multiple side effects at high power levels are a fundamental characteristic of mechanical systems.

One result of this fact is that mechanical system designers often spend more time anticipating and mitigating a wide array of side effects than they do assembling and satisfying the system's main functions. Gaps in engineering knowledge are mainly responsible for the consequent difficulty. This dilution of design focus is one reason why mechanical systems require so much design effort for apparently so little complexity of output. Correct accounting of "complexity of output" must include the side effects.

2. By contrast, VLSI systems are signal processors. Their operating power level is very low. Few if any mechanical signal processors exist any more (dial readouts on gas meters are about the only example). Since they process tiny amounts of power and because only the logical implications of this power matter (the effect of the equivalence of digital logic and Boolean algebra), VLSI circuit elements can be connected together in building-block fashion. The elements do

not back-load each other. (If fanout limits are reached, amplifiers can be inserted at some cost in space, power, and signal propagation time. But this is not fundamental.)

An enormously important and <u>fundamental</u> consequence is that a VLSI element's behavior is essentially unchanged almost no matter how it is hooked to other elements or how many it is hooked to. That is, once the behavior of an element is understood, its behavior can be depended on to remain unchanged when it is placed into a system regardless of that system's complexity. The result of this is that VLSI design can proceed in two essentially independent stages, of which the first (design of components) shares most of its features with mechanical design while <u>only the second</u> (design of systems) <u>is different</u>:

Stage 1: Logic elements are designed and processes are designed to make them. This requires enormous effort involving lithography, metallurgy, chemistry, electric field analysis, purification of fluids and gases, and training of people, to name a few.

Stage 2. Once this difficult step is done, the results can be expressed as design rules and the product designers can use the elements as described above. The problems in Stage 2 are almost completely logical or reducible to mathematical description because the systems are signal processors or logic implementors. Designers can focus their efforts on system issues like floor planning, timing, basic architecture, system logic, and so on.[13] Furthermore, due to the mathematical nature of VLSI digital logic and its long-understood relation to Boolean algebra, the performance of VLSI systems can often be proven correct, not simply simulated to test correctness. But even the ability to simulate to correctness is unavailable to mechanical system designers. Why is this so?

3. An important reason why is that <u>mechanical components themselves are fundamentally different from VLSI components.</u> Mechanical components perform multiple functions, and logic is usually not one of them. Multi-functions are partly due to basic physics (rotating elements transmit shear loads *and* store rotational energy; both are useful as well as unavoidable) and partly due to design economy. VLSI elements perform exactly one function, namely logic. They do not have to support loads, damp vibrations, contain liquids, rotate, slide, or act as fasteners or locators for other elements. Furthermore, each kind of element performs exactly one logical function. Designers can build up systems bit by bit, adding elements as functions are required. The absence of back-loading aids this process. Design economy dominates mechanical design: if one element were selected for each identified function, such systems would inevitably be too

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[13] The situations where this characterization is invalid provide valuable cautions: VLSI that streteches the state of the art encounters severe <u>system-level</u> difficulties. The separation described here may not be dependable in the future as processing speeds and chip sizes increase. Timing and heat problems are early harbingers. A 33 MHz 486 is in fact a 40 Mhz 486 that did not pass the 40 MHz test. This flavor of this story is distinctly non-digital.

big, too heavy, or too wasteful of energy. For example, the outer case of an automatic transmission for a car carries drive load, contains fluids, maintains geometric positioning for multitudes of internal gears, shafts, and clutches, and provides the base for the output drive shafts and suspension system.

Not only is there no other way to design such a case but the designers would not have it any other way. Mechanical designers depend on the multi-function nature of their parts to obtain efficient designs. Building block designs are inevitably either breadboards or kludges. But this forces them to design components over and over to tailor them to the current need, again sapping the effort that should be devoted to system design. VLSI designers, by contrast, depend on the single function nature of their components to survive the logical complexity challenges of their designs. One can observe the consequences of this <u>fundamental</u> difference by observing that in VLSI the "main function carriers" are standard proven library elements while in mechanical systems only support elements like fasteners are proven library elements; everything else is designed to suit.

