Electro-mechanical Design in Europe: University Research and Industrial Practice

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October, 1992

This is a preprint of the report. The definitive version was published by the Office of Naval Research European Office in its European Science Notes Information Bulletin, volume 93-01, pp 1 - 52.

Work supported by the Office of Naval Research IPA Agreement N0001492MD241UK. The statements and conclusions in this report are offered for information and stimulation of discussion only and do not necessarily represent the views of the US Government or the Office of Naval Research.
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LIST OF ACRONYMS

ACME Application of Computers to Manufacturing Engineering
AI Artificial Intelligence
AMTC Advanced Manufacturing Technology Committee
ASME American Society of Mechanical Engineers
BRITE Basic Research in Industrial Technologies
CAD Computer Aided Design
CAE Computer Aided Engineering
CALS Computer Aided Logistics System
CAM Computer Aided Manufacturing
CE Concurrent Engineering
CIM Computer Integrated Manufacturing
CIME Computer Integrated Manufacturing and Engineering
CPM Critical Path Method
DFA Design for Assembly
DFM Design for Manufacture
DOF Degrees of Freedom
dS Dassault Systemes
DTI Department of Trade and Industry
EC European Community
ECU European Currency Unit
EDC Engineering Design Centre
ESNIB Office of Naval Research European Science Notes Information Bulletin
ESPRIT European Strategic Programme of Research and Development in Information Technology
EURAM European Research in Advanced Materials
FC Function Carrier
FEA Finite Element Analysis
FEM Finite Element Method
FMS Flexible Manufacturing System
IC Integrated Circuit
ICD Interface Control Document
IGES International Graphics Exchange Standard
VDAIS German Motor Manufacturers' IGES Subset
IMIP Industrial Modernization and Investment Program
IMS Intelligent Manufacturing Systems
IPK Production Systems Technology Laboratory
IPR Intellectual Property Rights
IT Information Technology
IWF Institute for Machine Tool and Manufacturing Technology
JIT Just in Time
KB Knowledge Base
LAAS Laboratoire d’Automatique et d’Analyse des Systemes
LFM leaders for manufacturing
MANTECH Manufacturing Technology
MIT Massachusetts Institute of Technology
NIST National Institute of Standards and Technology
NSF National Science Foundation
ONR Office of Naval Research
PASS Product Data Standard Subset
Executive Summary

The objective of this study was to assess research and applications in electro-mechanical product design in Europe. Design is a high-leverage activity that can dramatically reduce the cost and time to make and use products, both commercial and military. It is clear that advanced companies and countries see design skills, methods, and tools as strategically important. This report follows a similar one devoted to Japan. [Whitney] Important similarities and difference were observed.

Ten companies, 13 academic research labs, and 4 government funding agencies were visited between April 4 and September 25, 1992. The statements and findings that follow are based on those visit sites and cannot necessarily be generalized to sites not visited. They are believed to be representative of the electro-mechanical design effort in Europe.

Conclusions

Many European companies are surprisingly far behind both US and Japanese companies in recognizing the need to reorganize their design processes and see the connection between design process organization and CAD software. A few have begun to form cross-disciplinary teams only in the last two to four years. But some European companies are very impressive.

Companies are in the process of revolutionizing their product design methods. Thus they want better, broader, and more sophisticated design tools and databases. Large companies face the uncomfortable choices of developing them in-house (the Japanese approach), buying basic commercial software and adding their own, or pressing the CAD vendors for more sophisticated tools.

None of these strategies is wholly successful: companies lack deep software skills, CAD vendors lack knowledge of manufacturing and design. Researchers usually are not seen by companies as direct contributors to this process. Small companies cannot even make these choices but must buy what is available. More attention needs to be paid to these problems because only by bringing these diverse actors together will real progress be made.

Good design research is going on in several academic research labs, but there is still not a reliable technology transfer path for new design methods. This is true even though academic research labs in Europe are in some cases better connected to industry than US labs, due to the required structure of many EC and nationally-funded research programs. Several factors are involved: The companies cannot accept stand-alone software directly from universities because they want something that can be integrated with their current software. Some research offers methods (not always based in software) that are so different from current ones that entire cultures would need to change along with software. Such changes would have to
include new educational methods. CAD vendors also are reluctant to acquire or support research efforts if their customers are not asking for what is being offered. The vendors lack the resources to work on things they cannot sell soon.

The best university research observed was in Germany (links between engineering and CAD) and in the UK (product data models, representation of engineering knowledge). Other good research is undoubtedly going on but I did not get the chance to observe it.

Good deep thinking about the nature of the design process is also going on at several companies. The problems companies face and put priority on are not just short term, but in most cases arise from real gaps in knowledge. These gaps take the form of missing engineering knowledge, lack of algorithms, lack of data organization methods, and lack of understanding of all the intricacies of design processes. Furthermore, these gaps are evolving rapidly as new technologies and competition force companies to rebuild their design techniques.

However, researchers still see design the way they have for years, as a primarily engineering or geometry-driven process that occupies a single designer who focuses on a single product; they do not see it the way the companies do, focusing on conflict and tradeoffs, aware of design process integration and organization issues, providing basic engineering knowledge and hooking it to design tools, managing large teams, designing product families. Researchers need to participate more in industrial design projects to see what really happens.

Industry's view of what happens in design is therefore so different from academic researchers' view that there is a sort of culture gap that contributes to industry's downplaying of academic research.

EC funding provides a good route for consortia of researchers and companies who want to advance manufacturing and design together; but the funds are running short and, as national funds dry up, the researchers are all applying to the EC with the expected result that too many proposals are chasing too little money.

Different funding mechanisms and laboratory concepts were observed: The UK is forcing industrial participation in research and demanding that potential end users participate from the beginning (a sort of Concurrent Engineering of research projects). The UK also has launched a one-time program to fund Engineering Design Centres modeled after Carnegie Mellon's in the hope of spurring design research linked to industry's needs. The German Fraunhofer Institutes and their associated university lab partners interact strongly with industry but some institutes want to keep all the industrial applications and consulting to themselves while the researchers know they need such contact with reality. The French have a national lab devoted to automation, but it deals mostly with software, controls, and robotics, not design. While all of these mechanisms have advantages and shortcomings, the Fraunhofer-university partnership model seems the best because research,
education, technology transfer, applications, and straight consulting are all occurring under (almost) one roof.

Major missing links in both CAD software and design research lie between graphic design on the one hand and support for business and engineering issues on the other. Conventional analyses like finite elements have long been available commercially, but deeper analyses of designs and systems are not. Researchers are trying to fill the gap with expert systems gleaned from talking to designers. But designers usually do not have good analytical bases for their approaches, so the "rules" are hard to deduce or apparently not there. Expert systems are thus of limited use and will remain so until more basic engineering knowledge is available and applied in design contexts.

A more important missing link in advanced design is a clear definition of a product data model. No one knows all the data that belong in it, much less how it should be structured. The idea is looming and blooming; without it, advanced design methods can neither be defined clearly, nor listed in priority order, nor brought together and dealt with by computers in a compatible way. The companies are forcing the issue onto their vendors, who do not know how to respond; almost no researchers are paying attention to it. At the end of this report is a proposal to establish a research program aimed at this problem. Such a program would need active participation and collaboration of university researchers, international standards committees, CAD vendors, and industry users.

**Academic Research Activities**

Research activities observed focus on extending the ability of computers to aid designers in various aspects of design, including developing concepts that meet requirements and generating geometric descriptions of mechanical or hybrid systems. Many labs are taking quite similar approaches and seem to have the same priorities.

Approaches to concept design usually take the form of "inspired sketch pads" that permit a designer to call forth library functions like "motor" or "bearing" and hook them together into systems. These systems can be simulated or analyzed in other ways; then they can be converted element by element into specific geometry. The analyses are supported by various knowledge and rulebases. At least, that is the goal. Most of the difficult conversions are done by the designer, not the computer.

Research into geometric descriptions comprises various efforts in feature-based design, generalized sculptured surfaces, and geometric realizations of specific engineering systems, such as machine tool spindles. Some labs support the designer with rule and knowledge bases while others are trying to create connections to engineering analyses like vibrations or finite elements. Efforts also exist in linking mathematical and geometric constraints to geometric modeling and feature-based design.
One UK lab is focusing on databases and data models for product design support. A data model editor permits new models to be constructed that contain both object-like properties and recursive structures. In the past, this group was heavily involved in developing new geometric modelers and Computer-Aided Design (CAD) data conversion software. It is one of the few that strongly integrates mechanical engineering and computer science in its research.

Company Activities

Visits were made to several companies that design and build highly engineered products, plus one visit to a CAD software vendor. Most of these visits revealed that few of the above research activities are of direct interest to the companies. Instead, the companies are trying to figure out how to implement Concurrent Engineering (CE), shorten their design cycles, and manage the enormous amounts of data that are typical of their products. Uniformity of data descriptions and smooth conversion from one description to another are also of concern, but workable solutions are in place. The main strategy adopted by companies is to buy commercial CAD software, add to it their own databases, analyses, and data conversion software, and forcefully press the vendors for better products.

Most companies are carefully examining their product design and organization methods. Analysis of individual parts' designs often reveals that the firm did not really know, in a management sense, how to design the item in question. Dramatic reductions in design time and cost have resulted from such analyses. Researchers are generally unaware of these issues and no formal methods for analyzing design processes seem to exist.

High on companies' priority list are stronger links between geometry, engineering, and design for business strategy. Familiar computer-aided engineering (CAE) (such as finite element calculations (FEM)) is well supported by all commercial software; the companies are now interested in tolerances, design of multi-part products, design of product families, design for manufacture and assembly, prediction of costs, and generation of documentation. As the companies explore new CAD capabilities, they discover new kinds of applications faster than the vendors can keep up. Each vendor often has a key customer that not only drives its development but nearly saturates its programmers.

The CAD vendor visited is aware of these needs and appears to be shifting the focus of its products toward supporting them and away from the industry's traditional focus on geometry. It will soon release a version of its three dimensional (3D) modeling system that permits dimensioning and tolerancing, geometric constraints, and limited mathematical constraint management. Companies using other vendors' software indicate similar trends. In several cases, capabilities that are subjects of research at labs visited are supported commercially now or will be soon. However, vendors' work mostly deals with individual parts and seeks to link the
analyses specifically to their geometry. Mathematical and conceptual design are not well supported, although research and development to generate that support is going on.

The vendor has just begun an important ESPRIT project to create assembly process modeling and assembly factory design. This project represents a turning point in CAD/CAM because it is the first really new application area since numerical control, as well as one of the first to deal with multiple parts and their interrelations.

**Government Funding Trends**

Both the UK and continental European countries are undergoing or instituting important changes in the way research of all kinds is funded. The UK has been reorganizing its university system, hoping to make it more responsive to actual demand from students, reducing overhead allowances, forcing more industry contributions, and imposing frequent reviews onto research projects. UK research strategy has evolved during the Thatcher years to emphasize more collaboration with industry, more in-kind or cash contributions by industry, and an explicit requirement for technology transfer of the results. Many areas of research are scheduled for real term decreases in funding. Fortunately, the Science and Engineering Research Council (SERC), with a budget of £437M this year, is programmed for a slight increase for the next two years.

The EC has also been reorganizing its manufacturing research, removing an overlap between the ESPRIT program and the BRITE/EURAM program. These programs double-covered CAD, CIM, and other aspects of information technology in manufacturing for many years. EC projects tend to have many partners from several countries, a situation that can get in the way of technical progress but has been very successful in building an international research community. Additional revision of EC funding strategies and project management methods is possible.

Germany has had to reduce research funds, in part to pay for reunification, forcing cutbacks at universities. Labs are being told to seek EC funds, but the success rate of ESPRIT proposals is said to be around 10%. The days of secure funding from the German research agencies and foundations appear over, even for the leading labs.

**Comparisons Between the European, Japanese, and American Situations**

**Universities**

The European university design and manufacturing research labs, driven by the above funding trends and environment, tend to have closer relations with industry than either US or Japanese labs. (The situation in Japan is changing toward more cooperation with industry, especially at the national universities where government support is thin.) The European universities, especially in Germany, have faculty with long industrial experience. These professors often express dismay
at the content of US research papers and PhD theses ("all math, no applications"). However, the focus of university research on the individual designer seems the same in all three regions, in contrast to industry's focus on the business issues.

Within this context, university research is similar in most respects to what one finds in Japan and the US, inasmuch as communication between these researchers is frequent and strong. English is the "lingua franca" of world research, e-mail is in wide use, and inter-region travel and exchanges of visits are common. Only a few labs anywhere recognize the need to merge engineering, CAD, and computer science disciplines in design research. Only a few labs are taking on even a hint of the management issues (resource management, risk management, design process structure, product data models) that industry knows are at the heart of the problems they face.

In this regard, the MIT Leaders for Manufacturing (LFM) program may be unique, since it aims to merge the Engineering School and the Management School in this topic area. Nothing like LFM was encountered in Europe or Japan, although the UK teaching company program is similar on a smaller scale. Teaching companies are one-on-one arrangements between a firm and a university, whereas LFM has about a dozen participating companies. It includes both a coordinated engineering-business curriculum and student theses jointly supervised by faculty from both schools.

Companies and Government Funding Patterns

There are wide differences in the maturity of design methods and tools in different European companies of similar size. In Japan, similar size companies were more similar in achievements, approaches, philosophy, and tools. The most impressive companies visited in Europe (Volvo, Aerospatiale, Peugeot) appear comparable on some scales to the best Japanese companies, while other firms have just discovered the essentials of Concurrent Engineering and its associated organizational requirements in the last two years or so. The same situation applies in the US.

Companies have better opportunities to work together and with universities in Europe than in the US due to the availability of European Community (EC) programs aimed at manufacturing, design, CAD/CAM, and computer integrated manufacturing (CIM). While EC programs like ESPRIT have been criticized for achieving less than expected in the way of long term real economic growth, they have nevertheless achieved several vital things that Europe has not had in the past. These are increased cooperation across national borders, links between companies that may someday merge, and an institution (the EC) that encourages cooperation in both applied research and technology transfer.

The US does not have government institutions devoted to applied research and technology transfer in design, manufacturing, and CAD/CAM. There are many smaller programs with different objectives that address portions of the spectrum
(NSF and ONR for basic research, MANTECH and IMIP for introducing new manufacturing technology into defense contractors, Department of Commerce Advanced Technology Programs for industry, for example). But these do not address some important collaborations or the full range of research, technology development, transfer, and hardening. Also, their commitment to civilian industry varies depending on the program. We have no national laboratories devoted to this topic, such as LAAS (Laboratoire d'Automatique et d'Analyse des Systemes) in France or the Fraunhofer Institutes in Germany.

Technology Transfer

Technology transfer of new design methods and tools must follow an uncertain and poorly documented path. Users look to CAD vendors for such tools so that they will be compatible with millions of lines of existing code and hundreds or thousands of trained users. Also the users look increasingly to vendors for products that are outside their traditional range of geometric modelers, requiring experience and knowledge they do not have. One would think that they would turn naturally to researchers for high leverage help.

However, this has not happened very much, often because the researchers' results are too far ahead of practice. "Our customers are not asking for that," is the reply often heard. Naturally, the researchers cannot go directly to the users because the former cannot offer the software compatibility or robustness that the latter require.

The EC and UK programs have tried to incorporate technology transfer plans and commitments, whereas NSF programs, for example, do not. However, the paths are not well understood and current ones appear inadequate. Because companies actually face the problems and have the clearest view of them, some "problem definition transfer" in the opposite direction, to the researchers, is also needed.

Japan Redux

In the year since I visited Japan, I have had some confirmation of my conclusions. In addition, discussions with a Briton who just returned from a year's stay with Mitsubishi Motors reveals that we may still not appreciate the depth of Japanese concepts like Just in Time (JIT) and Quality Function Deployment (QFD). He quoted Toyota as saying that even other Japanese firms do not fully grasp JIT. The detailed QFD notebooks he saw at Nippondenso amazed him, as well as the depth at which the engineers there understood the concept. Examples of failure mode analyses were so crisp that they implied a highly-developed ability to identify the critical issues and ignore the rest, the result of careful attention and years of record-keeping.

Do We Understand the Design Process and Are We Doing the Right Research?

The Main Research Gaps
It appears that industry is seeking research that makes two essential connections that are rarely studied by researchers: connections to business and to engineering. Business connections involve both "mundane" topics like predicting the cost to fabricate and assemble something as well as challenging "business strategy" issues like how to design a family of products. Cost dominates industry and is mainly ignored by researchers. Family design, to take an example, requires mustering market data, gathering information about past designs, and deciding how to cover a wide range of varieties with a limited number of subassemblies and modules. Some of these requirements are completely new and require new methods.

Engineering connections include being able to understand, evaluate, and analyze structures (such as shafts and their bearings) or multi-technology items (electro-optic, electro-hydraulic). Understanding that a preloaded bearing is in a load path requires knowing that abutting surfaces can support compressive loads, that load paths form loops of compressive and tensile forces around which the force sums to zero, that threaded fasteners can exert compressive force, and so on. In place of this essential engineering knowledge and supporting analyses, academic researchers are trying to substitute expert systems whose rules are gleaned from practicing designers. The results are falling short of expectations, probably because the designers do not understand the engineering at a deep analytical level and because the researchers do not realize this. In addition, the engineering knowledge may be too incomplete to permit significant design aids to be developed.

The companies visited emphasized business issues over engineering ones. In the last few years they have been driven to re-examine their design processes by force of outside competition, especially from Japan. The Japanese appear to be from 2 to 15 years ahead in this respect, depending on which company one evaluates. This re-examination has exposed multiple inefficiencies in typical design processes. So far, these inefficiencies have turned out to be specific to the item being designed and focus on missing or late information. Individual items' design processes are now being attacked as if they were manufacturing processes that need efficiency experts. One firm referred to "just-in-time design," meaning that the right information is available at the right time.

Companies are understandably looking to computers to help as they recreate their design methods. Such help must come from facilities not emphasized in the past by CAD vendors or researchers. In Japan [Whitney] the larger companies have responded by writing their own software with help from computer companies. In Europe almost no-one has taken this approach. In addition, companies in both Europe and the US appear ill-prepared to look far enough ahead to recognize useful elements or trends in ongoing design research.

The researchers seem to be unaware of the forces and events driving the companies. They see design the same way they have for years: as an individual activity that needs to be supported by computers: to design a single product, a single person must reduce a set of requirements to a geometric description, observing the needs of
manufacturing and revising the design as necessary to achieve those goals. Companies see this aspect of design but also see something most researchers do not: a complex multi-person activity that must be managed, dominated by huge masses of data and sharp conflicts between the needs of various constituencies.

