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State of the Art in Japanese CAD Methodologies for Mechanical Products: Industrial Practice and University Research

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Center for International Studies
Massachusetts Institute of Technology

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GENERAL NOTE

This paper is part of a larger research effort focusing on the United States, Europe, and Japan to determine how electro-mechanical products are designed, how the interests of manufacturing and other constituencies are included during the process, and how computers are used. Of special interest is the kind, depth, and source of software in use. Research is currently being conducted in Europe. This report summarizes only the findings from a 3.5-month on-site study of the Japanese product development practice, based on twenty-five visits to companies and eight visits to university laboratories.

EXECUTIVE SUMMARY

This paper summarizes findings from a 3.5 month on-site study of Japanese product development practice. Twenty five visits were made to companies and universities to determine how electro-mechanical products are designed, how the interests of manufacturing and other constituencies are included during the process, and how computers are used. Of special interest was the kind, breadth, depth, and source of software in use.

The main finding is that the companies visited are *vertically integrated in the skills and facilities of product realization* and take the broadest view of their mission as manufacturers. The most advanced companies take a thoroughly intellectual approach to defining and improving their product designs and design processes. Further, they often build their own key manufacturing equipment and write their own key CAD/CAM/CAE software. They see this four-way integration (design--design process--equipment--software) as a key to their competitive strength.

The majority of the innovations observed were accomplished by the companies themselves, mainly utilizing no more than manpower support from software companies and advice from university professors. These innovations include very effective integration of design, manufacturing planning, and fabrication of complex parts (Toyota), and widespread and coordinated redesign of products to permit mass production efficiency with high variety and model mix (Nippondenso). Investment in hardware and software is extensive even at small companies which cannot afford to write their own programs.

Most companies keep design teams very small (as few as 10 for items as complex as an autofocus SLR camera). Teams are multi-disciplinary and management thoroughly extends and exploits the cross-disciplinary nature of their employees' engineering education by rotating them through different aspects of the design on each redesign cycle.

A major unanswered question concerns the relative effect of design management methods (such as task overlapping) vis-a-vis use of highly focused and integrated software in speeding the design process and creating effective products. The IMVP has emphasized study of the management methods in the past. This report shifts the focus toward technological support for the design process and finds it extremely effective. Also observed is the fact that when management formulates an engineering base for its manufacturing strategy it forces creation of new design processes and new kinds of product designs, and sharply clarifies the priorities for new software. Thus the boundary between "management" and "technology" essentially vanishes, mooting the unanswered question.

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I. Background

A. Sponsorship, goals, length of stay

I spent from June 3 to September 13 as a temporary liaison scientist at ONR ASIA, the Far East office of the Office of Naval Research, while on leave from the Charles Stark Draper Laboratory, Inc., Cambridge MA. ONR asked me to survey Japanese use of computers in design of mechanical products, to report on the state of practice in Japanese companies, and to determine research needs and trends in both industry and academia. The resulting report contains a mix of engineering, management, science, and technology issues. This is appropriate for manufacturing, a complex and challenging area where practical solutions are often needed before theoretical understanding is available, and where major innovations have come from practitioners.

Japanese companies have approached manufacturing with skill and depth. Many of their solutions go beyond the usual day-to-day and include significant long range thinking, providing clues to the nature and structure of the underlying intellectual issues. A major objective of this report.is to present these challenges and responses in the hope of informing both the industrial and research communities about where some of the world's best companies think the frontier problems are and what they are doing about them.

B. Methodology and prior visits

This is my seventh visit to Japan since 1974. On prior trips I visited mostly industrial sites because I found that industrial people were closer to real problems and solved them with remarkable ingenuity combined with significant intellectual depth. This contrasted sharply with university research in robotics, which in my view (in the US as well as Japan) tended to focus too much on far advanced technology and attempted to solve all robotics problems by enhancing the technology of the robot. Industry took a more balanced view and attempted to improve robot technology in feasible as well as economically high-leverage ways (mostly by increasing motion speed) and improve robot applicability to tasks by redefining and redesigning the tasks (mostly by pervasive and thoughtful product redesign). This combination has proven to be very powerful. I have written about this contrast in several venues [Whitney].

Companies visited represent heavy, medium, and precision industry. I identified many of them from prior visits, while others were identified and contacted by Prof Fumihiko Kimura of the University of Tokyo, whose collaboration is greatly appreciated.

C. Caveats

In a three month visit, it is not possible to obtain a statistically significant sample. I visited companies and laboratories that are leaders in one way or another. A typical visit took most of one day and involved from three to ten company personnel. Where capabilities or activities of different companies are mentioned below, they should therefore not be taken as having comparative value. That is, if company A mentioned capability X and company B mentioned capability Y, that means X and Y are being pursued in Japan, not that company A lacks capability Y.

Similarly, just because a Japanese capability is mentioned does not mean that this capability does not exist in other parts of the world or that other countries' companies and universities are not ahead in some areas.

II. Types of Products Covered in this Report

A total of 15 companies were visited, some more than once. A breakdown of types of products is as follows:

Heavy industry - machine tools (3 visits), cars (5), aircraft engines (2), construction machinery

Medium industry - car components (2), home appliances (1)

Precision industry - video cameras (2), disk drives (2), dot matrix printers (1), cameras (2)

Three visits were made to industrial research and development labs that create computer design tools, and 8 visits were made to university labs that do robotics or design research.

III. Information Sought on the Visits

My long-term research interests focus on how to structure design processes so that they achieve products that can be easily made, sold, repaired, upgraded, and so on, and to create computer tools to aid the design process in these ways. Japanese companies are well known for being able to design high quality products, to perform the design process rapidly, and to manufacture the products efficiently. Japanese manufacturing methods have been extensively studied, but the supporting or enabling character of the product designs themselves has not been emphasized in those studies.

When visiting a company I tried to determine information of the following kind:

1) What is the main outline of the product development process, starting from conception and concluding with construction of the manufacturing facility?

2) What computer tools support this process and where do they come from?

3) How long does the process typically take and how many engineers are involved?

4) How are the needs of manufacturing and other interests integrated into the design process and how are the inevitable conflicts between performance, cost, and manufacturability resolved?

5) What are the main challenges to intelligent and successful product design (for example, dealing with product diversification, taking account of business forces, working with designers in different countries, deciding how to use automation effectively, and so on) and how do the companies plan to meet these challenges in the future?

Usually, I and the company exchanged informal presentations, followed by lab tours and general discussions. In most cases, these discussions were quite exploratory since the companies are also interested in the above questions and constantly evolve their ideas. There was no questionnaire or fixed list of questions.