VLSI elements don't back load each other because they maintain a huge ratio of output impedance to input impedance, perhaps 6 or 7 orders of magnitude. If we tried to obtain such a ratio between say a turbine and a propeller, the turbine would be the size of a house and the propeller the size of a muffin fan. No one will build such a system. Instead, mechanical system designers must always match impedances and accept back-loading. This need to match is essentially a statement that the elements cannot be designed independently of each other.

4. The <u>fundamental</u> consequence of back-loading is that <u>mechanical elements hooked into systems no longer behave they way they did in isolation</u>. (Transmissions are always tested with a dynamometer applying a load; so are engines.) And these elements are more complex than VLSI elements due to their multi-function behavior. This makes them harder to understand even in isolation, much less in their new role as part of systems. VLSI elements are in some sense the creations of their designers and can be tailored to perform their function, which is easy in principle to understand. Mechanical elements are not completely free creations of their designers unless, like car fenders, they carry no loads or transmit no power. The existence of multiple behaviors means that no analysis based on a single physical phenomenon will suffice to describe the element's behavior; engineering knowledge is simply not that far advanced, and multi-behavior simulations similarly are lacking. Even single-behavior simulations are poor approximations, especially in the all-important arena of side effects like fatigue, crack growth, and corrosion, where the designers really worry. In these areas, geometric details too small to model or even detect are conclusive in determining if (or when, since many are inevitable) the effect will occur. And when component models are lacking, there is a worse lack of system models and verification methods.

Thus a number of success factors in VLSI may be blocked from application in mechanical design. For example:

• Re-use of library elements may be inapplicable because inefficient designs would result. "Good" mechanical design usually does not reuse components. Many horror stories are available!

• Direct conversion of specifications to system design is unlikely to be applicable because logic is the language of VLSI's specifications and system description, and this language is not only conclusive and provably correct but it captures all the behaviors that the system will exhibit once the component design rules are known. In mechanical systems there is no specification language. Instead we have Quality Function Deployment or other semi-mystical attempts to convert what the customer wants into hard engineering specifications. It is premature to say that there will never be a mechanical spec language, but mechanical systems are not primarily driven by logic; instead they are driven by power flows among many physical phenomena. The mathematical representations we have here apply to single phenomena: stress, fluids, electro-magnetic fields, dynamics; but these are not integrated into one set of equations except in the case of Bond Graphs which imply a building -block approach, which has its own above-mentioned disadvantages.

• There may not in fact be a "clean separation between VLSI manufacturing and VLSI design" since the VLSI components must be designed as verifiably manufacturable. But there is a compensating separation between VLSI component design and VLSI system design. Since this separation does not exist in efficient mechanical designs, this valuable property may be blocked from exploitation in the mechanical world.

• The reason why "an enormous variety of VLSI products can be built" from the same process is that the variety is embodied at the <u>system level</u>. At the component level, only one item can be made by each process. VLSI escapes the consequences of the process-dependence of components because VLSI systems can be designed independently of component design. On the mechanical side, this separation does not exist, indicating why "a great variety of mechanical products" can't be made by the same process. The process-dependence of components has inevitable linkages to the whole product system.

• "Process-constrained design" can indeed be practiced in mechanical systems and routinely is. That's how we decide if a particular machine is suitable: can it deliver the tolerances needed, for example? If not, the design may have to be changed. But many factors contribute to tolerance capability, and it is a random variable, due in large part to the power needed to remove metal efficiently. So the process constraints are much harder to determine and the effort is not completely rewarded.

- "Tool hierarchies" can be used in VLSI because at the system level the information is entirely logical and connective, and the tools in question are used in system-level design. This information is transformed and augmented from stage to stage in the design process but its essential logical/connective identity is preserved all the way to the masks. This is not possible in mechanical systems, where the abstractions are not logical homologues (much less homomorphs) of the embodiments and likely never will be. Instead, there is tremendous conversion needed, with enormous additional information required at each stage. A stick figure diagram of an automatic transmission captures only the logic of the gear arrangements and shifting strategy. It fails totally to capture torques, deflections, heat (a basic property, not a mere side effect since huge energy is released during shifts, just like the heat that emerges when logic gates switch, and for exactly the same reason!), wear, noise, shifting smoothness, and so on, all of which are essential behaviors.