Both researchers and companies agree that design is a progressive process, but the researchers see it as an orderly quest. By contrast, the companies live with wild gyrations in risk, strong differences in approach by different design team members, and problems too big for one or even a few people to comprehend and manage. These differences are not just a matter of style but represent real gaps that strongly affect what researchers and industry, respectively, think computers will be able to contribute as well as how those contributions should be described and achieved.

The experience of actually designing a complex item appears indispensable if one is to comprehend the process and aim research at its most difficult points. Too few design researchers have such background. The exceptions are immediately obvious. In Germany, for example, most professors are former industry designers or engineers, and bring a very technical attitude to their research, with interesting results. But many of these people got their industrial experience before major advances in computer science occurred, and they do not integrate such knowledge with their research. This gap is apparent in most other countries as well. Thus actual design experience is necessary but not sufficient. New collaborations are needed, not only between researchers and companies, but between engineering and computer-oriented researchers.

An Emerging Research Priority: The Product Data Model

A major priority for both companies and researchers is the notion of a product data model (PDM). In the past, the drawings constituted the model. The shortcomings of drawings, and their computer incarnation as two dimensional (2D) drafting, are now well recognized. Adequate geometric representations now exist in the form of verified 3D surface and solid models. So, in industry, the focus has shifted to the other 90%\(^1\) of the information needed: tolerances, engineering calculations, process descriptions, design process information flows, assembly, and so on. Indeed, industry people seem to be coming to the conclusion that the PDM in some sense describes or is even driven by the design process. PDMs therefore represent a fundamental resource for companies interested in providing a solid base for improved product design as well as a formidable intellectual challenge for researchers: we need to understand what belongs in a PDM or even if its name should be changed to Product-Process Data Model. The best source for finding the answers is industry.

\(^1\) This is my "over-estimate" made for emphasis. While no detailed study has been made, and a metric has not been suggested, the 90:10 ratio offered here is likely to be fairly accurate.
However, companies are revolutionizing their design methods, recognizing the need for new kinds and arrangements of data, so the PDM is a rapidly moving target. This fact not only causes problems for researchers but also for the PDES/STEP activity, which aims at creating a standard for exchanging product data. Any attempts to define product data must track this target.

The fact that the "other 90%" includes a lot of traditionally non-product data is interesting because in some quarters (mostly among people with information technology backgrounds) it is hoped that there exists such a thing as pure product data. The model for this hope is VLSI where it is said that one can design purely in terms of function, leaving out any concern for process as long as the "design rules" are obeyed. There are many advantages to pure product data, and thus the goal is worth pursuing. At present, however, few in the electro-mechanical design community, either industry or research, would be likely to share this hope.

A major theme of the next few years in design research will be the question of what really belongs in a PDM and how it should be represented. Answers are coming in so fast (design process structure, engineering fundamentals) and from so many directions (industry, researchers, PDES/STEP) that we are presently in a state of divergence rather than convergence. As the question becomes better understood and answered, dependent issues like feature-based design, representation of engineering knowledge, encapsulation of design processes, and management of differing design versions in Concurrent Engineering will be easier to deal with.
I. Introduction and Background

A. Study Goals

I spent from April 3 to September 26, 1992 as a liaison scientist at the London Foreign Field Office of the Office of Naval Research while on leave from the Charles Stark Draper Laboratory, Inc., Cambridge MA. The focus of this tour was university research and industrial applications of computers in product development, particularly development of complex electro-mechanical products. Thus it is a direct follow-on to my study of the same topic in Japan. [Whitney] The issues are to determine what people think the product development process (PDP) consists of, what methods are appropriate for implementing modern PDPs, how computers can help, what is missing from commercially available computer tools, and what the researchers think the knowledge gaps are.

Design, properly defined, includes a great deal about manufacturing. However, the report deals with research about manufacturing processes only in such contexts as CAD/CAM interfaces or design for manufacture, not as separate topics, research projects, or visit sites.

Within the total spectrum of design, the focus is on "design as an enterprise activity" rather than "design as something a creative individual does." This focus accurately reflects the priorities of essentially all the sites visited. That is, the notion of "what designers really do" is set in the business context (define a product, get a computer model of it, estimate its cost, stress, manufacturing problems..., define the manufacturing and assembly processes, etc.); it is not set in the ergonomic or psychological contexts (what is creativity, how do we aid it, how do designers think while designing...).

Furthermore, the focus is on primarily mechanical engineering approaches rather than primarily information technology (IT) approaches. This focus, too, accurately reflects the sites visited, which in turn reflects my choice of sites to visit. Nevertheless, some sites visited have integrated IT partners and approaches very tightly while others have not. That is, the bias in my site choice did not create overwhelming bias in the findings.

B. Methodology

Compared to the Japan study, this one differs in several important ways. First and foremost, there is more emphasis on university research, although many companies were visited. Second, unlike in Japan, many of the sites are new to me, so I do not have the benefit of continuity over many years of visiting the same places. Third, this report inevitably lacks the single focus that the Japan report had. This last point deserves a little discussion. While Japan is known for its homogeneity, Europe is known for its diversity, and the Europeans are still
discovering how diverse they are. In addition, design research is known for its lack of consensus, so one finds a wide variety of problems being pursued. Third, and quite interesting, the companies visited are in widely differing states of maturity in their design methodologies. I believe that some did not really understand what I was trying to find out, and were unable to respond to my questions. This never happened in Japan. Every company visited knew exactly what I was after, prepared careful presentations to me, knew who to invite to meetings with me, and responded in detail to most questions.

The result of all these factors is that my European visits had a more ad hoc quality than the visits in Japan, which by contrast covered almost the same material each time and therefore permit comparisons to be made between sites. In this report I am obliged to make my own synthesis of what I learned, although this is a welcome opportunity. I use this opportunity at several points in the report to note where industry and universities differ in their assessment of needs and to offer my own suggestions on how to focus future research. The goals of this focusing are to reduce some of the diversity, create some consensus, and pose a set of questions that will address industry's needs while bringing out some important long-term research issues.

In all of the report that follows, it is important to note that my statements are based on research labs and companies actually visited and cannot necessarily be generalized to others. Readers are requested to keep this in mind when they read "researchers," "companies," and other such terms.

C. Structure of the Report

The report is broken down into four main sections, and a number of topics are dealt with along the way:

1. What companies are doing
   • what problems do they think are important
   • how are they approaching these problems
   • is university research of any use to them
   • where are they with respect to the Japanese and Americans in terms of design methods and technologies in use, and what strategies do they debate (make or buy CAD, for example)
   • where are they along the maturity spectrum of Concurrent Engineering (CE)
   • in what directions are they pushing the CAD vendor community
2. What universities are doing

• is there any consensus on the research issues

• what research is being done

• what contacts do they have with industry and what difference do these contacts make in their research topics or methods

• are funding and research management trends affecting research topics or choice of partners

3. What governments and the EC are doing

• are funding trends up or down and where will future funds come from

• are projects being managed or just funded; will research agendas and centers of excellence be managed or just peer reviewed

• are the political objectives (internationality, many players) getting in the way

• are the results being used

4. Larger Issues (dealt with along the way and summarized at the end)

• Is mechanical or mechatronic design really different from integrated circuit (IC) design; if so, how, why, and will it always be different

• Do we know what should go into a product data model: how much information about non-product things like tooling, fixtures, or the design process itself should be included (the ideal, from the IC world, is that design and manufacturing processes are separate)

• Is industry ahead in thinking CE through and what do the universities think about CE

• What is the right structure for a research project and a research group in design/manufacturing (models include the Fraunhofer Institute in Germany, the UK’s Engineering Design Centres, ESPRIT consortia, Cranfield Institute of Technology’s centers of excellence)

• Are any technology transfer routes being set up: what, and from which of the research groups/structures

• Can universities really do design research or should they just be centers of excellence while industry defines the broad problems
D. Redux of the Japan Study

To set a context, here are the goals and main findings of the Japan study [Whitney]. Based on conversations with Japanese who have read it, the findings are not only basically correct but the conditions observed in 1991 still seem to exist in 1992.

The Japan study sought to answer the following questions:

- What is the main outline of the product development process, starting from conception and concluding with construction of the manufacturing facility?
- What computer tools support this process and where do they come from?
- How long does the process take and how many engineers are involved?
- 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?
- What are the main challenges to intelligent and successful product design (e.g., product diversification, business forces, international teams, exploiting automation...) and how do companies meet them now and plan to in the future?

Important findings in Japan were:

1. Advanced companies write their own design software to suit their carefully conceived PDP, since such software cannot be bought; from the smallest company visited (1700 employees) to the largest, all had all their engineers on networked terminals

2. The PDP itself is the subject of "continuous improvement" carried out by full-time staff who are former engineers

3. Design teams are small, usually 10 - 15, rarely over 30, even for complex products like autofocus cameras having 500 to 1000 parts

4. Integration of design process steps into monolithic software systems with common data access is the main priority, with detailed accuracy of individual modules having lower priority

5. Design for assembly is being used in innovative ways

6. Japanese university engineering education is general and shallow, giving graduates a broad and integrated view; the companies exploit and extend this by rotating the employees through many work assignments, creating "universal
experience" that implicitly ingrains the ideas of Concurrent Engineering; deep expertise is shared over a group rather than being the property of an individual
II. What Companies Are Doing

A. European Companies Visited and Their Main Concerns

The European companies visited, and their main product lines, are listed in Table II. 1. Each company manufactures a highly engineered product in a variety of models, and each makes heavy use of computers in the process. All pay attention to their PDP but are at different stages of maturity. All see the PDP as a process and some are being innovative in finding new ways to think about it. One firm has recently completed reorganizing itself from a department-oriented structure to a project-oriented structure. “We learned a lot from our friends in manufacturing. We used to design the way a job shop operates. Now we do it the way a manufacturing cell works.”

Status and Maturity of Product Development Methods

While all the companies are working on improving their design methods, it is clear that some have begun thinking about team design, concurrent engineering, and other new methods only in the last two to three years, while others have been at it for as long as ten. This puts some of the companies nearly on a par with the best Japanese companies in duration of effort if not necessarily sophistication of approach, while others are just out of the starting gate.

<table>
<thead>
<tr>
<th>COMPANY NAME</th>
<th>MAIN PRODUCT</th>
<th>EXAMPLE VISIT TOPIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEROSPATIALE</td>
<td>AIRBUS</td>
<td>FOLDED PARTS, ASSEMBLY PROCESS MODELING</td>
</tr>
<tr>
<td>AMP, INC.</td>
<td>ELECTRICAL AND FIBER OPTIC CONNECTORS</td>
<td>HIGH PRECISION BUTT JOINTS FOR FIBER OPTICS</td>
</tr>
<tr>
<td>ARTHUR D. LITTLE, INC.</td>
<td>MANAGEMENT CONSULTING</td>
<td>CONCURRENT ENGINEERING</td>
</tr>
<tr>
<td>DASSAULT SYSTEMES</td>
<td>CAD SOFTWARE</td>
<td>CATIA SOLID MODELER WITH NEW CAPABILITIES FOR ENGINEERING</td>
</tr>
<tr>
<td>PEUGEOT</td>
<td>AUTOMOBILES</td>
<td>BOND GRAPH MODEL OF AUTOMATIC TRANSMISSION</td>
</tr>
<tr>
<td>ROLLS-ROYCE</td>
<td>AIRCRAFT ENGINES</td>
<td>INTERNALLY COOLED TURBINE BLADES, ASSEMBLY PROCESS MODELING</td>
</tr>
<tr>
<td>SIEMENS</td>
<td>ELECTRICAL MACHINES</td>
<td>FAMILY OF LARGE MOTORS AND GENERATORS</td>
</tr>
<tr>
<td>TELEMECANIQUE</td>
<td>AUTOMATION SYSTEMS AND CONTROLS</td>
<td>FAMILY OF MOTOR Controllers</td>
</tr>
<tr>
<td>VOLKSWAGEN</td>
<td>AUTOMOBILES</td>
<td>BODY PANELS</td>
</tr>
<tr>
<td>VOLVO</td>
<td>AUTOMOBILES</td>
<td>DESIGN PROCESS FOR ENGINE, STEERING KNUCKLE, CONNECTING ROD</td>
</tr>
</tbody>
</table>

Table II. 1. Companies Visited

Many companies have particular concerns that are based on the character of their product lines. Several (AMP, Rolls Royce, Siemens, Telemechanique) report that their task is to design a family of products rather than a single product. This has
interesting implications for required design tools and product data, as discussed below.

In addition to improving their product development processes, all the companies visited are concerned with

- converting and transmitting data between different computer programs and companies (most have written their own, and several industrial or national consortia often share the methods),

- getting software that will exchange data easily (including "hot links" that would, for example, put current statistical process control data right on the drawing for the designer to ponder)

- converting designers from 2D to 3D software, (mostly a user interface problem)

- improving the ability of computers to help their designers do engineering - as opposed to geometry - work

- pushing the CAD vendors to come up with solutions to these problems

- understanding "expertise" in the sense of how to compose design teams, how to create people with expertise, and how to capture expertise in computers.

To see more easily where different companies stand in their PDP improvement process, it is useful to define four stages of maturity in Concurrent Engineering:

**Stage 1:** Cross-disciplinary teams are formed, including people who have never talked to each other before during a product design exercise: market researchers, engineers, manufacturing and quality people, purchasing agents... They discover what the real design requirements are and, more important, that these requirements conflict. "Fights break out immediately," said one of my Japanese hosts.

**Stage 2:** Once the fight/discovery stage is passed, the team discovers that they really do not know how to design the product. Of course they know how to do all the calculations given the right information. But the process by which that information is generated has grown up *ad hoc*. No one has a clear picture of all the information that is needed or the problems that the existing decision structure causes downstream. For example, a decision structure based on "generate-and-test" will cause the process to iterate or oscillate with a dynamic of its own. The engineers are whipsawed and conclude wrongly that management can't make up its mind. Usually the designers and their management cannot fix such structural problems themselves, and outside facilitators are needed.

**Stage 3:** When it is understood that a wholesale redefinition of the design process, its decision sequence, and its information flows is needed, the group and its
facilitators can analyze the process and spot reasons why it is inefficient. A few formal analysis methods exist for helping this process, but familiar project management tools like PERT/CPM are usually of little help. All of the designers participate in this activity, giving them and their superiors their first collective and comprehensive view of the process, one they can agree on. The result is a much more detailed description of the process than they have ever had before. This activity can save 25% or more of the design/development time. Very few companies have recognized the need for this stage, however. The experiences of Volvo, described below, are among the best encountered during this study.

Stage 4: A main output of Stage 3 is identification of key tasks (decision drivers, time wasters, long lead activities, steps that generate revisions and redesigns). In many cases, redefining the process can reduce these problems, while in others a new computer tool or tools will be needed. For example, once it is seen that a critical top management final review always causes big design revisions, the big review can be replaced by a series of mini-reviews spread out along the process. Again, if it is determined, as in Japan, that assembly should be analyzed as part of concept design, then software can be developed to aid the required decisions. Such activities can save another 25% of the time.

The importance of the above discussion for the research community is that it describes a critically important activity that researchers are apparently unaware of and for which there are hardly any tools and no solid scientific basis. The state of the art is that execution of stage 3 and stage 4 appears to be a generic approach that has to be repeated for each specific item being designed (turbine rotor, steering knuckle, motor controller). The data, information flow, and calculation requirements generated for each item usually do not give much clue about those needed for the next item, at least not yet. Perhaps after this process has been repeated many times and the results compared, a more generic structure or analysis approach will emerge.

B. Representative Company Activities

1. Volvo

All of the companies visited appear to be in or past Stage 1, but only one appeared to be in Stage 3 - 4, that one being Volvo. For a relatively small company, Volvo has made substantial progress in design technology. In some areas, such as co-located design and development and paperless design processes, Volvo is on a par with some Japanese companies and ahead of some European and American rivals. They are keenly aware that design is a process just like typical manufacturing processes. Volvo is also the first place I have visited where there is an appreciation for the fact that conflict is an essential part of design, not a symptom that people can’t get along.

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2 Volvo is the subject of a separate and more detailed ESNIB article.
In one sense, Volvo's concept design process is more computerized than Toyota's since stylists can work directly on the computer rather than with sketches. The software being used for this (ALIAS) permits the stylist to deform the surface freely by grasping control points on it.\(^3\) ALIAS is fully compatible with CATIA, the solid modeler that Volvo is gradually standardizing on.

Some features of CATIA limit the amount of factory simulation Volvo can do. For example, robots can be programmed from part data to spray paint but not to weld car bodies. Other software is used for that. Also, CATIA cannot hold large solid models of many parts so that interference checks (part-to-part, part-to-robot, etc.) can be done. Many Japanese and European companies I visited said the same things about solid modelers in general.

However, CATIA’s mathematically firm solid model permits Volvo to employ data conversion and communication with suppliers with confidence, whereas they have no such confidence in converting ordinary 2D models made by drafting software. This shows that research efforts to create logically consistent 3D models have paid off in a serious way. CATIA’s historical evolution from 3D to 2D may put it in a good position to solve the 2D conversion-transmission problem.

Altogether, Volvo estimates that the use of CAD and numerical control has cut body engineering time by 50%. They are now turning their attention to engines and transmissions.

The process of improving the power train design process appears to be following a more deliberate path than in body engineering. The process has a name: Integrated Engineering. They have developed a procedure for accomplishing it and tried it out on some individual parts. Now they are in the process of trying it on entire engines. For this purpose, the CIM department has taken on the responsibility for modeling design processes, redesigning them, and proving to the designers that they can cut 50% or more from the time they currently take.

Two projects have been completed: a connecting rod and a steering knuckle (See Figure II. 1). Both are critical engineered parts where weight, strength, and safety are vital issues. The design process for each was cut from typically 40 weeks to 20 or less. They are now confident that similar reductions are possible everywhere at the single part level.

