LOCKHEED ADVANCED DEVELOPMENT COMPANY (LADC), AKA SKUNKWORKS, MAY 12, 1993

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Lockheed is one of America's largest defense contractors, with 71000 employees and sales of over $13B in 1993. While it no longer makes passenger aircraft, it produces C-130 transports, F-117A and F-16 fighters, and is a major contractor for the F-22. I visited LADC, also known as the Skunkworks, which has designed and built unique, advanced, low production quantity aircraft since the 1940s. LADC was formed as a separate company in 1991 after its existence was made public. Under the leadership of Kelly Johnson, it developed interdisciplinary design techniques that led to designs that broke the state of the art and delivered aircraft in very short times.

Some Characteristics of Aircraft Design and Production

Military and civilian aircraft are different in important respects but are similar in others. Major characteristics are summarized in Table 1.

Characteristic	**Military Aircraft**	**Civilian Aircraft**
Customer	Single Customer	Many domestic and foreign customers
Complexity and Equipment Density	High	Low
Design Driven By...	Performance over Cost	Cost over Performance
Level of Mechanical Stress	High	Low
Typical Number of Parts	Millions	Millions
Typical Development Cost	$2B (F-117, late 1970s-early 1980s)	$5B (Boeing 777, late 1980s-early 1990s)
Primary Structure Materials	Composites or Aluminum Plus Composites	Aluminum
Number of Development Personnel	Approx 2500 (F-117)	Approx 5000 (777)
Time to Develop	31 Mo to First Test Flight, 59 Mo to IOC (F-117)	Approx 5 yrs to First Test Flight (777)
Typical Cost to Customer	$50M (F-117)	$120M (777)

Table 1. Comparing Some Characteristics of Military and Civilian Aircraft

The point of this table is not to show that one type of plane is harder to design than another but to show that both are complex, expensive, time-consuming, and difficult. Military aircraft designers worry less about cost and more about achieving performance specifications. At the same time, the customer often changes the specifications during design and complicates the process with a variety of procurement procedures and regulations. One defense contractor estimated recently that its response to procurement regulations or actions accounted for 20% to 40% excess costs compared to civilian aircraft design and production at the same company. As described below, the Skunkworks, due in part to its secret status, the advanced nature of the planes it was developing, and the speed with which they were needed, was able to put in place a relationship with the Air Force that streamlined many of these difficulties. The principles of this relationship are called the 14 Basic Operating Rules. (See Table 2 below.) LADC tries to keep these Rules in force today when running new projects.

Civilian aircraft designers have customer relations difficulties of another kind. Different airlines demand their own design details, either to maintain a consistent look and feel for customers or to make maintenance and training easier. These details mostly affect the aircraft's interior, but they require most aircraft to be quite different from one to another. Prior to the 777, Boeing spent a very large portion of its design effort trying to satisfy the airlines' special demands, complicating both design and production. Another difficulty lies in "local content" laws. In order to sell planes to other countries, manufacturers must buy significant parts of the plane in those countries.

These problems add up. Until recently, one domestic manufacturer was experiencing 25% rework on every plane built, regardless of how many years it had been in production. One of the main benefits Boeing has gained from using CATIA for all of its 777 design has been reduced rework of parts during assembly, including improvements in the fitup of purchased parts and assemblies. The 777 is also the first Boeing plane to have a modular interior design, making it easier to suit different customers.

Designers of civilian and military aircraft face different technical challenges. The specifications of military aircraft usually focus on speed, range, and payload, while those of civilian aircraft include the above plus severe limits on cost. In many cases, design complexity rises because cost is a constraint, eliminating or restricting some kinds of design or manufacturing solutions and thereby reducing the designers' range of choices. If cost is not an issue, it may be relatively easy to find a solution.

A case in point is the use of composites in aircraft primary structure. When performance dominates the design process, as in fighter aircraft, composites are often the material of choice due to their high strength and stiffness to weight ratio. In fact, they may be the only feasible material when the plane must be invisible to radar.

However, a recent Boeing[1] study of a possible High Speed Civil Transport (HSCT) indicates that no economically feasible and technically adequate design is currently possible at all: planes made of aluminum weigh too much and cannot take off or land on common 11,000 foot runways while carrying an economical number of paying passengers; a composite aircraft will be light enough but, at current material prices and using current manufacturing techniques, will cost so much that it will never make money for the airlines given the prices people are expected to pay for tickets.