V. Closing Remarks

Over the past four years of this project, I have become increasingly aware that there are two kinds of design activity. These might be called design in the large and design in the small. These are quite different, being driven by different realities and supported, if at all, by different tools.

Design in the small is the typical technically-driven activity of the individual designer. The constraints are generally imposed by the laws of nature as they limit the strength of materials, the speed of fluid or heat flow, and so on. One can expect conventional CAD and CAE to support this kind of design.

On the other hand, design in the large is an organizationally-driven activity engaged in by groups of people in many locations. The constraints they operate under are imposed by human and corporate cultures, educational traditions, and group dynamics. No existing CAD tools address these constraints, and electronic communication may or may not have a beneficial effect.

In fact, just as design sets the conditions for manufacture, the various cultures set the conditions under which design will take place. The best design tools will fail to be used or used properly if there is not a proper set of organizational arrangements and incentives. In this sense, we return to the statement earlier in the report that processes drive design tools which in turn drive data definitions. Culture and organization drive the processes.

VI. References

[D H Brown] "Open CAx, STEP, and Objects," report summary dated March, 1995. D H Brown Associates, Inc, Port Chester NY.

[Chirillo] Chirillo, L D, and Chirillo, L D, "The History of Modern Shipbuilding Methods: The US-Japanese Exchange," Journal of Ship Production, v1 no 1, 1985, pp 1-6.

[Clark and Fujimoto] Clark, Kim, and Fujimoto, Takahiro, "Overlapping Problem-solving in Product Development," in K. Ferdows, ed., Managing International Manufacturing, Amsterdam: North Holland, 1989. See also Chapter 5 of Womack, Jones, and Roos, The Machine That Changed the World, New York: Harper Perennial, 1991.

[Cooper et al] Cooper, Stephen, Fan, Ip-Shing, Sehdev, Kamal, and Williams, Gareth, "Design for Manufacture in the Extended Enterprise," Cranfield University CIM Institute, June 1994.

[Goldman, Nagel and Preiss] Goldman, Steve, Nagel, Roger, and Preiss, Kenneth, Agile Competitors and Virtual Organizations, New York: Van Nostrand Reinhold, 1995

[Whitney 1992] Whitney, D E, "State of the Art in Japanese CAD Methodologies for Mechanical Products - Industrial Practice and University Research," Office of Naval Research Asian Office Scientific Information Bulletin, vol 17 no 1 Jan-Mar 1992 pp 89-111.

[Whitney 1993] Whitney, D E, "University Research and Industrial Practice in Electro-mechanical Design in Europe - Results of a Six Month on-site Study," Office of Naval Research European Office European Science Notes Information Bulletin v 93 no 1, 1993, pp 1-52

[Whitney 1993b] Whitney, D. E., "Nippondenso Co. Ltd: A Case Study of Strategic Product Design," Research in Engineering Design, #5, Dec, 1993, pp 1-20.

[Whitney et al 1995] Whitney D E and co-authors, "Agile Pathfinders In The Aircraft And Automobile Industries - A Progress Report," Proceedings of the 4th Annual Agility Forum, Atlanta, March, 1995.

[Whitney 1995b] Whitney, D E , "Is the Make/Buy Decision a Core Competence?" unpublished working paper, MIT Center for Technology, Policy, and Industrial Development, March, 1995.

[Womack, Jones, and Roos] Womack, James, Jones, Daniel, and Roos, Daniel, The Machine that Changed the World, New York: Harper Perennial, 1991.