\(^3\) Note that this "same" capability is the subject of research at MIT and is called "new to CAD" by Dassault Systemes. I do not know whether I am missing an important point here or whether research is not as far ahead as researchers think.
Figure II. 1. New Schedule for Designing and Prototyping a Steering Knuckle, Showing Key Information and When It Is Needed. This is a schematic schedule for the design, development, and testing of a car steering knuckle. It was prepared by the Volvo CIM team to present to its management the results of studying and drastically shortening the knuckle's design process. The schedule shows several tracks ongoing in parallel. The schematic also shows the kinds of information needed at various stages of the process. In particular, the draft angle mentioned in the text is indicated in the middle box at the bottom. (Courtesy Volvo Car Corporation. Used
The steering knuckle used to be a long and highly iterative part to design for two basic reasons. First, some design decisions had to be revised after the supplier was chosen. Second, some design details often led to the need for careful hand finishing of the parts to avoid stress concentrations and possible field failures. Both of these caused extensive delays while the part was redesigned and reanalyzed.

The supplier-related problem is especially interesting. The part is forged, and the issue is to choose the draft angle of the forging die. This angle is directly transferred to the finished part, so any FEM analysis will be affected by choice of draft angle. These analyses take a long time but must be redone if the angle changes. Also, redefining the CAD model to change the angle is cumbersome. Unfortunately, the supplier who won the contract often could not deliver at the original draft angle (smaller angles are harder to achieve). Thus the lengthy design and analyses had to be done over. To avoid this iteration loop, the integrated engineering team had to convince the purchasing department to permit the supplier to be chosen early in the design process, before a design existed and thus before the supplier could bid. Competitive bidding is thus ruled out. The net effect is still a win for Volvo due to the reduced design time.

This is not yet a scientific process and may never be, but some patterns can be discerned. These seem to me to be:

- identify all the necessary design steps and the information they require and generate

- find where this information is really available (not just at the official end of a given step in the process, but often earlier in that step) and decide if it can be made available right away to subsequent steps that need it

- find sources of iteration and identify the real reasons

- identify information whose availability is time-critical (if delayed, will delay the design) or content-critical (if revised, will cause large changes in the design) and separate it from less critical information even if both used to be grouped in past design methods

- find opportunities to work in parallel

- find long lead time items and try to start them earlier (noting that the information they will need must also be provided earlier)

- find precedence chains that can be broken so that tasks can be resequenced (this requires classifying constraints, much as Nippondenso does, into "must have," "would like," "due to physical law or material property," and so on)
- find ways to design-out problems that will take a long time during manufacture and assembly (a wasted minute making each of a million parts adds up to a lot of time, more than may be needed during design to avoid the waste)

Note that, in the steering knuckle case, "having the supplier on board early" is motherhood, but "deciding the draft angle early" is the critical decision that is accomplished once the supplier is on board.

2. Volkswagen

Space does not permit a lengthy description of this large and interesting company. While it is aware of the issues discussed above and has launched a series of integrated design activities, VW is not as far along and has not unified its approaches and CAD facilities as much as Volvo has.

My host emphasized the primacy of "process" in design over the skill required to design individual items. In this sense he felt that most university design research missed the key issues. The German design process standard VDI 2221 is also too general. It lists the broad steps that must be accomplished, he says, but does not fill in enough details. VW has hired engineers skilled in design methodologies in order to improve the process internally. It also understands the need to improve its suppliers' design processes and integrate them with its own.

This effort is now several years old and is being carried out differently from the way CAD was originally introduced. Twenty years ago, the R&D people led this process. They felt that geometry was enough and that manufacturing input was not needed. Now a more bottom-up method is being used to define design processes. For example, a person from logistics is defining the notion of "design for shippability." Also, by law in Germany, products will soon have to be designed for recycling, and their packaging must already be recyclable.

VW also defined "module" in an interesting way: a module is a feature of the car that helps differentiate the car in the marketplace. This is different from the way suppliers, engineers, and manufacturing people define it. It is important not to outsource the strategically important modules, those that are relied on most heavily to sell the car. This helps define core competencies that the company must retain and support with CAD and better design processes.

A major factor governing use of computers in design is the rapid growth in the amount of data required. Ten years ago an FEM model of a car for crash analysis purposes had 1300 elements. Now it has 40,000. Part models can occupy hundreds of megabytes. Another factor being tackled by all the German car makers together is transferring all these data back and forth with their suppliers. A subset of IGES (International Graphics Exchange Standard) has been defined called VDAIS (German Motor Manufacturers' IGES Subset). Within VDAIS, VW has set up its
own standard called PASS (Product Data Standard Subset). Most commercial 2D and 3D modelers conform or will soon. While most of the standards deal with representing drawings, a few of the defined items are there because of advanced design requirements: minimum radius notation needs to be standardized in part because design for assembly (DFA) will use the information.

VW feels that Germany is ahead in creating such standards and in holding ongoing industry-wide symposia to disseminate and improve them.

3. Aerospatiale

Aerospatiale is one of the largest aerospace companies in Europe. It designs and accomplishes the final assembly of the Airbus family of aircraft, as well as making many of the parts. It adopted the "design-build team" concept of design process organization in 1975 and practiced that method for two years before beginning to introduce computers. This gave it the opportunity to document the new organization and information flow patterns and decide what it wanted from computers.

The result is that the computerization has been focused on integrating the design process rather than on supporting one phase, such as geometry or conceptualization. Aerospatiale originally wrote lofting software but now relies mostly on Computervision for geometric modeling. The main in-house activity has been to develop an entity-attribute type of database in which a wide variety of engineering information and process descriptions can be placed alongside the geometry. All the designers have access to this database, which was described as "an industrial plant for processing data" rather than a "storage place."

Aerospatiale notes that assembly is the next frontier in computerizing the design process. The currently available tools offer little in the way of assembly process modeling and mainly support configuration control. Another weak spot is design of pressed or folded parts, where CAD tools offer no process support. What is needed is better engineering knowledge of materials behavior linked directly to the operating behavior of the machines in its plants. It appears at present that each company, or possibly each industry, must develop these tools. The CAD vendors, according to my host, do not have the expertise or the ability to divide their efforts across the needs of many customers.

The present way of designing aircraft consists of converting a preliminary design into single parts and then subassemblies. When assembly problems are discovered, the single parts must be redesigned. Aerospatiale wants to be able to validate assembly before single parts are designed, but there is a paradox in this hope: many

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4 In German: Productdaten Austauch Schnittstellen Subset.
5 Aerospatiale is the subject of a separate and more detailed ESNIB article.
assembly problems are caused by very small details on the parts. Checking assembly at a preliminary design stage will therefore not catch all the problems. However, major interferences, sequences, and access issues can be addressed. "You don't want to put an air conditioning duct where it might drip condensate onto a computer."

To encompass assembly properly, the database will have to be revised. Several views of parts and assemblies will be needed, including several degrees of detail and stages of subassembly. Also, a new kind of person will be needed, the assembly checker. Such a person may be needed for each main engineering system (air conditioning, for example). The subcontractors will have to be involved in this as well, and by remote access from various parts of Europe.

Comment

Predicting future problems in fabrication and assembly during concept design runs straight into the paradox cited above: small details can have big effects. This fact eliminates strategies that depend on scaling laws and forces one to track all the details down sooner or later. Thus a triage of problems needs to be carried out, so that those which really can be handled during concept design receive attention while the others are left aside.

On this basis, a priority list might look as follows

1. gross incompatibilities between assemblies in terms of function, malfunction, proximity, and so on (moisture, heat, flying parts due to engine failure, human access during normal operation, diagnosis, or repair)

2. access for routine things like original assembly or scheduled maintenance

3. access routes for interconnections between things, including approach paths to the items being connected

4. general "layering" of things: what’s on the outside, what’s next, etc.

5. incompatibilities or interferences between single parts

4. Telemechanique

Telemechanique designs, builds, sells, and uses internally a wide variety of automation equipment plus the associated controls and software. Its design research includes problems and methods in the design of multi-part electromechanical items that are made in a wide variety. How does one control the design process so that an easily made product family emerges? How does one assure high quality and low defects while switching effortlessly from one version to another in unpredictable batch sizes? What rules are needed to make sure that the design process is systematic, that the number of parts does not grow uncontrollably, and that the
varieties available meet the needs of customers without strangling the manufacturer?  

M. Albert Morelli, Director of Automation and Productivity at Telemechanique's R&D Laboratory, gives the example of contactors (relays that switch motors on and off): when looked at properly, a contactor is a subset, in function and parts complement, of a reversing contactor. To take advantage of parts commonality, it is necessary to design the reversing contactor first, since it bears the main design constraints. Designing them in the other order (plain contactor first, since it is sold in much higher numbers) will only require it to be redesigned when the constraints are discovered.

More generally, Morelli has developed an approach to designing high variety products. It includes several steps:

Functional decomposition
Modularity
Definition of subassemblies
Reduction in apparent variety by part commonality
Design for automatic assembly

Functional decomposition (conversion of functional descriptions into specific lists of parts) is a familiar step that appears in most design methodologies. It requires experience so that the functions are represented by an economical number of parts. This step is complicated when the product must be made in many varieties because some functions, and thus their respective parts, may be in some varieties but not others. Whether to make these as separate parts or merge them with their neighbors is a constant challenge. A similar challenge occurs when parts must change identity, shape, or composition at various points along the spectrum of varieties. Where along the spectrum should the transition occur? Does the change affect other parts? Which ones? etc.

An example is given below that shows how fabrication, assembly, cost, and market demand all must be taken into account. No systematic design tools for such decisions exist.

Modularity involves making up a function by combining several identical or related parts. At Telemechanique it shows up in products with repeated internal structures that implement repeated functional requirements. (N contacts, where N can be chosen by the customer, for example.) The design choice is between

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6 Telemechanique is the subject of a separate and more detailed ESNIB article.
7 Morelli says that modules are different from subassemblies. Modules are mainly of interest to the designer, while subassemblies are of interest to the manufacturer. They interact and must be defined carefully during design.
assembling the repeated parts or designing special parts that contain the required number of elements.

Morelli is not uncritically in favor of modularity, but recognizes its drawbacks as well as its advantages. Modularity brings flexibility but requires more parts, more careful attention to tolerances that build up when these parts are assembled, and more effort in logistics to muster those parts needed for each order. The choice is also influenced by the cost of making molds and the influence of production volume of the different types of product.

Consider the case where motor control protectors with three or four poles (contacts) must be made. Table II.2 shows four different ways they might be designed. The assumption is that the cost, complexity, and design/build time for a mold for making the parts will increase with the number of poles. Each different design alternative is intended to generate both varieties of the product:

<table>
<thead>
<tr>
<th>Design Alternative</th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
<th>Design 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Poles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Poles</td>
<td>a special 3-cavity piece</td>
<td>3 single-cavity modules fastened together</td>
<td>a special 3-cavity piece</td>
<td>3 single-cavity modules</td>
</tr>
<tr>
<td>4 Poles</td>
<td>a special 4-cavity piece</td>
<td>4 of the same single-cavity pieces as above</td>
<td>the above 3-cavity piece plus one single-cavity piece</td>
<td>a special 4-cavity piece</td>
</tr>
</tbody>
</table>

Table II.2 Design Alternatives for a Multi-Module Product

If 4-pole units are low volume sellers while 3-pole units are high volume sellers then designs 1 and 4 are not likely to be economically viable alternatives. Designs 2 and 3 are more feasible in this case but it is not immediately obvious which is the best.

This example shows that to design the product properly requires a good model of the market, plus the ability to predict the cost of the associated molds and the tolerance buildups in the alternative assembled units, and the ability to model the cost structure of the product as a whole: materials, logistics, fabrication, assembly, inspection, and test. Some of this information must either be in, or linked to, the data model of the product. Its presence would support the module-family design.
process, not just describe the product.

Taking a broader view, one must be careful not to offer so many modules that the customer becomes confused. One way of selling offers the customers the chance to "design their own" by choosing from a catalog of the modules. So one must understand the spectrum of needs and then construct the modules so that it is easy for the customer to see what modules to combine. Then, of course, one must be able to make and deliver them "just in time."

One must be careful not to confuse the designers either. When a large number of varieties must be encompassed and some common parts are involved in each variety, a design change in one part can cascade changes throughout the family in unpredictable ways. A strong database is needed to keep track of such interrelationships. It would need to know about related part features on different parts at a geometric level as well as about sets and relations between part families at the module level. This lends additional richness to the idea of a "product data model:" another example that contains data to support the design process, not merely to describe the product.

5. Siemens Dynamowerk, Berlin

This division of Siemens makes electrical generators and motors. Some are huge, over 16m diameter, and only a few are made each year. Midrange units are made in larger quantities and come in several types, for which a family of designs exists. The smallest units are made in relatively large numbers and a predictable modular design approach can be used, along with a lot of CAD and some numerical control. But the largest machines are always specials. They contain an enormous amount of material, which drives their cost, which in turn drives the designers to think up new shapes every time to save material. By contrast, the cost of the smaller machines is driven by labor, so the effort goes into automation. Thus three kinds of design are needed for the different size machines. "We always know the shapes of the small machines but the shapes of the larger ones are different every time," said Dr. Mario Schacht.

His job focuses on the largest ones. The designers deal with only a few each year, and the need (habit?) to make up new shapes for what are in fact almost the same parts has created a hodgepodge of part names, part numbers, and data that are unusable for later designs. To improve this situation, one would think that it would be enough to get the designers to use the same names each time, or to give out predefined sets of part numbers for the different types. This in fact has now been done. But in addition, Dr. Schacht has had to restructure the entire design process so that the generic elements of the generators are known to everyone and everyone thinks of the "same generator" when they are working. This means not only that everyone working on a given generator thinks of the same one, but that this one is "the same" in basic ways as all the past ones.
To accomplish this he has had to create a sort of standard design script, conceptualizing aspects of the design that even seasoned designers had not realized. He has drawn up design trees holding information such as "every generator has a shaft; every generator has a rotor shield that is either one piece or segmented depending on... If the rotor shield is segmented, then part A1 is eliminated and parts A2 - A5 are used." On the wall in the office are large sheets of paper showing this structure in detail, representing months of work.

These design scripts are very much in the spirit of the research of his former professor, Wolfgang Beitz, of the Technical University of Berlin.

6. PSA Peugeot-Citroën

André Rault, a 1966 PhD from Berkeley in controls, joined PSA three years ago with the goal of bringing a more systematic approach to its design methods, especially for mechatronic components like transmissions and brake systems. He has brought in software called CAMAS from the University of Twente that permits hierarchical Bond Graph models to be built. Several quite accurate models of complex items have convinced the engineers that this is a valuable method. Rault has now launched an ESPRIT project to create a library of proven bond graph models of common mechatronic components, together with their geometry (a link not supported by CAMAS) so that systematic bond graph modeling and design of complex mechatronic things can be done more easily in industry.

CAMAS is like the original bond graph simulation system ENPORT in many ways. It supports hierarchical models of complex hybrid systems. In an X window one can have a model with two nodes: ENGINE and TRANSMISSION. Clicking on one of these nodes reveals a more detailed model, and clicking on its nodes reveals even more detail. At each level, the graph obeys the bond graph notation rules. At any level one can substitute explicit mathematical statements in a FORTRAN-like language called SIDOPS to handle nonlinearities and other details. CAMAS automatically converts the bond graph model into a set of SIDOPS statements and evaluates them numerically.

CAMAS has been applied to modeling of automatic transmissions. These are good examples of mechatronics because they have either hybrid or all electronic controllers as well as many gears, clutches, shafts, friction elements, and inertias; bond-graphs are amply equipped to model such systems. The first model, while still approximate in some areas, accurately predicts that PSA’s current transmissions jerk the car somewhat while shifting. A previous analysis of manual transmissions correctly identified gear backlash as their main source of noise. These successes have impressed the engineers, making further applications likely. A complete car and suspension system model is being built.

8 PSA Peugeot-Citroën is the subject of a separate and more detailed ESNIB article.
7. Dassault Systemes

Dassault Systemes\(^9\) (DS) is the developer of the 3D modeler CATIA. CATIA started out as an aerospace industry product but recently has made major inroads in the car industry. New software plans include providing object-oriented databases, using free-form 3D sketchers, providing the ability to manipulate constraints, engineering equations, and tolerances, and modeling assembly processes. A new and quite large ESPRIT project on assembly called SCOPES has just begun, with partners Telemechanique, Cranfield Institute of Technology, the Ecole Polytechnique Federale de Lausanne, and two industrial partners. It's a turning point in CAD capabilities.

These projects are interesting in part because they represent topics that are being worked on at several university research labs. Either technology transfer is starting to happen very rapidly, or the universities are not very far ahead of some applications. Both may be partly true, and in some cases the universities may be behind. In others, DS's capabilities will be quite modest in these areas at first.

Apparently much of this development has been driven by the customers. "It's pretty hard to keep up with them," says Dominique Florack, Manager of R&D Strategy. Another technique for redirecting DS has been to hire people from engineering organizations, including its former parent Dassault Aircraft, so that new developments will be more focused on the needs of current and new customers. New techniques from research are obtained in part by hiring students who did the research. More recently, small research grants directly to universities are being made.

DS is also interesting in the way it develops new capabilities. According Florack, half of their internal R&D projects are co-funded with one or more industrial partners. These partners will have a two-year exclusive opportunity to use the results before they are sold generally.

The SCOPES project, as stated above, represents a totally new direction for CAD. Assembly is the first really new CAD/CAM application since numerical control, and assembly brings totally new issues to the surface. Among these are

- dealing with several parts at once
- understanding all the ways those parts will interact
- exploiting the integrative character of assembly to help tie the design process together
- understanding assembly as both a process that occurs in the factory and as a way that parts provide "engineering services" to each other\(^10\) (support, location, sealing,

\(^9\) Dassault Systemes is the subject of a separate and more detailed ESNIB article.
\(^10\) This way of looking at assembly was expressed to me separately by researchers at Leeds University.
heat transfer, fluid retention...) and then linking those "services" to the assembly constraints inherent in individual part mates (slide in, fit against, glue together, fasten with screw, compress O-ring,...)

The project, while ambitious, will not deal with all of these issues. It has three segments: off-line, on-line, and the off-line-on-line interface. In the off-line part, directed by DS, assemblies will be modeled geometrically and feasible assembly sequences will be found. The "best" sequence will be selected and converted into an assembly process plan, from which an assembly system will be designed. In the off-line-on-line part, (co-directed by DS and Telemechanique) this system will be detailed, including all the controls and sensors, and a discrete time simulation will be generated to test its operation, including failure detection and correction. In the on-line part, (to be supervised by Telemechanique) the system engineering will be done, including all wiring diagrams, diagnostics, monitoring, statistical quality control, user interface, and communication networks.

