

Integrated Design and Manufacturing in Japan

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In 1991 I spent four months in Japan visiting companies to study how they use computers in the design of their products. My goals were to determine the outlines of the product development process; to find out what computer tools are in use and where they come from; to learn how the needs of marketing, manufacturing, assembly, field service, and other areas are taken into account during design; and to ask what the Japanese see as the main blockages to better product design.

I made 25 visits to 15 companies, which range in size from 1,700 to 450,000 employees and represent heavy, medium, and precision industries. Several of these firms are in more than one industry segment, and in several cases I observed the same product at more than one company (e.g., cars, video cameras). Visits typically lasted one day and consisted of interviews with designers and their managers, plus visits to design and prototype laboratories and computer rooms. In terms of their approaches to product design, their priorities, and the methods they use, I found remarkable uniformity among them.

By product design I mean more than how a product looks and feels to its user. My findings comprise brake systems, machine tools, and other aspects of products for which appearance is far less important than engineering performance. Design in this context means the total-enterprise process of determining customer needs and converting them to concepts, detailed designs, process plans, factory designs, and delivered products, together with their supporting services. This has come to be called the product creation process (PCP).

The Japanese Approach to Product Creation

The largest and most advanced of the companies I visited generally take a total-enterprise approach to design. In my terms, they are vertically integrated in the skills and technologies of product realization. One of the most important findings was that Japanese firms – unlike American or European firms – recognize the strategic importance of creating both their own manufacturing equipment and their own design software. Similarly, they recognize the central importance of their design capability to their overall way of doing business. The main priority they cited was to shorten the lead time for developing new products and thereby to shorten the cycle from one product generation to the next. Among the advantages of shortening lead time are that designers learn to do design better and engineers get more practice at engineering. These improvements compound, adding up to a growing lead. Other priorities include shortening the response time to customer orders, standardizing design practices worldwide, deploying proprietary databases and design rules, connecting all the designers to a common database, and enabling unique manufacturing methods that give a competitive advantage.

I found that the principal management method being used is task overlapping, i.e., beginning to design the manufacturing system and equipment while the product is still being designed. This approach, commonly called „concurrent engineering“ in Japan, far exceeds the typical US. definition of concurrent engineering: that the manufacturing people give plenty of feedback to the designers so that the product can be made efficiently. The Japanese have been doing the latter for years and frankly wonder what U.S. companies mean by „concurrent engineering.“

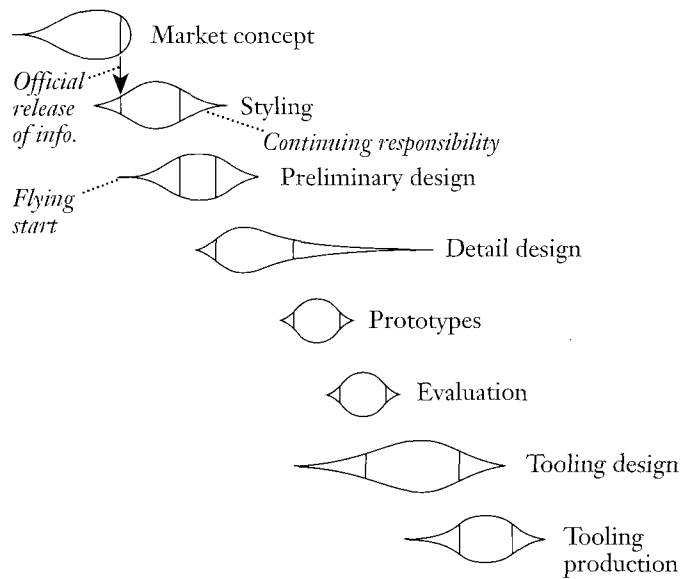
The Japanese meaning of „concurrent engineering“ is shown in Exhibit 1. Drawn for me by a Toyota design manager, this diagram breaks up the car design process into approximate generic steps and shows where the official release of information occurs from one step to the next. The height of each balloon schematically represents the manpower loading of a design step over time. The leading tail of each balloon, called „flying start“ at Toyota and „front loading“ at Nippondenso, an automotive components company, indicates early release of partial design information. When I asked at Toyota if this was an informal release „between friends,“ I was told emphatically, „No.“ Every release is approved by some manager, but official releases have approval from higher management. The trailing tail is called „continuing responsibility“ at Toyota, meaning that the designer continues to be responsible for the design even after it leaves his hands. If changes need to be made later to help manufacturing or another function, the original designer makes them, thus closing the information loop directly. At Nippondenso, the leading tail includes „early warning,“ meaning that downstream people provide critiques and updates on the suitability of designs to the upstream people. Nippondenso does not specifically identify a trailing tail activity.