IV. Summary Findings

A. Company Methods and Priorities

1. The most advanced companies take a total view of manufacturing; they are vertically integrated in the skills and facilities of product realization; these are too important to be given to vendors

- they write most or some of their own three dimensional (3D) computer-aided design (CAD) software as well as many computer-aided manufacturing (CAM) and computer-aided engineering (CAE) applications, which are tightly prioritized and focussed on their own careful formulation of their internal design processes

- these companies, and others less advanced, make most of the critical manufacturing equipment they use and buy many low-value-added components for their products; most US companies follow the opposite strategy, making components and buying equipment

2. Most companies continually study and refine their design processes, information flow, CAD/CAE facilities, and design management methods, striving for major improvements in design time, design cost, and product cost

3. One third of the companies visited have developed their own design for assembly (DFA) methods and software; in some cases DFA is used in the traditional way to simplify the product's assembly while in others it has been reformulated and elevated to a new status of enabling new manufacturing strategies or focusing conceptual design efforts

4. Every company wants to design products faster, even though they are already the fastest in the world

- this requires vastly increased ability to predict performance and fabrication/assembly problems and costs very early in the design process

- the main strategy in use to design faster is to begin designing manufacturing systems and equipment before product design is finished; this is called "overlapping tasks"

- using incomplete information in this way is risky and requires intense human communication and carefully supervised release of partial design information; most companies say that designers' experience is the crucial factor in this process, not use of computers

- most companies have used cross-functional (i.e., product and process) design teams for years and also cross-train their engineers; the term "concurrent engineering" does not mean cross-functional teams but instead means beginning production system design well before product design is finished

- this process has not been perfected and many barriers between disciplines and departments remain

5. Companies boast of the strength of human communication and experience in explaining their design prowess, but underneath they worry about how to transfer this experience to computers

6. Japanese design teams are surprisingly small; except for cars, no team for products like cameras, copiers, printers, car components, or videocameras (up to 1000 parts each) was larger than 30; computers are unlikely to be of help purely for communication within teams, and this particular use of computers may be what the companies feel is not useful

7. Every company (except Sony) has trouble finding new engineers; increased design automation is the main response, but capturing real knowledge and experience is a serious barrier, and the overall quality and experience of some companies' design staffs may be slipping

8. Another way the companies attain rapid design is to overwork their engineers; long work days and small design teams are effective, but take their toll in other ways (fatigue, mistakes, difficulty hiring new engineers)

B. Computer Capabilities

1. Most companies use commercial CAD and CAE software made in America and many run it on US mainframes or workstations; the applications are typical

- the depth of penetration of CAD and CAE (numbers of terminals, degree of paperless operation, number of CAE examples) is impressive, even in small and medium size companies

- every company visited (ranging from 1700 to 250,000 employees) has equipped its designers with networked CAD systems;

2. Current commercially available CAD is weak in representing engineering information and in supporting process design and production engineering; it is strong only in drawing pictures

3. The best CAD observed was realistic rendering, and the best CAE observed was integrated car body styling, body engineering, and stamping die design and manufacturing; both of these were in-house developments

4. Companies feel that commercially available 3D solid modelers are too hard to use and cannot represent parts and products in sufficient detail to permit serious process analysis without bogging down under all the data; wireframe models are unintelligible to anyone except the original designer and thus are useless for cross-functional communication

5. CAE of products and computer-aided design of fabrication and assembly processes are either not performed at all or are done in a non-integrated way using collections of different stand-alone software sometimes linked by awkward data conversions; the exception is a few application-specific design systems written by the most advanced manufacturing companies themselves

V. Underlying Themes

Japanese companies' achievements in design and manufacturing warrant study. In approaching this project, I formulated several underlying themes in the hopes of fleshing them out. Readers of this report will find me returning to these issues repeatedly:

Management style vs CAD
What is manufacturing, what is design
Role of research at universities
Structure of the CAD industry

A. Management style vs CAD-which is more important?

The business schools and the engineering schools have differing views of product design. Several business schools, notably Harvard and MIT, have extensively studied the world automobile business to determine why the Japanese auto industry can deliver new models faster than their European or US competitors. The marketing value of doing so has long been recognized, and Japanese companies in other industries such as laptop computers and consumer electronics are similarly adept. Prof Kim Clark of Harvard and his former student Prof Takahiro Fujimoto now at the University of Tokyo say that the main reason is specific management methods such as overlapping design tasks that are normally done in sequence [Clark and Fujimoto]. In offering such explanations, the business researchers tend to ignore or downplay the role of computer design aids, such as computerized drafting, solid modelers, data management, rapid electronic communication, and so on. Several companies agree.

Engineering schools and researchers tend to ignore the management factors and look exclusively at the computer tools. To put the contrast bluntly, the business researchers think computers are commodities that anyone can buy and use, while management techniques are the product of decades of "corporate learning" that others cannot buy or copy. The engineering researchers feel that management practices can be copied and learned too, or are merely "social factors," whereas design and manufacturing engineering software, knowledge, and data about past designs, properly captured and deployed in computers, can convey considerable competitive advantage in terms of design speed, accuracy, and quality. Toyota says its integrated CAD/CAM system for stamping die design and manufacture has shortened this process by 23%. Most companies also stress the long term "corporate learning" that has gone into building their engineering experience and several databases of this experience that they have created.

In the following pages, readers will find plenty of evidence for both positions; opinion among the Japanese is divided and discussion is lively.

It should be noted that considerable misunderstanding can arise during discussions with Japanese engineers and managers concerning computers. The Japanese think of computer aids in three categories: data management, design software, and communication between designers. They tend to call the last one Concurrent Engineering software, a confusing and limited definition. They tend to want to avoid computer communication and so they often say they do not see the need for computer tools for concurrent engineering. It takes a lot of discussion to clear up this issue. Then they tend to agree that they can use all the engineering design and manufacturing/assembly software they can get their hands on.

B. What is manufacturing, what is design

"Manufacturing" used to mean metal removal or metal fabrication. In the US, the word has gradually gained generality but only a few people associate it with all the processes required to make a product. In Japan, among the most sophisticated of industry, university, and government people, "manufacturing" means all the activities of a manufacturing company, from marketing studies to shipping the product and following it up in the field. Financial and management factors must be included. There is no boundary between them. The broader term "product realization" is used among university researchers to capture this process and place it in the joint engineering-business context.

C. Role of the universities

University research on design in Japan is supported by many large and medium size companies who either join specific consortia initiated by one professor or who contribute equipment to a professor's lab. Government support is growing, although budgets are restricted at the national universities. The engineering and business schools take separate tracks much as the US ones do, but in both areas a lot of the research seems well targeted on industrially relevant problems and has a near-term character similar to what one sees in Germany.

A core goal of long term design research is to flesh out the idea of a computer-based "product model" that will link specific market and engineering specifications for a design object with general company design and manufacturing knowledge and capabilities. Knowledge is defined very broadly as including expertise, test data, past designs and their field performance, deep engineering understanding, catalog data, government regulations, and company standard practices and design rules. The companies do not yet think in quite these terms and currently see wide area distribution of, and common access to, existing conventional CAD data as their main problem.

D. Structure of the CAD industry and technology transfer routes

Japan does not seem to have a CAD industry such as the US or Europe has. Companies comparable to Computervision, Structural Dynamics Research Corp (SDRC), and Mentor Graphics do not exist. No Japanese workstation has yet gained the popularity of those made by Sun or Hewlett-Packard. Japanese companies have taken three routes to obtaining CAD and Computer-aided Engineering (CAE): buy hardware and software from the US, invest over decades in writing their own software, and a hybrid of these. Companies that write their own face the problem of long term support as technology and needs change, such as migrating to new hardware and integrating new programs into their existing software. But they have developed at least near-term solutions for these. (Nissan and Toyota have joint ventures with IBM and Unisys to support their home-grown CAD and sell it to their suppliers.) Companies that buy from the outside must accept their vendors' solutions to these problems and most have switched vendors at least once, a painful event. New switches will occur as workstations replace mainframe computers.

VI. Current Pressures on Japanese Industry That Affect Design Practices or Suggest Research Issues

Japanese society is changing rapidly. Some trends visible now are recent while others date back years or decades. Those that follow were brought to my attention during my visit but are echoed in many publications, most recently in [Cutler].

A. Labor shortage

Japanese industry has faced chronic shortages of factory floor labor since the early 1960's, when it was forecast that GNP would grow faster than population. This has forced pervasive and relentless automation onto Japanese industry, which has in turn forced a revolution in how products are designed. Now the shortage has extended to engineers and scientists. To maintain the standard of living, automation will have to extend to the field of design.