DS is moving CATIA from a geometry modeler to an engineering design support system. It appears to be actively seeking recent research results. At present CATIA is still primarily geometry-oriented, and the hard engineering capabilities have only recently been considered. But this is the long-term trend, and other CAD companies are moving in the same direction. This trend should present challenges and opportunities for the research community.

C. Summary

The companies visited are trying to figure out how to implement Concurrent Engineering, shorten their design cycles, and manage the enormous amounts of data that are typical of their products. Uniformity of data descriptions and smooth conversion from one description to another are prime concerns.

High on companies' priority list are stronger links between geometry, engineering, and design for business strategy. Familiar computer-aided engineering (such as finite element calculations) is well supported by all commercial software; the companies are now interested in tolerances, design of multi-part products, design of product families, design for manufacture and assembly, prediction of costs, and generation of documentation. As the companies explore new CAD capabilities, they discover new kinds of applications faster than the vendors can keep up. Each vendor often has a key customer that not only drives its development but nearly saturates its programmers.

The CAD vendor visited, like its competitors, is aware of these needs and appears to be shifting the focus of its products toward supporting them and away from the industry's traditional focus on geometry. It will soon release a version of its three dimensional modeling system that permits dimensioning and tolerancing, geometric constraints, and limited mathematical constraint management. Companies using other vendors' software indicate similar trends. In several cases,
capabilities that are subjects of research at labs visited are supported commercially now or will be soon.

However, vendors’ work mostly deals with individual parts and seeks to link the analyses specifically to their geometry. Mathematical and conceptual design are not well supported, although research and development to generate that support is going on. The user, on the other hand, are looking for more capability for handling assemblies and for supporting hard engineering. When they cannot get this from the vendors, they are trying to develop it themselves. Few companies said they found much that was useful in current university design research, and some doubted that the vendors could supply what they need either.
III. What Researchers Are Doing

A. Laboratories Visited and Their Main Activities

The research labs visited, and their main activities, are listed in Table III. 1. These labs differ widely in their research focus and approach, but some common threads were observed. The main focus is on individual designers dealing with various stages of the design process from concept to details. Concept efforts include helping designers to focus their thinking during concept design, helping them link requirements to possible functional and physical realizations, and presenting simulations of concept system behavior. Detail design efforts include creation of part designs with both geometric and semantic (non-geometric items like constraints, symmetries, comments) features, creating and analyzing complete engineered systems in a limited domain, and providing feedback on a design's suitability for manufacture or assembly.

Only one laboratory is trying to develop product data models as a separate research activity. Only one laboratory is trying to integrate aspects of design process management into its research on design of complex systems. Several laboratories are trying to apply Artificial Intelligence (AI) methods or neural nets in an effort to bring engineering knowledge into the design process. Other researchers feel that AI will be of little help.

Several labs are studying assembly. One is focusing on helping designers of assembly equipment while the rest are dealing with product design issues: determining assembly sequences, trying to encourage designers to conceive a product as a set of parts rather than one part at a time, and seeking to link part sets to product functions.

Only one lab appears to be thinking critically about concurrent engineering as a human activity, defining roles for different experts to play at different stages of the process.

<table>
<thead>
<tr>
<th>LABORATORY</th>
<th>MAIN ACTIVITIES</th>
<th>EXAMPLE VISIT TOPIC</th>
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<td>CITY UNIV. LONDON</td>
<td>PRODUCT DESIGN</td>
<td>QUALITY</td>
</tr>
<tr>
<td>CRANFIELD INSTITUTE OF TECHNOLOGY, UK</td>
<td>CAD, CIM</td>
<td>AI IN DESIGN, ASSEMBLY MODELING</td>
</tr>
<tr>
<td>ECOLE NATIONALE SUPERIEURE DES ARTS ET METIERS, PARIS</td>
<td>PRODUCT CONCEPT DESIGN</td>
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<tr>
<td>ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, SWITZERLAND</td>
<td>MICROTECHNIQUE, ROBOTICS</td>
<td>DESIGN OF ECONOMICAL ASSEMBLY SYSTEMS</td>
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<td>INSTITUT DE PRODUCTIQUE, BESANCON, FRANCE</td>
<td>AUTOMATION AND DESIGN</td>
<td>ASSEMBLY PLANNING, ASSEMBLY MACHINE DESIGN</td>
</tr>
<tr>
<td>INSTITUT FUR FAHRZEUGBAU WOLFSBURG</td>
<td>EDUCATION OF ENGINEERS FOR CAR COMPANIES</td>
<td>CAD, ROBOTICS, EMISSION TESTING</td>
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</tbody>
</table>
Table III. 1. Research Laboratories Visited

<table>
<thead>
<tr>
<th>Institution</th>
<th>Focus Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPK PRODUCTION TECHNOLOGY CENTER BERLIN</td>
<td>FEATURE-BASED DESIGN, SEMANTIC FEATURES</td>
</tr>
<tr>
<td>LAAS NATIONAL AUTOMATION LAB, TOULOUSE, FRANCE</td>
<td>MOBILE ROBOTS FOR FACTORIES AND PLANETARY EXPLORATION</td>
</tr>
<tr>
<td>LANCASTER UNIVERSITY, UK</td>
<td>DESIGN METHODS FOR ELECTRO-MECHANICAL SYSTEMS</td>
</tr>
<tr>
<td>LEEDS UNIVERSITY, UK</td>
<td>DESIGN, CAD, GEOMETRIC MODELS</td>
</tr>
<tr>
<td>KATHOLIEKE UNIVERSITEIT LEUVEN, BELGIUM</td>
<td>MECHANICAL ENGINEERING</td>
</tr>
<tr>
<td>TECHNICAL UNIVERSITY OF AACHEN, GERMANY</td>
<td>MECHANICAL DESIGN OF MACHINE TOOLS</td>
</tr>
<tr>
<td>TECHNICAL UNIVERSITY OF BERLIN</td>
<td>SYSTEMATIC DESIGN OF ELECTRO-MECHANICAL SYSTEMS</td>
</tr>
</tbody>
</table>

The sections below are organized as follows. First, the approaches of several labs to the same research area will be discussed in two contexts: AI in design, and computer aids to the concept design process. Following this, several sections describe activities at individual labs.

B. Representative Research Activities of Interest

1. Artificial Intelligence in Design

Design seems to require so much specialized knowledge that AI methods have long been attractive as a way to improve computerized design methods. Now that several years’ work exist, we can ask

- can Artificial Intelligence really contribute significantly to design and, if so, in what way?
- are AI’s existing methods adequate, and if not, then what improvements are needed or what other methods should be added or substituted?

One can conclude from what follows that AI is earning a place as a training aid or expert-simulator that can duplicate what good designers do now on design problems that fall in a previously defined class of a given object. However, new kinds of designs of such objects cannot be tackled. The exact limits of "new" have not been well defined. Communication between designers and knowledge engineers is weak, with the result that deep knowledge is not obtained. It is possible that the inability to get deep knowledge is a symptom of weakness in basic engineering models rather than or in addition to weakness in the methods of knowledge engineering.

11 AI in Design is the subject of a separate and more detailed ESNIB article.
The researchers do not deem existing knowledge representation schemes adequate to capture what designers do. Possible explanations include the fact that designers do not explicitly know and use rules, that their thinking processes are not strictly linear, and that they do not in fact know some basic engineering or perform necessary and feasible analyses. Instead they may copy their own or others' procedures.

AI methods may not be able to escape these limitations until they are combined with analytical methods based on first principles.

Three AI-design projects, two at Cranfield Institute of Technology in the UK and one at the Technische Universität Aachen, are summarized below. These are then contrasted with some design methods based on first principles of engineering mechanics and thermodynamics. Each is introduced by a quote from a researcher.

a) "Regarding knowledge bases and rule chaining for aiding designers, the methods are weak but the knowledge of designers is pretty shallow, so for now the methods are adequate."

This trenchant comment was gleaned from discussions at Cranfield with Dr. Jaz Saggu, associated with the College of Aeronautics. AI has important opportunities in aircraft design, manufacturing system design, and design for manufacture, he says.

The group's general approach is to regard AI as creating an environment that contains an array of tools useful to the designer. Some of these will be traditional AI tools while others will be traditional engineering tools. The designer should be able to apply any tool he needs without being an expert in its use. AI should also provide a front end with an explanation facility so the designer can see why a decision or recommendation was made. The group does not develop new AI methods and is not committed to one style or approach.

Example projects they have worked on include

- critiquing designs for manufacturability

- preparing designs for FEM, or recommending which parts of a design should be subjected to FEM

- structural optimization

- design of safety-critical software

An important new project, funded by the EC, is called EDID. This project involves using AI methods to merge two versions of the same design and detect mismatches.
Part of the AI component will be to combine two people, a rule base, and an agent to negotiate the mismatches.

The project will also generate a new kind of Interface Control Document (ICD). It will have a hierarchical structure as well as several data classifications or views: geometry of parts, minutes of design meetings, lists of mismatches, and so on. The hierarchical tree arrangement will list the systems and subsystems of the item being designed (a communications satellite) and the subcontractors are expected to choose what to work on by making reference to this tree.

Prof. Alan Morris provided a different view of this project.12 He stressed the need to better understand how designers operate when trying to merge portions of a design and negotiate mismatches between sections designed by different people or companies. An important question is: "what information should be provided, especially concerning the nature of a mismatch?" Where will this information come from? For example, suppose two pipes must be joined across an interface and they turn out to be misaligned. Simply having the computer report "mismatch" is insufficient. More likely, it must report not only the directions of mismatch but also the physical and economic freedoms available within which adjustment strategies can be found. Is either pipe flexible; will they break if they are simply pulled together during actual assembly; is there space around them to reroute them; what negotiating strategies will the different designers use?

2. "AI-design folks think they are in the home stretch providing tools for design."

This equally trenchant remark came from Mr. Graham Jared, an engineering-oriented researcher in the School of Industrial and Manufacturing Science at Cranfield who is studying design for assembly using both AI and other approaches.

Jared apparently bases his opinion of AI in design in part on his experience trying to build rule-based Design for Assembly (DFA). The project is an outgrowth of work by Prof. Ken Swift of the University of Hull and Lucas Engineering, a large mechanical engineering company. Swift built a software-based DFA system similar to the famous one made by Prof. Boothroyd. Both systems ask the designer a series of questions about each part in a product design (is the part easy to pick up; is it symmetric - thus easy to feed automatically to a robot - and so on). From the answers, the computer computes a score that predicts how long assembly will take or indicates whether the part should be redesigned to make assembly easier. The software can also detect the opportunity to make two adjacent parts into one.

Swift found, to his and Lucas' disappointment, that the computerized system did not create results any faster or better than answering the questions with pencil and paper, a result others have found. Also, the method seemed incapable of helping

12 A more detailed description of Morris' view of the project is given in a separate ESNIB article on Cranfield.
design really new things or of handling situations not anticipated when the questions or scoring method were developed. Finally, they found that the users did not really understand the questions and often answered optimistically when asked to judge ease of assembly.

So Jared and Swift determined to automate or assist the DFA evaluation process, and for this they needed a geometric model and a set of rules and AI methods for doing the evaluation. Some of the required information can be located and identified as features, as long as these are identified in some way. For example, chamfers (bevels) around the rims of holes are known to make peg-hole assembly easier. Checking for the existence of chamfers can be easy if the CAD data are properly organized. [Sherrin et al]

It turns out, however, that they knew only some of the features that would be the "knowledge-carriers" relevant to DFA evaluation. Only some of these are geometric. Other kinds of relevant information do not show up in CAD data bases: smoothness of surfaces or likelihood that there will be oil on the surface during assembly (both fundamental to ease of assembly of rubber seals, for example, or to the likelihood that a person might drop the part), amount of resistance force that might oppose assembly (such as in spring-loaded parts), and so on. They stress the amount of "lore" that they must get out of the designers.

In addition, there is a built-in conflict in using CAD as the source of the data for the evaluation: companies would rather have the evaluation done on a concept, not a fully developed CAD model. Such models take a long time to build and can be hard to revise. No way out of this conflict has been devised. You can't do geometric reasoning without some geometry or a workable representation of the geometry that contains the necessary information. Defining "necessary information" is the challenge, since some of what we now deduce from geometry might be expressed another way if we knew what it was and how it would be used. An example is the mutual direction of assembly of two parts. This can be deduced by geometric reasoning about the shapes of the mating surfaces. Alternately, the designer can create mating surfaces by picking them out of feature libraries as data objects (pegs, holes, slots, chamfered holes...). These objects can contain the mating direction as a numerical/text attribute.

So the question is not just whether AI methods can help but also what information must be available before AI methods can contribute to their best advantage. Consider part count reduction. The current method of detecting the opportunity to eliminate parts operates by having the designer answer three questions about adjoining part pairs:

- are the parts made of the same material?

- is the method used to join them permanent?
- is there some important reason why it should be possible to separate them after assembly?

If the answers are YES, YES, NO, then the two parts should be considered for consolidation into one. The first two questions can be easily answered from properly structured and augmented CAD data but the third one requires real knowledge: it concerns the product's function, intended use, failure modes, repair methods, modularity, and so on. The third is in fact the only really interesting question, and it is more than just difficult to answer. Like the question of how to choose tolerances, the required knowledge can be said to reflect the entire design process. It is not general knowledge but rather specific information about the product. Is it reasonable to expect future product data models to contain such information, even if designers, rather than algorithms, make the decisions about how to use it?

3. "When we tried to determine the designers' rules for machine tool spindles, we found that there were far too many for an efficient rulebase. The designers could not verbalize many of them. Also, many steps in design do not seem to follow a logical path. So we turned to neural nets instead to capture what the designers were doing."

This comment is an evaluation of the limits of AI methods and indicates a novel use for neural nets as a substitute. It was made by Mr. Baer, a Dr.-Ing. candidate at the Technische Universität Aachen. He is building an aid for designers of machine tool spindles. The design system being developed covers basic requirements, types of machining it will do, geometry, choice and placement of bearings, stress analysis, and design evaluation and redesign. The neural net has been built for the evaluation and redesign phase. So far, its performance cannot be judged successful.

Several more conventional AI techniques suffice to aid parts of the design process. Rule bases are used to hold information about the amount of friction or types of failure modes of different lubrication methods (grease is stiff and can dry out, but it takes high loads). Design requirements are expressed as fuzzy categories like "the load is high but the speed is low". A set of precalculated decision tables is used to combine the requirements and the rules and present the designer with a prioritized set of solutions to choose from. "Duplex greased roller bearings are the first choice. Their cost is X."

To aid generation of spindle geometry, many spindle designs were studied and characteristic regions were identified: the tool mount end, the step-down from the tool mount to the first bearing region, and so on. Each region can have a variety of shapes, which are modeled with adjustable parameters. A geometry description language was developed to generate these regions and hook them together. An example statement in this language is "The step is on the same axis as the mount and the first bearing region." A rulebase looks at this description and the requirements and tries to find what type of region should be picked from the
available ones. The designer can substitute his own choices if he does not like the computer's.

Evaluation is the step that could not be captured by rules. Two large neural nets are being tried instead. One creates an evaluation while the other suggests design changes. A large number of designs was studied and designers' revisions of them were recorded. These before-after pairs were used to train the net.

This large and ambitious neural net is still under development. Recurring issues are how many hidden layers to use and how many neurons to put in each layer. Too few layers or neurons will cause the net to fail to capture the desired nuances, while too many will cause the training session to fail to converge. Neural nets are rare in design software, so there is not much experience to go on.

Taken as a whole, the spindle design aid has occupied Mr. Baer and others for four years. He says it can do well on types of spindles it has "seen" before but not for ones that are new. Variants of standard types are the easiest. It is a great training aid, and it permits a student to design an acceptable spindle in about a day. An experienced designer takes an hour, while a designer with 20 years' experience can design a better spindle without the computer.

Comments

Expert systems appear to be primarily empirical. They are often applied when the developers conclude that there is no hope of an analytical solution. A classic case is that of medical diagnosis: the resulting expert system is a model of the doctor, not a model of the sick person. Many expert systems hoping to capture design are similar.

There is no doubt that systematic attempts to model processes bring large rewards. Asking doctors to think about their diagnostic methods revealed an underlying structure that had not been taught explicitly in medical school. Companies have learned that modeling design processes reveals important opportunities for improvement.

But it worth reconsidering the conclusion that spindle designs, for example, cannot be evaluated analytically. What we can tell is that the designers who were questioned did not use analytical methods. This in itself is not really sufficient proof that an analysis is impossible, but only that one has not been attempted, or has not been pursued with enough vigor, or that the designers questioned were not aware of existing or potential analyses. Too much reliance on expert systems puts off the day when better understanding of the underlying phenomena must be obtained.

Expert systems at least have the positive feature that one can read their rules and perhaps even learn something from them. By contrast, a neural net is completely
numerical and empirical. No one knows how to "read" them. They represent the ultimate in avoiding better understanding of the engineering.

A counterpoint to AI in design is provided by researchers studying design methodology. Examples include Professor Beitz' systematic design (see below) and Professor Suh's design axiomatics. Here I would like to discuss the work of Prof. Michael French of Lancaster University in the UK. In a recent book [French], he uses a series of examples and first principles in mechanics to bring out a number of considerations that designers often use implicitly. He says that these can be made explicit and, in line with the above argument, can be dealt with analytically.

Examples of these design considerations are:

a) **Disposition.** The essence of many design problems is to identify a key commodity, such as space or energy, whose allocation dominates the problem. Once the commodity has been identified, the allocation can often be made analytically.

b) **Combination or Separation of Functions.** It is often efficient in terms of space or weight to make one item perform several functions. A classic counter-example is James Watt's invention of the separate condenser for steam engines. Prior designs used the piston cylinder as the condenser, making it too hot to be efficient as a condenser and too cold to be efficient as a driving element. A thermodynamic analysis was not available to Watt but one can be done and the advantage of making the separation can be calculated.

c) **Structural Efficiency.** J. C. Maxwell proved that the integral of force times distance over a stressed elastic structure depends only on the pattern of applied loads and not on the geometry of the structure. French calls this integral "pertinacity." Efficient structures have minimum pertinacity and the designer obtains it generally by maximizing the tensile loads and minimizing the compressive loads inside the structure. Minimizing the pertinacity will reduce the amount of material required to support a given set of loads. The designer will try to reduce the material until every element is stressed to its safe limit. Using first principles, French shows that efficient structures are also stiffer than inefficient ones.

French says in the book's preface that it is likely that good designers create efficient structures but it is not obvious that they are aware of pertinacity or that they calculate it explicitly. My questions are: If they do not use pertinacity, what do their "rules" for designing structures look like? Could something like pertinacity be deduced from their designs? Is that the right way to discover pertinacity?

