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Research in Mechanical Engineering Design: A Review.

Part II: Representations, Analysis, and Life Cycle Design

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Abstract:

This is the second of a two-part paper summarizing and reviewing research in mechanical engineering design theory and methodology. Part I included 1) descriptive models; 2) prescriptive models; and 3) computer-based models of design processes. Part II includes: 4) languages, representations, and environments for design; 5) analysis in support of design; and 6) design for manufacture and the life cycle. For each area, we discuss the current topics of research and the state of the art, emphasizing recent significant advances. A final section is included that summarizes the six major areas and lists open research issues.

Introduction

This two-part paper, the first in a series of reviews to be published in Research in Engineering Design, summarizes and reviews the state of research in engineering design theory and methodology, concentrating on mechanical engineering design. Subsequent reviews will concentrate on other areas of engineering design or on special sub-topics. The goal of the series is to inform the community at large of advances in the developments in engineering design research. We also hope that it will enable researchers to place their work in context and thus guide continuing work. The series of papers is also intended to be an efficient starting place for those who wish to become familiar with the engineering design literature relevant to their interests. There are, of necessity, limits to the nature and scope of this review. First, the review is not intended to be a substitute for reading complete papers; it is intended only as a brief summary of, and guide to, the literature. Although we have made every reasonable effort to be complete, omissions are inevitable. There can also be errors of commission caused by misinterpretation or lack of full understanding on our part of papers included in the * Reprint requests: Robotics Institute, Carnegie Mellon Univarsity, Pittsburgh, PA 15213, USA review. We apologize to both readers and researcherrs for these errors. The scope is limited in several ways. We intend only to include research in engineering design, and then only that portion of engineering design broadly called "mechanical," which includes products, machines, structures, and the like. Research in geometric modelling, architectural design, manufactureIng, expert systems, and optimization are included only when the research is directly relevant to design of mechanical systems. We have also not attempted to cover the many new, commercial computeraided design (CAD) systems which have begun to incorporate the research ideas discussed in this review. The research discussed in this review paper has been conducted primarily in the United States. Work outside the U.S. has not been excluded, but is not covered systematically. Finally, research on mechanical design in very specific technical domains (e.g., mechanisms and heat exchangers) is not covered unless it is clearly extendible to other mechanical design domains. This review is organized into six sections based on our current view of the active design theory and methodology research areas. These six areas are:

1. Descriptive models of design processes

2. Prescriptive models for design

3. Computer-based models of design processes

4. Languages, representations, and environments

for design 5. Analysis to support design decisions 6. Design for manufacturing and other life cycle issues such as reliability, serviceability, etc. These six categories are certainly not mutually excollusive, and some research overlaps two or more areas. In such cases, we have done our best to inform readers where research projects have been placed. In Part I, the first three of the above six topics were reviewed. In Part II, we review the last 122 Finger & Dixon: Research in Mechanical Engineering Design three, beginning with languages, representations, and environment for design. 5 Languages, Representations, and Anointments In some areas of engineering design, such as circuit design, formal representations exist for the artifacts being designed which capture their important physiccall, functional, and logical attributes. A fundamenttall concern in mechanical engineering design research is that complete representations do not exist for mechanical artifacts. Intensive effort over the last fifteen years has resulted in the creation of valid, robust computer-based models for the genometry of mechanical designs. However, except in limptied domains such as kinematic linkage design, no formal representation exists for the physical and functional attributes of mechanical designs. This section discusses research in mechanical engineerIng design that has begun to address this concern. Another related topic is the environment within which the designer works and within which the design evolves. Currently, many of the tools used to create designs, whether computer- or paper-based, are incompatible with one another, so a design may be transformed from one representation to another many times as it evolves. In addition, even if the design tools all used a common representation, the coordination and interaction of the tools with the designer is still an open research issue. 5.1 Representation of Form The representation of the geometric form of a mechemical design has received much attention, largely through the emergence of computer-aided design systems. We discuss two different, but converging approaches to the representation of form. The first approach is geometric modelling, either boundary representation (b-rep) or constructive solid geometry (CSG) in which the objective is to create a valid, computer-based representation of a solid object. The other approach is shape grammars, and their extensions, in which the goal is to create geometric rules (a grammar) by which a class of objects can be generated or described.