For both civilian and military aircraft, the result of these and other characteristics is that design is becoming more and more difficult, requiring more and more specialized knowledge about materials, manufacturing, avionics, costs, stresses, electro-magnetic radiation, safety, and government certification. The natural response to this increase in complexity is specialization of the design force. In many industries, such as shipbuilding and automobiles, this was the trend for decades. But specialization brings several problems. The number of design engineers rises and their knowledge of the others' skill areas drops. To manage the design process under these circumstances, design was converted into a factory-like operation in which each step was done by a different group of experts, who passed their work on to the next group. Even when the design is a relatively routine extension of past designs, as is often the case in automobiles, this "assembly line" method of design resulted in products that took too long to design, were hard to make, had low quality, and cost too much.

When Kelly Johnson put together his first design-production team at the Skunkworks in the 1940s, he was aware of all these problems and tried to overcome them with his own management methods and tightly knit team. The methods bear a strong resemblance to what is called Concurrent Engineering (CE) or Integrated Product-Process Design (IPPD) today.[2] Now, LADC is faced with the challenge of extending Johnson's methods and making them work without some of the advantages of a special relationship with an understanding customer that obtained in the secret past. A major challenge is to recapture the benefits of a small team (originally 23 engineers and 103 mechanics) when modern aircraft require teams ten or twenty times that size.

Outline of the Skunkworks Methods[3]

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[1] "High Speed Civil Transport," Program Review, anon, Boeing Commercial Airplane Group, no date.

[2] In the automobile industry, these are called Platform Teams. Now that they have been in use for 5 to 10 years, their shortcomings are starting to emerge. This issue is discussed in accompanying reports on the auto industry and specific companies.

[3] Adapted from "The Skunkworks Approach to Aircraft Development, Production and Support," LADC, August, 1992.

The SW's methods derive from the principle of simplicity in every aspect of work, from administration to design solutions. The push for simplicity operates in the face of strong pressures from within and from the government to increase the number of people, reports, specifications, oversight meetings and briefings, pages of contracts, and so on.

SW programs are characterized by

- need to get a new capability operational rapidly
- requirement for technological breakthroughs
- willingness of the contractor and the government to accept risks
- use of prototypes to reduce risk
- design for low quantity and low production rate, including avoidance of hard tooling
- customer acceptance of the SW's management methods in return for rapid creation of breakthroughs in secret programs.

The Operating Rules that emerged from running programs like this are summarized in Table 2.

1. The Program Manager has complete control.
2. SW and customer each have small program offices.
3. The number of people with any connection to the program is "viciously" restricted.
4. The drawing release (approval) system is very simple and permits changes to be made easily.
5. Reports are few but important developments are documented thoroughly.
6. Costs are reviewed monthly, including final cost projections.
7. SW has customer approval for taking over most of the subcontracting process and choosing the best vendors, using commercial bid procedures.
8. Use minimum necessary inspections to assure production and vendor quality. Make the vendors guarantee their own quality.
9. SW retains responsibility for flight tests, mainly to permit corporate learning, especially of new technologies.
10. Specifications are agreed to in advance, including deleting a number of otherwise "standard" requirements.
11. Funding must be "timely" so that SW can concentrate on producing the plane.
12. SW and customer must develop a relationship based on mutual trust.
13. Utilize security procedures to limit access to the program, regardless of whether the project is classified.

14. Projects are kept small deliberately, so personnel must be rewarded based on the quality of their work, rather than on how many people they supervise.

Table 2. SW's 14 Operating Rules

Behind these rules lie several other characteristics of the method. In the early days, all team members had offices in the same area of the hangar, adjacent to the area where manufacturing took place. Every Monday morning a staff meeting reviewed all outstanding problems and tracked their solution. People in manufacturing, inspection, and test were involved early in the design process. Drawings contain all the information required for procurement, manufacture, test, inspection, acceptance, and maintenance of the part. It usually took only one day to get a drawing approved, with signatures normally required of the program office, the design office, and the weights office. (Presumably, manufacturing already had its say.) Changes were made directly on the drawings (called "red marking") to speed accommodation of changes. A satisfactory method comparable to red marking in the CAD environment has not emerged.