**Conclusions**

AI methods obviously have a lot to contribute to design. The limitations of AI acting alone are becoming clear, however. It assumes a type of thinking process that
designers may not use, or may not use exclusively. Designers may not have clear enough or analytical enough views of their work to make rule-based or neural net methods efficient or to permit these methods to innovate in a meaningful way.

For the time being, fruitful approaches appear to combine all of the methods we know of: rules, mathematical and geometric models, extended data models, object-oriented descriptions, calculations, numerical searches, and so on. Only a few labs are pursuing such a combined strategy and none is using a large number of methods together.

2. Converting Functional Specifications to Concept Designs

Most commercial computer aided design (CAD) is not really design software but instead either supports two dimensional drafting or three dimensional geometric modeling, with added text representing dimensions, tolerances, process notes, and so on. The most advanced commercial CAD software permits geometry to be parameterized by numerical or symbolic arguments, with some equality and inequality constraints on these variables. However, such software mainly supports creation of geometry at a detailed level and does not directly permit engineering, exploration of rough concepts, or discovery of conflicts and tradeoffs.

Researchers have taken note of these gaps and are trying to create CAD that will help designers explore non-geometric concepts and to create rough realizations from loosely stated design goals and required functions. Their approaches include one or more of the following:

• scripts or design procedures that guide the designer from the specs to classes of realizations in terms of known elements

• diagramming methods that permit the designer to hook elements together in different data views

• engineering-oriented approaches that permit the designer to think functionally about groups of predetermined elements, with the computer providing some engineering knowledge or constraints

A summary sense of the state of these efforts can be gained from the following generic anecdote. Each of these research groups showed me points in their software at which a conversion was made between a more abstract representation and a more concrete one (from the statement "convert energy" to a diagram of a motor-generator set, for example). In every case, when I asked "Did the computer do that or did the designer?" the answer was "The designer."

Research on Concept Design is the subject of a separate and more detailed ESNIB article.
I believe the fair thing to say at this time is that concept design research software can be characterized as "inspired sketch pads," capable of generating and searching structured lists, constructing graphs that connect elements in various ways, or accessing rules or tables to help evaluate performance of elements. Good graphical user interfaces are being developed to support these activities. But little has been done so far to exploit the structures thus created in a systematic way, such as checking for correctness and completeness. Neither has anyone taken the obvious step of converting a correctly constructed graph into any existing systematic dynamic simulation modeling methods such as Bond Graphs, although most say they plan to do so.

Behind all of the research projects reported on here is the assumption that "product design" consists more or less of a set of steps that one engages in and passes through successively, while establishing and refining information. This relatively clean view contrasts sharply with what many in industry actually experience: superimposed on (and often dominating) this set of steps, there occurs sharp conflict, wide gaps between specifications and possible realizations, and a constant struggle to predict future problems and costs, understand the needs of other designers, and so on. No lab visited or known to me represents design as a struggle to identify and resolve conflicts or bases its research on such a view. Yet this view describes real design better than existing research or teaching paradigms and implies great needs for computer aids of a type that no one is trying to create.

The bottom line is that except for focused situations which essentially constitute redesign of an existing item using the same kinds of fairly simple elements, there is not very much progress on systems that really aid the designer other than bookkeeping, lookup of rules, and domain-specific calculations. The reasons for this situation may be a lack of basic engineering knowledge that can link form and function, the lack of a mature concept of a product data model, and/or the lack of a mature concept of the "product design process."

Work at three labs is described below:

- Technische Universität Aachen
- Lancaster University
- Technische Universität Berlin

a) Technische Universität Aachen

i. Machine System Design

This project is being carried out by Mr. Repetzky, a Dr.-ing. candidate. He calls it CAE of the future. The goal is to integrate all of the tools a designer needs for designing a complex machine: CAD, dynamics, simulation, FEM, machine elements
like gears and bearings, hydraulics, controls, and so on. A major goal is to combine
the different kinds of data that a designer would need in order to attack such a
problem, and store the data in a unified representation.

The project is an outgrowth of the general problem of putting functional design
capability into conventional CAD. His view of function in machine system design
is that each machine element responds to inputs and delivers outputs. So his first
efforts have gone into defining data objects for the elements and placing calculations
(methods) into the objects that define the input-output relationships. A major
problem for him is to decide when he has described an element in enough detail.
For helical gears, for example, must he include the helix angle?

The software at present supports a mouse-menu interface that permits the designer
to extract objects from a library, put icons for them on the screen, and hook them
together. The elements have the required hooks on them already, and a design is
not complete until all the hooks have been connected to something. For example, a
drive motor has a hook for fastening it to the ground and another for fastening it to
a rotating shaft on another element. The hooks are each responsible for fixing one
or more degrees of freedom (DOF), and the software will eventually be able to tell if
all DOFs have been accounted for.

If he hooks together a motor, a shaft, some bearings, a gear reducer, and a load, he
can calculate the shaft torques on both sides of the gearbox. He could add tooth load
calculations to the gear object but has not done so yet.

He has considered using Bond Graphs as a way to link these hookups to simulation,
but has not done so. Bond graphs trivially calculate the above mentioned torques;
in addition, they are designed to model hybrid systems, such as electro-hydraulic,
using the same symbols and math throughout. More fundamental, the Bond Graph
method contains a number of internal consistency checks that prevent some kinds
of basic modeling errors, such as failing to conserve energy or attempting to define
both the force on, and the velocity of, a moving object.

Combining the consistency checks of Bond Graphs with the DOF accounting he now
plans would give his system some capability for evaluating the correctness and
completeness of a model. I think this would be an important property for a
modeling system to have. No researcher I have visited has given this kind of thing
high priority. In some cases designer can draw what he wants and the computer
will try to model it.

ii. Assembly-Oriented Design

Mr. Baumann, another Dr.-ing. candidate, described a system called DEMOS, on
which he and others have been working for many years. It supports design of
mechanical items and has several objectives. First, it seeks to bring assembly issues
to the concept design phase. To do this, it permits the designer to describe the
product in terms of graphs that link parts whose geometry has not been specified. Second, it allows the designer to study the design and improve its assembleability. This, however, is done after geometry is defined. A paper contains additional information [Eversheim and Baumann].

The system's strongest features deal with development of two data structures: the function structure and the assembly structure. The designer inputs both of these and the software supports the process by keeping track of all the parts, logging the designer's choices for connection or assembly methods that link parts, later accepting the shape of each part, and finally performing Design for Assembly (DFA) analyses. By ordering the process this way, Baumann hopes to encourage assembly-oriented thinking by the designer before the geometry is completely described, even though the last steps require geometry. The sequence also adheres to the German design standard VDI 2221.

Both the function structure and the assembly structure are hierarchical graphs in which nodes are single parts or subassemblies, while links indicate some kind of relationship. In some cases, the relationship is that of assembly. In others, it represents some functional aspect of the design. The functional graph and assembly graph of a gearbox are shown in Figure III. 1.

![Figure III. 1. Illustration of Function and Assembly Structure of a Simple Gearbox.](image)

Once the assembly structure has been drawn up, the system attempts to generate an assembly sequence. To do this without knowing much geometric data, the system uses several heuristics. For example, the part with the most connections to it is selected as the "base part" onto which others are added. (The upper housing or lower housing would be chosen in this example.) Parts with lots of connections to
each other are candidate subassemblies.

When the assembly structure and assembly sequence are determined, the designer can assign types of part mates to the assembly links. Library features like bearing seats can be called forth, including dimensions if the designer wishes. Last, the designer uses the CAD module to make up the actual shapes of the parts that contain these part mates. When the system has all the geometry and assembly structure information, it carries out a DFA analysis and suggests places where part count can be reduced. Tables from the Boothroyd method are used for this purpose.

The assembly sequence strategies used by the DEMOS software raise some interesting questions. For example, it is not obvious that maximizing the number of subassemblies is always a good idea. The reasons for doing or not doing this may depend on information from marketing or assembly machine experts, for example. Some of the considerations are discussed in the section on Telemechanique, where product modularity is the driving consideration.

A larger issue is whether one can make significant design decisions without having defined specific geometry. Assembly decisions illustrate the question here, but it comes up in many other contexts. DEMOS is a bold effort to create an environment where decisions can be made without geometry but at present it seems to me that many of those decisions are destined to be revised later.

The next question is whether the design is better anyway, even if the decisions were redone, just because the designer had to think about assembly much earlier than would normally be the case. No one is thinking about design processes this way: revisions are usually thought of as a sign of waste or inefficiency in the process.

b) University of Lancaster, UK

Two projects described below are funded by the UK government under the Engineering Design Centre (EDC) program. Professor Michael French's EDC project is aimed at mechatronic design, that is, design of mechanical systems that contain computation, measurement, and control as well as familiar kinematics, dynamics, fluids, strength of materials, and so on.

i. Schemebuilder

Schemebuilder is like Mr. Repetzky's system in many respects, with similar aims but perhaps a more analytical underpinning. It is written entirely in the commercial expert system shell KEE. There are two windows: a "building site" and a "model library." The building site is like Repetzky's hookup window and functions in basically the same way. The example here is mechatronic, in keeping with the theme of the Centre: an autopilot for a yacht. A compass provides a control setpoint for a servomechanism that will drive the boat's tiller to correct a heading error.
Two kinds of elements can be called forth, those capable of transmitting power, and those dealing only with signals. These can be joined in ways similar to those provided by Bond Graphs, including keeping track of causality. But the full force of Bond Graphs has not been utilized in the sense that no generic components (inertia, compliance) have been defined. Instead, each element represents an individual physical type of thing (tiller with rotational inertia, boat with translational inertia...)

Design begins by calling forth specific elements, such as the yacht’s tiller. These elements are described only qualitatively, such as noting that the water will exert a force on the tiller in one direction while the steering motor will exert a force the other way. The motor will act through an Acme screw, whose function is described qualitatively as converting rotational input into translational output. Quantitative descriptions are going to be added later in the project.

Each element has hooks that permit restricted kinds of connections to be made. A browser is available in the model library that helps the designer find suitable elements for a given hook type. For example, to provide translational power for the tiller, the list could include electric or hydraulic actuators but would not include things incapable of driving a load.

Several extensions of the current system are planned. One deals with design concepts like function and advice/warnings to the designer. The other deals with linking the concept to a CAD system so that space can be allocated for each of the components as it is placed in the building site.

Prof. French does not feel that the warnings and advice feature should be based on making the software understand engineering fundamentals. He feels that would be appropriate for design of really new things, whereas here he is dealing with hookups of already designed and understood things. Instead he would like to link the advice and warnings to a more sophisticated formulation of function. He uses the term "function structure" to describe statements of functions perhaps at a semantic level, to which the system would respond with solution types built of library components that match the description. Once a pattern of solutions began to emerge for a given problem, the advice might draw on the existing design; for example, if the designer has selected some hydraulic components, the system might suggest more hydraulic components in order to exploit the hydraulic power supply that is already required.

ii. System for Improving Mechanical Assembly Design

This piece of software is a model editor for assembling cylindrical things with a single rotational axis of symmetry. It is a deceptively simple context and a brilliant one because its simplicity forces certain basic issues into sharp focus while keeping side issues from clouding the discussion.
One type of assembly is involved, namely placing gears, turbines, bearings, spacers and their required fasteners onto stepped shafts. The designer must create the stepped shape and indicate the steps onto which the parts will rest. Each set of parts starting from a step and proceeding along the shaft through bearings and spacers to a fastener is called a "stack." The system has been programmed to recognize stacks and to understand some of their inherent constraints. For example, a stack with no fastener is incomplete.

The system understands several geometric facts about such assemblies. For example, it can recognize stacked stacks: a step followed by a bearing, a spacer, another bearing, another spacer, and finally the fastener. It can also recognize the opportunity to create a stacked stack out of two serial stacks by responding to the command "Reduce number of fasteners." Finally, it knows when assembly is impossible because a step is too high to permit a bearing to pass over it on the way to another step. This error can occur if the system discovers that a step is too short to support the bearing assigned to it, and attempts to make the step higher.

However, the system is unaware of some basic engineering facts. For example, it does not really understand the concept of load path, that is, the idea that the fastener is going to push the spacer against the bearing which will in turn push against the step, trapping the bearing with a compressive force. At present, when the designer places a bearing near a step the system will not place the bearing against it in anticipation of the direction the force will ultimately point; instead the designer must move the bearing with the mouse until it coincides with the step visually on the screen.

An extension of this idea is to recognize when axial forces must be resisted. Helical gears generate such forces. In such cases a load path to a fastener or step is needed, and the design is incomplete until this path is provided. All such paths comprise loops through the structure, with alternating loop segments in tension and compression, all adding up to zero net force around the loop. This is another case where "correctness and completeness" could be checked systematically.

The potential benefit of adding it to the system is that this provides an opportunity to study in a simple but non-trivial context the question of how to link geometric design to real engineering (elements cause loads that have to be supported using steps and fasteners). It would be very satisfying to see a system of this type developed as a counter-example to other research where such physical facts are deduced as "rules" employed by designers.

c) Institut fur Maschinenkonstruktion, Technische Universität Berlin

Professor Wolfgang Beitz is just coming to the end of a 10 year government funded project to computerize the systematic design methods outlined in the well-known book co-authored with Professor Pahl. [Pahl and Beitz]
The earlier years of the systematic design project included developing design methodologies for many typical engineering systems, such as pumps, transmissions, and motors. About two dozen PhD's contain this evolution. In addition, his work has developed the systematic approach and transferred it to the German standard VDI 2221, which he and Professor Pahl helped to write. This standard describes a step-by-step procedure for designing things to meet specifications. More recently the work has turned toward software.

The software is intended to consist of an end-to-end design system for converting a set of requirements into a detailed design. It has been put together around an example problem, an emergency power unit. Another example is being worked up. The software consists of modules that some day will communicate with each other, comprising a solid modeler (CATIA), a user interface, several knowledge bases, some calculations, and several browsers. In its present state, the software is preliminary and not completely integrated. Many desirable capabilities, such as linking one stage of systematic design to the next, have not been completed. All other research labs that I visited where similar efforts were under way have taken basically the same approach to this most difficult problem: the software basically acts as an aid to the designer, who must make the important transitions himself.

The software consists of a series of modules that are used one at a time, apparently unidirectionally from the beginning. At the beginning is a program that permits requirements to be listed as text with modifiers and keywords. ("Provide backup energy source." "Convert energy from one form to another." And so on.) One can browse this list, searching for repetitions of the keywords in this or other task lists from other problems. A more structured final requirements list can be made up from this rather unstructured beginning.

The next stage is a product structure, consisting of elements that receive, process, and pass along such things as force, energy, structural stability, and so on. These elements are represented as symbols and are linked to each other. (Energy flowing out of one element can flow into another, for example.) In the future, this will be the basis for a functional simulation but right now it seems to be a graphical display. One can use this structure as the basis for a search through a database for similar structures in past designs, or one can expand one of the blocks into a substructure of similar elements.

The next stage provides ways to link the combined requirements list and product structure to possible ways of realizing the product. I believe that there is no automatic way of creating this new list from the old one; the designer does it. Again, the computer shows symbols representing physical items like bearings, gears, shaft couplings, and so on. Beneath each of these is a knowledge base (KB) describing its rules.

One of these KB's has been extensively developed, that for connecting shafts to hubs. There is a VDI for this which has been implemented in the software. It gives
rules for sizing shaft and hub diameters for shrink fit assembly, for example, including recommended tolerances. The recommendations are based on a detailed calculation that takes into account tolerances, friction coefficient, and safety factor. However, if the designer chooses tolerances that do not agree with those recommended, he must search manually for a consistent set. There is no automatic search support.

Another level of this software is the design management system. Here a chief designer is assumed, and he works from the functional requirements and product structure. He deals out tasks to other designers, utilizing the concept of a "function carrier." The FC is ideally a conceptual link between the desired function and a physical realization; in some cases it is an easy-to-identify thing like a bearing (carries the function of supporting the shaft). I did not get a clear impression of any other way to make this link, giving me the feeling that this approach is useful for the "catalog component" method of design, but not for approaches that require several functions from the same item or cases where new items with unusual functions must be made up.

If this project were to obtain follow-on funding, there is the potential for a significant result, namely a system that would show how to link functional, physical, geometric, and management aspects of a complex design process into an integrated activity governed by a standardized approach. No other lab with similar objectives visited on this tour has made any attempt to integrate design management with design engineering the way this project has.

Comments

After reviewing the above projects, it is tempting to ask why all this seems to be so difficult. One researcher I visited spoke wistfully of gate synthesis in electronic logic. This was a done deal at least two decades ago. Algorithms exist that will convert a given Boolean algebra or truth table representation of a desired logic function into the minimum number of logic gates and their required hookup. Why is this possible?

There may be a good mathematical answer to this question, but I do not know it. This researcher and I surmised that logic gates have certain basic properties that mechanical elements just do not have, and these make the difference:

- each gate is discrete

- the gates do not back-load each other but instead behave as a one-way logical cascade

- a gate's behavior is dominated by logic; any physical behavior (heat, thermal expansion) is secondary to its behavior and does not affect it except catastrophically)
- each gate does exactly one thing, does it purely with no side effects, and does it so repeatably that tolerances are not an issue

Typical mechanical and mechatronic elements simply do not have these simple properties.

Conclusions

Each of the projects described above is attempting to tackle a genuinely difficult problem, one that often has been left to "creativity" and deemed too unstructured for systematic attack and computer aids. In spite of impressive progress in restricted design domains, it appears that the problem is living up to its reputation. There may be some underlying reasons for this.

The most likely one is that the problem is indeed too difficult because reduction of requirements to a concept requires too much knowledge; furthermore that knowledge is not well structured.

Thus I return to the theme of the previous section on Artificial Intelligence in Design: the weakness in current approaches is due at least in part to insufficient understanding of the underlying engineering facts or insufficient effort to model them (the load paths in this section, or the machine tool spindle in the previous one - also involving load paths). The designers are probably the wrong people to ask since their approaches are too intuitive. In the near term it may not help to continue trying to build design aids using graphical interfaces, word searches, rule bases, or neural nets because they stand on a weak foundation in the engineering fundamentals.