B. Deterioration of lifetime employment

Professionals are starting to discover the advantages of job mobility. At least 5% of employees voluntarily change jobs each year and the number is rising. Headhunter firms are springing up. An important result is that future design activities may not be carried out by people who have known each other for years. Risky design methods like task overlapping (see below) are likely to suffer. Computer design aids could help but the companies do not yet want to place strong reliance on them.

C. Shortening the design cycle

At the same time as the number of engineers is threatening to fall, the measure of competition has become rapid introduction of new products and new versions of existing ones. Companies have responded by intensively studying their organization and design process, automating key portions of the process, innovating management methods, and over-working their engineers. Several companies I visited spoke openly of lengthening the design cycle, possibly by silent industry-wide mutual agreement. Others resort to cosmetic redesigns, postponing more thorough efforts.

E. Globalization

Japanese companies are finding that they cannot export their management methods to their branches in the US and Europe. Overlapping of design activities is a risky approach since it requires starting a job before all the necessary information is available. Careful structuring of the design process, identification of the crucial information, and steady, deep communication between designers are required to keep serious errors from occurring. Non- Japanese engineers are not used to such communication, they shun the risks of this approach, and they do not work long enough hours to accomplish it. Few companies outside Japan study and improve their design practices.

VII. The Main Intellectual Issues

A. How Japanese Companies Approach Product Design

1. Definition of a manufacturing company

Several Japanese companies take a total view of their existence as manufacturing companies. They not only develop their own CAD software but also the most critical elements of their manufacturing and assembly equipment. On the other hand, they buy many of the components that go into their products. This keeps design staffs small (see below) and focuses the company on the essentials. *That is, they are vertically integrated in the essentials of product realization and see this end-to-end capability as a major competitive strength.* US companies are often vertically integrated in components and tend to buy their manufacturing and design facilities from a fragmented and undercapitalized vendor community. The Japanese approach reveals a stronger commitment to internal manufacturing excellence and provides vastly better opportunities for communication between product and process designers. As one person put it, "You learn by trying, not by buying."

Consistent with this commitment, many Japanese companies maintain production engineering as a corporate headquarters activity; it is often represented by an executive director, equivalent to an executive vice president in a US company. Thus production engineering has a strong voice at the very top of the company. US companies are often product-line oriented.

Toyota and Nissan provide most of their own CAD software, while Nippondenso provides a significant portion of its. Sony, Hitachi, Seiko-Epson, Fujitsu, and Nippondenso make their own robots (over 3500 at Nippondenso and currently increasing at 1000 per year). Matsushita makes its own circuit board assembly equipment. Toyota and Nissan have commercialized several of their CAD programs. Data and software compatibility are the goals.

Toyota, Nissan, and Nippondenso appear to have long term strategies for allocating resources to computerization of the design process. For Toyota and Nissan, the focus is on the engineering-intensive and time-consuming process of body styling and engineering, which normally suffers from huge data requirements and much trial and error. For Nippondenso the focus is on supporting both routine mechanical design and breakthrough product-process design for flexible production. Trial and error is not a big issue.

All three seem to favor achieving some level of end-to-end integration from concept to production engineering using admittedly approximate methods rather than delaying integration while perfection is reached in each of the calculation steps in this process.

Smaller companies naturally cannot afford such activities but many in the range of 13000 to 35000 employees make their own CAD software and most in the 4000+ employee range make key manufacturing equipment. An interesting exception is Mazda, which is selling off machine tool and transfer line divisions and using the funds to "in-source" some high tech, high value-added components that they once bought. This is the route of "survival" in their view.

2. Systematic approach

Every company I visited has a systematic, step-by-step plan for how products are designed. This is typical and not surprising. There is often a set of two to six prototypes spaced out at intervals during the process. Companies differ on when is the right time to introduce manufacturing and cost constraints and when to involve manufacturing engineers and factory personnel.

At Nissan, the first prototypes are built at the design center, whereas the last are made at the factory by manufacturing engineers or line workers. At Hitachi, VCR mechanism designers build the first prototype with their own hands. At both companies, design responsibility shifts from the advanced design office to the factory's design staff beginning with the manufacturing prototype. At Nippondenso, the design process is so closely tied to increasing automation that process engineers are involved from the first day so that the necessary novel process methods can be developed. At Sony, product function designers are led by someone with at least 10 years' experience, and they take account of assembly sequence and assembly-related tolerances during functional design. Hitachi and Nippondenso have each evolved rather different design evaluation techniques for improving assembly. Neither has integrated them with CAD but both would like to. Companies disagree widely as to whether functional designers should be equipped with computer tools to critique manufacturability and assembleability of their designs, or whether these tools should be used by process engineers.

The more sophisticated companies constantly review their design practices, including their deployment of computers. These "restructurings" and "reformulations" of the design process are intellectually challenging and involve defining new work styles, data requirements, and software support requirements. "We used to buy software and adapt our work style to it," says a CAD director at Nissan. "Now, we will define our next generation work style and obtain or write software to suit."

Many American companies went through "painful" reformulations of their engineering design methods in the early 1980's and typically report that they are now satisfied with the results. Japanese companies are never satisfied.

3. Integration of engineering and business

Many of the companies visited have identified a theme for their business that is reflected in their efforts to deploy computers and other automation. At Nissan, this theme includes world-wide design activities with uniform standards, techniques, and supporting software. At Nippondenso, the theme is to conquer product diversity efficiently in a mass-production environment using a combination of product and process design. At Mazak it is to be the prime user of the manufacturing equipment it sells, both to gain experience and to act as a living laboratory for its customers.

The consumer product companies recognize that marketing and product design are tightly linked. Nippondenso is especially good at identifying ways to design its products to meet the rapidly varying product mix of its biggest customer, Toyota. Toshiba's laptop computer designers spend part of every week going over customer inputs so that new designs will be well-received. Top executives set the specifications for the new product. At Nippondenso, the speed of the design process and the overlapped task method require top management involvement and fast decisions throughout the design process.

The long term trend toward, and competitive advantage of, smaller, lighter, and quieter products (computers, cars, and everything between) is driving companies into more CAD and CAE. Strength, noise, and vibration characteristics of products are more critical. Lighter parts have thinner walls that vibrate or magnify noise more than heavier ones. Extensive finite element analyses are the only design tool available. Super computers and super workstations are being increasingly recruited.

4. Integration of product and process design

Japanese companies have known for years what US companies once knew and apparently forgot, namely that product and process design need to be carefully coordinated. Until a few years ago, there was no special name for this in Japan; it simply was a fact expressed by the multi-disciplinary composition of design teams. Now the names simultaneous engineering, concurrent design, and concurrent engineering have come into use. In the US these are associated with attempts to apply computers to achieve this integration. The Japanese are puzzled by this development, and wonder if it is something new. Their ability to assess US activities is limited and I was questioned repeatedly on this point.

Many companies actively fear an invasion by computers into their human communication methods, thinking the US will catch up and that computer communications will be too weak to support the intensity that Japanese currently achieve. (See below for discussion of small design teams.)

5. Overlapping tasks

Overlapping design tasks, described above, presents numerous problems. Some academic researchers in engineering predict that overlapping can be used only on repetitive products like cars where there is a well-developed design process in place. However, Nippondenso claimed that it uses this method when developing quantum step improvements in existing products, an effort that means total redesign and many new manufacturing and assembly processes.

To support overlapping with analytical and computer methods requires creating ways to systematically detect and structure data and information flows in ways that are more sophisticated than IHI's methods for resequencing. Right now, all the companies depend on communication between engineers who have worked together for years. They can anticipate each others' actions and compensate ahead.