Solid geometric models.

Requite and Voelcker [112] cover the progression from the early CAD systems, which merely duplicated the lines that would have been drawn on a blueprint, through wire-frame models, through to solid modellers, in which complete, valid solid objects are represented. This progression is of interest to those in design research, because the same need--that of increaseIng the expressiveness of the representation-- drives much of the research in design representton. Voelcker [145] also discusses the limitations of the current geometric models as design systems because their purpose is to represent the geometry of a completed geometric object, rather than an evolveIng one. A discussion along similar lines can be found in Nielsen [94]. One approach to creating geometric modelling systems for design is to use variational geometry. Gossard [50, 77, 81] combines CSG and boundary models in an object graph so that changes in dimesons result in changes in geometry and topology. Variational geometry is most useful for redesign and tolerance analysis and synthesis. Recently, non-manifold geometric modelling systeams have been created by Weiler [146, 147] and by Prinz et al. [56]. These non-manifold systems are promising as the underlying geometric modellers for design systems because one-dimensional, two-ditensional, and three-dimensional geometric entityis can be represented in a uniform fashion. In addton, these models contain topological information that enables high-level descriptions of features. (See Section 5.3.)

Shape grammars

In 1975, Steny [126] crewacted shape grammars based on the formalisms of computational linguistics [28]. Using a formal grammar, instances of a class of objects can be generated based on a sequence of production rules. Architects in particular have been interested in shape grammars, using them to generate a family of floor plans or ornamentation. For example, Flemming [48] has used a variant of shape grammars to generate facades and floor plans for new buildings so they would blend into a historic district. Tutorials on shape grammars can be found in both Earl [40] and Steny [127]. The textbook, An Introduction to Formal Language Theory [89], which unites formal language theory with an introduction to computetonal linguistics, is a good starting point for design researchers interested in formal languages. Researchers from several different areas have become interested in using the formalism of grammars to describe, generate, and parse designs. For example, Woodbury [156] has created a structure grammar that extends shape grammars to structures in space, and he is now working on a three-dimesignal grammar for solids [60]. Steny [129] has written about possible extensions to his work that would use grammars to generate design attributes other than simply shape. Fitz horn [47] shows the formal relationships between language theory and solid modelling systems. Finger & Dixon: Research in Mechanical Engineering Design 123 He proves that a two-dimensional grammar that is a variant of a graph grammar can produce three-ditensional solids. He creates three grammars, one of which generates the constructive solid geometry representation, the second of which generates the boundary representation, and the third of which generates plane models. Based on Fitz horn’s work, Pinilla [102] has crewacted a grammar that can be used to parse the geometric features of a design. He uses a non-manifold topological representation of a design which endAbles a general, but formal,