3. Berlin Production Technology Center

The Berlin Production Technology Center combines the Fraunhofer Institute for Production Systems Technology (IPK) Institute for Machine Tool and Manufacturing Technology (IWF), which was founded by Kaiser Wilhelm II in 1904. It is divided into the following departments, with some of the professors holding dual appointments:

**IPK**
- Robot Systems - (formerly Professor Gerard Duenen, now retired but not yet replaced)
  - Design Technology - Professor Krause
  - System Planning - Dr. Kai Mertins
  - Process Technology - Dr. Wolfgang Adam
  - Computer Engineering for Machine Tools - Dr. August Pothast
  - Service Technology - Professor Spur (education and knowledge engineering)
Professor Krause deals with design, especially computer-aided design (CAD), a field he has pursued throughout his entire 25-year career. His department has 40 full-time staff members and many TUB research assistants. There are four activities:

- Design systematics (NOT what Prof. Beitz does, although Beitz uses exactly the same title.)

The goal here is to enhance the use of existing CAD tools as well as to speed up the creation of new ones.

- Systems ergonomics

This group works on scanning existing drawings and interpreting the results.

- Geometric Modeling

His goal here is very broad and ambitious, namely to build up feature-based design so that it encompasses feature modeling, product performance simulation, and physical modeling (finite elements, for example). The goal is to create a complete product model so that the same data can be used for all these activities.

Professor Krause has been careful to define two kinds of features, the traditional form features and the non-form ones that he calls semantic features. He separated these two in order to confront the PDES/STEP community, which he says recognizes only the traditional kind. A nice example of a semantic feature is "X number of something arranged equally spaced in a circle of radius Y." Another is a "centering or pilot hole," which automatically will be positioned symmetrically once the designer has indicated what surface to place it in. A third is any kind of technology description or constraint, such as a surface roughness or the fact that a certain boundary must not be pierced or broken by any other feature.

- Technology planning

This means deciding how to make something, including equipment selection and process planning. He has had a hard time convincing others that this is really part of design. "It simulates manufacturing, so how better to know if design for manufacture has been achieved?" He feels that some companies are ahead intellectually since technology planning has been taken over by the product design
department. (I found the Japanese of two minds on this; some favor integration in one department or even in one person while others want separate departments. Companies in faster-moving technologies like video cameras wanted the former, thinking it might save time. Companies in slower-moving technologies like cars favored the latter, noting that car manufacture takes a great deal of special knowledge.)

The topics he works on include FMS (flexible manufacturing system) design, laser cutting, fixture and clamping design, scheduling, and tool management. Interestingly, he says that expert systems and knowledge bases seem to be more necessary here than in design because every process and every product is different. There is such a tight coupling between processes, tools, machines, and products, and only people have all the knowledge, which they get from shop floor experience.

**Software Being Developed**

The most interesting software is the feature-based design system mentioned above. It contains a feature-definition language that permits designers to make their own. The research engineer is just starting to address some important issues. One is how to tell the computer where the feature should be located. He is considering using geometric placement notation like "parallel" or "normal" to other surfaces or features. Another is tolerances, which he will root in these constraints. He can say "parallel" but he has no way to check if the designer or the computer achieved parallel. Third is parametric feature descriptions. There is as yet no integration between these parameters and the ACIS geometry engine. He agrees that a way needs to be found to chain parametric constraints and dependencies in technically sound ways, but none exists yet. That is, if one is not careful, one will get spaghetti code in the form of dependency chains that have unpredictable interconnections. I believe that some other researchers are using expert systems and truth maintenance in an effort to keep track of such inference chains. Another way to achieve consistency is to bring more basic engineering rigor to the design process.

It is important to note that Dassault Systemes (see discussion of Dassault above and "New CAD Software from Dassault Systemes: Starting to Combine Design and Engineering" in the ESNIB) is already prototyping software that addresses some of the issues that this research engineer is just starting on. This is one of several cases where industry may be ahead in this field.

4. University of Leeds, UK

The Computer Aided Engineering Unit in the Mechanical Engineering Department at Leeds University, led by Prof. Alan de Pennington, has built its expertise on increasingly sophisticated geometric modelers over the last 15 years. From this base, two main trends have emerged. The first is increased sensitivity to the need for structured data to represent products as a whole, not just their geometry. The second is a broadening view of design beyond creation of geometry to include
concurrent engineering. In both cases, the Unit has established strong ties with the Computer Science Department and has also hired individual staff who combine engineering and CS backgrounds. These ties give the Unit's research a quite different character from that of most other CAD/CAE labs, especially the German ones. Most research has industrial partners. The test cases they provide are "really challenging."

Some results from this lab have had practical consequences. One is an institute devoted to standardizing data formats and promoting data interchange. The other is active participation in the PDES/STEP process; a member of the Unit is the editor of STEP Part 41, which is a top level document defining product configuration data.

Recent research has focused on a product data editor. This is an interactive software tool for designing product data descriptions. The implication is that product data represent a generic need but each product will require its own structure. An important issue is how to define the appropriate structure in each case. Right now the editor creates essentially elaborated, hierarchical parts lists with links to important design algorithms and references to relevant data. The structures contain information about single parts but no information about assembly or other technical interrelations between parts other than set membership. STEP Part 41 has the same character.

New research with UK government and industry funding is dealing with defining product data models that will support concurrent engineering. Both fabrication and assembly will have to be dealt with. Questions to be addressed include:

- what is a specification for a product?
- what is an assembly data model?
- what is a manufacturing model?
- how can conflicts between specialists on concurrent engineering teams be resolved?
- how can different specialists' models be harmonized?

The work is just starting and no definitive results are available.

The Product Data Editor

"Product data model" is new terminology since the mid 1980s. While the Unit's appreciation for such data goes well beyond geometry, in practice the research deals mostly with geometry. So its product data model organizes geometric data, provides a hierarchy for it, and provides hooks for applications that will work on it. Typical applications check for intersections between solids, define or check relationships
between entities (parallel to...), and plan numerical control machining.

The goal of the product data editor is to permit creation of organized and coordinated data structures that allow the applications to get the information they need from one central database. This contrasts with current commercial capabilities in which data are created and structured during the design process by the CAD software. The data must often be massaged or converted to a new form before a new application can work on it.

While recent object-oriented data structure efforts have produced hierarchical trees, the Leeds structure editor creates directed graphs. In order to support recursive structures like {products contain parts or subassemblies which contain parts or subassemblies}, the graphs can be cyclic. They thus can support a "part" which is actually an assembly of parts.

I was shown the proposed general structure. (See Figure III. 2) Interestingly, it contains "FEA analysis" as one of a collection (COL) of nodes fairly near the top of the hierarchy, indicating that a finite element model was presumably needed at the "product" level. This is quite unusual. (Note in this figure the repeated patterns enclosed in the shaded contours and the repeated occurrences of FEA analysis at the "assembly" and "component" level.)

It is necessary to point out that this structure was carefully made and not arbitrary, but did not represent a tested model of a real product. Yet the inclusion of the FEA node at this unexpected place provides an irresistible opportunity to ask where such structures might come from in the future. All the previous data models I have seen in industry are in some sense mimics of a product design/development process. Hence they contain essential elements of time and logical precedence, indicating data that are needed first, then second, and so on, plus the data flows as inputs and outputs.

The Leeds structures are not typical time-based models of design processes like PERT/CPM diagrams (and of course they need not be). Instead, they are something else, but it is not clear what. They are not just descriptions of the product because they have references to engineering analyses high in the structure. These references correspond to a time relationship in the design process: when an assembly model is available, do an FEA on it. Why are these FEA references there? How did someone decide that they belonged there? What is the relationship, in other words, between this structure and its designer's image of the time-based design process?
Figure III.2. Fragment of Hierarchical Product Data Model

This discussion also points out, again, the fact that one can include data in a "product" data model that actually support or even describe the design process rather than the product itself. This is an important and perhaps paradoxical point. It may be an admission that there is no such thing as pure product data. A similar point is made by Prof. Herb Voelcker [Voelcker] of Cornell: 50 years ago designers annotated drawings with notes like "drill and ream." That is, the designer put process planning instructions on the drawing. In more recent times, the ideal has been to separate design from process. The designer says what tolerances he needs but a process planner decides whether or not reaming is needed to achieve the tolerances. The choice may hinge on what machines are available or how many of the part are needed. This is a nice ideal but it plays a big part in separating design from design for manufacture. The disadvantages of this separation are now clear, but there is still no agreement on whether designers should resume saying "drill
and ream.” Similarly, product data designers are investigating whether, when, or on what part sets FEA should be done.

Many people familiar with electronic product design and manufacture (VLSI for example) point out that one of the main reasons why VLSI has advanced so rapidly is that designers need not concern themselves with process issues. The process limitations are represented by design rules that can be expressed purely in geometric terms (minimum radii, minimum line width and separation, etc.). These rules can easily be checked and enforced by the computer. Furthermore, most elementary functions in VLSI are represented by standard cells of basic devices and interconnects which the designer can lift from a library. This leaves the designer free to think almost completely in terms of functions.

If the Leeds work is a harbinger, then it adds evidence that mechanical product design will never be accomplished as pure data manipulation at the function level the way VLSI design is.

A final point: this research clearly shows the influence of sophisticated computer science, provided not only by collaborators Prof. Peter Dew and David Holdsworth from the CS department but also by staff members Susan Bloor and Alison McKay who combine engineering and CS backgrounds. Dew spent several years working on VLSI data architectures and automated design methods. None of the German CAD research observed on this tour of Europe contains anything like this level of CS participation or sophistication.

5. Ecole Nationale Superieure des Arts et Metiers (ENSAM), Paris

The ENSAM Lab for New Product Concepts is an interesting mix of research, teaching, continuing education, and industrial consulting. Without the aid of fancy computer tools, this group has carefully and pragmatically elaborated a product development strategy that is considerably richer than typical concurrent engineering methods. Products are described at three levels and roles for each of the actors in a CE process are spelled out for each level. This is considerably more sophisticated than just forming teams and letting them figure out what to do.

The procedures they have so far constitute a manual methodology rather than computer tools. The main steps in the process that they describe are the familiar ones of identifying the need, converting need statements into function statements, searching for possible implementations, choosing one, testing and prototyping, and so on. In this regard their work sounds like that of Prof. Beitz and others.

However, most labs take a heavily engineering-oriented approach whereas the ENSAM people work at a more conceptual level and are not as technically focused. Interesting aspects of their methods include making a semantic characteristics list to describe a product, making diagrams that show how each part or assembly satisfies each requirement, and looking at a product at different levels called "minimal..."
The PhD work of M. Le Coq attempts to tie all of this together by laying out the elements of a systematic product design method. Every product development project has four components:

- the product concept itself: This is a clear statement of the first idea of how the needs might be met, stated in such a way that all the people who must participate in the design process can understand it.

- the procedure: This is a statement of the actions that the design team must carry out in order to design the product.

- the structure: This tells the designers how they must interact with each other in carrying out the procedure. Two different types of structure are identified: the multidisciplinary team method and the series of experts method.

- the tools: These comprise engineering, computers, and so on, plus their software and methods.

The procedure operates at three conceptual levels: the minimal set of parts or elements that can satisfy the requirements, an architecture (spatial arrangement and physical connections) that links those parts, and all the individual parts in a complete design. These are pursued in that order. The main job of the designer is to think up architectures and their minimal parts, while the engineer must determine the flows of energy, fluids, heat, stress and so on between these minimal parts. In the best of situations, the work is carried out by a designer-engineer who can work at all levels. This procedure is similar in most respects to typical product development methods.

The interesting part of this is a chart (Table III. 2) which shows how each of the players in a multi-disciplinary design team might see the minimal parts, the architecture, and the individual parts. [Le Coq] For example, the assembly person would look at the minimal parts from the point of view of trying to standardize them and their required assembly processes. He would look at the architecture from the point of view of assembly sequences and process optimization. Finally he would look at individual parts to see how to speed up their assembly and lower the cost of doing so on an individual part basis.

<p>| MARKETING, SALES | IMAGE, IMPACT OF TECHNOLOGY, SALE PRICE | MARKET NICHE OR LEVEL, DIVERSITY, DIFFERENTIATION, COST | FINISH, COST, MARKET NICHE OR LEVEL |
| DESIGN, STYLING | CONCEPT CHOICE, TECHNOLOGY | MARKET NICHE, IMAGE, USES | APPEARANCE, SHAPE, VISUAL AND TACTILE ASPECTS |</p>
<table>
<thead>
<tr>
<th>ERGONOMICS</th>
<th>TECHNOLOGY, CHOICE AND REALIZATION OF ACTIONS AND FLOWS OF ENERGY AND INFORMATION</th>
<th>RESPECT FOR CONSTRAINTS ON THE FLOWS BASED ON THE CONCEPT REQUIREMENTS</th>
<th>MICRO ACTIONS, VISUAL AND TACTILE ASPECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESIGN OFFICE</td>
<td>TECHNOLOGY, CHOICE AND REALIZATION OF ACTIONS AND FLOWS OF ENERGY AND INFORMATION</td>
<td>RESPECT FOR CONSTRAINTS ON THE FLOWS BASED ON THE CONCEPT REQUIREMENTS</td>
<td>MICRO ACTIONS, VISUAL AND TACTILE ASPECTS</td>
</tr>
<tr>
<td>FABRICATION</td>
<td>TECHNOLOGY AND STANDARDIZATION OF PROCESSES</td>
<td>PROCESS CHOICE, COMPLEXITY OF PARTS</td>
<td>PROCESS OPTIMIZATION</td>
</tr>
<tr>
<td>ASSEMBLY</td>
<td>TECHNOLOGY AND STANDARDIZATION OF PROCESSES</td>
<td>CHOICE AND OPTIMIZATION OF PROCESSES, TRAJECTORIES, SEQUENCES, TOOLS...</td>
<td>OPTIMIZATION AND REALIZABILITY OF CYCLE TIMES, AUTOMATION</td>
</tr>
<tr>
<td>TESTING</td>
<td>TECHNOLOGY AND STANDARDIZATION OF TESTS</td>
<td>TESTING SCENARIOS AND STRATEGIES, CREATION OF FUNCTIONAL SUBASSEMBLIES</td>
<td>INTERFACES, SYSTEM CONNECTIONS, REPAIRS</td>
</tr>
<tr>
<td>MAINTENANCE</td>
<td>STRATEGY, COST AND EXCHANGE OF PARTS, WARRANTIES</td>
<td>ACCESSIBILITY FOR DIAGNOSIS AND REPAIR, CHANGES TO THE SYSTEM</td>
<td>EASE OF REMOVAL AND REPLACEMENT, SPECIAL TOOLS</td>
</tr>
<tr>
<td>PURCHASING</td>
<td>POLICY, CONSTRAINTS ON SUPPLIERS, MAKE-BUY DECISIONS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RECYCLING</td>
<td>STANDARDS AND CONSTRAINTS (TOxicity...)</td>
<td>HOMOGENEITY OF MATERIALS, ACCESS TO DANGEROUS ELEMENTS</td>
<td>MATERIAL CHOICE, REMOVABILITY, DISPOSABILITY</td>
</tr>
</tbody>
</table>

Table III.2. Three Levels of Product Specification and the Roles of Team Design Process Participants at Each Level

There is at present no firm plan to computerize this procedure. Instead, ENSAM teaches it, mostly to small firms.


The laboratory of Prof. Jean Figour is devoted to design of automatic assembly systems. These typically consist of transfer systems and a series of fixed stations or stations containing limited motion fully programmable robots. Equipment and system design methods capable of handling different versions of a product to another are a central feature of the research. It covers all the interrelated aspects of system design:

- assembly sequence analysis of products
- design for assembly
- assembly machine elements
- assembly system controllers and languages for driving them
- discrete event simulation languages and software
- continuous event simulation languages and software

The simulation software is similar in many respects to others of its kind, but is well-
presented on Silicon Graphics displays. The discrete event version uses Petri Nets to model the system. It can simulate not only the physical activities of the machinery but also the operational aspects of receiving an order and processing it. Simulation of delivery of multi-version products from semi-flexible systems is a key aspect of its capabilities.

The continuous event version combines animation of workstation and human activities with statistical performance displays on the screen. Behind this software is the capability to design the system from a library of actuators and machines whose cycle times are known or calculable. Thus it will be of interest to companies that build such systems. Some of the above research will apparently play a part in the SCOPES project.

More interesting from the research point of view is recent unpublished work on assembly sequence derivation. It is based on the disassembly method, as is most recent work on this topic. Parts are analyzed via CAD models to see if they can be removed in one of the cardinal directions X, Y, or Z. A node-node incidence matrix is used to record the blockages found. (A 1 in the X: A-C entry means that part C blocks the exit of part A in the X direction.)

An interesting feature of this work is the use of powers of node-node incidence matrices that model the interconnection diagram of the parts in an assembly. An entry of "1" indicates that a part is directly connected to another. The square of the matrix contains "1" to indicate that two parts are separated by one part; that is, there is a path of length 2 between them in the interconnection diagram. Successive powers of this matrix are able to elucidate longer paths.

This property is used to find how many parts intervene between one part and another that blocks its removal in a given direction. Another matrix is constructed showing if parts are fastened to each other, by screws for example. If this matrix is combined by inclusive OR to powers of the interconnection matrix, one can deduce groups of parts that are fastened together, thus leading to the ability to identify one type of subassembly. Stability of subassemblies can be checked in a similar way.

This work is still in a preliminary stage and no large scale tests of the algorithms have been made. A definitive explanation of the method awaits a formal publication.

C. Summary

The research labs visited are carrying out a wide variety of activities. These can be grouped roughly as follows:

1. Concept design methodologies and aids

2. Detail design improvements, including some engineering aids in the form of AI
Approaches to concept design usually take the form of "inspired sketch pads" that permit a designer to call forth library functions like "motor" or "bearing" and hook them together into systems. These systems can be simulated or analyzed in other ways; then they can be converted element by element into specific geometry. The analyses are supported by various knowledge and rulebases. At least, that is the goal. Most of the difficult conversions are done by the designer, not the computer.

Research into detail design comprises various efforts in feature-based design, generalized sculptured surfaces, and geometric realizations of specific engineering systems, such as machine tool spindles. Some labs support the designer with rule and knowledge bases while others are trying to create connections to engineering analyses like vibrations or finite elements. Efforts also exist in linking mathematical and geometric constraints to geometric modeling and feature-based design.

The researchers seem to be unaware of the forces and events driving the companies. They see design the same way they have for years: as an individual activity that needs to be supported by computers: to design a single product, a single person must reduce a set of requirements to a geometric description, observing the needs of manufacturing and revising the design as necessary to achieve those goals. Companies see this aspect of design but also see something most researchers do not: a complex multi-person activity that must be managed, dominated by huge masses of data and sharp conflicts between the needs of various constituencies.

