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Research in Engineering Design

Designing the Design Process

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1 Introduction

This paper was invited by the editors of this Journal in response to an informal presentation the author made to the 1990 NSF Design and Manufacturing Research Conference [NSF]. It comprises the author's opinions and does not constitute research. The author's background is a mix of academic and industrial, with less emphasis on theory in the abstract and more on methods responsive to an identified need. The author believes in "design theory" but the reader will find different elements, emphases, and priorities in this paper than are customary in past treatments (for example, [ASME, Spillers and Newsome]). The editors expressed a desire that this alternate view be presented in the journal to encourage debate and discussion.

2 Design Theory and Practice Today

Attitudes toward design in academia and industry have been changing for several years. Some decades ago, universities backed away from design because apparently it seemed too practical and lacking in a scientific basis. Mathematical analysis replaced design, manufacturing disappeared from curricula, and both faculty and graduates lost touch with how engineering, design, and manufacturing interact in the "real world." Companies similarly "slimmed down" or "restructured" by giving "excess white-collar workers" early retirement.[1] Both developments have strong implications for design theory and methodology (DTM).

However, the recent desire for a theory of design has emerged in an atmosphere of dissatisfaction with the research field itself rather than from urgent recognition of the need for better practice. Even sympathetic observers could say of increased emphasis on the manufacturing context in design theory:

> ". . . it appears that in a declining economy we have become unsure of the worth of 'ideas' from the frontier of knowledge and technology and work more to bolster all discussions with some utilitarian concerns."—*[Spillers and Newsome]*

It is fair to say, however, that design practice has rapidly and forcefully evolved right out from underneath the feet of academic teachers and researchers, driven by the needs of advanced industries and technologies. The frontier of designed objects comprises an ever-increasing multitude of technologies packed into ever-decreasing space[2]; by contrast, design is taught in single-technology academic departments and the issues that make design of such things really difficult—competition for space, substitution of function by new technologies, part-in-a-million quality, ease of manufacture, need for self-explanatory user interfaces, large teams of geographically separated designers, inability to predict where or by whom the item will be made—are barely mentioned in class and are not represented in textbooks.

> "Design is 100 people in a room arguing."—*AI design researcher at DEC*[3]

> "I'd give my wife for a tenth of an inch."—*Subsystem designer at General Dynamics*

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[1] Recently, they have had to hire them back as consultants because only they know how to do the company's business and no one new and knowledgeable is available.

[2] An example is a prototype 20-bit rotary position encoder by Canon. It divides 360° of rotation into 1 million pulses. The pulses are generated by passing laser light through a 200,000 slit grating made by semiconductor fabrication methods. The pulses are detected by photocells that observe and beat the first side-lobes of the interference pattern created as the light passes through the slits. The design is thus a mix of mechanical and electrical engineering, signal processing, optics, and basic physics.

[3] Most of the quotations are personal communications to the author unless otherwise specified.

Leading industrial firms have responded to this gap mainly by ignoring the academic approach to design theory and methods. Recognition that design is a crucial element in industrial competitiveness has come slowly to American industry, although design appears to have been a major ingredient in European and Japanese industry for decades. Its reemergence in the United States cannot be dated precisely, but the late 1970s, with activities at Xerox and Ford, provide a convenient reference [Bebb]. The emergence of "concurrent design" [Nevins and Whitney] has made it evident that not only products, but also materials, production processes, factories, and distribution channels *all can be designed,* that these design activities can interact, and that the result can comprise a very effective and mutually reinforcing system.

"My hosts were proud of the machine because it contained a robot. I later realized that the machine and its product exemplified the company's method for succeeding as a major supplier to Toyota."—*The author's reaction in 1980 to a machine that makes 40 varieties of dashboard panel meters in unpredictable model mix on 24 hours' notice. Details may be found in* [*Nevins and Whitney, pp 57–58, 303*]

The methods these companies have adopted come largely from foreign sources: robust design, statistical process control, systematic generation of alternatives, low-inventory manufacturing, rapid tool, and die change.[4] Computers and computer-aided design (CAD) do not play a large role in these processes, even though most American observers cite computers as the main advance and driving force of design today. Yet, in US industry there is dissatisfaction with computers: one notes the lack of productivity increases in the computerized service sector; traditional CAD—actually computerized drafting—has not deeply penetrated industry even after 20 years of commercial availability.