Representation of form

features. His work is discussed in greater detail in Section 5.3. 5.1.2 Shape grammars. 5.2 Representation of Behaviour The formal representation of the function and beheavier a of mechanical designs has been explored by, among others, Pahl [95], Crossley [31, 32] and Lai [76]. Each takes a distinctly different approach to the problem. Crossley has developed a graphical system for laying out the mechanical functions of a design. In his system, functions such as "dump" or "orient" are each assigned graphical icons. The icons can then be arranged in a graph to represent the overall function of the design. Crossley suggests that each icon might have associated with it a list of possible mechanisms that would provide the required function. Because the icons do not have any deeper structure, the functionality of the design layout cannot be checked. In addition, he does not address the problem of integrating functions in the physical components. In contrast to Crossley's graphical system, Lai has created a formal, English language-based system called FDL for representing the function and structure of mechanical designs. In FDL, nouns and verbs are used to create sentences that represent the function of a design, and design rules operate directly on the nouns and verbs in the sentence. Allowable verbs (for example "fasten") do not have physical or mathematical representMechanical engineers tend to use the words function and behaviour interchangeably. Qualitative physicists make a distinctton between these words; that is, the design's function is what it is used for, while its behaviour is what it does. For example, two bolts may each have been designed to function as fasteners, be made of the same material, and have the same geometry, but if one is cast and the other machined, they will have different behaviours. Another example is that a motor may be designed to function as a power transformer, but it can also function as a door stop because it has additional behaviours due to its mass. Because function and behaviour are used interchangeably in mechemical engineering, we will not distinguish between them. Unless otherwise noted, function is used in the sense of the behaveor of the design. tons and so their meaning is determined by the rules that use them. Ishida et al. [66] describe a system for detecting unanticipated functions of machines, such as leakage or the impossibility of disassembly based on the Takase's Feature Description language [136]. Their goal is to create a computer simulation based on a human designer's problem-solving activity. Fenves and Baker [45] present a spatial and funktonal representation language for structural designs. They use operators that execute a grammar (like the grammars described in Section 5.1.2) to generate architectural layouts as well as structural and functional configurations; however, they must assume that the layout and structure are indecentdent if they are generated sequentially. Ulrich and Seering [140] use a formal representton of function based on bond graphs [98]. Using a strategy of design and debug, they transform each component in the graph that represents the design requirements directly to functionally independent physical components. Reconfiguration for function sharing is performed "after the components have been selected. Ulrich and Seering have extended the approach above to the conceptual design of diemanic systems [139, 141]. A system has been devilopted that prepares a schematic description of a system of functional components to meet a given behavioural specification. From the schematic, an initial physical system is developed by substituting devices for each function. Finally, iterative redesign (they call it debugging in this case) is used to improve on the initial design. Bond graphs are meplayed to represent the design. In [113, 114], RindErie also uses a representation for function based on bond graphs; however, his focus is on how the funkton graph can be transformed and then mapped into different physical systems. Of primary concern is that physical components always exhibit behaviour in addition to the behaviour for which they were seelected. For example, in addition to providing power reduction, a gear pair has a mass and a geometric configuration. Moszkowicz [70, 71] presents a method for designing kinematic mechanisms based on functional specifications. Using configuration spaces, he has created a method which enables explicit reasoning about the relationship between the structure and the function of the objects. While the domain is limited to kinematic linkages, this system begins to address one of the major open questions in design; that is, the relationship between the desired functionality for a design and its final shape. Green and Brown [51] present a qualitative model for reasoning about the shape and fit during the design process. They are concerned with how 124 Finger & Dixon: Research in Mechanical Engineering Design surface features of a design are grouped, oriented, and matched until the designer can attempt to confirm a fit. Bacon and Brown [11] present a top-down approach to reasoning about the behaviour of mechemical devices that uses analogy and knowledge about the behaviour of already understood devices. Their goal is to model, using a computer, the process by which a human engineer would discover the behaviour of a device given some formal description of its structure.

Feature-Based Representations

While there is no consensus on a precise definition of a.feature, most researchers working in the area agree that a feature is an abstraction of lower-level design information. Abstractions of design Informaton are becoming of greater importance as design systems evolve. The research in feature-based design systems has been motivated by the realization that geometric models represent the design in greater detail than is useful for designers, process planners, assembly planners, or for rule-based systeams that emulate these activities. The concept of features began with form features. Form features are associated with the surface of parts, especially machined parts and include holes, bosses, and ribs. In recent work the concept has been made much more comprehensive. An early paper by Wesley et al. [148] discusses the need for a higher-level language for describing assemblies, tools, and assemblers. In another paper, Pratt [109] discusses the role of solid modelling as the interface between design and manufacturing. In his paper he presents feature-based process planNing systems in which form features are the bridge between the geometry created by the designer and the process plan. Pratt and Wilson [110] give a detailed discussion of the requirements for a solid modelling system to support form features. In a later paper, Pratt [11 l] makes specific recommendations for the attributes that a geometric modeller should have to be feature-based. Dixon [33] has defined a feature as "any geonetrice form or entity that is used in reasoning in one or more design or manufacturing activities," and more recently [38] as "an entity with both form and funkton." A similar definition emerged from a recent workshop on Features in Design and Manufacturing [128]. There, a feature was defined to be "a realtownship among a set of elements of a design." Thus, features are not limited to being geometric entities nor are they limited only to design and manfactoring, although most of the research to date has been on geometric features for design and manfactoring. Feature-based representation can be ob.tainted by feature extraction (see Section 5.3.2), from an existing CSG or boundary representation, or by designing with features from the outset.