One should not conclude that the companies depend solely on this unstructured communication. In fact, Toyota insists that all information release is approved, but incomplete or preliminary information can be released with only low level approval whereas final information requires high level approval. Mazda has a highly structured set of over 20 design reviews that guarantee input from and information for all the relevant departments.

6. Small design teams

At many companies, the number of designers and engineers assigned to one product seemed small. For example, the following rough statistics apply to product function designers designing new products (not minor redesigns of existing ones) at several companies visited:

Videocamera	20 (two companies)
VCR mechanism for video camera	10 engineers
Car styling and body engineering	200 - 400 (range for three companies)
Auto alternator	20 - 40 (range for two companies; varies depending on degree of new manufacturing technology needed; includes some manufacturing engineers)
Auto engine	30 - 80(?) (estimates for two companies)
Machine tool	5 - 10
Autofocus conventional camera	20 - 30 (range for two companies)
Dot matrix printer	10 - 15 (depends on complexity)
Copier	30 for low-medium complexity
Construction crane/digger	30 - 40
Fuzzy control washing machine	15
Low-end hard disk drive (for PC's)	30

These figures accurately reflect the total manpower employed. Few or no assistants such as draftsmen are used.[1] "Engineers make their own drawings." Technicians and test engineers for laboratory evaluations of designs are not included, however.

Part count in these products (except cars) are in the range of 100 - 1000. As a rough average, one designer may be responsible for 20 to 50 parts. These statistics are remarkably consistent, as are the times quoted for converting market requirements into a final product: one to 2.5 years for all of the above except cars (4 years).

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[1] In Japan, "designer" and "engineer" are synonymous. In the US, a "designer" is a draftsman with a high school education.

Teams of 20 engineers are unlikely to have serious communication problems, indicating that face-to-face communication and phone calls will be sufficient and computerized methods will be unnecessary. My Japanese hosts agree with this.

7. Living with change

Many US companies structure their design processes by sequencing the tasks in the hope of maintaining control and avoiding change. This usually requires many formal design reviews and formal transfer of information packages from one stage of the design to the next. Yet changes routinely occur and have to be absorbed. When it comes to change, Japanese companies put their heads in the lion's mouth by adopting the overlapping tasks methodology. I asked repeatedly if this did not risk many design changes. In every case I was told that external pressures from the marketplace force even bigger changes on the process. The choice is to resist change or to learn how to live with, or even profit from, it. These companies have chosen the latter.

8. Standardization of design tasks

This topic, while mentioned by several companies, means something different to each. Basically, companies do not want their engineers to grope, but instead to know what to do, when to do it, and how. They want to reduce the detail that must be communicated as well as the need for lubrication from personal friendships and past design efforts. Global companies want all their overseas engineers to act like domestic ones so that their designs will be predictable and uniform. They want computer tools that contain the design process steps and have the necessary data ready for the engineer. In some cases, such as electromagnetic design (motors, alternators), companies have developed spreadsheet-like design interfaces that take in specification data and output performance curves. Only manual tradeoff analyses are available so far, but design optimization is being sought. One company wants a computer system that will literally orchestrate the actions of many designers on a network, requesting parameters from them one by one, performing some portions of the design automatically, and distributing the results back along with the next round of requests. It would base this system on its existing "design standard books."

Feature-based design and constraint-based design are current research topics that have a potential bearing on standardization. These attempt to provide a designer with the ability to deal with geometry on a CAD screen that is linked to a data file of attributes which give the geometry an engineering identity. Thus a cylinder becomes a feature called a tapped hole, complete with process plan, tolerances, and assembly insertion direction. A rule or constraint can say that the hole must be at least one diameter away from the edge of the part. The data files and constraint rules underlying the geometry provide standardization and save the designer time. The rules warn the engineer if a violation occurs.

No companies have such software, and none is commercially available. However, a few companies have implemented their own primitive feature-based design for some machined items and linked it to semi-automatic, knowledge-based process planners. These computerized process plans are more consistent than those produced by human planners. Everyone asks for rule-based systems that not only warn of violations but also recommend how to change or improve the design. The difference between these two capabilities is vast.

9. Bottom-up computerization

A researcher at IBM Tokyo Research Laboratory said to me "The US is too top- down oriented and Japan is too bottom-up oriented." He was referring to the two countries' different tendencies regarding use of computers. The US, in his opinion, rushes in to computerize something without really understanding it first. Often this means converting an existing manual process, in a factory or office, step for step into a computerized one. Grave inefficiencies are often converted at the same time. A careful analysis of the requirements on the process combined with the new capabilities of computers to meet those requirements would likely produce a rather different and more efficient process. The Japanese tend to study and improve a process manually for years ("kaizen" or continuous improvement) before computerizing it. Ironically, this often produces a process that runs very well without computers. This must hurt IBM Japan's sales, but the contrast is a real and instructive one.

The attention paid to design process organization in Japan is impressive. Where computers have been applied by buyers of CAD, the applications reflect availability of software. But where it has been applied by user-developers like Nissan, Toyota, and Nippondenso, it reflects their own assessment of priorities. All companies have basic two dimensional drafting on computer. Only a few have supercomputers for detailed fluid dynamics analyses. An informal survey of visit data indicates that product analysis has priority over process analysis, and that, among process analyses, forming (cutting, molding, bending) has priority over assembly.

B. What Some of the Research Issues Are

1. Rationalization of the design process itself

Many Japanese companies see study and improvement of the design process as a crucial element of corporate development. They take different approaches and emphasize different things. Few have systematic approaches. Apparently they conduct post-mortems, although no direct evidence of this was observed. The main topics I identified before and during this project are:

task sequencing
prioritizing design improvements
identifying tradeoffs
mustering experience

a) Task Sequencing

Understanding the design process requires seeing it in enough detail that opportunities for improvement can be identified. Saving time by resequencing has been recognized by one company, IHI, and an attempt to implement it with CPM is starting. Our own research [Eppinger et al] has identified an approach developed originally to help solve systems of simultaneous equations.

b) Prioritizing Design Improvements

Setting the priorities for which areas of the process need improvement usually involves the expected factors of time and cost. Car manufacturers early identified body engineering as a long pole in terms of time and cost and have focussed rationalization and CAD/CAE/CAM on it. Nippondenso studied the cost structure of automation as a function of how many models the machine was supposed to handle. They found that the cost of handling and feeding the many different parts grew faster than any other cost component. Nippondenso's highest priority is designing product and process together so that a change from one model or version to another can be accomplished essentially without stopping the production line.

c) Identifying Tradeoffs

Functional and process designers have conflicting needs. When design begins, "fights start almost immediately." Successful negotiation of these conflicts often benefits from finding a win-win solution. In a complex design, this can be difficult to do, and zero-sum solutions often appear to be the only ones. At present, engineering models of most products and processes are too weak to permit modeling a product completely in mathematical terms, preventing use of formal analyses of mathematical structures, for example, as a way of finding tradeoff opportunities.

d) Mustering Experience

Every Japanese company is proud of its accumulated experience and how it is used to make better products. This is both a source of strength and of weakness. Two potential approaches to capturing this experience have been taken: knowledge capture in expert systems, and data archiving. Several companies have internally-developed expert systems for specific tasks (shop floor scheduling, design of turn signal lamps, layout of car trunks and exhaust pipes, machining process planning) but everyone complains that there are few knowledge engineers, and methods of knowledge capture that engineers themselves can use easily are scarce. Several companies maintain datafiles of test results not only for comparing new and old designs but for direct transfer into design software. None has a good way to search such data bases.