"Conventional CAD is just an electric pencil. The potential for using the computer to integrate technical and business aspects of design has not been touched."—*Prof. Kim Clark, Harvard Business School*

Large companies have also set up internal "universities" and "design institutes" to teach engineers what they missed in school. Sometimes companies contract local universities to teach company-designed curricula. The attitude behind these efforts is not quite that graduates are ill-prepared (although many companies think so), but rather that design is complex and takes a long time to learn; only part of that time can occur in a university education of reasonable length. Yet one wonders who would teach what, if industry and universities shared a strategically conceived view of design and undertook to share design education. Surely, the "generic" component would be taught in school, while the particular and proprietary would be taught by the companies. But what should the generic component consist of? No one has addressed this. DTM researchers will have to participate in its formulation if the field is to be relevant.

In the midst of enormous change and opportunity, it seems that the DTM community has yet to respond forcefully. In particular, it lacks a consensus on what the pressing research needs are. By contrast, in the atmospheric sciences, the agenda is clear and accepted: model circulation and temperature rise, and find out where the CO_2 goes. In immunology, the agenda is: find out how the immune system tells friend from foe, especially at the cellular level, so that AIDS can be cured or prevented and tissue transplants will not be rejected.

"The PI's are all top-down people. It's theory first. They don't have real design experience."—*NSF Program Director*

"I asked University of X if I could teach there but they wouldn't touch me with a 10 foot pole. They felt I wouldn't be able to publish."—*Engine designer with 20 years' experience at Ford*

NSF's DTM program was launched after a study sponsored by ASME [ASME] undertaken by academic design researchers from many fields. The list of topics and categories—obtained with the help of a survey of academic deans—shows a firm grasp of the intellectual issues and includes design practice and industrial relevance without apology. Yet it seems to focus on the designer and activities that designers do without placing them in a context. It does not contain a prioritization of the issues and thus does not give a strong leading light to the community.

3 Traditional Foci of Design Research

Where does academic design theory stand today? How does the field organize itself? If it responds to the practical problems cited above, will it lose its scientific base and become merely "utilitarian?" Can the field reposition itself responsively and still find problems of a serious theoretical nature? These questions will be addressed as this paper unfolds.

[4] Many of these practices originated in an earlier America.

Table 1. Views of design and associated computerized design tools

"Design is . . ."	Type of tool that results	Accompanying problems
Drafting or drawing single parts	Conventional 2D CAD Good when the product is flat and the drawing is the design rather than a coded representation or abstraction: printed circuit board, VLSI, tubesheets, sheet metal	People confuse engineering, design, and drafting. Some think that design has now been automated. Design of things with more than one part (the majority) is not addressed
Rendering	3D computer graphics Good for visualization and presentations	People confuse the rendering with reality and do not comprehend manufacturing difficulties
Creativity and synthesis	No tools? Pugh's methods, Pahl & Beitz tables, "conceptual blockbusters"	People declare that it can't be taught or done systematically
Optimization with constraints	Numerical search programs Good when there is one overwhelming goal, such as weight, when the problem is completely captured mathematically, and when it is not too complex	People forget that few problems meet these restrictions

Design theory seems to have three traditional foci:

- The design itself—its representation, evolution, and verification
- The designer—behavior of individuals, thought processes, and access to and interaction with tools
- The process of designing—conceptualizing, detailing, and calculating

The question is not whether these are subjects worthy of inquiry—they are—but whether they will ever come together to form a coherent set of theories and methods that will address real design problems. The author's own educational background (30 years ago) gave him a variety of views of design born of the above taxonomy, each view tied to its time and isolated from the others:

- Design is rendering, the making of nice pictures
- Design is creativity, responding resourcefully to a need while respecting constraints
- Design is optimization, tell the computer what you want and you will get it
- Design is drafting, the act of making lines on paper and, in the main, allocating space
- Design is a lone wolf activity carried out by great people whom I was to emulate

When the author finally graduated and began to work with real designers struggling with daunting problems, he decided that all of the above definitions missed the essence, failed to capture the activities that preoccupied designers and made their task difficult. Yet most of the research and even the commercially available computerized tools respond to this day to the above list rather than to the reality he discovered. In Table 1, each of these "design is . . ." statements is paired with a description of the type of design tool that has resulted and some of the successes and accompanying practical difficulties.