The Human Element

Another important finding was that the bulk of Japanese design effort is, in fact, human. The penetration of computers is very uneven, though growing in focused and fascinating ways. Human experience dominates calculations and formal data; and human communication, mostly face-to-face, is the main tool for linking design activities.

Exhibit 1

Flying Start and Continuing Responsibility



My hosts boasted of the strength of their engineers' „universal experience,“ gained in on-the-job training. They feared electronic concurrent engineering based on electronic mail, expressing concern that it would impair face-to-face communication. On-the-job training is required because new Japanese engineering graduates have surprisingly little specific, deep knowledge in any one engineering field. University curricula do not contain required subjects, and many classes resemble survey courses. Students thus graduate with wide exposure to many technologies but without much deep knowledge or commitment to a particular technical discipline. Though American graduates are trained far more deeply, their backgrounds are narrower. Whereas U.S. companies complain about American students' lack of preparation for the real world and see the necessary in-house training characteristically as a burden, Japanese companies recognize that schools cannot provide real-world experience and look on in-house training as an opportunity.

The first year or two of employment at a large Japanese company has some of the features of boot camp, stamping the new hires – sometimes quite forcefully – with the desired features and style of the company. For example, a company that needed electronics engineers could not convince any to apply, so it retrained the most promising mechanical engineers who showed up. Such tactics are becoming increasingly necessary as more graduates opt for jobs in finance or insurance rather than manufacturing.

Because of this emphasis on human experience and communication, design teams are kept quite small. Teams that design products with 100 to 1,000 parts (autofocus cameras, dot matrix printers, internal combustion engines) typically consist of 20 engineers, with the largest team numbering 40 and many as small as 10. Much current U.S. interest in the use of computers to aid designer-to-designer communication appears irrelevant to the Japanese, since managing such small teams manually is relatively easy.

This small team size also supports deliberate efforts to broaden rather than narrow the engineers' expertise. For example, at a camera company, mechanical design typically falls into four areas: film transport, mirror box, autofocus lens, and shutter. Even though shutters are very difficult to design, there are no „shutter gurus.“ Instead, each designer rotates from area to area until he or she has done them all. Because new camera models emerge about every two years, in eight years each engineer has passed through the entire design range and at age 36, after two complete cycles, is ready to supervise a design team.

Doing Better Each Time

Japanese companies apply the „continuous improvement“ approach to each product design cycle. In fact, the term „continuous improvement“ sounds too easy going; „continuous compulsion“ might capture the sense more accurately. One consumer electronics company used the simple slogan „By Half,“ meaning, „cut development time, product cost, and product weight by 50 percent“ – and they very nearly succeeded.

Behind the effort to improve the product and the process on each cycle is continuous study of the PCP itself. Design by the overlapping tasks method is risky. It requires studying the specific process for each product and determining what information can be released early from design to manufacturing or from one step to the next. The ideal choice is information that is both unlikely to change later (or will have minimal impact if it does change) and useful enough to launch a significant downstream design effort. Identifying such information involves breaking up the typical design packages into smaller ones and determining the key precedences to find the earliest availability of,

or need for, information – or even to make that information available earlier by rearranging decision sequences.