The Skunkworks Today

The people I visited are in the midst of defining the SW's methods in today's environment of reduced DoD expenditures, increased use of the as-yet undefined term "affordability," a proliferation of companies that say they are accomplishing Concurrent Engineering, and rapidly increasing use of CAD and CAE. They must do this knowing that 25 person teams are no longer feasible, at least given the current state of computer support for design. Their concept is based on a "core team" of approximately that number, a key idea being that each team member must be multidisciplinary, not a specialist. While the old SW methods were based primarily on "culture," today's methods must increasingly be based on "culture plus tools," according to Bouchard. The hope is that new tools will help keep the teams small.

Interestingly, in spite of the SW's history of developing new design and management processes, the people I met are among the few there that think about processes today. Management focuses on the product and the customer, feeling that process thinking is too academic. In addition, management is not convinced of the power of computers to speed up the process, reduce the number of people needed, or improve communication between them. My hosts are seeking ways to demonstrate cost and time savings conclusively, or to show how these can grow as new computing technology appears. Management seems to see the value of computing as an aid to management but not as an aid to design.

My hosts therefore have two strategies. One is to develop a computing infrastructure and use it regularly, while the other is to create demonstrations that they can show to management. The former is a highly intellectual activity while the latter consists of impressive videos documenting design activities. Both of these are described in detail below. Of more immediate interest is the fact that in both branches of the strategy, the stress seems to be on visualization. That is, I detected a strong reliance on the idea that if one can give a designer (or manager) a sufficiently vivid display of an artifact, he or she will know what to do. This emphasis appears in the video as well as in other kinds of displays and the use of stereolithography. The aim is to let the designer see and thus to know. Vivid displays and the opportunity to communicate via computer appear to be the main kinds of "tools" envisioned, although there are striking exceptions, also described below.

This apparently grass-roots campaign to create awareness of the importance of "process" and enhance computing in design contrasts sharply with the policy in some Japanese companies. These firms have CAD Planning departments whose mission is to survey the design process and recommend new tools or "working styles."[4] Few US companies have such departments. A researcher at a US automobile firm stated flatly that his company "has no technology policy" in engineering. Each division follows the dictates of its top manager, using or not using particular CAD or CAE tools in what are otherwise identical design activities.

High Performance Aircraft Design

SW designers, like others in the industry, follow a design process that proceeds from a general concept to details. The process description below is based on Bouchard's presentation and does not necessarily represent LADC policy. His view is interesting because he is trying to put the process on a more formal basis. The process breaks down into Requirements Analysis, Concept Design, Parametric Design, and Surface/Volume Design. The working definition of design is to produce the instructions for making an artifact that meets a set of requirements and is optimized to some figure of merit. The tools the SW has developed emphasize product performance: few tools exist other than visualization for addressing design problems associated with fabrication, assembly, or cost estimation.

Requirements Analysis: To arrive at the requirements, designers or the customer conduct mission studies comprising simulations and system analyses. These studies do not result in aircraft geometry but instead determine some of the design parameters, such as range, speed, payload weights, navigation accuracy, and so on. For example, a reconnaissance aircraft may have to fly rapidly and accurately to a very small area, hover over

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

it while photos are taken, then fly rapidly to another location and do the same thing. Two quite different flight regimes are involved: transit and hovering. There are no formal design tools to support this kind of study, and it is not clear what would help. Too often the same kind of design is arrived at, a derivative of some past effort. Some kind of database that would support the generation of new ideas is needed, along with tools that would help designers trace impacts of different decisions on performance, manufacturability and cost. Human memory and experience are the main "tools" in use now.

Concept Design: In this phase, the overall arrangement of the plane is studied, including the type of flight regime and aerodynamic phenomena to be exploited, basic wing shape, consideration of a canard, tail or no tail, number and type of engines, location of payload, structural materials, fastening methods, key manufacturing processes, and so on. This step differs from the "textbook" method in its attention to manufacturing and fastening methods at this stage rather than during detailed design. The reason is that among the main conceptual decisions are the major subassembly definitions. The feasibility or desirability of different subassembly options depends on the materials and fastening methods to be used, as well as important maintenance or access requirements, assembly tolerances and tooling, assembly sequences, and resulting strength of the aircraft.