All of this adds up to conflict and frustration. Design researchers argue about what is science in their domain and seek to define it in traditional terms, such as combinatorics, topology, cognitive science, and protocol analysis. They find it difficult to convince other researchers that what they do is scientific and difficult to convince potential industrial users that what they do is relevant. As design practice marches ahead, design researchers wonder why they are not making progress on the "big problems."

4 Different Views of Design Leading to a Different Research Agenda

As indicated by the author's reaction to design practice, it is possible to view design radically differently from traditional views. Consider the following:

- Design is a technical process to be accomplished (1)
- Design is an organization process to be managed (2)

The first focuses on the individual designer, whereas the second focuses on the group. These two views are not only of equal importance but they are in fact inseparable. In other words, they have the potential to lead to a unified view of design in contrast to the views listed earlier. People unfamiliar with design practice may doubt this. Engineers may dismiss the second view as "management," that is, devoid of technical content, just budgets and schedules or motivation and groupthink. Managers may see technical designers as just another type of labor or costly resource that overruns time and cost constraints and is thereby no different from marketing, material handling, or accounting.

In pursuit of support for views (1) and (2), let us examine three more detailed views that span (1) and (2), that are grounded in design practice, and that have a mission orientation in contrast to the traditional actor-action orientation.

4.1 Design Is the Technical Component of the Product Realization Process

The "product realization process" is the method by which a company identifies the need for a (new or revised) product, determines the customers' expectations for it, converts those expectations into engineering specifications, and uses those specifications to design both the product and the methods for making, distributing, and supporting it. Factors that are treated include quality,[5] performance, materials, cost, equipment and processes, training of assemblers and salespeople, marshalling of suppliers, and location of facilities, to name a few. Advanced companies have exquisitely honed their product realization processes, fortifying them with new theories and methods. The main driving forces are competitive: to generate new products of high quality in less time.

"There are only three questions: will it work, can it be manufactured, and how much will it cost?"—*(no attribution available)*

"It is the speed of the development and manufacturing cycle that appears as technical innovation or leadership. It takes only a few turns of that cycle to build a significant product lead."—*[Gomory and Schmitt]*

"Design" in this context comprises all the aspects following determination of the customers' expectations. (Some Japanese companies even involve designers in this nontechnical activity.)

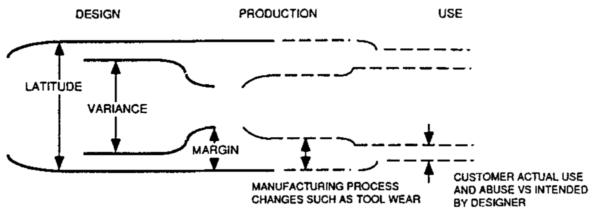

Fig. 1. Evolution of latitude and variance during design, production, and use (adapted from Brom [Bebb]). During production, latitude is assumed to remain constant but variance deteriorates. During use, both latitude and variance deteriorate; the latitude of a copier is less than design intent if a customer attempts to copy wrinkled originals and the variance is greater than design intent if the copier's internals wear due to overuse.

Mustering design resources and doing the job well clearly spans both technical and organizational process issues. Companies whose products take twice as long to bring to market as those of competitors or whose products fail in the field when rushed to market will vanish unless they can learn to do this process better. Who will help them? What form will that help take?

The second different but related view of design is presented below.

4.2 Design Is the Process of Attaining Wide Latitude and Narrow Variance

This definition is adapted from Xerox [Bebb] and is illustrated in Fig. 1. It is an operational definition of design that imbeds it firmly in both manufacturing and customer use of the product.[6] It also makes explicit and technically approachable the broad advice by Taguchi to "design quality in." "Latitude" refers to the ability of the product to perform in spite of departures from the specifications of materials, dimensions, manufacturing processes, customers' usage patterns, the product's physical environment, and so on. "Variance" refers to the standard of performance itself, and reducing variance means that performance will not vary even though latitude has been widened. The challenge of the above definition is clear because wide latitude is usually assumed to produce high variance. Design methodologies thus must be created that will counter this trend. Taguchi's robust design ideas comprise one approach. These ideas stress selection of parameter values to reduce the design's

[5] Note that "quality" is often defined very generally: more than merely having a long life or a long time between failures, a high quality product meets the customers' expectations, even in ways the customers may not have initially realized were inherent in the product.