2. Managing data - integrating, sorting, classifying

Car, ship, and airplane designs involve huge amounts of data. More than one company said their use of solid modeling has been held back by its inability to handle the huge amounts of data efficiently. Instead, the companies must use simplified solid models or wireframes. Simplification omits some crucial details that are necessary for interference checking or mold filling analyses, for example. Wireframes are impossible for factory personnel to interpret, impeding communication and product-process integration.

3. Converting experience to algorithms

Expert systems have been used in limited ways to capture expertise at some companies. Rules, "knowledge," and formulas are combined to create a machining process planner: the rules include METCUT data and the type of tool to use in certain circumstances, the knowledge includes how big radii should be or how feeds and speeds should be chosen, and formulas calculate wear rates and tool heating.

Such applications are relatively straightforward. On the other hand, no one has a way to convert the experience of a process or industrial engineer who judges whether something is easy or difficult to make or assemble. At an auto company, we saw an assembly engineer studying a 3D wireframe model of wrench access to tighten screws on several engine compartment parts: headlight assembly, washer tank, battery bracket. All are near each other and some interfere with the tool during fastening of the others. His priority was to use the same length wrench extension for all, adjusting the assembly sequence to make it possible.

4. Improving CAD for process engineers

Product designers have all the toys, it seems: FEM, supercomputers, etc. This helps them win a lot of arguments with the process engineers, who agreed heartily when I pointed this out. The first priority of the companies after supporting functional design and analysis is to make product design data available to the process engineers. Then they can at least simulate tool motions, robot actions, and cutter paths. No company I visited had fully accomplished this. The assembly engineer mentioned above had to position the wrench on each screw himself, using his mouse, buttons, and database information on the coordinates of the screw's axis. The screw head did not exist as a feature with an easily retrieved location, and no command "put the wrench on screw 22" existed. In fact, only one company showed me any assembly simulation.

No company has thought about assembly sequence analysis, much less disassembly (for repair) analysis. Nissan claimed that sequences can be worked out on the factory floor; once learned, they are not worth changing since model changeover time is too short for the necessary retraining. Sony says its engineers "know" how to plan assembly while doing functional analysis.

5. Understanding what DFM and DFA really mean

DFM (design for manufacture) and DFA (design for assembly) are well-known terms. They typically mean adjusting the design to make fabrication or assembly easier or less costly. I was told that our group's work and that of Boothroyd have been very influential in Japan in simplifying designs. Boothroyd & Dewhurst, Inc. and Hitachi's DFA evaluation software are popular. Sony, IBM, and Fujitsu have developed their own DFA methodologies and software.

At Nippondenso, these commercial DFA systems are not used. The explanation goes beyond the fact that Nippondenso's products apparently are a little too big in their opinion or that the rules in those methods do not seem to improve Nippondenso's current designs. Rather, Nippondenso has raised DFM and DFA to a higher level, meaning the creation of a design that permits a new kind of manufacturing strategy to be pursued.

Nippondenso has classified product flexibility into increasingly difficult accomplishments and reached each level after about a decade's work on each. The goal is to make different models of a product on the same equipment with essentially no changeover time penalty. The simplest level permits combinations of different versions of an item's parts to be assembled. The next permits different numbers and kinds of parts to be included in a housing that is always the same size. The hardest and most recently achieved permits different sizes of the same product to be made on the same equipment. Each step required increasingly radical innovations in how parts are designed, fabricated, and assembled. Nippondenso has identified increasing flexibility (or "managing diversity") as a corporate research topic and is seeking ties with universities in order to pursue it. A collection of good internal examples is also being compiled.

Nippondenso has its own DFA evaluation method which is consistent with the above approach. Appropriately, it spans much more than the act of mating the parts, which is the focus of the Hitachi and Boothroyd methods. Instead, Nippondenso evaluates 65 factors covering such high-leverage items as ease of switching from one model to another.

Fujitsu's DFA method stands between Boothroyd's and Nippondenso's in sophistication. It classifies parts in several ways (main, subsidiary, rigid, flexible) and scores the assembleability of each class separately. Assembly time and cost are estimated. An assembly score profile results, and is compared to the scores of other products. Priority in redesign is given to eliminating non- rigid, non-main parts, and to simplifying the assembly of the remainder.

Sony has a DFA method very similar to Hitachi's. A difference in emphasis is that Sony requires its designers to use it while sketching possible designs. The DFA score is one important way that alternate concepts are prioritized during this conceptual stage.

Toyota uses no formal DFA and asks quite seriously why anyone would need such a tool. Regarding well-publicized DFA activities at GM and Ford, Toyota designers ask if communication between designers and manufacturing engineers is really that weak at those companies.

These differences in approach and attitude indicate that the role of assembly analysis in product design is still evolving and capable of considerable improvement.

VIII. Typical Applications of Computers in Design

In general, US computers, both mainframes and workstations, and US software dominate in Japan. Due to space limitations in offices, Japanese laptop computers are seen everywhere. Except for a few programs, nearly all commercial software is from the US.

Specific applications of computers in design were much as one would expect. What is sometimes surprising is the depth of penetration of networked computerization at some companies (3000 workstations, 1000 Macintoshes, etc.), the degree of integration of many design steps in one computer system, and the commitment to growing their own capability internally and through joint ventures with software houses. In design, most companies visited are paperless or nearly so.

Figure 1 is a summary of design and product realizations actually observed at 13 companies visited.

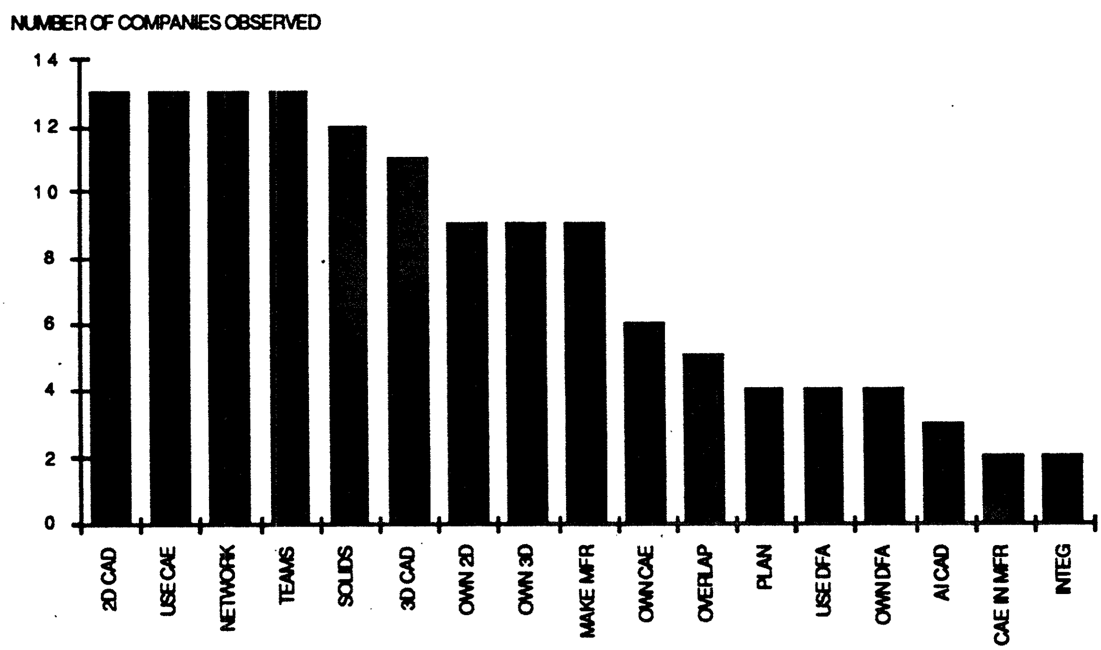

Figure 1. Distribution of Computer Technologies in 13 Companies Visited (See Notes)