Appendix 1. CAD/CAM SURVEY

Following are the results of an informal survey taken to determine who the users of CAD/CAM software are and what kinds of things are currently designed using CAD/CAM. I queried people I knew personally who have direct responsibility for providing CAD/CAM capability to their respective companies. I surveyed two Japanese car companies, all three US car companies, one US and one European aircraft manufacturer, and a US precision instrument manufacturer.

My interest in this topic started from some studies our students have been doing concerning manufacture of products that are made by different suppliers and assembled by those suppliers and the final assembler company. We found that many parts, subassemblies, fixtures, and manufacturing lines were designed and bought through a complex web of suppliers. Communicating all the design and quality information among these suppliers is difficult. I was curious to know where in this web the information is created, who creates it, how much is CAD/CAM used, and where the information is lost or misinterpreted.

To explore some of these ideas I conducted a small informal survey of companies to see how CAD is used and who the users are. I had several hypotheses. They are stated below in *italics* together with my tentative findings. Following this are some charts with the most interesting data.

1. *CAD operators in the US are high school graduates, not graduate engineers, whereas in Japan and Europe they are engineers with university educations.* This hypothesis is supported by the survey results as far as the auto industry is concerned, but not as strongly for aircraft andother industries. In the US, CAD operators tend to get their work instructions and supervision from engineers who give them sketches or marked-up drawings of previous designs. The engineers have formal educations and also have nearly all the contact with customers and suppliers.

2. *CAD operators are not regular employees of US companies, whereas they are in Japan and Europe .* This hypothesis has been partly confirmed. US companies are more likely to have a large fraction of temporary employees operating their CAD terminals. Such people are hard to integrate into a company culture that depends on sharing knowledge. Their private knowledge is their greatest asset. Furthermore, learning their current employers' internal knowledge takes longer than many of them can expect to be working for them.

3. *As a consequence of hypothesis #2, US CAD operators leave the company more frequently, or are subject to dismissal when work loads fall, so they walk out with valuable corporate knowledge.* This hypothesis has been partly confirmed. Typically temporary employee CAD operators stay at one company

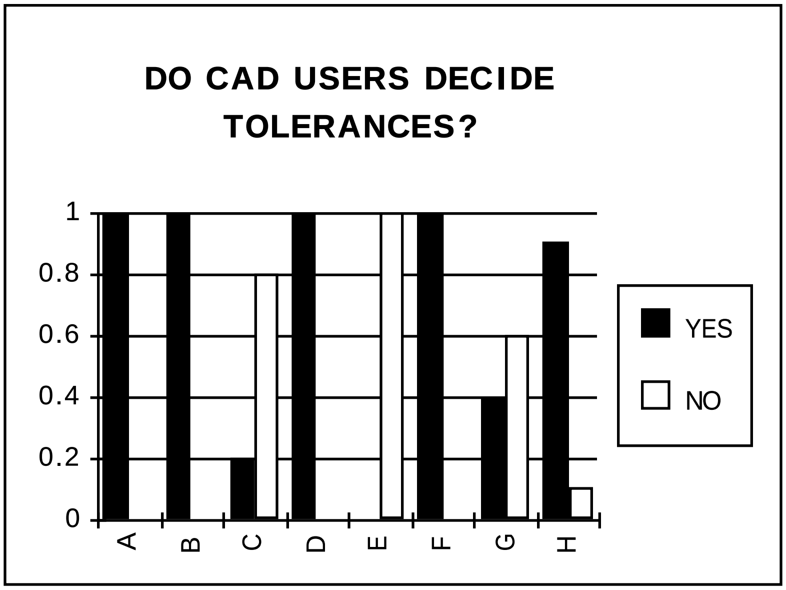
less than three years. These employees do not have any contact with customers or manufacturing people, but spend their time 100% at the CAD terminal.

4. *CAD operators are the people who assign dimensions and tolerances.* This is generally confirmed, except that in the US such people are not generally graduate engineers whereas in Japan they are. So the degree of skill with which this essential task is done differs from region to region. In some cases, tolerances are assigned based on history rather than analyses. In other cases, especially in the case of fixtures and tooling, there may be no tolerances at all.