For example, in preparing to make jet engine shafts, the manufacturing equipment designer needs to know first the length of the shaft and its maximum outside diameter. Then the engineer can tell whether existing machines can make the shaft; if so, the materials can be ordered. Only much later does the engineer need to know the inside diameter and details of smaller steps in the outside profile. Similarly, designers of blades that attach to the shaft can begin designing these, since they too do not depend on the inside diameter. If the shaft's design is released only as a finished package, after lengthy engineering analyses have determined the best inside diameter and detailed outside profile, neither blade nor equipment designers can start early.

While it is expensive for companies to develop and maintain the people and skills necessary to provide their critical manufacturing equipment and design software, having these people and skills gives companies the ability to set agendas for continuous improvement, based on their own experience. As one company engineer put it: „You learn by trying, not by buying.“ Developing equipment and software in-house also allows a company to integrate design and design methods with manufacturing and manufacturing methods in ways that are impossible if design tools and manufacturing equipment are bought. Depending on computer-aided design (CAD) vendors for design software, for example, means that one gets what the vendor thinks will sell widely – guaranteeing that one's capabilities will be no better than the competition's.

The ultimate goal of continuous improvement is perfection – an objective that the Japanese companies acknowledge they have not attained. Comments I heard include: „Our engine and transmission designers don't talk to each other.“ „We can't get our designers to switch from 2D drafting software to 3D modelers. They are comfortable only with the old ways.“ „I sure wish I could get the Taguchi method into this place, but our management is so conservative.“ „The disk drive designers will not explain or justify any design decision. We just have to make the drives as best we can.“ „The design cycle is getting so short that we are all tired out. Designers are making mistakes; some analyses are not being done at all.“

Going Their Own Way

One of the most striking observations to emerge from the study was the fact that many Japanese companies, large and not so large, write their own software to aid the design and manufacture of their products. Most U.S. companies of similar sizes and in the same industries buy such software. While it may be argued that this do-it-yourself approach is an artifact of conditions in Japan, I believe that it is part of an important new pattern in how advanced companies design and produce their products. One may cite several circumstances to explain why Japanese companies create their own design software. For one thing, Japan seems to have no domestic CAD industry. Companies such as Computervision, Mentor Graphics, and Unigraphics have no Japanese counterparts. Second, Japan faces a growing shortage of engineers and must take steps to leverage the existing ones with software to replace company-specific manual procedures that conventional CAD products do not support. Third, one often sees a puzzling degree of NIH (Not Invented Here) in Japanese companies that causes them to duplicate internally many things they could easily buy.

On the other hand, several clues indicate that the do-it-yourself strategy is more than an artifact of these circumstances. Companies write their own software knowing full well the disadvantages, some of which are discussed below. While bigger companies do it more extensively and better than smaller ones, the best I observed are not by any means the biggest. Instead, these high-performance organizations are distinguished by their particularly sharp focus on excellent product creation and their clear understanding of its central role in empowering their overall business strategy. Nippondenso is a prime example.

All the companies I visited do indeed buy some software from the U.S. CAD industry. What they write often duplicates what can be bought. This software becomes interesting when it extends beyond capabilities that can be bought or creates new ones. Since much of what is new comprises large bodies of code and does what cannot be bought, it is easier overall to duplicate the (often smaller) part that could be bought (usually the geometric modeler) in order to achieve software integration more easily.

My conclusion is that writing one's own software to support one's own PCP is part of a larger pattern of identifying strategically important PCP methods, skills, and technologies and developing them internally, rather than depending on commodity suppliers for them. This approach generates proprietary capabilities that convey unique competitive advantage.

Other elements of this pattern are:

- Seeing design as a basic corporate skill that combines management techniques (cross-functional teams, task overlapping, information structuring) and engineering technologies (3D graphics, relational databases, electronic mail, finite element analyses, computerized process planning)
- Achieving a new level of sophistication in concurrent engineering by capturing in computers the processes learned (the right sequence of decisions, the right people to be on a team, the most efficient patterns of

information flow) while developing team design

- Taking control of the skills and technologies of the PCP, including making proprietary critical manufacturing equipment, by taking responsibility for creating and continually improving them
- Identifying those chains of many design, analysis, and process creation steps that are essential to product performance or are on the critical path and converting them to integrated computerized systems

Many people are unconvinced that any such pattern exists. Others see only parts of it. Separating the idea of broad computer support for PCP from conventional CAD is difficult because many U.S. managers associate computers in design with commodity CAD, such as drafting. „We wouldn't write our own word processor, would we?“ asked an American manager.