In shipbuilding, a complete change in design philosophy emerged when welding replaced riveting as the main fastening method. Welds are as strong as the parent material, so welded joints may be placed anywhere. Riveted joint locations are influenced by the size of the largest steel plates available as well as the spacing between stiffeners. With the advent of welding in the US in the 1940s, designers were able to decompose the ship into modules based on ease of manufacture and assembly, independent of intermediate or final module shape or joint location. In the 1950s and 60s the Japanese extended this idea to include modules of piping and machinery. More interesting, they applied modularity to management of the shipbuilding process itself, creating work packages of parts, people, instructions, and equipment. Individual work packages of a given type were designed to be similar in all their technical requirements so that the same work crew and equipment could accomplish them efficiently.[5]

Subassembly definition is an example of a basic activity in concept design, that of decomposition. Sooner or later a design must be broken down into subproblems, subsystems, subassemblies, subgroups of designers, and so on. No systematic way of doing this breakdown exists. Instead, it appears that designers develop and then accept certain styles or morphologies of a

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[5] Japanese shipbuilding is described in more detail in Concurrent Design of Products and Processes, eds. J. L. Nevins and D. E. Whitney, McGraw-Hill, 1989. This book also contains references to other sources on Japanese shipbuilding.

particular artifact. There are now only two accepted ways of decomposing and arranging the drive train elements of a front wheel drive car, for example. When steel battleships were being designed for the first time in the late 1800s, there was no agreement about where to place the main gun turrets: along the side as in wooden ships or along the centerline. As guns and their supporting turrets got larger and heavier, the centerline design won out, an evolution that took almost 30 years.

Even if designers agree on how to break an artifact into sub-elements, there is still no agreement on how to decompose the design team and assign them to the artifact. When products were simple, one person had all the necessary knowledge, but now dozens or hundreds of people are needed. Bouchard notes that "complexity requires more specialists, more design time, more information transfer, and more chance for error. Whether the decomposition is done by functional discipline, by major subsystem, or even by geometric region of the aircraft, the result is local optimization and incompatible interfaces... There may be an upper limit on the complexity of the artifact that can be designed using present design technologies, and we may be reaching that limit. To counteract this trend, we are trying to get back to Kelly Johnson's principle of simplicity. We are also hoping to exploit new computer technologies so that a small core design team can still accomplish the major part of the conceptual work."

Another basic problem in concept design is how to explore alternatives. Design can be seen as a search through a decision space with many branches, of which only a few can be explored in any depth. When a branch proves unrewarding, the process must back up and try another branch. The problem is to remember the train of decisions that brought the process to the last promising branch point, as well as to locate the people who made those decisions. At each point, there is also the issue of deciding which aspects of the decision are the most important to explore. These are sometimes called "design drivers." Different aircraft will be driven by different issues, and it is not possible to predict in advance what will be critical, or at what stage in the design process it will become critical. A kind of general unstructured database is needed to record decisions, unexplored alternatives, the reason why a branch proved unsuccessful or was not explored, and the evolving rationale for the emerging design.[6]

<u>Parametric Design</u>: Once a concept design has been chosen, its basic dimensions must be determined. These include gross weight, wing area, sweep, and thickness, length and cross-section of the fuselage, tail area, engine thrust and bypass ratio, and so on. These parameters cannot be chosen

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[6] In the Boeing HSCT study cited above, an important design driver was the cost/weight ratio of the airframe in relation to the revenue/weight ratio of the passengers.

without reference to the mission requirements, so some preliminary values must have been explored in the previous stages. However, at this stage the studies become more detailed, and elaborate computer codes are available for the purpose. However, these codes are partially empirical and are based on wind tunnel studies of particular types of designs. They are difficult to modify because extensive verifications are needed. A similar situation exists in surface ship and submarine design. While computational fluid dynamics (CFD) codes are making some progress, few aircraft designers are prepared to rely on them exclusively, relying instead on wind tunnels. However, wind tunnel tests are not capable of verifying all flight conditions. Actual flight tests are needed, making verification dangerous and costly as well as expensive. In addition, there is a shortage of large wind tunnels capable of testing new kinds of designs.[7]

In some design activities, massive numerical optimizations have been attempted. As many as 10,000 equations and constraints are involved, and, again, a decomposition approach has been taken. Individual subproblems are suboptimized, and then a master search attempts to adjust the individual suboptimal solutions into a global optimum.[8] A shortcoming of this method is that only traditional decompositions are feasible, based on these same verified codes for the individual subproblems such as structural vibrations and fluid flow.