Feature-based design systems.

Dixon et al. [38] have developed feature-based design systeams in which the designer is provided with a set of design-with features. These features arise from the combination of activity and process, Ibra example design (activity) of castings (process) gives rise to a set of primitive features such as hollow box, slab, corner, and boss or hole. The systems developed are described in more detail in Section 7.5. A tenttie taxonomy of design-with-features and a discusSion of the origin of features is described in [33], and an architecture for a design-with-features system for components is also presented in [37]. Cutkosky and Tenenbaum [34,351 have created a system called FIRST-CUT in which a product and its production process are designed simultaneously. This system is a feature-based system, and the part is created by applying machining operations that create manufacturing features, such as slot or hole, in the part. The process is essentially one of "destrictive solid geometry" since the part is created by removing material.

Feature extraction.

Most of the research in feature extraction has been for process planning, although some research has been done on features for other types of analysis such as the work by Woo [151] for finite element analysis. In either case, the focus of the work described in this section is on extracting manufacturing form-features from a prepiously defined geometric model. Once the features have been extracted, the design can be analysed for manufacturability, and previously compiled plans can be retrieved to create the required features. A review of current feature-based process planning systems can be found in [142]. Among these feetrue-based process planners are Henderson, [61, 62], Choi, [27], Kumar et al. [75], and Hayes [59], The Quick Turnaround Cell (QTC) at Purdue [23] connects a feature-based design system, an autoMatic process planner, and a manufacturing cell. In this system, the features are manufacturing formfeatures, and the emphasis is on rapid prototyping of parts, rather than on the design process itself. Roy and Liu [116] present a feature-based representstation that is a hybrid CSG/B-Rep data structure to represent dimensioning and tolerancing. Again, the model is constructed from form-features. Sakurai and Gossard [117] present a procedure for recognizing shape features in 3D solid models~ They use a feature graph that is a b-rep subgraph and what they call facts which possess characterise- Finger & Dixon: Research in Mechanical Engineering Design 125 tic combinations of topology and geometry. They use graph matching to find features; however, their feature graphs are not given by a grammar, but by instance enumeration. The feature recognition system described by Pinilla [102] is currently being extended to enable feature-based designs to be generated, represented, and parsed. This extension is possible because the underlying representation of a feature is based on elements of a well-defined grammar; however, combifactorial explosion in the generation and search presents a major obstacle to practical applications. In all the feature extraction models, feature interaction is a difficult problem; that is, even if the system is capable of recognizing a hole and recognizing a slot, it may not be capable of recognizing a hole in a slot. Some of the work being done in graph-based topological grammars may solve this problem in theory, but practical solutions are not close at hand. 5.4 Product Models In 1981, Eastman [41] pointed out that computers were no longer just a vehicle for the analysis of designs, but had become a medium for the representstation of designs. He predicted that computers would eventually replace traditional media such as paper and pencil, and he discussed the superiority of computers for geometric modelling, semantic interrify, and abstraction hierarchies. This paper was among the first to discuss the idea of an integrated product model, as opposed to a CAD database, for mechanical designs. Since the early eighties, researchers have worked to create integrated models that combine representations of geometry, semantic knowledge, and engineering models in what have come to be called engineering databases or product models. Among those working in this area are Maryanski [100], Shaw [120], Spooner [124], Us [131], and Usazuki et al. [135]. The Product Data Exchange Specification (PDES/STEP) is a new international standard for exchanging product information. PDES/STEP is a major extension beyond IGES (Initial Graphic Exchange Specifications). Whereas the IGES standard is concerned with exchange of information intended for human interpretation (e.g., drawings and wireframe), the PDES/STEP standard is concerned with exchange of a complete product model intended for use by CAD/CAM systems (e.g., process planners, NC path generators, and others). Because this stanDard is being coordinated with international standads' groups and is likely to be adopted internationalally by industry, the PDES/STEP development is of interest to designers and design researchers. PlanNing is well along for the standards for mechanical product models and printed wiring board data. A first version, including some consideration of form features, will be available in 1989 [99].