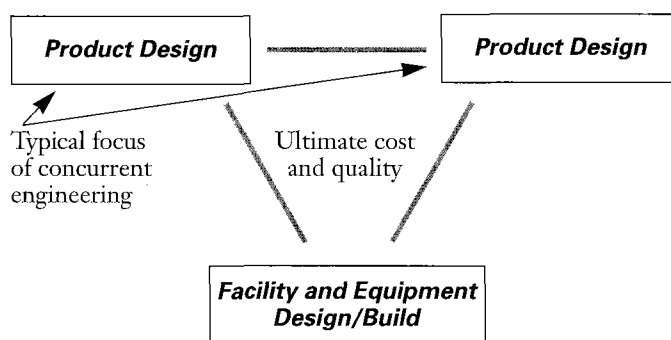
Separating the computers from the software inside them is also difficult. An experienced Japanese management professor said to me, „Computers are commodities. Anyone can buy them. The management processes are the unique capability and are the product of long-term corporate learning that cannot be bought or easily duplicated.“ An equally experienced Japanese engineering professor said, „That management stuff is just social factors. The computers contain data and calculation methods, including experience, that also take years to develop.“ The most telling quote, however, comes from a Japanese director of advanced CAD planning who said to me, „We used to buy computer systems and adapt our work style to suit. Now *we* are formulating our next-generation work style and will write or buy software to suit.“ This person, like his counterparts at other Japanese companies, is a former engineer – not from MIS – and he knows the situation and trends better than either of the professors. To him, it is not a matter of management methods versus computers but a combination of both that must be tailored to a company's methods and markets and to the particular technologies of its products. He is saying three very important things:

- His company recognizes something called a „working style.“
- The company pays very close attention to it, assigning a separate team to oversee it and subject it to continuous improvement.
- Working style is tightly linked to, and sets the requirements for, design software.

Closely related to in-house design of software is internal design and construction of facilities. In Exhibit 2, the two elements across the top are most often cited in current U.S. literature on improving design and manufacturing. According to the Japanese company that offered me this diagram, the picture is not complete until the third leg is added. To support all three legs, this company has written its own CAD software, several additional programs that calculate important engineering performance gauges, and its own design-for-assembly software, which it uses in a unique way as discussed below.

Exhibit 2

Ultimate Cost and Quality



The role of computers in the PCP is governed by long experience with a manual design process. A number of my hosts contrasted the U.S. tendency to computerize quickly without understanding the process, thus automating some very inefficient procedures. At the same time, they criticized themselves for being too slow to computerize, always looking for the next improvement in the process. *Yet* their logic is compelling and has a strong parallel in traditional process automation: You can't automate something you don't understand.

From Islands to Systems

The Japanese technique is to develop and learn the process manually, subject it to continuous improvement, conduct postmortems, and establish separate organizations charged with identifying opportunities to computerize. These organizations are staffed by veterans of the process and are often called CAD planning departments. Their job proceeds in two steps. The first is to create what are commonly called „islands of automation“ in the manufacturing arena; the name applies equally in the design arena. An engineer or member of a CAD planning department writes a program to do a specific calculation, such as a stress analysis of a connecting rod or fluid flow in an intake manifold. Repeated use of the program improves its accuracy, and perhaps other programs are written to do other calculations.

This process may continue, with the islands getting better and better. Alternatively, someone may decide that the time has come to link these programs together so that all the calculations for design and manufacture of the item can be done without manually transferring the output of one program into the input of the next. The obvious question is whether the individual islands are accurate or mature enough to justify the large effort of integration, or whether some steps required for a fully integrated system are still unsupported except by primitive estimates, experience, or other manual methods.