Getting the decomposition right is a serious challenge because most elements in complex electro-mechanical products perform multiple functions. In aircraft, the skin is part of the structure in the sense that it supports a large portion of the structural stress. If a design or design process is made too modular, or if the decomposition breaks are put in the wrong places, a very inefficient design (too heavy, too big, too energy-consuming) can result. For example, when skin and structure were considered separate items in an aircraft, the structure needed guy wires to give it strength. Since these wires were in the outside airflow, they caused huge drag. Combining skin and structure eliminated the wires, in some cases doubling the speed of the aircraft with the same engine.

Surface/Volume Design: Specific geometry enters the design at this point for the first time. Actual contours of wings, fuselage, and tail are explored, along with internal structural elements and internal ducting for the engines. In the case of stealth aircraft, detailed shapes of the external surfaces must be chosen and evaluated. Also, locations of radar-reflecting items under the skin must be selected. CFD codes are used again to study lift, drag, and other factors. Only at this point can cost be analyzed with any accuracy, because no methods exist for predicting cost if the geometric shapes are not known. The

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[7] McMasters...xx

[8] Sobieski...xx

advice of skilled people is sought in order to avoid serious mistakes, but no analytical methods exist for determining on a general or large scale what the cost or manufacturing impacts of various details will be. Among the issues of interest are options that mix machining (usually drilling) and assembly in different sequences, and the effect these options have on tolerances and the need for fixtures.

For composite aircraft, detailed design is even more difficult. Composite construction involves laying up material which has strength in one direction only. Material must therefore be laid up in layers in several directions to withstand predicted stresses. There are no machines for most of the jobs in composite aircraft construction, so manual labor is required. Not only is this expensive, but errors can occur because people cannot follow the instructions exactly the same way every time. Thus the parts may not come out as strong as required. To overcome these problems, the designers may add layers, making the structure heavier, and they may require additional and costly inspections. The problem of predicting the cost of such aircraft is therefore more difficult than for metal aircraft.

The cost of composite parts consists of materials cost and labor cost. There is little automation of composite parts manufacture due to the complexity of the parts' geometry. Human skill is indispensable in smoothing the material around the contours of the parts. In addition, people also compensate for some inadequacies in the parts' design. This point deserves some discussion.

People performing assembly in most industries, not only composite parts fabrication, are very good at compensating for problems they encounter. Such problems include poorly designed or incorrectly made parts. Because assembly always "gets done," it is incorrectly concluded that it was done properly and that there were no errors. However, this is usually not the case. The truth is most often discovered when automation of the tasks is attempted. Machines cannot accomplish the compensations done invisibly by people, and in cases where the process depended on such compensations, the automation usually fails. The automation is usually blamed, but the blame lies elsewhere.

Composite parts manufacture presents many opportunities for human compensation, due to the difficulty of laying up wide and stiff materials onto complex shapes. Designers currently have a poor grasp of these difficulties, and the ingenuity of the people in the factory has up to now shielded the designers from them. Therefore a new level of design sophistication will be needed before automation of layup onto complex shapes has a chance of being successful. Until that is achieved, it will be difficult for composite parts to compete economically.

Specific Design Tools Being Developed

My hosts discussed four kinds of design aids, of which they have worked with three:

- The Engineer's Scratch Pad (ESP)

- Computer-Integrated Design

- Stereolithography

- Unstructured Design Databases

The Engineer's Scratch Pad was developed by Bouchard and has been in use for about 5 years. It applies to problems that can be defined by a set of equations with no inequality constraints. Unlike the large specialized computer codes, ESP is unstructured, permitting the engineer to write equations at will without concern for which variables have values given in advance. The user can also import existing code or tabular data from other sources. The system will link these blocks of code together at runtime. However, the system will not invert equations; if the solver cannot determine a solution, the user must insert a root-finder.

Once the equations are soluble, the system can use a variety of search algorithms to optimize the design according to a given optimization criterion. Past applications include design tradeoff studies, aircraft sizing, heat exchanger designs, and other typical aircraft design problems. Output is given in tabular or graphical form.

The advantage of ESP over existing analysis codes is its flexibility. The disadvantage is that the user starts from scratch, defining the physics of the problem. It is possible that users could develop libraries of useful routines that would serve as the starting point for their analyses.