[6] The author notes that nowhere in his education or practical experience had he ever come across such a clear and unifying statement of the goal of design. An entire education could be built on pursuing this statement with examples, methods, theories, and design tools.

"sensitivity," and advise tightening tolerances only as a costly last resort.

"Our company was able to design high cost high rate copiers that required constant adjustment and justified full time technical support. But we were incapable of designing a home copier that would simply work and keep working as soon as it was assembled."—*Former copier designers*

"I designed well: it worked flawlessly under the conditions I anticipated, and when it was loaded to four times my rating it failed in the places I figured it would."—*Designer of a weight-constrained power transmission*

Table 2 lists a few examples of designed items along with some features that embody latitude and variance.

Finally, the third alternate view of design is discussed below.

4.3 Design Is the Process of Recognizing, Consensualizing, and Resolving Conflict During Creation of an Entity that Meets a Set of Goals

This is the author's own formulation, expressing the essence of why design is difficult and indicating without much reference to context or missions where the design enterprise needs theoretical help. Conflict is the essence because designs must meet multiple goals and vague objectives while predicting the unpredictable about poorly modeled materials, processes, and people. Successful design requires that the major conflicts be recognized early in the process and that their existence and importance be agreed upon. Only then can they be resolved. Basic conflicts will emerge ultimately, but their late discovery or appreciation will cause delay, increase cost, or kill the project.

"The paper path seems to have the least priority and must be fitted in where space is left. Yet convoluted paper paths are difficult to design and are the source of most field failures."—*AI copier design researcher*

The author is unaware of design tools that are applicable to this issue, such as systematic methods for identifying conflicts. Negotiation is a common way of resolving conflicts, but negotiation research typically focuses on labor or international disputes and has an interpersonal rather than a technical focus. Much is made of the emerging practice of team design, but the issues deemed worthy of study include displays, wide band communication, motivation, and imparting new attitudes of cooperation to replace confrontation and pecking orders.

"Right now product designers have all the fancy computer tools. This gives them an unfair advantage when negotiating with manufacturing people."—*Design tool developer for Texas Instruments*

Table 2. Latitude and variance: Achieving these goals can range from easy to impossible, depending on the circumstances

Domain	Examples of widening latitude or limiting variance
Electromechanical	Parts won't fail if materials, dimensions, or loads vary, within limits
	The product won't break if the user does something unexpected but not overtly destructive
	The product will function satisfactorily when its environment changes: temperature, humidity, experience, or training level of the user
Software	Program allows user to save results and quit at any time and resume later
	Program won't crash if user presses the wrong key or issues an unexpected command
	Program will function with different systems (memory size) and degree of complexity of application (document size)
Organic chemical	Compound can be produced with good yield and purity even from variable feedstock and process conditions, within limits
	Compound won't decompose into toxic components or be a hazard in its complete form
	Compound won't become dangerous or ineffective if mixed with commonly available contaminants

"We don't have a problem. It's those dummies in manufacturing."—*Engineering VP's parody of designers who do not recognize basic conflicts*

"Engineering proposes designs. Manufacturing counters with problems. There is a lot of conflict, but it is creative."—*Supervisory engineer at Honda*

"When you have to get a new product out in 9 months, as we do, you don't have time for conflict."—*Response by Supervisory engineer at Toshiba*

4.4 Theoretical Issues

The above three views of design emerge from the field of practice. They provide a mission context (the product realization process), a technically explicit challenge (widen latitude and narrow variance), and identification of a pervasive core diffi-

Table 3. Three types of design and their features

Type	Main focus of designers	Main blockages to better design and methods	Possible future implementations
New product concept phase	Push technology Make quantum increase in performance or totally new function	Lack of models of phenomena	Creative people with cross-disciplinary backgrounds
New product detailed phase or improvement of existing product	Incremental increase in performance Constraint negotiation Cost and schedule	Lack of engineering knowledge Approximate models Knowledge in people's heads, not codified Lack of computer integration Institutional issues	Team design Concurrent design with computer-based decision support
Ongoing reconfiguration of existing product	Cost and schedule	Lack of computer integration Many designers, big database	Automatic decision-making, expert systems embodying codes, regulations, design rules, and routine knowledge

culty (conflict). Together they provide enough richness and relevance to fuel interesting and useful design research. The theoretical issues they raise are formidable:

