

**Design Research at the Fraunhofer Institute of Production Technology  
and the Technical University of Berlin,  
and an Industrial Application of Systematic  
Design Methodologies**

Daniel E. Whitney, Liaison Scientist, Manufacturing

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**SUMMARY**

A significant portion of design research in Germany is carried out by mechanical engineers who focus on basic issues like machine elements. In some cases they appear to have backed into computerization of design and have not made many significant collaborations with computer science researchers. Their research thus tends to emphasize the mechanical side and de-emphasize the information technology side. So it is primarily "bottom-up," stressing the basic processes (design of gears or mechanical systems). The research assistants I visited in Berlin have more confidence in the potential for expert systems than the professors do: the assistants cannot see any other way to capture all the diverse criteria that designers must consider; the professors doubt that the necessary expertise can ever be captured by this technique.

This article is based on visits and interviews with design researchers Prof. Frank-Lothar Krause at the Fraunhofer Institute of Production Technology (IPK), Prof. Wolfgang Beitz of the Technical University of Berlin (TUB), and their assistants. "Design" can be divided into several phases. Two important phases are *conceptualizing* and *detailing*. Professor Beitz is trying to combine these with a technique called Systematic Design. Professor Krause is working more at the detail level, trying to strengthen the engineering aspects of geometry creation as well as the links between design and production. Feature-based design is the main technique being applied. Both want to include search and conflict resolution but have not really made provisions for doing so.

I got a close-up look at how reunification is affecting this city and these two institutes. The TUB has 34000 students, including 20% from the former DDR. The western students say that the "easties" are "different," fairly well educated but "not free" in their expression in or out of class. The one eastie I had a chance to talk to privately said that people from his side are astounded by the west's concentration on money. But he is part of and witness to a sharp contraction in funds. Berlin has lost its 20% subsidy from Bonn, and TUB has had to shrink its 22 faculties down to 10, along with a budget cut. Both Krause and Beitz are scrambling for research funds, having seen projects end without follow-ons coming through. The Bonn government is advising the researchers to seek funding from the EC but this, too, is proving difficult. Both the labs I visited have recently failed to get renewals of large EC grants.

**Professor Frank-Lothar Krause, Fraunhofer Institute for Production Systems and Design Technology (IPK), Berlin, Director for Design Technology and holder of the chair in Industrial Information Technology at TUB.**

Professor Krause is very familiar with Japan, both the researchers and companies. (By contrast, Prof. Beitz said that he is not.) Professor Kimura visits regularly from Tokyo, and the two are planning an IMS (intelligent manufacturing system) proposal. On the wall over his desk are two photos distributed by Toyota at several recent international committee meetings and conferences: before and after in finding design errors under the hood of a car. "Before" shows designers crawling around on the floor over an enlarged drawing. "After" shows them sitting around a projection television looking at a multicolored wire frame drawing. "International cooperation is basic to international competitiveness. In fact, international is like interdisciplinary—the only way to get ahead," he said.

IPK was started by Prof. Gunther Spur in 1976. It is allied with the Institute for Machine Tool and Manufacturing Technology (IWF), which was founded by Kaiser Wilhelm II in 1904 as part of the TUB. The combination is today called The Berlin Production Technology Center. It is now in an enormous new circular building whose outer ring holds offices that look down on a huge circular central laboratory/atrium. IPK's budget is currently around 25M DM, (about 1.55 DM per \$, as of August 1992), of which 13% comes from the Fraunhofer Society, 50% from competitive industrial contracts, and the rest from competitive research funded by Bonn or the EC.

Professor Krause said that of some 100 Ph.D.s who had graduated over the last 40 years, 13% are in top management and 40% in middle management; the rest are engineers or consultants (22%) and 25% are at universities. Thus IPK has succeeded in having a strong effect on how German industry is managed. In the U.S., most such people would go to universities right after graduating. This is unheard-of in Germany, where one must have at least 5, preferably 10, years of industrial experience before starting to teach and do research. He is amazed at some of the PhD theses and papers he sees from the US. "They're all equations, no applications, no prototypes."