Computer-Integrated Design is aimed at demonstrating the power of advanced CAD in design. Both CATIA and ProEngineer are being used in this effort. CATIA is the most widely used CAD tool in the aerospace industry. While Boeing has adopted CATIA for the 777 and Chrysler has made it the standard for all its car designs, it appears that LADC management has not put a formal CATIA program in place. Instead, one person is looking into how it can be extended with commercially available add-ons. (This strategy is also being used by Chrysler.) But CATIA is usually judged to have an awkward user interface, so ProEngineer has also been tried, especially for parametric studies.

Among the things that have been demonstrated are the use of CAD during conceptual design to study major configuration and manufacturing alternatives, and CAD-driven stereolithography.

Two CAD-based concept studies were described to me. One was a rib and spar joint in a wing. There are about 100 of these in a plane, so making them easy to manufacture can bring big savings. Five concepts were generated in a few hours using ProEngineer, and experts from manufacturing narrowed the choices down to one. For this demo, no analyses were made of tolerances, stresses, or cost. However, the example is noteworthy because it took place during concept design when the major subassembly breaks were being decided. As a result, it had tremendous impact on the overall design process.

The other concept design demo was an impressive video of a complete CAD-based concept and producibility analysis for a hypothetical 70 passenger supersonic business jet. Initial concept design created a delta-wing metal structure comprising three main sections: a nose cone, a constant diameter midbody, and a tail section. A producibility study was shown, involving where to place the joint between the midbody and the tail. Each of four choices had different impacts on stress, pressure section integrity, and manufacturability. (The forward joint location was determined trivially by the requirement that the fuel tanks not be cut by the joint.) Other aspects of the design included detailed studies of wingbox design alternatives and overall aircraft assembly sequences. Animation was used to explore factory floor layout, major assembly alternatives, parts flow, and access to work areas inside the plane. The final scene shows the concept aircraft taking off, superimposed on actual video of Burbank airport.

This video is interesting because it was made in real time as the design study proceeded over a 6 week period. As such, it represents documentation of the design process itself, including post-mortems. However, it is the strongest indication I saw of reliance on visualization. It suggests many places where new analytical capabilities would be useful but it does not introduce any. An important purpose was to use it to show management how new computer tools could help spur rapid design explorations. Its value as a sales tool to potential customers has also been recognized.

Stereolithography has been used for applications such as making trial parts for wind tunnel experiments. However, a more interesting use is in synthesizing radar cross-sections of stealth aircraft and other visualizations of electro-magnetic phenomena. The resulting figures look like spiky quartz crystals. Experts are able to trace the bigger spikes back to particular structural sources, enabling a lower visibility design to be made.

Summary

Aircraft design is a complex process even when cost is not a major driver. In the new DoD environment, this unfamiliar factor must be brought into the process. The most complex phase of design, that of exploring the space of conceptual alternatives and reducing them to specific system requirements and structural shapes, has almost no computer support.

Exceptions include vivid visualizations provided by CAD and the use of ESP for studying sets of equations.

More broadly, there is no way to document and re-use the information flows and decision histories that characterize concept design. This most creative and unstructured part of design, which so heavily influences both the performance and the cost of the final product, is therefore conducted essentially manually by experts. The problem is that there are only a few of them. They do not get to practice their craft very often and many are near retirement. Corporate learning and knowledge capture are high priorities. It would appear that computer tools offer a way to attack this problem.

Lockheed has a mixed record at developing in house the computer tools that might support such design activities. It pioneered 2D CAD with CADAM, a product that IBM now owns and supports. It also had its own solid modeling effort, but this was terminated a few years ago and passed to its developers, who now have their own company. Northrop and McDonnell-Douglas also developed their own CAD systems. Northrop will likely move to CATIA. McDonnell-Douglas commercialized its product as Unigraphics and recently sold it to GM-EDS.

Like other major firms, Lockheed relies on commercial CAD. The advantage is that the cost of support is shared with other users. The disadvantage is that users get what the vendors can deliver, and the vendors cannot satisfy every user's specific requirements. Only a few users can dominate a vendor and get what they want, so the others take what is available. The Japanese tend to avoid this problem by writing their own CAD systems, at great cost. But their managements see the connection between design excellence and CAD excellence, and realize that a company's own highly tuned design process, supported by computer tools, is a major competitive strength.

In addition, only a few companies realize that computer-supported design extends well beyond the traditional realm of CAD, which is detailed mechanical and electrical design. Pushing computer support further forward into parametric and concept (or even requirements) design is therefore a major technical and institutional challenge.