I have found that several Japanese companies have identified this integration step as distinct and worth pursuing even if the islands are unevenly developed. There seem to be two reasons: First, integration brings great speed advantages, eliminates manual data transfer errors, and puts many dispersed decisions in the hands of one or a few people, whose expertise thereby rises. Manual intervention, such as correcting oversimplified computer results, may be used to bridge over the weak spots. Second, integration represents a learning opportunity and challenge of its own, which can be carried on concurrently with longer-term efforts to perfect the islands. Integration requires marrying previously separate data, methods, and people, and reveals previously undetected errors in data and inconsistencies in methods. It also tends to connect and even equalize functions that are often culturally separated, such as drafting and engineering calculations, creating an engineering-driven process rather than a drawing-driven process. In this way, CAD changes character entirely.

The most vivid example is Toyota's integrated car body styling, body engineering, body stamping die design, and die manufacture (see Exhibit 3). This is an unbroken digital design, data, engineering, and fabrication chain from the input of stylists' sketches to the machining of the dies. The process includes a crucial step called „formability analysis,“ which determines whether the stylists' shapes can be made or not. The analysis must be done early and quickly so that the outer body data can be frozen and follow-on design can occur. Time-consuming clay models are not used to create design concepts, but only as displays; they are carved by computer-controlled milling machines directly from the database.

At Toyota, body styling and engineering is almost paperless. The stylist sketches original designs as before, but these are entered into the computer by a skilled computer graphics operator. These two people then refine the design together. They use simulations of many common design studio tools. For example, they shine simulated lights on the shape in order to judge the reflections. The final shape is carved into a quarter-scale clay model for executive review. Such a cycle takes only a few weeks, compared to several months by the old clay model method. The resulting data are used to launch body engineering, formability analyses, design of inner support panels, creation of stamping dies and associated tooling, generation of manufacturing schedules, and creation of cutting machine and inspection machine commands.

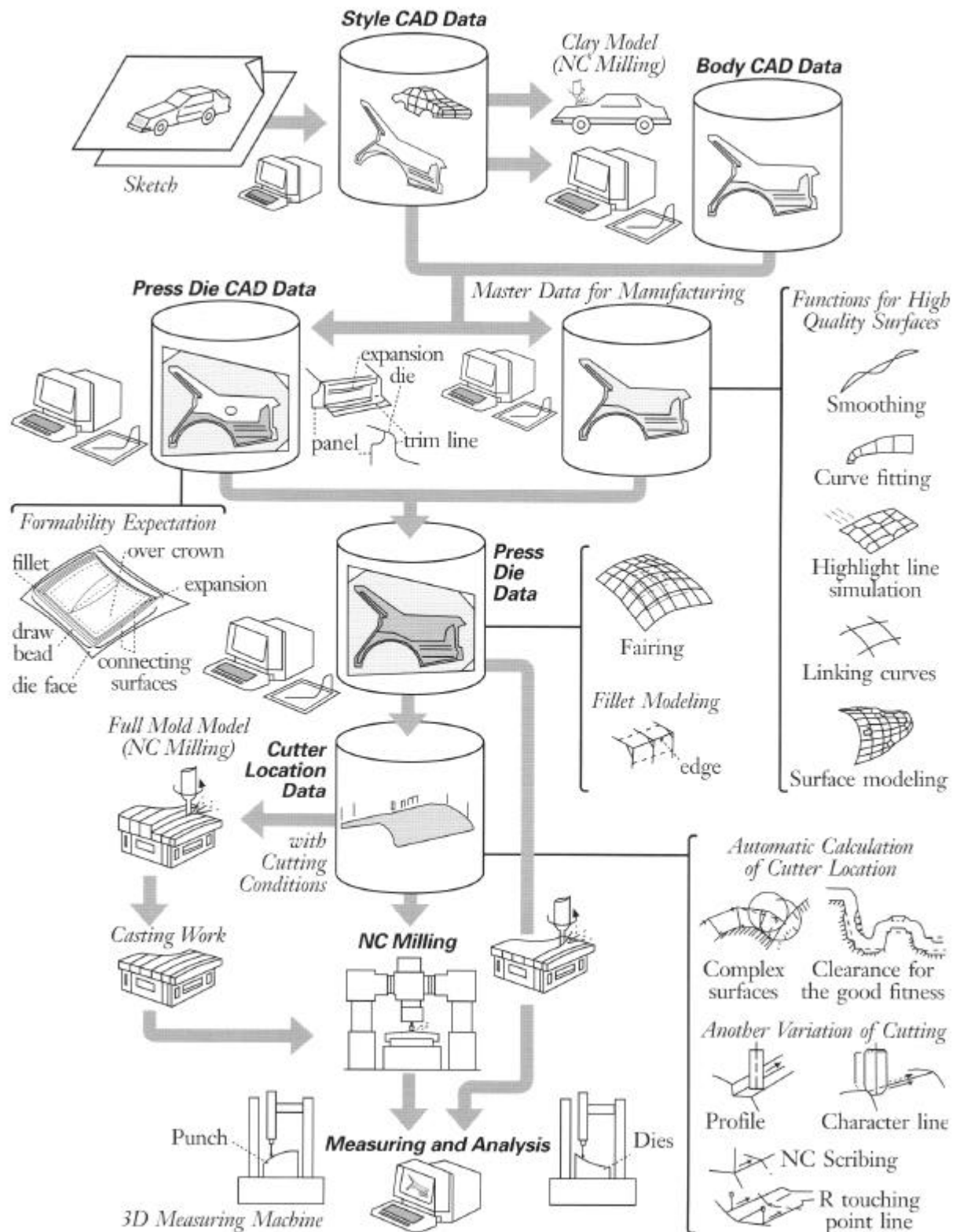
Toyota has been using this system for about five years. While it is not without shortcomings, it's the best of its kind. Of course, every car company does the same calculations in its own way, and many of these are computerized. But none are as fully integrated. Though Toyota's advanced formability analyses are admittedly simple and based on pre-existing hand-calculation methods, they are familiar to the engineers, avoid all known disasters, and ensure that die design, always a time-consuming and expensive process, is shorter because much of the trial and error has been eliminated. The simplicity of the analyses ensures that the engineers understand and trust them – an essential ingredient in getting the engineers to use the system.