Both researchers and companies agree that design is a progressive process, but the researchers see it as an orderly quest. By contrast, the companies live with wild gyrations in risk, strong differences in approach by different design team members, and problems too big for one or even a few people to comprehend and manage. These differences are not just a matter of style but represent real gaps that strongly affect what researchers and industry, respectively, think computers will be able to contribute as well as how those contributions should be described and achieved.

The experience of actually designing a complex item appears indispensable if one is to comprehend the process and aim research at its most difficult points. Too few design researchers have such background. The exceptions are immediately obvious. In Germany, for example, most professors are former industry designers or engineers, and bring a very technical attitude to their research, with interesting results. But many of these people got their industrial experience before major advances in computer science occurred, and they do not integrate such knowledge with their research. This gap is apparent in most other countries as well. Thus actual design experience is necessary but not sufficient. New collaborations are needed, not only between researchers and companies, but between engineering and computer-oriented researchers.
Furthermore, the trend to adopt AI methods and neural nets may be suffering from a lack of basic engineering knowledge or absence of sufficient analytical foundation. Expert systems have not delivered on the most optimistic hopes and have instead found a place as training aids and ways of accessing standard information of various kinds. This is a useful result but not one on which long term improvements in design methodology are likely to rest. Opportunities to link AI methods with more analytical and fundamental expressions of engineering are needed.

In the face of these gaps, more than one person in industry questioned whether universities really can do research in design and manufacturing. An alternative offered was to let industry set the agenda since it has direct contact with the problem, while universities should be "centers of excellence" in specific areas. Many companies follow this formula now. The trouble with it is that industry too often sees limited horizons or the problems of its operating environment alone. The ability of researchers to find generalities and underlying principles should be valuable in forming the research agenda and finding broadly useful solutions. For this reason alone, universities should not be relegated to centers of excellence, which in reality would amount to consulting practices.
IV. Trends in Government Funding of Research

Government funding for research in Europe comes from two different sources, each nation’s own research ministries plus the European Community (EC) programs such as European Strategic Programme of Research and Development in Information Technology (ESPRIT), Basic Research in Industrial Technologies (BRITE), European Research in Advanced Materials (EURAM), and Research and Development in Advanced Communication Technologies for Europe (RACE). EC programs operate under rules that require partners from at least two member states. Projects usually contain both companies and universities and are initiated by companies in response to calls for proposals. Unlike design and manufacturing research in the US, European and EC research in these areas has a permanent and deep applied component. This component is enforced by the required industrial participation as well as requirements, especially strong in the UK, for a defined technology transfer plan in most projects.

ESPRIT and BRITE-EURAM are major components of the EC Framework program for R&D. For the time period 1991-94 the total Framework funding is 5.7 billion ECU. Of this, ESPRIT has about 2.2 billion and BRITE-EURAM has 748 million. (One ECU = $1.30, approximately, as of September 21, 1992.) A breakdown of funding by topic area appears in Table IV. 1. ESPRIT and BRITE/EURAM programs have been combined in this table.

<table>
<thead>
<tr>
<th>PROGRAM ELEMENT</th>
<th>1990-1994 BUDGET (MILLIONS OF ECU)</th>
<th>PROGRAM TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ENABLING TECHNOLOGIES</td>
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<tr>
<td>1. INFORMATION AND COMMUNICATIONS</td>
<td></td>
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<tr>
<td>TECHNOLOGIES</td>
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<tr>
<td>INFORMATION TECHNOLOGIES</td>
<td>1352</td>
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</tr>
<tr>
<td>COMMUNICATION TECHNOLOGIES</td>
<td>489</td>
<td></td>
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<tr>
<td>TELEOMATIC SYSTEMS</td>
<td>380</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>2,221</td>
</tr>
<tr>
<td>2. INDUSTRIAL AND MATERIALS TECHNOLOGIES</td>
<td></td>
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</tr>
<tr>
<td>INDUSTRIAL AND MATERIALS TECHNOLOGIES</td>
<td>748</td>
<td></td>
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<tr>
<td>MEASUREMENT AND TESTING</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>888</td>
</tr>
<tr>
<td>3. ENVIRONMENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>414</td>
<td></td>
</tr>
<tr>
<td>MARINE SCIENCE AND TECHNOLOGY</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>518</td>
</tr>
<tr>
<td>4. LIFE SCIENCES AND TECHNOLOGY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIOTECHNOLOGY</td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>AGRICULTURAL AND AGRO-INDUSTRIAL RESEARCH</td>
<td>333</td>
<td></td>
</tr>
</tbody>
</table>
Major changes, reassessments, and new programs are emerging within the EC's research programs. Two research Directorates (Computer Integrated Manufacturing and Engineering (CIME) in ESPRIT and portions of BRITE) have recently been merged to eliminate overlaps in objectives and projects. In addition, the Intelligent Manufacturing Systems (IMS) program proposed by the Japanese is causing important international connections to be established and new methods of cooperating to be developed. Underlying the policy issues are basic research questions such as whether manufacturing research is important enough to be funded separately, and whether a top-down application of information technology R&D alone can solve problems in design and manufacturing.

A. BRITE/EURAM

This program sponsors research into materials, manufacturing processes and design, and computerized methods of operating complex factories. The budget for 1991-1994 is ECU 748 million, allocated as follows:

- raw materials and recycling: 12%
- materials in general: 35%
- design and manufacturing: 45%
- aeronautics: 8%

The latest round of funding drew proposals in April 1992 and another round ends in February 1993.

The program's former director, David Miles, noted that BRITE was designed to be a "bottom-up" program driven by the needs of users, that is, manufacturing companies. However, these needs are not well understood by researchers, indeed not well understood by most companies. The main reason appears to be lack of awareness of system issues, such as inability to write a proper specification for a flexible manufacturing system or determine the reasons why it is not operating properly.

Table IV. 1. 1990-1994 EC Framework Budget

<table>
<thead>
<tr>
<th>Category</th>
<th>Budget (ECU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIOMEDICAL AND HEALTH RESEARCH</td>
<td>133</td>
</tr>
<tr>
<td>LIFE SCIENCES AND TECHNOLOGIES FOR DEVELOPING COUNTRIES</td>
<td>111</td>
</tr>
<tr>
<td>ENERGY</td>
<td>814</td>
</tr>
<tr>
<td>NON-NUCLEAR ENERGY</td>
<td>157</td>
</tr>
<tr>
<td>NUCLEAR FISSION ENERGY</td>
<td>199</td>
</tr>
<tr>
<td>CONTROLLED NUCLEAR FUSION</td>
<td>458</td>
</tr>
<tr>
<td>MANAGEMENT OF INTELLECTUAL RESOURCES</td>
<td></td>
</tr>
<tr>
<td>HUMAN CAPITAL AND MOBILITY</td>
<td>518</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5700</td>
</tr>
</tbody>
</table>
In order to bring more structure to his research program, he has been looking at the whole supplier chain in order to identify the necessary steps in producing products, find the technology gaps, and focus research on them. He notes that this approach has a shortcoming with regard to design, whose necessary elements and procedures are not well understood. In particular, the constraints on products are changing rapidly, with recycling and environmental effects rising in importance. No one knows how to take these systematically into account during design, which is the only place such accounting can occur. On this point he cautions that one can place too much responsibility on design and over-burden it, making it so complex that no one can accomplish it, especially small businesses.

B. ESPRIT's CIME and IMS Programs

(CIME = Computer Integrated Manufacturing and Engineering. IMS = Intelligent Manufacturing Systems which are discussed later in this section.)

The ESPRIT program has had two Phases and is now in Phase III. The funding history is:

Phase I (1984-88): ECU 1.5 billion (12% was for CIM)
Phase II (1988-92): ECU 3.2 billion (16.5% for CIM)
Phase III (1991-94, deliberately overlapped): ECU 2.7 billion (20% targeted for CIME)

The "E" in CIME is new with the start of ESPRIT Phase III in 1991 and reflects a strategic decision to apply CIM methods and technologies in areas outside of traditional manufacturing, such as agriculture and construction. This decision appears to include extending the CIM idea beyond data exchange, networks, and traditional metal cutting to include the whole product life cycle. These new areas are the source of more proposals than the EC expected, so budgets in the traditional areas are being squeezed. It is my impression that Mrs. Patricia Mac Conaill, the Head of Division responsible for these programs, has had to fight very hard to keep funding active for CIM. Perhaps this is due in part because manufacturing research is not viewed in the same light as more traditional discipline-oriented areas.

A major role for her has been to foster and develop a community of researchers and government officials in the member states who agree on a broad research agenda. The differences in culture and style between the member states of the EC must always be kept in mind. For these reasons she is particularly pleased with progress in data exchange standards and a technology diffusion program called CIMEUROPE. The latter helps small and medium size enterprises (SMEs) find partners for technology transfer, consulting, business contacts, and EC research program participation.

Another impression gained from talking to her as well as to others is that the EC programs, regardless of degree of technical success, have over many years achieved
something Europe has never had before, namely this community of people in industry, universities, and government who understand some of the technical challenges and now know each other as well. Mrs. Mac Conaill is one of the builders of this community. She has also kept up informal collaborations in the U. S. with NSF, NIST, and until recently, CALS.

C. CIME Program

In the CIME program, funding averages ECU 130 million per year and covers 60 projects now with 60 more coming on stream next year. The average is thus a bit over one million ECUs per project, each lasting several years.

The overall goals of CIME are to improve European industry's competitive position by:

- applying IT solutions in processes and products, with emphasis on "applying"
- seizing new markets
- producing cleaner industrial processes

The application areas are discrete parts manufacturing and its associated processes; engineering, mining and extracting of materials; construction; and agriculture. The "tools" for this push are IT architecture and infrastructure, management and design of enterprises (all the necessary software for CIME), and mechatronics, robotics, and sensors (all the hardware necessary for CIME).

The architecture issues to be dealt with include open architectures and neutral data, "information engineering and management," how to migrate to an open environment, and how to achieve cost-effective integration of software tools. These are "user-driven" concerns, and are similar to the priorities of many US software researchers. The emphasis on "user-driven" is a new one in ESPRIT, however.

Design and management of enterprises includes

- integration of software tools into systems
- how to implement software changes, i.e., the human and organizational issues
- concurrent engineering (which here means many designers working on the same design at the same time)
- manufacturing and the environment
- consideration of the entire logistical chain from raw material to end user
- economics and performance monitoring of CIME
- quality management

Mechatronics includes
- design and modeling of multi-disciplinary items
- coherent database and interface specifications for multi-technology activities
- micromachines

These are very extensive lists and appear to reflect some of the cumulative effect of long-term community discussions mentioned by Mr. Miles, as well as some obvious overlaps with BRITE.

Among the accomplishments cited are the program's influence on standards, especially the STEP process; some neutral data definitions; new products such as open architectures, interface boards, CAD tools; several actual CIM implementations; and enhanced education and training programs.

D. Intelligent Manufacturing System (IMS)

The IMS was presented to ESPRIT by the Japanese in November 1989. After the original Japanese call for proposals, the US Department of Commerce requested that the contacts be handled under the provisions of existing US-Japan agreements. A long series of informal trilateral discussions has taken place seeking to determine methods of funding, clarify ownership of intellectual property rights (IPR), and reduce the academic character in favor of one more oriented to industry.

The current status (summer 1992) of these negotiations is as follows:

1. Instead of launching the IMS directly, there will be a feasibility study lasting about two years, during which the "modalities" (ways of working together), IPR, funding mechanisms, and overall viability of the IMS will be assessed.

2. A complex committee structure has emerged, giving rise to some concern that bureaucracy will dominate the program. This structure consists of a Steering Committee, a Technical Committee, and an IPR Committee.

3. The Technical Committee has recently agreed on six research themes for the feasibility study period:

   a) enterprise integration
   b) global manufacturing
   3) system component technologies
   4) clean manufacturing (environmental concerns)
   5) human and organizational aspects
   6) advanced materials processing

E. UK Funding Trends and Strategies

Until five years ago, English universities had line item budgets from the
government that were based on "planned" enrollments. If enrollments fell short of the plan, the universities kept the extra money. This has been changed so that funds are now based on actual enrollments. The government also gives funds that match industry contributions and contracts. This trend has forced research into a more applied mode in order to capture industry support. It also has tended to tilt the research more toward bottom-up in the sense that particular processes or design steps must be emphasized even if there is a generic goal in the minds of the researchers.

Another change that is affecting universities is a triage by the government. The result of the triage will be three classes of universities, those that have broad curricula and unrestricted research opportunities, those that will revert to teaching only, and a group in the middle with teaching and limited research topics. The same triage is happening in Germany.

The nature of government funding for design and manufacturing is also changing. The two sources, SERC (Science and Engineering Research Council, like our NSF) and DTI (Department of Trade and Industry, like our Department of Commerce) have different goals, funding sources, and management techniques. SERC's design research\textsuperscript{14} is currently a single program, not an ongoing process with a recurring budgetary line item. DTI on the other hand funds more broadly defined manufacturing research through its line item for the ACME (Application of Computers to Manufacturing Engineering) directorate within SERC. A joint DTI-SERC steering committee called the Advanced Manufacturing Technology Committee (AMTC) oversees the ACME program. AMTC operates in a sort of contract mode rather than a grant mode. It establishes milestones and frequent reviews. It can stop a project if it is not making progress, and it often does so. Since its founding in 1984 ACME has spent £40 million.

The November 1991 edition of the ACME Strategy booklet defines what looks to me like an "industrial policy" and appears to me to be

- declaration of a mission to use research funds to help British manufacturing
- recognition that something beyond "basic" research is needed to help manufacturing
- identification of classes of research and industries
- conscious allocation of projects and resources to some of these classes
- recognition that manufacturing spans technical, social, and financial domains, and that spanning research is needed

\textsuperscript{14} The SERC's program is the subject of a separate and more detailed ENSIB article.
- A **time-line structuring** of each project from idea to "product" so that suppliers and users of potential results are part of the project from its initial planning stage until its conclusion (the concurrent engineering of research projects?)

- A **cross-disciplinary structuring** of the projects requiring collaborators from different backgrounds, companies, and universities

- Rejection of collaboration or diversity for its own sake

Close reading of the strategy book indicates the following:

- Overall, research funds in manufacturing will shrink over the next three years

- Since several university centers of excellence have emerged over the last few years, it is they that will get the bulk of the remaining funds, while others will be squeezed out

- Funding for robotics and textile manufacturing will be reduced while funds for management and planning research and for manufacturing processes will rise; funds for CAE, integration methodologies, and advanced production machines will remain the same (integration was boosted significantly last year)

- Compensation for the funding falloff will be sought from industry

- Projects will be actively monitored

- The entire portfolio of projects and research topics will be reviewed in two years

F. Funding Trends in Europe

Along with many other things, the structure and funding of the EC research programs attracts comment and internal reviews. As noted above, several obvious overlaps between BRITE/EURAM and ESPRIT have recently been removed. Other changes may occur as the EC attempts to improve the technology transfer from its projects.

National research funds in several countries are on the downturn. This is especially evident in Germany, where a general contraction due in part to financing unification has hit both research and education. Grant funds are becoming hard to get, even for famous research institutes. Universities are being forced to reduce the number of faculties (roughly equivalent to departments). In several countries (UK, Germany, France) increased attention is being focused on Polytechnics (Fachhochschules, Ecole Polytechniques, respectively) in an attempt to increase the number of trained engineers and technicians, possibly at the expense of PhD's.

The downturn in national research funds has forced more and more universities
and companies to turn to ESPRIT. The result is more projects with numerous partners, with all their advantages and disadvantages, plus a lower likelihood of obtaining funds. Several researchers are frustrated and have seen major projects stop for lack of renewal money.

G. Comments

It is not clear that multi-partner projects are a good idea. From the point of view of research output, they are hindered by problems of coordination as well as communication. Typically projects have 5 or 6 participants but some have 20. From the point of view of fostering European unity and mutual understanding among EC member states, as well as between companies and universities, the projects probably are beneficial in the long run. The researchers themselves, both in industry and universities, often remark on the disadvantages while the EC program administrators often point out the advantages.

It takes a lot of discussion to bring about big international projects; both Japan and the EC have benefited from existing (inter-) national infrastructures for doing these negotiations. The US has much less experience in this area and needs to get more soon.

A French research manager said that ESPRIT projects last three years, of which the first 1.5 are used to establish a common technical vocabulary and understanding of the partners' goals and methods. An American Professor of Management at Cranfield whom I met on a bus said, "We all speak English and look alike so we assume that our cultures are the same. This mistake takes a long time to discover and correct."

A good deal of underlying mistrust must also be overcome. Several Europeans told me that they do not like the IMS because it is too likely to result in one-way technology transfer to Japan. A major goal of the feasibility phase should be to establish two-way transfer and show how it can be made a permanent part of the program.

Finally, the structure of EC and UK programs has both benefits and drawbacks that need to be considered. It is useful to have industrial participation in research projects, as well as to enforce a degree of technology transfer. Direct contact with industry’s problems is usually revealing to researchers, who find the complexity of real problems challenging. On the other hand, longer term research may fail to obtain funding, either because companies do not see where it will lead or because universities deliberately restate the objectives in order to appeal to industry, on whose funds they increasingly depend.
V. Conclusions and Recommendations

A. Conclusions

I have drawn several conclusions from this survey:

1. Design research is extremely diverse. Everyone says "design" and means something different.

2. Most design research focuses on the technical activities of an individual designer, attempting to increase the quality of his/her output.

3. Companies do not see much in ongoing design research that appears useful to them. The main reasons are that some research is quite far ahead of industry’s self-perceived needs, that industry is not skilled at recognizing potentially useful research, and that researchers’ view of design is too different from industry’s view.

4. When asked to identify their problems, industry people focus on organization and management of the design process, finding out its true structure, requirements, and information content; they do not cite problems with the quality of individual engineers' work. This priority, in advanced companies, dates back as much as 15 years, while in lagging companies it is as recent as 2 years. (Companies do care about the quality of individual designers even if they do not talk about it. But they deal with that issue differently, usually with in-house training. In the US one often hears complaints that university graduates are not well-prepared.)

5. The most advanced companies (in Europe and Japan) view computers primarily as an aid to this information management problem and only secondarily as devices for doing calculations or defining geometry. (From Nissan: "We are presently defining our next generation working style and will write or buy software to suit." From Aerospatiale: "We introduced design-build teams in 1975 and CAD in 1977. Computers, from the outset, were used to support this new way of working. Our database is the most important element.")