Notes: 2D CAD = essentially all engineers have access to 2D CAD and few or no paper drawings are made except as informational output

USE CAE = the company uses some CAE in design

NETWORK = the engineers' workstations or terminals are networked together

TEAMS = the company uses cross-functional design teams

SOLIDS = solid modelers are in at least limited use

3D CAD = 3D modelers (solids, wireframe, or surface) are in use

OWN 2D = company uses 2D CAD software it wrote

OWN 3D = company uses 3D CAD software it wrote

MAKE MFR = company makes key manufacuring equipment it uses

OWN CAE = company uses CAE software it wrote

OVERLAP = overlapping tasks design methodology is used

PLAN = company has a long range plan for development of advanced CAD and design methods

USE DFA= company uses a formal DFA methodology

OWN DFA = company developed the DFA methodology itself

AI CAD = artificial intelligence applications to design are in use or being developed

CAE IN MFR = CAE is used in design of processes (molds, press dies)

INTEG = the company has at least one integrated end-end CAD/CAE/CAM software system

The data in Figure 1 were sorted and cross plotted and appear in Figure 2. Companies are arranged across the top, sorted left to right by decreasing number of the Computer Technologies observed at each company during my visits. The technologies listed above are arranged down the left side, sorted top to bottom in decreasing number of how many companies they were observed at. An entry of "1" means that the technology was observed at the company. A "0" means it was not observed.

	WIDE CAPABILITY						COMPANIES						LIMITED CAPABILITY
COMMON TECHNOLOGIES	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	0
	1	1	1	1	1	1	1	1	1	1	1	0	0
CAD/CAM/CAE TECHNOLOGIES	1	1	1	1	1	1	1	1	1	0	0	0	0
	1	1	1	1	1	1	1	1	1	0	0	0	0
	1	1	1	1	1	1	1	0	1	0	0	0	1
	0	1	1	1	1	0	1	1	0	0	0	0	0
	1	1	1	1	0	0	0	1	0	0	0	0	0
	1	1	1	0	0	0	0	0	0	1	0	0	0
	1	0	0	1	1	1	0	0	0	0	0	0	0
	1	0	0	1	1	1	0	0	0	0	0	0	0
	1	0	1	0	1	0	0	0	0	0	0	0	0
RARE TECHNOLOGIES	1	1	0	0	0	0	0	0	0	0	0	0	0
	0	1	1	0	0	0	0	0	0	0	0	0	0

Figure 2. Cross Plot of Companies vs Technologies

The "data" behind this plot are not particularly sound statistically since they represent what was observed. Especially at a large company, something not observed is just that and is not necessarily missing. Nonetheless, the "data" are interesting and suggestive.

Sorting the technologies by their common-ness across the companies shows that some technologies are very common, and the ones that are do not surprise us. Sorting the companies by how many technologies they have undertaken shows which companies are the most aggressive and advanced. Comparing these two kinds of data by cross-plotting the sorted lists allows us to determine if companies have built up their computer-design capabilities from the common to the rare or whether companies can jump in at any level in the hierarchy.

The ability to draw the diagonal line and contain most of the "1" s above and "0" s below indicates that computer technologies in design are accumulated and represent a long term company effort to build capability, understanding and infrastructure. It argues against computers being commodities. If it were possible just to buy computers and be able to "play with the big boys" then one would see "1" s all over the above chart.

A. CAD

CAD is naturally used by all companies visited for ordinary drafting in two dimensions. Obvious 3D applications like layout and interference checking have been mentioned above. However, most companies check interferences by eyeball inspection of 3D wireframe or 2D cross section drawings. Few use solid models for this purpose.

The most interesting computer applications are those in which the external appearance of a product can be so realistically represented that physical prototypes are not needed. Examples include Toyota's work on cars and Sony's on videocameras, but there are many. Toyota's goes beyond anything commercially available since it contains models of how their paints reflect light under different light and weather conditions in different cities in the world. Toyota has gone to great lengths in its home grown surface modeling software to guarantee that the designers can easily manipulate the surfaces (always difficult in past methods) and can evaluate them by methods they are familiar with, such as simulating reflections of fluorescent tube lights.

Toyota and Nissan both can simulate how a car interior looks; at Nissan the display is in stereo. The driver's field of view and windshield wiper clear areas (both subject to government regulation) can also be simulated. At Toyota, integrated CAD/CAM is used to design car interiors as well as exteriors, including use of numerical control (NC) machining to cut out full size clay models of dashboards and shift lever consoles.

B. CAM

All the obvious applications are represented here, too. The main one is creation of NC cutter paths directly from CAD data. Other commercially available applications in wide use are mold flow simulations and some kinds of process planning. The Australian mold package called Moldflow is popular. Most companies seem to use SDRC's solid modeler as the front end for most CAM and CAE applications since SDRC resells a wide range of third party software of this type and has taken care of the data conversion process.

C. CAE

Common applications in this category include FEM for stress, vibration, and heat flow problems, plus extensions thereof for complex turbulent flow studies. Commercial applications in use include NASTRAN, MARC, ADINA, and PAMCRASH (vehicle crash simulation). ADAMS is a kinematic simulator that is almost 20 years old but has recently come into wide use after SDRC attached it to their solid modeler. I was shown interesting simulations of how a washing machine rocks when the load is unbalanced, how a vacuum cleaner would track on its casters, and how a crane would react while swinging a heavy load.

Ambitious fluid flow simulations are used on super computers to evaluate exterior car designs for drag and to see if manifolds and injectors provide uniform distribution of fuel particles. Curiously, in spite of the progress made reducing the noise of products, no one admitted having CAE for noise evaluation. Structural vibration and rotor dynamics were often used as proxies for machinery noise studies, but fluid noise is not being simulated. One interesting simulation was of active noise suppression of air conditioner noise. Spectral analysis is involved, I think, but not fluid turbulence.

Except for some limited Monte Carlo methods, no one has software for evaluating tolerances or predicting fitup of non-perfect geometries. IBM Tokyo Research Lab plans to start such research, and some is underway at the University of Tokyo. No one agrees as to whether a statistical approach should be taken or a deterministic one. Statistical approaches sacrifice some accuracy in the highest precision studies, but deterministic approaches are threatened by combinatoric explosion.

Several companies perform failure modes and effects analyses (FMEA) on their products and one does so on manufacturing equipment, but there are apparently no computer tools for doing so as part of the design process.

Several companies acknowledge interest in design of human interfaces and one has some expert system work under way. Examples include how to position foot pedals and hand grips in cars and crane cabs.

IX. Research Needs and CAD Improvements Identified from Company Visits

The following list comprises both what companies specifically asked for plus what I think they would use if it were available, based on what they said, complained about, reacted to, or implied. Several companies have launched improvements to their present capabilities but would not discuss them with me.

A. Conventional CAD

In this category are simply enhancements to existing capabilities that may require considerable effort.

1. Better user interfaces to 3D design systems

Designers are trained on 2D systems and have a hard time adjusting to 3D. No really natural user interface to 3D solid modeling via a 2D screen is in use. Even for skilled operators, construction of a complex 3D model takes a long time. The mechanical designers rightly argue that current surface modelers were designed for cosmetic exterior design of cars and cameras, and are not suitable for mechanical parts. Exterior surfaces are in fact quite simple and the parts contain few features and have no "inside." Mechanical parts have substantial insides which contain a lot of detail, plus many complex features. This problem appears to be a major blockage to further penetration of solid modeling in Japan. Several companies felt that feature-based design might provide an avenue for attracting mechanical designers to 3D.