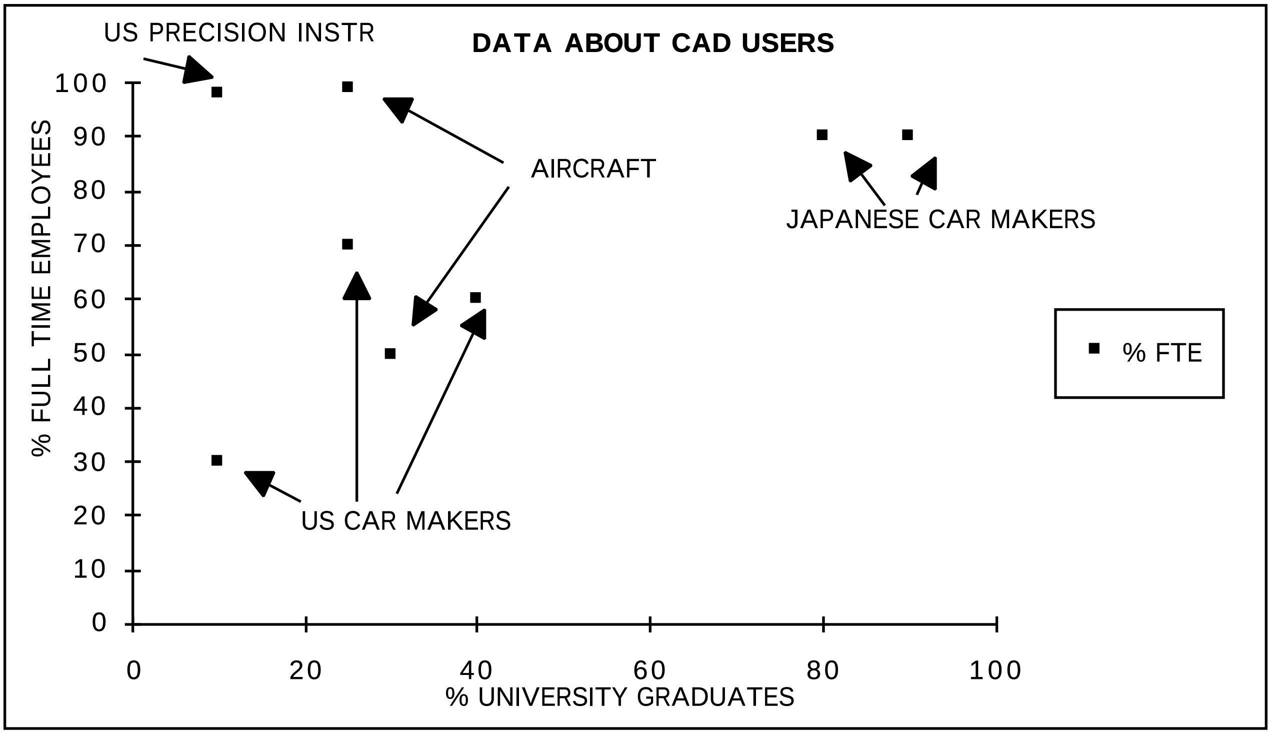
5. *As a consequence of #2, 3, and 4, a lot of vital detailed information and knowledge is in the heads of people who are not regular employees and who do not have an engineering understanding of the problem.* This hypothesis is partly confirmed, in the sense of #2 and #4, but only partly confirmed in the sense of #3.

6. *While CAD may be used to define parts, it is not used much for defining tools and fixtures.* This is confirmed. As a result, many of the advantages of designing parts in CAD are not reaped. Individual parts can be machined using direct numerical control code extracted from CAD parts models. But assembly often requires fixtures, and assembly is where many problems arise that could be alleviated if CAD extended to this area.