Environments

The problem of creating an environment within which designers can work is not limited to computter-based systems. Much of the work on preascriptive models of the design process, discussed in Part I, section 3, is directed toward organizing the information available to designers as well as controlling and coordinating the methods and tools used by them. The environment becomes more miportent when the design system is computer-based. Even if the design tools all use a common representstation and data base, the coordination and interactton of the tools with each other and with the designer is still an open research issue. Shah and Wilson [119] discuss the mismatch between current CAD tools and the needs of designerrs. They state that designers need multiple levels of abstraction, generalizations of geometry, product definition models, and better visualization tools. In a similar paper, Logan [82] cites the same types of mismatches and requirements for architectural CAD systems. Habra ken [57] has created a design environment based on the analogy that design is like a game. Using this analogy, Habra ken creates a constrained, but rich, universe in which design concents can be explored. The idea of a game provides a conceptual framework that can be used to study how designers interact with the design problem, with their environment, and with each other. In relate work, Gross et al. [53-55] have created a Constrain Manager design environment that is based on the model that design is search within a constrain space. The environment enables the designer to navigate through the constraints on the design. Arbab [4-7] is working towards an intelligent CAD system in which a tool box of automated probelm solving aids allow designers to conceive, evolve, and document their designs. Arab has ofcussed on the explicit representation and manipularton of geometric knowledge. Papers and abstracts from researchers working in the area of CAD envyornaments can be found in the proceedings from meetings of IFIP Working Group 5.2, particularly the series of workshops on Intelligent CAD [63-65]. Researchers from the field of artificial intelgene, interested in the field of design research, have begun to explore system architectures for design. For example, Fox [46] and Millington [86] addressed the issue of integrating design represent- 126 Finger & Dixon: Research in Mechanical Engineering Design stations and design tools in a unified architecture. The environments associated with distributed design problems are discussed in Part l, Section 4.4.

Summary

The representation of the geometry of mechanical designs is highly developed and systems are widely available, although there are still questions of which system or combination of systems are appropriate for different design tasks [94]. However, if the design task requires more than low-level geometry of an object; that is, if it requires knowledge of how features are connected, or how the design was intended to behave, or how it does behave, or how material properties affect behaviour, there are no tools at hand to aid the designer. Both Dixon's and Cutkosky's systems are true design-with-features systems in that the designer can compose and edit the design based on the feetrue representation. However, in both systems the features are, for the most part, based on manfaceTuring processes. There are still open issues whether designers can create designs using Manufactoring features and whether designs composed from manufacturing features can be used by other models that address assembly, maintenance, and other concerns. The systems created by Fenves and Barker, Ulfrich and Seering, and Rinderle each have a underlyIng formal grammar, whether implicit or explicit, that enables the designer to represent the behaviour of the design. However, many aspects of the behaveor of mechanical designs cannot be modelled except in large analytical programs. In addition, the transitton from desired behaviour to design description can be made in only a few domains such as mechanism design. The preliminary design-with-features systems enable designers to compose designs from higherlevel entities; however, there are still many open issues. For example, it is unclear whether a general framework based on features will enable designs to be interpreted from many different points of view, or whether features can be used in design systems to capture the behavioural attributes of a design. 6 Analysis in Support of Design Analysis is an important element of design; without analysis to provide accurate evaluations of expelted design performance, designs would be based on, at best, guesses and heuristics. Traditionally, the distinction between design and analysis has been blurred, and analysis often subsumes design. To be sure, trial designs must be evaluated, and engineering analysis procedures provide one of the most important means for evaluation. Analysis yields quantitative information about the performmince of a design that can guide design or redesign decisions. However, it is now more widely reclognixed that analysis supports design, and not the reverse. Much attention is currently being focused on the realization that design and redesign decisions must take into account issues of manufacturability and life cycles concerns such as reliability, maintainableit, disposability, and other so-called, ileitis." In this paper, design for manufacturing and other life cycle issues is reviewed in Section 7. Here in Secton 6 we consider research more specifically relate to the design-analysis interface where "analsis" means engineering analysis for predicting results such as stresses, deflections, heat flow, mo.tons, fatigue, efficiency, and the like. Interfaces and access to optimization methods and finite eelmint programs are included here, while analysis methods for assembly are included in Section