B. Advanced CAD

In this category are capabilities that are not available in any commercial CAD system but creating them may be a near-term proposition, since one can imagine what means and information could be mustered.

1. Practical kinds of feature-based design

Providing catalog information, routine engineering calculations (such as how to design bearing seats or choose fasteners), and national and international standards (such as standard fit classes), should be relatively easy to implement. Ready-made geometry backed up by parameterized models would provide a natural interface. The necessary calculations for bearing preload and life, for example, could also be stored for easy access. It would be a start on changing CAD from a "draftsman's interface" to an "engineer's interface." A little more challenging would be constraint-based rules such as enforcement of safety factors. Since Japanese designers are in most cases university graduates, this kind of CAD might be well received.

Commercial US software that offers or offered similar capabilities is that of Cognition and ICAD. Neither company seems to have made an impact in Japan.

2. Data archiving and retrieval of past designs

Some of this is being done now. It is unlikely that advanced data retrieval methods are being used, however. To do so would require developing ways of classifying designs, a decidedly non-trivial task that no one here is working on. Only rudimentary library search methods were seen in regular use.

3. Cost feedback to designers

It has been said that most designers do not know the cost impact of what they design. Presenting such feedback requires cost analyses of processes plus ways of analyzing the design to determine its cost components. Determining process costs would require doing some preliminary process planning. Materials costs would require a straightforward database. Vendor costs would require more than a database since estimates of negotiation results, discounts, shifting competition and currency exchange rates would be needed.

C. Broad-based CAD that Supports Full-scale Concurrent Engineering

1. "Experienced designs"

This interesting term was used by a researcher at a company to mean a feature- based datafile of previous designs that included proven process plans, statistical quality control results, process times and costs, customer feedback and so on. That is, the data would represent actual experience, not just plans. This would be of more than historical interest if a way were available to extrapolate the experience in the database as the designer altered the design to suit a new requirement.

2. DFM and DFA advice to designers

As mentioned above, companies want more than just design critics in their CAD systems. They want corrective advice. Providing this will likely require deep knowledge to be represented, although near-term implementations of some valuable kinds of feedback and advice could be easier. For example, a tolerance stackup analysis could be followed by advice on which elements in the chain contribute the most to the final error. The required size of a compensatory chamfer could readily be calculated. The opportunities for part consolidation could be identified based on kinds of material and joints between adjacent parts.

It will be much more difficult to provide advice on whether a particular assembly action is "easy" or not. At the moment, companies rely on experienced people who usually do not use hard criteria to make their judgements. No one tries to predict whether a particular assembly task design would cause fatigue or carpal tunnel syndrome, or how hard it would be to retrieve a dropped part. Some companies use simulation to predict robot cycle time but none feed this information back to the designer in the hope of finding a design that will yield a shorter cycle.

3. Ways to use partial information

The essence of the overlapping tasks method is to launch designs based on partial information and assume values for information that is delayed. Companies want ways to categorize this information according to how important it is, when it is needed, and how the impact varies depending on how much the delayed information, once it arrives, deviates from what was assumed. Among the possible difficulties are wasting time in extra design iterations or creating grounds for product liability if incorrect assumptions are not eliminated before the design is released. Past data, experienced designs, sophisticated change notification methods, and standardized designs will likely be utilized to solve this problem.

4. How to automate in the face of diversity and design change

Only Nippondenso appears to have given deep thought to this problem. Most companies use people where more flexibility is needed than current automation can provide. Most researchers try to make smarter automation. However, Nippondenso has merely applied a form of sophisticated planning to such designs as the alternators and radiators. They have extended the range of types or sizes they can handle in one automated system but they are still totally restricted to the factors they planned and designed for. One or two dimensions can be varied within a fixed range, for example. No major product configuration change can be accommodated without the same equipment redesigns that any other company would face.

X. Main Thrusts in University Research

I saw a great deal of very innovative university research in design during my stay. Some projects were motivated by discussions with industry while others were clearly the brain-children of the researchers. Topics covered below and in accompanying detailed reports are:

Knowledge Representation - qualitative reasoning
Direct Support for Designers - feature based design, partial designs,
 and conversion of requirements into realizations
Management methods and best practices

A. Knowledge Representation

Generally, there is a lot of artificial intelligence work going on in Mechanical Engineering. Most of what I saw is at University of Tokyo, but I also saw some at Kyoto University.

1. Tokyo University

In Prof Tetsuo Tomiyama's lab the emphasis is on creating a "meta-model" of engineering. A meta-model can contain sub models of typical engineering and can represent various "aspects" of a design, such as the kinematic, thermal, or structural portions of the behavior of something.

These meta-models are being constructed using Qualitative Physics, which provides symbolic representations of what are normally modeled by equations or logical constructions. Facts about nature (if a body with positive velocity experiences positive force, the velocity will increase) and about logical state changes in a system (if the wire melts, the coil will stop conducting electricity) can be expressed. These are stored in a library. A designer can construct a model of a physical system by describing geometry roughly, and placing library objects in relation to each other. The computer augments this basic model with a number of side effects (the engineer describes the coil but the computer describes the heating effect that might lead to melting). When the model is complete, the computer can determine that the motor will turn continuously between some discrete angular states if it starts in the right state.

Two applications of this idea other than analyzing designs are under way. One is "self-maintenance machines," and the other is simulation of designers' actions while designing.

The self-maintenance machine currently under study is a photocopier with sensors for copy density and other quality issues. The computer has a network model of causes and effects input by the user which tells what happens to each visible variable (copy density) as each internal variable (lamp brightness, lamp voltage) varies up or down. From this the computer can calculate a failure modes and effects analysis for certain failures. When a failure is observed, the computer reasons backwards to a set of possible causes and reasons forwards to determine a set of possible remedies. The remedy with the fewest side effects is chosen.

Simulation of designers' actions is less well developed. It employs several logical techniques to follow a protocol recorded from a real designer and can imitate his reasoning from a first concept to the discovery that the concept will not work, to trying a second concept, and so on. However, this system has no physical knowledge and apparently only simulates the logic. Future work will connect this work with the meta-models more directly.

B. Direct Support for Designers

At Prof Fumihiko Kimura's lab at the University of Tokyo, several varieties of CAD are being pursued. Some of their recent work on solid modeling and constraint-based design has been overtaken by new releases in the commercial world, such as SDRC's Level VI, but other work is farther ahead and will yield practical results soon. These include methods for predicting configurations of assembled parts, taking tolerances and imperfect geometry into account, and design of sheet metal parts where only part of the design is given explicitly by the designer.

The sheet metal design project is interesting because it attacks an aspect of design mentioned above, namely operating with partial information. In this case, flat sheet metal parts must obey requirements, such as having holes in certain places. However, portions of the part, especially of the perimeter, are unspecified in detail. It is known that other parts will intrude at some places, and that all the given holes and slots must be included within the part's boundary. The computer then suggests a perimeter shape, which the user can modify.

Another interesting area is called Top-Down design. This is similar in broad spirit to Prof Tomiyama's work but is more focussed, less general. The idea is to provide the designer with geometric features that have engineering knowledge attached to them. These features often come in pairs that operate together but normally belong to different parts (bearing and seat, screw and hole). The required knowledge is actually shared in the pair and ought not be separated out to the single parts. Some precalculations are also represented. For example, if the designer specifies the load on the shaft, the correct size bearing is recommended.