6. Companies are evolving increasingly sophisticated approaches to product design and need new tools to support these approaches: design of product families, of products that will evolve into different models, that must be made in a JIT environment and sold into complex and shifting markets, or that will be made in different countries using different mixes of people and machines. These are all "integration-rich" areas which pose quite different challenges from those recognized and supported by computer tools in the past.

7. The CAD vendors have followed rather than led this process. Their emphasis used to be on accurate geometry, which is important but not an end in itself. More recently the emphasis has shifted to data management, engineering knowledge, and
"integration-rich" processes like assembly.

8. Industry's experience with Concurrent Engineering has revealed many of these new requirements as well as the need to better meet customers' needs, exchange information in new patterns and sequences, take account of assembly, predict costs, improve reliability, account for recycling regulations, and so on. More data, diverse and conflicting, must be found and combined, in order to respond. New algorithms are needed to sift and combine data, resolve the inevitable conflicts, and reach good design decisions.

9. Unless they commit to defining the requirements and writing the necessary software themselves, the companies face a difficult task explaining the requirements to the vendors. However, the skill to write this software and the commitment to maintain it do not exist at very many companies.

10. The knowledge needed to respond to these challenges generally does not exist inside the CAD vendors. Typically they offer a new product or capability and, if "successful," they are inundated with demands to change it to do what is really needed. This "generate and test" approach is not very efficient. Since the vendors are small, they often must choose which customer to respond to and hope that the others will like the result. But sophisticated design methodologies are increasingly industry-, product-, or company-specific.

11. Rarely do companies try to explain these new requirements to design researchers, whose research does not reflect much awareness of them. Much of the US research on Concurrent Engineering, for example, reflects awareness of the need for electronic communication, again necessary but far from sufficient.

12. Thus the companies must supply the majority of the knowledge and experience required to define new design paradigms and software requirements. The "right" strategy of combining the skills and knowledge of users, vendors, and researchers has not emerged and remains a major barrier to improved design methods.

13. Only the largest companies have the resources to take on this task themselves. Medium and small size companies are left to buy what the CAD vendors offer, compatible with lower cost computers. Only in Japan is there an approach to this problem: the multi-tiered supplier system in which higher level companies teach new methods and, recently, provide software to their next-lower tier suppliers.

I am convinced that design researchers can play an effective role as design goes through a revolutionary and exciting phase. To make this role possible requires establishment of new technology transfer mechanisms and changes to the research agenda.

The gist of the recommendations which follow is that the design process needs additional and broader attention by researchers, working together with end users
and CAD software suppliers. The collaboration must be structured this way because the design process and the computer tools are so intimately linked. The users have the clearest view of design, while the suppliers have the best chance of delivering well-designed tools; the researchers have the longest view, a (possibly) better view of allied knowledge that could be brought to bear, plus the drive to generalize and find scientifically-based solutions.

B. Recommendations

1. Define a focal issue for design research: to determine the required content of a product data model.

The design research community needs a large focal issue to work on together. Design research is at present too fragmented; a critical mass has not formed behind any particular topic. This is understandable given the complexity of design and its relative immaturity as an intellectual field. Too many different things are called "design" and not enough differentiation and prioritization have emerged. The physicists are all looking for the top quark. The atmospheric scientists are all trying to find out where the CO$_2$ is stored. The molecular biologists are mapping the human genome. The latter two activities are especially application-driven in the long term, even if the immediate results must be fundamental advances in knowledge.

In addition, many of the ongoing research activities face uncertain futures because the path to application is blocked by some basic knowledge gaps. The major gap is the lack of a clear concept of a product data model. Ongoing efforts in tolerance representation, feature-based design, assembly planning, and design critiques, to name only a few, will have nowhere to go if there is not an agreed data representation that has a place for them. Their internal data structures are presently developing independently and there is the threat that long term results will be mechanically and (worse) conceptually incompatible.

Not only is a "place" needed, but each of these areas, and others, strongly interact with each other during any challenging design. Thus the research results cannot stand alone in the data model but must be interconnected. An understanding of how they interconnect is presently lacking, another serious barrier.

In recommending a long term effort at developing a product data model (see below where this is spelled out in detail), I am taking the approach I observed in Japan, namely that efforts at integration need to begin before the separate islands are completely understood. Integration brings a totally different learning experience, uncovering sometimes fatal incompatibilities in basic assumptions, methods, and data representations among the previously developed islands of (design) automation.

2. Shift research emphasis away from expert systems and toward fundamental
engineering models of phenomena and activities that are presently approached via expert systems.

The present trend to apply expert systems and neural nets to design needs to be regarded as a clue that basic engineering models are lacking in many areas of design. This "lack" may mean that the knowledge is genuinely non-existent or that it exists but has not been systematized and applied in design methodologies. We need to identify classes of design problems where engineering knowledge could feasibly be improved, and then mount research efforts to make those improvements.

3. Broaden the scope of design research to encompass the industrial contexts.

The design process needs to be looked at by researchers in a new way. A product design is a business concept that contains many engineering problems; it is not a set of engineering problems in a business context. The current research view of design as a purely engineering issue needs to be broadened. The problems of business strategy, data management, conflict identification, and process improvement all need attention. New models of design processes are needed, models that explicitly represent iteration, conflict, constraint propagation, negotiation, and tradeoffs. These issues are bound to be very broad and incommensurate, and people are likely to be left to make the final decisions. That is, an algorithm for resolving basic design conflicts should not be sought as a top research priority. Instead, novel data access, assimilation, and presentation methods may be preferable. Naturally, solutions to these challenges will have to be tied closely to emerging models of product data, inasmuch as the design process appears to be the reason why much of the data are needed.

4. Broaden the engineering scope of design research.

New kinds of design challenges need to be recognized and made the subject of research. These include design of product families, design of products that will be made under specific production constraints (very low volume, Just-In-Time, recyclability, multi-national production, for example), and design/production by multiple firms. In the past, a lot of attention has been devoted to new manufacturing processes to meet such challenges, such as intelligent robots for low volume and model mix production. I am here suggesting that product design be regarded as the weapon of choice for attacking these problems. There is plenty of precedent for this strategy in industry and it has generally been quite successful.

5. Define new kinds of intermediate or partial designs to help resolve problems during concept design.

The basic challenge of predicting future manufacturing and cost problems during concept design is asserted repeatedly by companies. This problem contains an inherent paradox, namely that future detailed information may completely upset decisions made when only rough information was available. The kinds of
information wanted at each stage of the PDP must be pruned to what is most useful and reasonably possible to provide. New forms of intermediate data are needed. For example, to support assembly planning, one needs part "designs" whose shape consists of rough "keepout zones" while only their interfaces to other parts are modeled accurately. Using such data, designers could answer many of the main product architecture questions but would have to accept the possibility that some decisions would be upset later. This compromise is not only necessary but probably worth making in exchange for the benefit. Such data would later be overwritten by the final design but would nevertheless have served their purpose in supporting the design process.

6. Study and improve the design technology transfer mechanism.

Better technology transfer paths need to be developed so that design research results have a better chance of being used. This topic is separate from the need to provide a common data representation. The issues here involve relationships between companies and industries. The basic structures of the industries (where new ideas come from, how information is passed around, how development is paid for, etc.) need to be better understood so that the blockages can be removed. Examples of successes and failures need to be developed in detail so that lessons can be learned.

C. Main Recommendation

Design research would benefit from having a common focal issue, assuming that issue were chosen carefully. The characteristics of a well-chosen focus might be that:

- it can be crisply defined and made specific (not: "better design," "a science base," "more process knowledge")

- researchers, users, and CAD vendors agree that the result will be widely useful or adaptable, perhaps even generic (i.e., it is ultimately application-driven and derives its content from a vision of how it will be used)

- it is obvious that increases in basic knowledge will be needed to achieve it (i.e., it has genuine intellectual content and cannot be achieved with today's knowledge)

- as it evolves it provides the basis for other research issues to be attacked, reflecting a prioritization and sequencing of the knowledge development process in design

- it provides meaningful roles for researchers, users, and CAD vendors to play in its evolution

- it does not require detailed or specific knowledge that only a single company would have or that describes a single process

As a candidate focus issue I would like to offer the Product Data Model (PDM). The
Given the diversity of the community and the intellectual difficulty of design, I would judge this candidate a success if even 30% of those asked agreed with its choice.

I will not dwell on other issues that might have been offered. I lack the time and wit. However, I can justify the central place occupied by this issue by giving my reasoning, indicating that it lies at the end of a logical chain which can be converted into a research plan. This chain passes through other candidate issues on the way to the PDM.

The chain begins with the observation that companies know a well-thought out product development process (PDP) is crucial to their success. An emerging model of the PDP is that of gathering, manipulating, transforming, and transmitting information. A useful analogy has been made between design as a process that transforms information and manufacturing as a process that transforms material: While manufacturing consists of a series of operations performed on material, design consists of a series of questions asked of an information base, a plan for when to ask each question, sources of data to support answering, and a destination or destinations for the answers, which are used to help answer later questions.

The answers come from two types of sources, namely other data bases (including people’s experience) and algorithms. These algorithms can be as simple as “Call Joe” or as complex as optimizations, crash simulations, or other advanced methods. But any algorithm, however simple, will not function if the needed data are not available, and will not function efficiently if the data are not arranged congenially. Given the scale of advanced design problems (hundreds of parts, thousands of finite element cells, tens of thousands of assembly sequences), inefficiency can be equivalent to non-functionality.15

Thus the content and structure of design databases are driven by the needs of the algorithms that will use them. The algorithms, their inputs and outputs, are in turn driven by the structure of the PDP. So the PDM is at the end of this logical chain, the child of the main deliberations concerning how PDPs should be structured and how their inherent questions are to be answered.

One might conclude at this point that the PDM cannot be specified generically because each company or product will require a different PDP, giving rise to a

15 A generic issue in database design involves what data should be explicitly represented and what should be merely derivable from the explicit data. This issue is finessed here, on the assumption that even derived data is available in some sense. It is not a trivial issue but neither is it one whose resolution stands in the way to first order. We should decide first what data must be available somewhere and then decide, based on efficiency, where/how it should be stored.
different PDM. In any specific case this is likely to be true. But one can also argue that any particular PDM will have elements that can be seen in a more generic data model. There may be intellectual and practical advantages to seeking a broad model from which to select elements for specific applications rather than to continue to discover new data that should have been present in the first place. Faith in the usefulness of a generic solution surely underlies the ongoing PDES/STEP activity.

I take the generic PDM view because I have been repeatedly surprised during this study by the wide range of kinds of data that people have already identified as being essential to product design, data which are a) not presently available except perhaps in people’s heads, b) not supported by existing or foreseeable "CAD" products, and c) not being given high priority by the design research community. Furthermore, I get the impression that designers themselves are surprised by what data they have discovered are necessary, and that they are prepared to be surprised in the future. The main surprises will come from the need for data that are about the design process. Table V. 1 contains an example if this kind of data.

| 1. Assembly is receiving increasing attention and is playing a role in early phases of product design that it never played before. Past concepts of product data have focused on representing individual parts because, based on perceived cost, fabrication is the most costly part of manufacturing. But considering assembly early provides a different view of design and provides better designs that are easier to assemble, easier to make in modules, etc. What information is needed to support a rearranged design process in order to permit assembly to play these roles? |
| 2. Integration of assembly into design would be made easier by the concept of "mating features" on parts. During design they can be taken from a standard database in many cases, together with their tolerances, fabrication process plans, and assembly instructions. These features are the information carriers for much of DFA as well as the starting point for a database of part mates, part interconnection lists, part-part tolerance propagation, and so on. |
| 3. Typical machined, cast, and molded parts get their mating features during fabrication. Actual assembly on the shop floor consists of putting the mating features together. However, airframe parts obtain only a few mating features during fabrication. Assembly is accomplished by placing parts in fixtures and match-drilling and riveting using still other fixtures. So, key points on the assembly fixtures play the role of most mating features. Thus even rough assembly planning of airframes must include data about the fixtures, something that is necessary only for very detailed planning of the assembly of other kinds of parts. |
| 4. At the moment, airframe assembly planning and fixture design is not part of the early design process in most companies but is instead accomplished later by the tooling department. Neither the plan nor its dependent fixtures can be optimized by recourse to a different frame design (different module boundaries, for example). Concurrent Engineering would likely move that work upstream in the process. But placing those tooling designers directly in the path of early design decisions would require them to have access to data and algorithms that are presently unavailable. Existing assembly planning algorithms (all in research labs now) deal only with parts that have assembly features on them or that mate using recognizable surfaces on the parts. Fixtures that substitute for mating features are not part of assembly planning research. Formal assembly planning is not yet part of any ongoing product design process that I know of. No CAD databases contain information such as mating features and sequence algorithms that would support assembly planning. |
Table V. 1. Discovering New PDM Requirements

The idea that a PDM is not simply a description of the product but must contain additional information solely to support the design process is a recent one. Because designers are still discovering the implications of Concurrent Engineering and the questions it raises, new information to support the design process will continue to be found.

I also strongly believe that the intellectual ferment in design today focuses squarely on this issue, not on the more traditional issues in design research, to which a great deal of attention is being paid. No one doubts that tolerances need to be represented, or that stresses need to be analyzed, or reliability predicted.

Furthermore, I think this issue is a showstopper. That is, if a satisfactory definition of product data does not emerge (allowing that it will evolve because technology advances and people get smarter) then design will continue to be more risky, experience-based, and inefficient than it needs to be, and major advances, totally new ways to use computers in design for example, simply will not happen, or will have restricted applicability.

Finally, I think this issue fills the requirements set forth at the beginning of this section. It is clear to me

- that this is a sharply defined question,

- that basic knowledge about what constitutes design and engineering is needed to answer it,

- that all the main players have clear and obvious roles to play in answering it,

- that, as answers come in, other research areas will be fostered (feature-based design, data compatibility, efficient change management, capture of engineering and physics knowledge, recognition of "similar" designs...)

- and that progress will be easy to recognize and put to use as it emerges.

The current PDES/STEP activity is the first broadly based attack on this problem. It will not be the last. It must go forward because we need something we can test, react to, and use to formulate the next generation PDM.

A rough research plan for generating the next PDM is as follows:

1. Researchers should go to companies and obtain as many diverse detailed PDP examples as possible. The totality of issues recognized as being relevant to design, plus their interactions, should be collated and presented for comment. These issues
will include questions asked of the design (what's a good assembly sequence?) as well as those asked of the design process itself (what's a good design decision sequence?).

2. From these PDP examples, a list of common design process questions or question types and their interactions should be drawn up, and alternative sequences for asking these questions listed. (It is already known that unique optimum sequences do not exist because many questions depend implicitly on each other, giving rise to iteration. [Eppinger et al])

3. If possible, discernible classes of design processes should be separated out for individual consideration. An obvious example is "redesign" of something whose basic architecture is the same as in past designs.

4. Each of the identified questions or question types from item 2 should be graded according to the long term feasibility of answering it algorithmically and, if judged not feasible, then alternate methods should be identified. Naturally, judgments either way are subject to revision later.

5. At the same time, missing engineering knowledge that would help answer the questions should be identified. Any place where the method "expert system" is proposed under item 4 is a candidate for this category.

6. The data requirements for algorithms and engineering knowledge must be identified. For algorithms that do not yet exist, this is clearly not possible, but a rough description of the required information may be possible to construct.

7. A triage of the identified problems must be carried out and a priority list made so that individual attacks can be planned.

8. A requirements and capabilities list for the next generation PDM must then be drawn up, based on the priority list from item 7. A PDM capable of supporting existing algorithms is clearly the first target. In parallel, the most feasible algorithms should be developed. They must be scalable to the problem sizes evidenced in the survey in item 1.

9. Demonstration projects must then be carried out to test the usefulness of the resulting PDM. The results of these projects must then be fed back into item 1 and the process repeated, taking account of the advances in technology and technique that have undoubtedly emerged during the cycle.
VI. Acknowledgements

I would like to thank the following organizations and people for their help, support, and hospitality. They worked hard for me and made my stay enjoyable and educational:

**Government:**

Office of Naval Research: Dr. Donald Polk, Dr. Ralph Wachter, Ms. Roberta Perry

ONR European Office: CAPT John Evans, Dr. Arthur Diness, CDR Barth Root, Mrs. Sharon Poch, Mr. Ron Wimberly, Mrs. Dar Ford Kayuha

UK Science and Engineering Research Council: Prof. Peter Hills

Commission of the European Community: Mr. David Miles, Mrs. Patricia Mac Conaill

US Mission to the EC: Mr. Anthony Rock

**Universities:**

City University of London - Prof. Alan Jebb

Cranfield Institute of Technology - Prof. Peter Sackett, Prof. Alan Morris, Mr. Graham Jared

École Nationale Superieure des Arts et Metiers - Mr. Marc Le Coq

Ecole Polytechnique Federale de Lausanne - Prof. Jean Figour

Fraunhofer Institut für Produktionsanlagen und Konstruktionstechnik - Prof. Frank-Lothar Krause

Institut de Productique - Prof. Alain Bourjault, Dr. Jean-Michel Henrioud

Institut für Fahrzeugbau Wolfsburg - Prof. Gerhart Rinne

Katholieke Universiteit Leuven - Prof. Joris de Schutter, Prof. H. van Brussel

Laboratoire d'Automatique et d'Analyse des Systemes - Prof. Georges Giralt

Lancaster University - Prof. Michael French

Leeds University - Prof. Alan de Pennington
Companies:

Aerospatiale - M. Bernard Vergne

AMP, Inc. - Mr. Peter Glaser, Mr. Gerry van Alst

Arthur D. Little, Inc. - Mr. Jean-Philippe Deschamps

Charles Stark Draper Laboratory: Dr. David Burke, Mr. Richard Riley, Mr. John Lanfranchi, Mr. John Kingston, Mrs. Pamela Connolly

Dassault Systemes - M. Bernard Charles, M. Pascal LeCland

PSA Peugeot - Dr. Andre Rault

Rolls-Royce Ltd - Mr. John Cundy, Mr. Chris Moore

Siemens AG - Dr. Mario Schacht

Telemecanique SA- M. Albert Morelli, M. Manuel Pedrosa

Volkswagen AG - Dr. Klaus Pasemann, Mr. Klaus von Holleben

Volvo Car Co. - Mr. Kurt Larsson
VII. References