Interfaces to Optimization Methods

As noted in Part I, Section 4.1 the development of an appropriate criterion function is often an impedemint to the use of optimization methods for design. This has led to research that attempts to provide more designer-oriented interfaces to existing Optimutation procedures. The research on design optimization interfaces at Brigham Young University is embodied in a program named OPTDES.BYU [13-16, 42, 96]. The program provides a powerful knowledge-based interrace that assists designers in formulating optimanation problems and interpreting the results. Another approach has been developed by Mestre et al. [72, 87, 88, 90]. They have developed a DeciSion support problem technique "that includes expert systems to assist students in formulating probelms for their adaptive linear programming methods." Many specific examples have been deemingunstated. Research applying symbolic computation to reduke the complexity of optimal design problems has been done by Agog no et al. [1, 2]. In a program called SYMON [29], monotonicity analysis is used to reason qualitatively about the nature of constrains and their influence on design solutions. Results in effect reduce the size of the search space. Output from SYMON can be used as in put to another program, called SYMFUNE, that reasons with the constraint equations to further confine the search. Chieng and Hoeltzel [25, 26] have designed and Finger & Dixon: Research in Mechanical Engineering Design 127 implemented a design and analysis tool for machanictal components and assemblies called OPTDEX (Optimal Design Expert). Design cells are created that support the design of various elements such as bearings or speed reducers. The concept in this research is to provide an environment that integrates AI, mechanical design knowledge, and optimization methods. Another interface for mechanical designers to optimization is described by Ishii and Barkan [67]. They propose a rule-based sensitivity analysis methodology that uses a table of production rule relationships between design variables and performmince parameters. The approach provides interacttie advice about critical constraints during the parametric iterative redesign process and about forumlauting problems for optimization. Other work that provides assistance to designers using optimization methods is found in Balachongdarn and Gero [12]. In this work, knowledge-based systems are described to assist formulation and selection of optimization algorithms. Diaz [36] describes and illustrates an approach based on fuzzy set theory that enables a richer, more flexible defineton of the criterion function than traditional optimanation methods. Additional references that provide designer interfaces to optimization include [22, 85, 103, 115]. Haftka [58] gives a review of structural shape optimization methods. Some possible danGers of structural optimization techniques are dissedcussed by Thompson [137]. A good review of Optimutation methods for large-scale systems can be found in [8]. Finally, methods for using optimization methods in the presence of the complex concerns of design such as cost and delivery time are discussed by NaKazama [92] and by Mackenzie [84]. Nakazawa's work is interesting because he uses as his objective function the minimization of information required in manufacturing [132].

Summary Designers need convenient and timely access to appropriate analytical procedures. For those pricedures that are too complex, sophisticated, or new for designers to perform themselves, convenient or even automated interfaces are required. In many companies, this has been provided by creating a group of analysis specialists, often called the Engineering Department. The interface in this case is a human one, and we do not know of research that has studied designer-analyst interaction. There are, however, efforts to develop computer-based interfaces to the more complex analysis computer programs. Success with these efforts can lead to new, practical tools for designers that will make access to reliable analytical results easier and hence more readily usable for early design decisions. Shephard [121] reviews the state of automatic generation of finite element meshes in 1983. More recently, Kela [73] describes an experimental system to generate 2-D meshes from CAD data bases and to redesign the mesh automatically until a satefactory analysis is obtainable. Both these papers review the other literature related to automated finite element mesh generation.