C. Management Methods

Prof Fujimoto's research on design practices in the world auto industry have been discussed above. Generally these follow a common business school research paradigm called "best practices." The goal of such research is not to work out new inventory control algorithms or accounting formulae but to determine what the best companies do and how it differs from what less-capable companies do. The research approach involves interviews, questionnaires, and statistical analyses of questionnaire results. One may find, for example, that companies with high model mix, JIT production methods, and democratic management methods are more likely to have high quality and low cost than companies with other management and operating practices.

Prof Fujimoto is about to launch a new study on how companies deploy assembly automation. Another project will study design and automation in auto companies, semiconductor manufacturers, and precision instrument makers. Each is a rather different industry with different production rates, quality requirements, and processes. In our discussions, I noted that differences in automation penetration in these industries do not depend as much on the attitude of managers as they do on production rate and the degree to which the processes are understood.

The questionnaire method has revealed some penetrating information that was not widely appreciated outside of the companies themselves. However, it can be difficult to make hard statistical analyses because the method does not admit the usual checks and balances, namely control sets and double-blind techniques.

D. Role of the IMS and other government activities

The IMS was originally proposed by Prof Hiroyuki Yoshikawa of the University of Tokyo, a pioneer thinker in product realization. While the current state of the IMS is beyond the scope of this report, it is important to note that the Japanese are not waiting for international consensus and are beginning to fund exploratory projects. However the IMS proceeds, it or its derivatives will improve communication between companies and top level researchers in product realization. The result will be new and more powerful design technologies built on the accumulated experience of the companies and the intellectual power of the universities. Conversion of the IMS results into useable software will be an interesting and instructive exercise because, as discussed above, some companies extensively develop their own design software while others buy it almost exclusively from the US. A successful IMS will probably cut Japan free of further dependence on the US for this vital ingredient of manufacturing excellence and at the same time solve a serious long-term problem.

XI. Are Japanese Companies and Universities Different from US or European Ones?

The major manufacturing companies of Japan, as discussed above, see themselves as responsible for the main skills of product realization. The resources are technology and people, and major investments have been made in both. European companies are similar, and in Germany, both the government and industry invest heavily in human resources through national apprentice programs.

Japan's smaller companies can keep up in technology with their bigger brothers (usually customers) because both the big companies and the government help. Big companies provide training and sell technology. Prefectural governments maintain large field services for training small companies on new manufacturing technology and software. America's Agricultural Extension Service operates the same way for the benefit of farmers but no corresponding program exists in manufacturing.

In the US, most manufacturing companies focus on selected aspects of manufacturing and leave the rest to vendors. In Europe, large companies (VW, Bosch, Siemens, Aerospatiale) tend to be more like the Japanese ones in the sense that they develop manufacturing and CAD technology internally.

Japanese companies tend to take time to mold their employees to their liking. This is facilitated by the lack of professional concentration in Japanese engineering education. Classes at the Bachelor's level are general and do not convey much deep knowledge. The curriculum is wide ranging and contains no required subjects. Students in "mechanical engineering" take subjects in software, information theory, image processing, and robotics. They graduate without seeing themselves as strongly mechanical in outlook or commitment. One company with a low-tech, mechanical image, needing electronics engineers for its modern products, hired the ME's who showed up and retrained them in electronics.

It is also easy to cross-train such engineers in design and manufacturing. This gives them what is called "universal experience." At Nissan, several key people planning and managing new CAD spent 5 to 15 years in manufacturing engineering or product design first.

XII. What Will Happen Next

I believe that we are on the threshold of a major increase in the capability of CAD/CAM/CAE, and my Japanese academic contacts agree. The stage has been set for implementation of first-level feature-based design. Once a few applications of this come into use, people will see the real potential and demand will grow rapidly. There are two elements to this potential: mustering of engineering knowledge, and redefinition of the user-computer interface.

Routine knowledge will be the first to be captured, such as catalog information discussed above. Second will be procedures that experts follow, initially without any deep background other than mimicry, later with some logic branching and case-based methods. The major output from such computer applications that will differentiate them from all past applications will be the first data models of products, in contrast to today's models of the drawing on the computer screen.

These data models will provide significant new capabilities linking product function design to fabrication and assembly process design. Even a little data on product topology defined by feature-connections has proven powerful in permitting complex assembly process planning to be automated [De Fazio et al], for example. The right kind of data structure definitions will make it relatively easy to create many new and significant tools of this kind; applications will snowball. Providing users with the ability to create these applications will be especially powerful.

The redefined user-computer interface will make computers routinely used for complex engineering, in contrast to today's use for complex drawing. The kinds of information than can be linked will broaden to include some basic process engineering at the functional design level.

However, process engineering in general still takes second place to function engineering on industry's priority list. The potential for redressing this exists in several areas, but neither the companies nor the universities have pressed the issue hard enough. The companies all offer the same explanation, namely that they have experienced people who can do that now. But they could have said that 20 years ago about ordinary CAD. In other words, the potential is huge, especially if it is joined to functional design to produce true concurrent engineering. Since many Japanese companies have newly-launched projects to improve design methods on top of their current capabilities, it is likely that application of computers in these projects will increase and will be extremely effective.

Design process management, information flow analysis, and design process improvement are just starting to be recognized as subjects for research and technology. Rapid progress can be expected in these areas because the main issues are not hard to model and several existing approaches are waiting to be applied. More generally, the potential for joining engineering and management methods in unified computer models of design is large.

Geometric dimensioning and tolerancing is one of many functional and process design areas that resists major improvement because there exist as yet no firm mathematical models of many of the geometric variations that have been used loosely in the past. The advent of solid models brought these shortcomings to light and international committees are working on them, but a complete model may take some years to create.

The most long range research involves trying to capture deep knowledge in new ways. We already have very sophisticated mathematical models of some phenomena that permit impressive simulations, such as crash and skid tests of cars. It will be a long time before current research on qualitative methods can challenge existing models. In the meantime, people will always be able to do better, faster.

The result is that researchers in many areas will have to choose what roles they think people and computers respectively should have in future design systems. One approach is to try to capture deep knowledge so that the computer can in many ways become the designer. The other is to acknowledge that such capture may be impossible for a variety of reasons. Then one would focus on aiding the designer in doing things that he/she could do in principle but should not waste time on or may not do accurately enough. Examples include sorting, matching, enumerating, searching, optimizing, maintaining constraints and enforcing rules, drawing evocative pictures, and otherwise empowering people to apply their deep knowledge.

The advantage of the latter approach is that practically every research result will be immediately applicable, and verification of the underlying methodology appears practical. Companies will thus tend to trust and adopt the methods.

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Office of Naval Research: Dr. Arthur Diness, CDR John Sheridan, Dr. Donald Polk, Ms. Roberta Perry

Charles Stark Draper Laboratory: Dr. David Burke, Mr. Richard Riley, Mr. John Barry, Ms. Judith Repetti

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XIV. References

[Clark and Fujimoto] Clark, K. B. and Fujimoto, T., "Overlapping Problem Solving in Product Development," Working Paper 87-048, Harvard Business School, rev April, 1988.

[Cutler] Cutler, R. S., ed., Engineering in Japan, papers from an invited session at the 1991 AAAS Meeting, Washington, DC. Indianapolis: Technology Transfer Society.

[De Fazio et al] De Fazio, T. L., and 10 co authors, "A Prototype for Feature- based Design for Assembly," proceedings of ASME Design Automation Conf, Chicago, Sept 1990.

[Eppinger, et al] Eppinger, S. D., Whitney, D. E., Smith, R. P., and Gebala, D. A. "Organizing the Tasks in Complex Design Projects," MIT Sloan School of Management Working Paper 3083-89-MS, Rev Oct., 1990.

[Whitney] Whitney, D. E. "Real Robots Do Need Jigs," Harvard Business Review, May-June 1987.