Careful attention to the user interface is also essential. For example, the item labeled „highlight line simulation“ in Exhibit 3 allows the stylist to continue using studio skills and methods in the new software environment.

Computerized integration has another powerful advantage; It permits rapid changes in the design and allows those changes to ripple efficiently through the process. I noted that the overlapping tasks method is risky. The risk, of course, is that later tasks will use information that is incomplete or imprecise and will have to be partially done over if that information changes. I asked my hosts about this and was told repeatedly that change is inevitable. „Much larger changes come from watching the market and our competitors. Changes caused by task overlapping are usually less severe.“ The message seems to be that, rather than fighting change, these companies have decided to learn how to live with it. Integrated computer tools are one way of doing so.

Exhibit 3

Die Design to Fabrication Integration



Source of information: Toyota

The design software these Japanese companies are writing is mostly advanced three-dimensional solid or surface modeling, although some companies are still using two-dimensional drafting software they wrote years ago. While Toyota and Nissan both date their first efforts in CAD to around 1965 (when Ford and GM also made

their first efforts), the software I was shown appears to have been first written in the late 1970s, with many upgrades since. The smallest company I found to have written such advanced software has 13,000 employees; smaller companies had bought nearly everything. The largest companies have integrated some key design and analysis sequences, such as the Toyota approach discussed above.

Whether or not they have the resources to produce their own design software, Japanese companies implement massively whatever they decide to use. In Japan, engineers do their own drawing; there are no draftsmen. Every company I visited had its engineers working on networked computer terminals, not drawing boards. One computer or terminal for every two engineers is judged sufficient, though most companies have fewer computers at the moment. It was impressive to walk into one automotive company's design center and be told that there were 1,400 design terminals and 3,000 PCs (including 1,000 Apple Macintosh computers) all networked together.

Computer-Aided Engineering

Most companies buy their generic computer-aided engineer (CAE) software, principally from the United States. This includes stress, thermal, fluid flow, and car crash simulations (the latter from France), analyses of how molds and castings fill and cool (from Australia), how robots and machine tools move, and so on.