- can a better design process be designed? (rather than how to support what either is imagined that designers now do or what companies actually now do)
- How can solid engineering predictions be made in the absence of traditional engineering models? (rather than focusing on making better engineering models of problems for which models of some sort already exist)
- *What* information is needed *when* so that concurrent design of products and processes can proceed rapidly and confidently? (rather than what information is needed for traditional serial design methods)
- What design tools are needed to support that part of what designers do that is truly difficult? (rather than developing tools for the routine part)
- Exactly what questions would such tools answer and what information would they need?

"Designers make million-dollar decisions every minute without ever knowing it."—*Manufacturing executive*

"A designer never gets any feedback about a decision unless it causes a problem."—*(attribution unavailable)*

5 Linking DTM to Design Practice

5.1 Types of Design in Practice

As one approach to linking DTM opportunities and design practice, consider Table 3. This table categorizes design into three types (other observers identify four or five, but this list will serve): conceptual design, new product detail design or existing product redesign, and routine reconfiguration of existing designs (called "purchase order engineering" by General Electric). It lists the main preoccupation of designers engaged in each type of design, cites some major blockages to better designs and methods, and speculates on some future ways that each type might be accomplished. It is worth nothing that most DTM research applies to the first type, whereas most designers actually work in the second and third types. (GE says that 85% of its designers do "purchase-order engineering".)[7]

Concept and early detail design are vital phases because much of the cost of manufacture and use is determined by decisions in this phase [Nevins and Whitney]. One can question whether typical research results on the concept phase, often emphasizing the lone designer, will scale to redesign with its large groups of designers and different problems: complexity, combinatorics, and conflict—problems that do not get much attention in the DTM community.

In 10 years, you could see some [of these concept cars] on the road. Then again, you may not. As Mr. Walling of Chrysler put it, the designers and engineers who build concept cars, testing their ideas, "don't pay a great deal of attention to manufacturability."—*New York Times* (Sunday July 1, 1990, Section 3, page 5)

[7] Leonard Morgan, GE Corporate Engineering Staff, personal communication.

Table 4. Examples of Availability/Utilization of Automation in Design or in Design-data-driven Production Methods for Several Technologies

	COALESCING OF REQUIREMENTS	UNDERSTANDING INTERACTIONS	FORMULATE TECHNICAL CONCEPTS	MAKE SYSTEM REALIZATIONS	MAKE COMPONENT REALIZATIONS	DETERMINE COMPONENT FABRICATION	DETERMINE SYSTEM FABRICATION AND TEST
SOFTWARE SYSTEMS		Top-Down	Design	CASE	Compilers Cross-assemblers	(step usually skipped)	
ELECTRO-MECHANICAL SYSTEMS	Quality function deployment	Steward diagrams		Bond graphs Kinematic simulators	CAD, FEM Printed Wiring Board Routing	CNC	Discrete Event Simulation PWB Assy Planning FMS, CNC
VLSI ITEMS				Chip layout via CAD Circuit simulaton	Cell libraries CAD FEM	(step usually skipped)	Wafer steppers Automatic test equip.
ORGANIC CHEMICAL ITEMS		Structuring of mathematics for analysis and simulation		CAD models of molecules Simulation of plant operation	CAD for pipes and plant layouts		

"Just because something can be made doesn't mean it can be manufactured."—*Manufacturing engineer at DEC*

On the other hand, purchase-order engineering derives its routine character precisely from the fact that there is no conflict. A prime example is heat exchanger design. This can be made so straightforward, for a defined range of items, that even a small company [Basco Div, American Precision Industries] armed with only an IBM PC, a CNC drill, and a CNC flame cutter can have any of its catalog items on the shipping dock in 24 hours from the time an order is received, starting from raw materials.

5.2 A Strawman Product Realization Process

As another tack, let us set up a strawman for the steps of product realization and use it to sketch out the information and design tools that might be needed. The steps include:

1. Identify and coalesce the requirements
2. Understand the interactions, not only in the requirements but in later topics, and establish (or modify) a design procedure that minimizes them
3. Generate technical concepts that meet the requirements and do not suffer from adverse interactions
4. Translate the technical concepts into system realizations, identifying assemblies, components, and physical quantities
5. Identify individual parts and subassemblies: characteristics, tolerances, costs (including make/buy decisions), mutual compatibility, and contribution to the system
6. Determine how to make the parts and subassemblies or how to specify them to an outside supplier
7. Determine how to assemble and test the parts, subsystems, and the complete unit.