The Fraunhofer Institute for Production Systems and Design Technology (IPK) and the Institute for Machine Tool and Manufacturing Technology (IWF) are divided into departments, and some of the professors hold dual appointments:

**IPK**

Robot Systems - (formerly Professor Gerard Duelen, 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)

## **IWF**

Machine Tools - Professor Spur

Manufacturing Technology - Professor Spur

Assembly Technology - Professor Gunther Seliger

Industrial Information Technology - Professor Krause

Control Technology - Professor Duelen

Quality Science - Professor Gerd Kamiske

Professor Krause deals with design, especially computer-aided design (CAD), a field he has pursued throughout his entire 25-year career. He says he and Prof. Spur did everything Doug Ross and Ivan Sutherland did in America, just 10 years later, following the same intellectual path: numerical control came first, followed by the idea that if the computer could plot the cutter paths that make the shape, the computer could hold the shape, too. His CAD 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. This has to be made more efficient and user-driven, he says. He agrees with the Japanese that only the users know what they need, so they should be empowered to make their own. There is no such thing as generic CAD, he says. He also feels that at best CAD can help the designer; it cannot automate the design. Expert systems and knowledge bases will just be sources of organized data that speed up human decision-making.

- Systems ergonomics

This group works on scanning existing drawings and interpreting the results. He is concerned about this effort; the problem is really difficult, and industry is not strongly interested. (Philippe Villers told me in 1974 that he was trying the same thing at Computervision. It finally became a special machine for the U.S. Geological Survey that scanned maps, but it never became a design tool.) Another activity of this group is similar to work being done by Herb Voelcker at Cornell University: creation of parallel computing engines to speed up three-dimensional geometry processing. It works by splitting the geometry into three levels of granularity, perhaps like the octree approach. Currently, three processors run on a VME bus. When I asked about the potential for commercializing this effort, he became pessimistic: "German companies do not have long-term strategies. Think of Nissan saying they will be a paperless company in five years! No German company has such an objective."

- Geometric Modeling

This clearly is his favorite activity. It also probably is the one where he has made the most contributions—starting with the COMPAC solid modeler in the early 1970s. Now they use ACIS, a commercial modeler with an open architecture. 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 product model so that the same data can be used for all these activities. In this respect, his work closely resembles that of Kimura and Yoshikawa.

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 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.

The output of the design module is in the EXPRESS language, a part of the PDES/STEP activity. This guarantees that the output will be readable by any other software that conforms to the standard. The data are stored in an object-oriented database, with forward and backward links between the feature modeler and the geometry engine. This means that design changes in either model will be automatically reflected in the other. This is a nice feature that Prof. Beitz, who uses CATIA, cannot replicate because current versions of CATIA are in a closed architecture and do not permit its modeler to be driven from another program.

This work was demonstrated for me by a research engineer. It is impressive. However, it really focuses on individual features. He could not explain any overall structure to hold it together. For example, the assistant has provided for constraints and parametric descriptions of features but he seems unaware of conflict in design that leads to the need to revise. Thus he has provided no way to see how the constraints and parameters should be altered to meet a new requirement or resolve a conflict. (The same provision is also lacking in Professor Beitz' work. See below.) More worrisome is the fact that this important project has stopped for lack of funding since ESPRIT turned down the follow-on proposal.

#### – 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.

## **General Remarks**

Professor Krause expanded on the last item above, remarking that designers are taught in school, while process people come up from the shop. He feels that, even in Germany, designers do not have enough contact with the shop. The education system creates specialists, just like in the U.S. He admires not only Japan's more general education system but also the Japanese ability to stick to a decision once it is made. It is hard to both get and keep consensus in Germany.

## **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.

It is important to note that Dassault Systemes (see "New CAD Software from Dassault Systemes: Starting to Combine Design and Engineering") 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. Another case is that of Prof. Kimura who abandoned research on new solid modelers and simply adopted ACIS.

## **Professor Wolfgang Beitz, Institut fur Maschinenkonstruktion, Technische Universitat Berlin**

Professor 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 coauthored with Professor Pahl. (See reference 1.) Unfortunately, no funding is available to continue the research. Instead, Profs. Beitz and Krause will soon start a project about the use of telecommunications technology to support cooperative design. The project will expand the existing 100-terminal university computing network in Berlin.

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 Ph.D. theses contain this evolution. In addition, his work has developed the systematic approach and transferred it to the German standard VDI 2221, which he and Prof. 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.

I spent part of a day with Prof. Beitz' research assistants as they demonstrated the systematic design software. Briefly, its goal is to mechanize VDI 2221. In principle this is an excellent process; it tries to make very careful links between functional requirements, functional descriptions of proposed solutions, physical embodiments of those solutions, and detailed design of the embodiments. The software is an attempt to show how this might be done with the aid of a computer. The software is described below.