Many Japanese companies have written specific engineering analysis programs. Examples include optimizing internal shapes of dot matrix print heads so that the print wires can be inserted by robot; tracing rays of light through multiple lenses, accounting for a camera company's wide range of proprietary optical glasses; following individual fuel particles from the injector exits to valve openings so that gas mileage can be raised; and improving strength-to-weight ratio of mechanical parts so that products will be lighter but won't rattle or vibrate, even though they are thinner or more slender.

Except in the areas of car body styling and engineering, there is less integration of CAE than there is of conventional design and manufacturing. CAE still consists of islands of automation with awkward conversions of data from the design database to the form needed for analysis. On the other hand, integrated conventional design and manufacturing, without any intervening analysis, is much more common. A typical example is the creation of three-dimensional part shapes in the computer, followed by automatic process planning for manufacturing them and automatic generation of numerical control commands to the machine tools.

Such applications can be found at many advanced companies worldwide. However, the number of small companies in Japan that are at this stage may be unusual. This fact may reflect the strength of the supplier base underlying the large companies.

Design for Assembly

While automation of the design and fabrication of single parts has received a great deal of attention for decades, assembly has only recently been recognized as an important area for design improvement. Thus, attention to assembly is an indicator of maturity in a company's PCP. One-third of my hosts have written their own Design for Assembly (DFA) software. All have taken different and interesting approaches, either in defining what to judge about an assembly or in choosing how to use DFA to influence the design process as a whole. What I saw was at least as sophisticated as the DFA practiced in the United States. Some companies have raised it to an art. Others wonder what the fuss is about and have not identified a specific DFA step in their PCP or conceived specific procedures or software for accomplishing it. Instead, assembly is considered more or less continuously throughout the process.

One company I visited must deal with an enormous number of versions of its products. Its DFA process gives preference to parts and assemblies that can be switched easily from one version to another or that are common to many versions. Another company makes intricate mechanical devices to be assembled by robots; product life is about 18 months. Assembly analysis has been compressed into the concept design phase, and DFA scores are used in selecting concepts for further development. Another company classifies parts and assemblies into „critical“ and „secondary,“ then attempts to simplify the critical ones and eliminate the secondary ones. Secondary ones that present assembly difficulty (a floating attached wire, for example) get especially low scores. In the United States, DFA at its best is used to simplify the design by consolidating parts. However, it is often delayed until the details of the design are known, sometimes even until prototype parts are available.

The most limited scope for DFA is to make assembly easier. The broadest scope I found in Japan was at Nippondenso. Here, DFA has been merged with Design for Manufacture (DFM). The intent is not just to simplify manufacturing and assembly, but to enable entirely new methods of making a product. New methods are required because Nippondenso faces a relentless increase in the variety of its product models. Its products are sold mostly to OEMs and face stiff cost-performance competition. At the same time, because its customers practice just-in-time manufacture, ways must be found to switch models at arbitrary intervals without any „cost“ in downtime, investment in fixtures, or excess capacity. To meet the high production volumes and high quality

standards of its customers, Nippondenso automates as much of its assembly as possible. But automation normally does not support the rapid changeovers that are needed. Nippondenso identified this basic challenge nearly 20 years ago and has had an ongoing program to meet it ever since.

Over this period, the company has solved successively harder variety-changeover-automation problems. First, it attacked small items, using a method in which parts of nearly the same shape and size but different function were substituted for each other to create the required variations. It then extended this method to large products. Most recently, the method has been applied to products in which different models have radically different sizes. This is the hardest kind of variety to absorb on one piece of automated equipment; the typical response is to build one machine for each size or to narrow the size range. Since demand for each size is so unpredictable, the usual method results in overcapacity, wasting money and floor space, the latter being critically short in Japan.