Table 4 poses these steps alongside several types of "product," and attempts to indicate (in gray) the availability of design tools or automated approaches to both their design and manufacture.[8] Manufacture is included because the design of many types of product is driven by the most effective fabrication or assembly method. Examples include VLSI, where later phases of design consist largely of preparing patterns or instructions for elaborate processing machinery, and modular shipbuilding, where design consists of creating modules and work

[8] Here as elsewhere in the paper the author has attempted to be general enough to include design and manufacture of both physical and logical goods (i.e., palpable objects and software).

breakdown structures suitable for appropriately trained and equipped work crews.[9] Additionally, of course, design is driven by anticipated customer demands (such as Toyota's JIT demands on its suppliers) or the company's plans for future models of the product (for example, providing expansion slots in a computer and publicizing the bus architecture to encourage third-party products).

The pattern of the above list is to proceed from the general to the particular, which is typical, but also to proceed from the whole product to its parts and, what is not typical, back to the whole again. This return to the whole serves as a check on the process and identifies new classes of possible design tools. The steps are presented in a sequence but in fact they cannot be executed without profound overlap.

"Nissan designs all of the parts of an assembly at once while GM designs them all in series. How do they ever finish?"—*Attributed to a Nissan design executive*

"They will let us into their factories but they won't send a design manager to work with us."—*American design executive speaking of his company's Japanese subsidiary*

6 Design Interactions

Of the items listed above, number 2 may strike the reader as unusual. It is discussed in detail here because it exemplifies a different attack on design that goes to the heart of why design is difficult and time-consuming. The term "interactions" is used to express complexity, not in the sense that particular design tasks are difficult but rather that they affect each other in circular ways that are difficult for designers to detect and managers to control.

Furthermore, some variables or decisions in the design sooner or later are found to dominate others in the sense that these decisions ordain others or make them moot. (For example, in design of submersible vehicles for ocean exploration, different modes of hull failure dominate at different diving depths; one must know the desired maximum depth first in order to decide how to stiffen the hull. At some depths a particular stiffening method may be simply irrelevant.) These dominating variables are often called "design drivers." Failing to identify them early in design often results in a failed design or the need to start design over. Yet there exist no reliable ways to find the design drivers in a new problem, and in some design shops the very idea of a design driver may be unknown.

[9] A synopsis of Japanese shipbuilding may be found in [Nevins and Whitney, pp 61–65].

"Very rarely do people understand how their organization works. People at the bottom see their little part well and see nothing else. People at the top have a broad but shallow view and have no idea what the people at the bottom are doing."—*Instructor at IDEF training seminar. IDEF is a graphical technique for modeling organizations and their procedures*

"No one had ever undertaken to model the brake system design process at this company before."—*[Black] Black did not use IDEF*

There are several consequences of design interactions. First, design appears unavoidably iterative and takes a long time. Second, the result may be of lower quality than it might otherwise have been because the iteration had to be stopped for lack of time or resources or because its obscurity masked better designs. The "design process" is thus somewhat confused and lacks directness. Under these circumstances it is prone to unhappy discoveries late in the process, inability to reach closure promptly, overlapping or underlapping of responsibility, inability to get the right information when it is needed, lack of awareness that the right information was available, or inability to use it.[10]

Two promising approaches are being developed. For problems that are primarily in equation form (equalities and inequalities), design would appear to be a matter of solving the equations numerically. But real problems are so big that even computer speed is not a weapon against them. In response, the field of hierarchical optimization has grown up [Sobieszczanski-Sobieski]. The issue is to identify which variables to assign trial values to first, while others are optimized subject to those trial values. This amounts to designing a numerical solution sequence, which is equivalent to designing a decision or design sequence. Rogan [Rogan] has called it "meta-design," which means the same thing. The field is at least 10 years old and as yet no general methods for assigning a decision sequence have emerged. A promising approach involves using the matrix of partial derivatives of the parameters as sensitivity guides and choosing, say, the "most influential" variables first.