First, it is necessary to say that not everyone in industry agrees that this approach will be useful in practice. The method seems to me to be too clean and unidirectional, lacking room for the essential dirtiness, conflict, backpedalling, and groping that usually characterize design. My hosts at both Volvo and Volkswagen (visited in June 1992; for Volvo see "Dramatic Reductions in Lead Time at Volvo Based on Restructuring the Design Process and Introducing Computers.") stressed that design, especially concurrent design, has a strong element of conflict, sometimes requiring outside mediators to smooth things over! Professor Beitz says that the method is really best suited for teaching, where clear cases can be presented and students learn the ideal. The intellectual issue is an important one: how systematic can one afford to be if a design problem is quite new, or full of uncertainties about such things as fabrication or assembly methods? Does being more systematic help or hinder the design process? What kinds of design problems are best served by the systematic approach?

The research assistants are of two minds. Some agree that the method does not really support search and iteration, while the others defend it. The defenders say that without discipline, design becomes chaotic. They point to some recent industrial applications (one of which I report on below—Siemens), saying that without the systematic approach the problems could not have been solved.

The Siemens case is one where a former research assistant has used the systematic method in spirit. But his problem is to reform a chaotic design management situation for his new employer, not to establish or improve a functional design process. The assistant's education prepared him well for this task. Mr. Morelli of Telemechanique (see "Systematic Design of Modular Products at Telemechanique") is doing the same thing for HIS employer.

The final word belongs to Prof. Beitz. He says that industry wants too much from the educational system, much as U.S. industry does: students who are ready to design when they graduate. He feels that education tells students what to do, but industry must teach them how to do it. Each industry or company is different; only the elements of the systematic approach are generic. The students carry the method to industry and are better prepared to tackle the specific problems they encounter.

He also says that although industry in Germany says it is using concurrent engineering, one should not believe what one hears. Even the automobile companies still have some high, hard walls. Concurrent engineering is a long way off because the walls are high and people are hard to change. From what I heard on later visits, I think he is substantially correct. I heard much the same thing from Prof. Krause.

## **Software Being Developed**

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 someday will communicate with each other. The software comprises 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. Establishing these links, both in data and in algorithms, would be a substantial achievement. Right now, people make the links. It is an open question whether such links can ever be made any other way, except on a case-by-case basis.

All other research laboratories that I visited where similar efforts were under way have taken basically the same approach to this most difficult problem: the software 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. A program at the beginning 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 final list can be arranged into sublists headed by titles such as "geometry" or "energy." Numerical requirements can be added, with modifiers such as "fixed" or "desired." These notations serve to remind the designer but have no computational impact.

The next stage is a product structure, consisting of elements that receive, process, and pass along such things as force, energy, and structural stability. 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. This structure can be used as the basis for a search through a database for similar structures in past designs, or one of the blocks can be expanded into a substructure of similar elements.

The next stage comprises 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; a person seems to have done it in the demonstration I was shown. Again, the computer shows symbols representing physical items like bearings, gears, and shaft couplings. Beneath each of these is a knowledge base (KB) describing its rules.

One of these KBs has been extensively developed—that for connecting shafts to hubs. A VDI for this 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 coefficients, and safety factors. 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.

There is no link yet between this or the other KBs and the original geometric models of shaft and hub in CATIA, because CATIA will not permit itself to be driven by another program. This will change within a year, according to my sources at Dassault Systemes.

Another level of this software is the design management system. Here a chief designer is assumed who works from the functional requirements and product structure. This chief designer deals out tasks to other designers, utilizing the concept of a "function carrier" (FC). Ideally, the FC is 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. This gave 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 laboratory with similar objectives visited on this tour has made any attempt to integrate design management with design engineering the way this project has.

### **Siemens Dynamowerk, Dr. Mario Schacht**

Dr. Schacht got his Ph.D. from Prof. Beitz two years ago and joined Siemens right after school. This division of Siemens makes electrical generators and motors. Only the electrical ends are made here. Some are huge, more than 16 meters in 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 for flame cutting and welding the pieces together. 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 and meet the challenging specifications. By contrast, the cost of the smaller machines is driven by labor, so the effort goes into automation. So, says Dr. Schacht, 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."

His job focuses on the largest ones. The designers deal with only a few each year; 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. A way was needed to organize all of this, and Dr. Schacht has the perfect background for it. 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. This is quite in the spirit of his Professor's work. Reference 2 provides an overview of this approach.