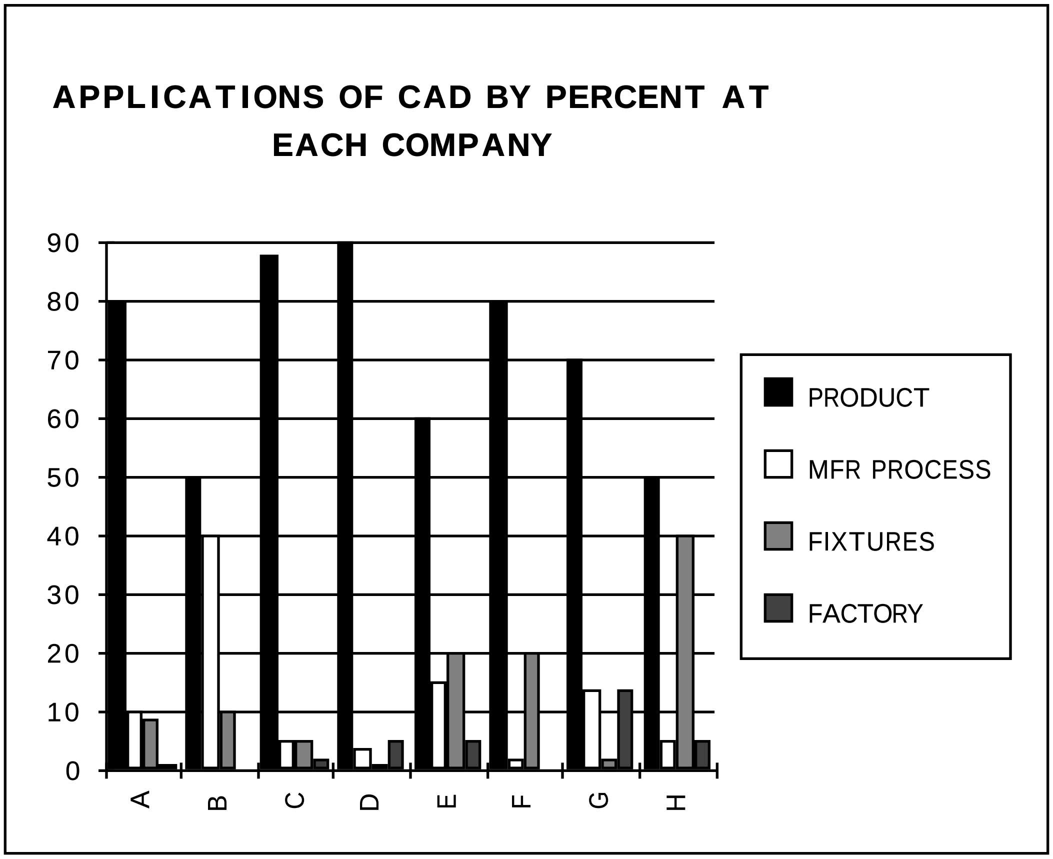
7. *We have observed a lot of problems during the assembly of products, indicating either that the parts were not made correctly or that their assembly jigs and fixtures were not made correctly. Perhaps this is caused by #6 and made worse by #5.* There is insufficient information at this time to say if this is confirmed or not but the evidence in hand points in that direction. A simple survey of this kind cannot be used for such a complex question but this is the type of question that really needs to be answered. Anecdotal evidence gathered by phone contacts indicates that tolerance datums indeed get dropped; occasionally the error is detected by the tooling manufacturer who has to convince the parts designer. In other cases it appears, especially in car body tooling design, that tolerances are simply not part of the tooling design data package. Instead, nominals are used, parts are assumed perfect, no design gaps are included, and all tools have shims which are adjusted during product launch. This is evidence of a process that is largely held together by people. It lacks a systematic base and does not support problem solving, documentation, or improvement in the overall process.



Tolerances are determined by the CAD operators overwhelmingly at most of the companies surveyed, but sharp departures from this policy were observed.



Of companies surveyed, only Japanese car companies assign CAD operation to college educated people who are full time employees. In the other companies, the majority of CAD operators do not have university degrees, and many are temporary employees.



CAD is used overwhelmingly to design components of the product. Only at two of the companies surveyed does CAD have a strong role in manufacturing process or fixture design relative to its role in product design.