For problems that are not equation-dominated, that is for most problems, an allied technique called the Steward diagram has been proposed [Steward]. While promising, this method has not been used very much. Compared to hierarchical optimization, it is qualitative and seeks merely to identify which

[10] Clark and Fujimoto note that Japanese car design often goes more quickly than American because Japanese designers will begin a downstream design step before all the upstream steps are done if selected output from these steps is available or can be guessed well enough [Clark and Fujimoto].

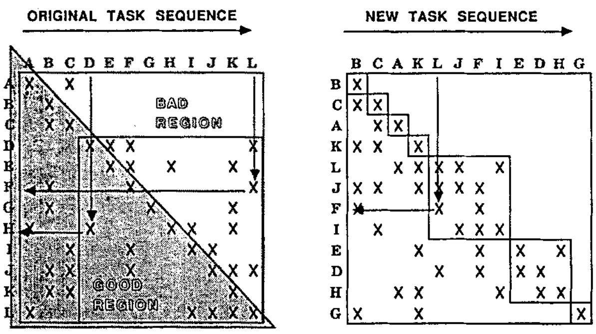

Fig. 2. Design structure matrix method for representing complex design tasks and seeking more efficient design process. Original task sequence: design structure matrix as originally stated; task D feeds information downstream to task H; task F needs information from task L. New task sequence: design structure matrix reordered and partitioned; task L feeds information downstream to task F.

decisions provide information to which other decisions. The decisions are arranged in an incidence matrix and the rows and columns are rearranged in an attempt to find a sequence in which a "waterfall" decision sequence exists, one in which the decisions can be made one after the other without iteration (see Figure 2). Since this is almost never possible, one seeks to minimize the number of decisions that must be iterated. The result is often a set of iteration groups which themselves lie in a waterfall sequence. Management can identify each group as a team and each team's engineers can establish a computational procedure if applicable. The time to carry out such a process may possibly be estimated [Rogers and Padula, Eppinger et al., Ojimi and Nakajima]. One can see the hint of a union of design aspects (1) and (2) in this approach.

No unique rearrangement of the matrix is guaranteed and only heuristic rearrangement methods exist. Work is underway to make the method more quantitative.

A concrete example of a revised design sequence comes from the author's research in concurrent design (CD). This research uses the process of mechanical assembly to focus the work of a CD team because assembly is inherently integrative and inspires the team to think about groups of parts in ways that traditional design sequences do not. While making assembly design part of early product design, the author and his colleagues found that the assembly sequence should be considered early rather than late in the design process. That is, traditionally, the assembly sequence was considered a consequence of the product's design and was used merely to optimize the line balance in manual assembly. We have determined that the assembly sequence *should itself be designed* as part of early product design because assembly sequence influences assembly cost, assembly yield, fixturing needs, tolerancing of fixtured surfaces, in-process test opportunities, modular model mix assembly, and other factors important to CD. Thus, information about assembly sequence has been identified as being needed at a new time in the design process, and specific uses for this information have been identified. Computer tools to generate and prioritize assembly sequences have also been created [Baldwin et al.]. The author believes that many other similar opportunities exist for rearranging the information sequence in design and that better designs and design processes will result.

At a more general level, Suh [Suh] has proposed that design theory be approached from the point of view of identifying and eliminating interactions. Under this theory, lack of interaction characterizes a good design.

7 Tools for the Individual Designer

The preceding discussing concerned view (2), design as a process to be managed; we could call it design in the large. What of view (1), what we might call design in the small? Where does the individual designer need help?

The designer's problem has become much more difficult since the usual challenges of meeting performance requirements have been augmented by those of meeting, as opposed to postponing or avoiding, the requirements of manufacturing, field service, and so on. Two broad types of "design tool" have emerged: infrastructure support and technical support, with the latter falling into three classes—guidelines or rules, expert systems, and decision support systems.