## SOME OBSERVATIONS

"Design" can be partitioned into many phases, including conceptualizing and detailing. Professor Beitz is trying to combine these two phases, while Prof. Krause is working more at the detail level, trying to strengthen the engineering aspects of geometry creation as well as the links between design and production. Both want to include search and conflict resolution, but neither have really made provisions for doing so.

Both groups are also primarily mechanical engineers seeking to apply computers to design as they see it. Software people are present only as facilitators, to keep the computers running. So the research stays focused on three-dimensional geometry. It still does not include much professional data structuring or manipulation, even though graduates like Dr. Schacht are doing just that (and could have done much of his work by using ICAD or WIZDOM, two commercial programs that permit geometry to be combined with rule bases). They also do not seem to have a basis for approaching mechatronic problems, a topic that would require more sophisticated datastructures that could link several kinds of models together. The result is that their approach is resolutely bottom-up.

It is also interesting to hear their comments about expert systems. The older professors have no regard for them at all, believing that too much knowledge would have to be codified and put into them before they would be the least bit useful. Now, expert systems are just for simple rules and design rule checking. The younger assistants have more faith, perhaps because they see no other way to gather all of the diverse knowledge required for concurrent engineering — "ten different sets of criteria for the designer to obey." But they do not see how hard it will be to build and verify such rulebases, or how they will deal with the

fact that the criteria conflict.

Only Prof. Krause had something interesting to say about expert systems, namely that design has some generic elements but technology planning is all specific rules. Would that distinction become less sharp if design and technology planning were more tightly integrated?

## CONCLUSIONS

Professor Krause seems to be more in the mainstream of design research, looking at features and trying to link them to both geometric models and engineering requirements. Professor Beitz is sometimes regarded as a bit too idealistic, trying to capture something that is too difficult to capture, doing so by systematizing something that should be less constrained. Each one's research has limitations because of the lack of real collaboration with computer scientists.

Thus their approaches are mostly bottom-up, based on the engineering requirements in one way or another, and not too sympathetic to approaches that claim to be able to design many kinds of engineered objects. Infrastructure issues have also, up to now, been of little interest.

Their work, both the parts that are successful and those that have yet to be, point to the following areas where more research is needed:

- \_ understanding the relationships between constructing geometry and constructing an engineering description of an item (for example, when two surfaces are placed together, a force or a geometric reference will be transferred from one to the other: what are the size and direction of the force, or the direction of the reference? Are the surfaces strong enough or carefully enough toleranced for the intended purpose? etc.)

- \_ extending the first item by separating engineering issues of function from those of manufacture and assembly and recognizing the latter's importance more explicitly. [Except for numerical control fabrication of single parts from their geometry (a capability that is now commercially available), research tends to focus on function, with attention only slowly shifting to other topics. Also, no strong coordination of these topics has entered the research stream yet. That is, how something functions, at several levels, is affected by how it is made and assembled, but this link has not yet shown up in research.]

- \_ understanding how to move systematically from high-level functional descriptions of items to low-level specific descriptions, including listing completely what should be in a specification at each level. (All of the European and U.K. research I have seen so far requires the designer to make the essential connections; the software can be characterized as "inspired sketchpads.")

\_ learning how to include explicit recognition of conflict and revision in design. (Few researchers, even with industry experience, see the central nature of conflict and tradeoff in design. But these issues will rise in importance as concurrent engineering (CE) spreads because CE brings in more criteria and these usually conflict.)

\_ learning how to describe design as a process and identifying several styles or metaphors for this process (sequential tasks with regular, planned feedbacks; overlapped tasks with feedforward and feedback between adjacent tasks, and so on) (My hosts at Rolls-Royce Aerospace - see "Object-Oriented CAD and Expert Blade Design at Rolls-Royce" - said they had learned a lot about design from emulating manufacturing.)

## REFERENCES

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## Points of Contact

Professor dr-ing Frank-Lothar Krause  
IPK Berlin, Pascalstr 8-9  
D-1000 Berlin 10  
(+49) 30 390 06 243  
fax 391 1037

Professor dr-ing Wolfgang Beitz  
Technische Universität Berlin  
Institut für Maschinenkonstruktion  
Strasse des 17. Juni 135  
D-1000 Berlin 12  
(+49) 30 314 23341  
fax 314 26481

Dr ing Mario Schacht  
Siemens AG Dynamowerk  
Bereich Antriebs-, Schalt- und Installationstechnik  
Siemens AG - ASI 1 DW TDG 2  
Postfach 130169  
D-1000 Berlin 13  
(+49) 30 386 5833  
fax 386 5640