Risks and Advantages

Companies that commit to making key manufacturing equipment shoulder the responsibility for creating and maintaining a wide variety of capabilities and skills. As with other things, this responsibility is either a burden or an opportunity. At one U.S. company that rejected it as a burden, a somewhat dissident engineer told me, „When we have a problem and do a root causes analysis, one of the causes often is ‘we do not have control over design and production of the manufacturing equipment.’ Yet top management does not see the importance of this lack of control.“ On the other hand, at a Japanese car company known for buying non-strategic components (i.e., components not in the crucial body-drive-train-interior group), I saw equipment being built to manufacture a simple commodity suspension strut that could easily have been bought. Apparently, building a nonstrategic part and the necessary manufacturing equipment in-house is deemed a small price to pay for having the skills available when they are really needed for building strategic parts.

Similarly, a well-known risk in „rolling your own,“ as in-house software development is called, is that the company must keep up the software, support training and user manuals, and absorb changes in computer technology. The Japanese are now facing the last of these tasks with some urgency, because most of their integrated CAD/CAM/CAE is based on large mainframe computers that can no longer provide the speed of response that more complex product designs and modeling software demand. Conversion to workstations is on their agenda, but this technology is changing so rapidly that no one is eager to make the switch. Even so, Toyota has 350 outside programmers plus 200 of its own constantly writing and supporting a wide variety of software in-house. Both Toyota and Nissan have long-standing strategic alliances with IBM Japan and Nihon Unisys to write design software for in-house use and for sale to their respective suppliers in order to unify the design process and data formats up and down the supplier chain. PC versions are available to smaller suppliers.

For these companies, the advantages of „doing it yourself“ clearly outweigh the risks. These advantages include the obvious ones, such as design speed, ease of sharing data, and accuracy of results that come from integration. Less obvious advantages include the ability to absorb change more easily; to accumulate and retrieve corporate design data; to capture a home-grown and carefully tuned design methodology, standardize it, and make the designers use it; to empower new hires to operate at nearly the level of experienced engineers; to transfer Japanese methods to U.S. and European employees as the companies expand worldwide; to transfer design skills and facilities to members of the supply chain Keiretsu as part of the larger process of improving suppliers’ capabilities (a major strategy of Japanese supplier relations); to gain control of the process of continually improving the PCP; and to decouple the creation of advanced design methods from the somewhat limited capabilities of CAD vendors who want to sell generic products.

Long-Term Trends

The boundary between design and engineering is blurring. Design is crossing cultures and time zones, playing a key role in a company’s ability to create products and production methods mated to customers and markets. Old-style geometric modeling is now less important than the management, organization, retrieval, and processing of all the information, including geometry, that characterizes modern design.

The capabilities needed to support these trends are not available as off-the-shelf products from the CAD industry. A company that wants a distinctive and superior PCP must take responsibility for first developing its own and then supporting it from within.

Once, one person could hold in his or her head all the knowledge needed to design and manufacture a musket, a bicycle, or even an automobile. When products became too complex for this method, the „Ford approach“ was applied, in which designers and engineers were specialized. Each did his or her little part of the job and passed it on, along with the responsibility, to the next person. The disadvantages of this approach were eventually recognized, and assembly lines gave way to the cross-functional team approach.

As we head into the next century, many U.S. companies are using the team approach – while in Japan the next-generation approach is emerging. There, the individual steps in the team approach, including the data require-

ments and flows, the calculations and displays, are being studied in detail. Places where the process depends on increasingly scarce human experience are being targeted for extra data gathering or artificial intelligence approaches. The arrangement and structure of the PCP are being optimized, and key portions are being transferred to computers. The most advanced companies realize that a computerized PCP is not a commodity, but a proprietary resource that captures internal knowledge and data that were developed from and depend on the technical characteristics of their products and the experience of their people. This kind of PCP, almost by definition, cannot be bought, but must be built in-house.

Daniel E. Whitney is with the Design and Automation Technology' Group at the Charles Stark Draper Laboratory in Cambridge, Massachusetts. His work includes research and consulting in product design, design methodologies and best practices, and development of computerized design tools. He wishes to thank the Charles Stark Draper Laboratory, Inc., for its support during this study; the Office of Naval Research Washington and Tokyo offices; and the staff of the companies and universities who served as his hosts.