7.1 Infrastructure Support

Infrastructure includes databases, graphics, and communication networks. In fact, one view of "concurrent design" is literally *simultaneous* design in the sense of many designers working on the same design at the same time [DICE]. The required infrastructure includes wide bandwidth communication, which will presumably develop of its own accord, and the ability of many designers to access and modify the same design database, which is a frontier research issue [Hardwick et al.]. Even the seemingly mundane prerequisite issue of "version control" is an unsolved problem in database research which must be brought under control before simultaneous design can become a reality. Issues include:

- Distinguishing between scratchpaper and the latest agreed on and approved design
- Composing a new consistent database (design) from different and possibly inconsistent changes made by several independent designers
- Filtering early design decisions made from preliminary data and replacing them with decisions based on final data (see footnote 10)
- Helping designers sift through changes made by other designers and identify those that are relevant

7.2 *Technical Decision Support*

In recent years the need for guidance, data, and help sorting through and evaluating alternatives has been recognized. The response has included guidelines like Design for Assembly, a large number of expert systems focused on individual problems (selection of aluminum alloys, design of paper paths in copiers, Cognition's Design Cost, and Manufacturability Guide), and new ways of structuring design data so that design intent and data are captured in forms that formal decision aids can use. All of these in their present form have their strengths and weaknesses.

"Word came down from headquarters that we were to eliminate screws. So we redesigned it with all snap fits. Then Shipping told us it had to pass a drop test. So we dropped it and it fell apart."—*Consumer product designer*

"You can get part in a million quality with screws today. Don't use adhesives, staking, ultrasonic bonding, or snaps unless you don't need location accuracy or strength. If you use adhesives on dissimilar materials, that's a sure sign that you're desperate or you've got a lousy design."—*AT&T researcher who reverse-engineered several Japanese consumer products*

"We've carried part count reduction almost to its limit. One of our eleven main parts has over 1100 toleranced features. It takes us four months to get a mold designed and made."—*Camera designer*

A case in point for representing design intent is "feature-based design" [Dixon]. The hope here is that designers will be able to use "features" (local places of interest and accompanying data) to express the underlying physics or engineering when describing items being designed. This has been largely achieved in VLSI. The domain of electromechanical products is not nearly so well developed: there is no unified modeling method except for lumped parameter systems, no solid links between performance and tolerances [Tipnis et al.], and insufficient data on behavior of materials, to name a few basic problems. Worse yet, as mentioned above, electromechanical design representations are separated from the physical objects by at least one layer of abstraction and probably always will be, whereas in VLSI there is no such intervening layer.

"New tooth shapes? We're stuck with the old involute while we try to develop basic data on material behavior to predict the life of the tooth shapes we have."—*Technical director of a gear research laboratory*

The challenge for feature-based design is to decide just what a feature is, what performance or manufacturing factors can be captured by features, and more generally, is there such a thing as a "feature language" that can describe a product? The PDES [Smith] effort aims at this, but it is a huge challenge.

"We finally decided to take the initiative. We went to the manufacturing folks and asked how we should design it for assembly, and they said 'We don't know.' "—*Chief of concurrent design team for truck transmissions*

For example, manufacturing processes, such as assembly, can create a demand for features and accompanying information. Assembly sequence algorithms need nominal approach directions for mating features, tolerance propagation data for fixturing features, and topological "mates-with" information for the parts to be assembled. Assembly difficulty advisors need mating tolerances, mate type, material properties, and approach paths with supporting data to calculate clearances for tools passing near the already assembled parts. As processes become better understood and decision support algorithms are developed, the need will grow for underlying feature libraries, feature-linking techniques, feature-grouping and ungrouping methods, etc.

As another example, what about capturing econometric data as (or in) features? It is well-known that production rate hugely influences choice and cost of fabrication and assembly processes. Yet most feature-based design to date is aimed at supporting single point cutting processes, with a little on casting and assembly. Each of these is suited to certain econometric domains, or is carried out differently in different domains. These important differences are presently being passed over.

When processes are better understood and new decision support algorithms raise new questions and demand new feature data, will the sequence of the design process have to be thought through yet again?

8 Closing Remarks

The author has attempted to frame the opportunities for DTM in terms of definitions and missions for design that spring directly from ways that design is practiced and aspects of design that are truly difficult. Many topics have not been mentioned that deserve mention. Many aspects of design similarly have been omitted. The hope is that the spirit has been captured and that this alternate view of DTM will prove helpful in guiding formulation and evaluation of research ideas.

The author has doubts about the possibility of creating a "general theory of design;" is there a "general theory" of anything? However, he has no doubt whatsoever that serious scientific research into design processes, methods, and tools will bear fruit. He also has no doubt that this research can be theoretically rich and very relevant to basic national needs, and that both academic researchers and industry already recognize the opportunity.

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