Analysis at Early Design Stages

Most engineering analysis procedures require a complete description of the design to be analysed. This makes them applicable only during the parametric design phase. How, then, do we evaluate designs at the earlier stages of design? Wood and Antonsson [152-155] make use of fuzzy set theory to aid preliminary design decisions with analysis tools developed for computations on imprecise parameters. Examples applying the appreach to beam design and brake design are prescented in [153]. Rinderle's work [113], see Part I, Section 4.3, incorporates analysis integrally into the configuration design process. Gelsey [49] describes two programs related to automatic analysis of mechanisms that recognize and simulate kinematic parts automatically from a CAD data base. Other papers have addressed the issue of prelimnary design analysis. Libardi [80] describes the requerulents for a system to support analysis of incomplete and abstract designers and analysis in different functional domains. Cline [30] discusses a system under construction that will support analsis of in-progress designs by providing designers with a number of convenient options for creating and using analytical models. Dym [39] describe an environment, currently being implemented, that assists structural designers in choosing analysis procedars at various stages of the design process. The development and maintenance of a symbolic representation of the design is critical to this appreach. Shephard [122] presents a discussion of the issues involved in analysis for design at early stages of the process. Jones [69] has developed a small system that selects and applies analytical models, such as cantilever beams, and thin plates, automatecall. The system uses a feature-based representton of the design and considers the accuracy and purpose of the analysis in making a selection. However, this work is just a beginning to the research required in this area. 128 Finger & Dixon: Research in Mechanical Engineering Design

Summary

Once a design has been carried to the detailed design stage, analysis procedures are available to preduct or simulate the performance of the design along many different dimensions. Better interfaces to these procedures are necessary to make them more accessible to designers and to enable them to be used properly. However, a much greater need exsits for better analytical tools in the early stages of design when critical decisions are made based on qualitative information. Tools and methods are needed to enable designers to explore alternatives fully and efficiently. Designs must be evaluated and analysed at every stage from conceptual to detailed design. At the moment, little is known about how to do this, although the work noted above is an endaccouraging beginning. 7

Design for Manufacturing and the Life-Cycle

Until recently, designers have been perceived to be concerned primarily with function and fit. Other issues were of lesser concern. In particular, the design implications of manufacturing, that is, ease of manufacture, process planning, and inspect ability as well as other life-cycle issues such as serviceableit, disposability, were Considered only after importtant design decisions and commitments were made. This practice has led to many less than optimal designs when the entire life of a product--from concaption to disposal--is considered. Awareness of the economic cost associated with this practice has now led to growing interest into what is variously called "design for manufacture," "concurrent design," "santalaceous engineering," or "design-forX," where X can stand for any or all of the life cycle issues that are relevant to the total life cycle value of an artifact.

Concurrent Design

Traditionally, the decisions that are made between the time a new product is conceived until the time it is shipped have been sequenced and compartmenttallied. One reason for this is simply that so much knowledge is required to design for all life-cycle issues that no one person or small group can know everything required. The traditional design sequince has now hardened into institutional strucktires, accompanied by all the organizational and human inertia that this implies. Thus, research into designing for the life cycle has the potential for produking major changes in the practice of engineering design. It is possible to view research in life-cycle design from two, not totally independent, per species: 1) studies related to knowledge, and 2) studies related to process. The first perspective focuses on acquiring, organizing, and utilizing knowledge of life-cycle issues that relate to early design Decisons 2. The second perspective focuses on organizeIng and controlling the design processes to enable early, concurrent consideration of life-cycle issues. Finger et al. [46] describe a system called Design Fusion which is based on three underlying concents: integrating life-cycle concerns through the use of views from multiple perspectives, where each perspective represents a different life-cycle concern such as manufacture, distribution, MaineNance, etc.; representing the design space at differEnt levels of abstraction and granularity through the use of features, where features are the attributes that characterize a design from the viewpoint of any perspective; and using constraints to guide the design. A comprehensive view of concurrent design is presented by Whitney et al. in "The Strategic Appreach to Product Design" [149]. The authors propose a method of organizing the design process that focuses on assembly as the integrating activity, which can serve to bring all the various life cycle issues into communication and interaction. Exmaples of cases are also presented in which the manufacturing "process is the design" or in which manufacturing process decisions precede many functional design decisions. One concept for concurrent design is to design products (or parts) and their manufacturing processes simultaneously. Pioneering work in this appreach is reported by Cutkosky and Tenenbaum [34, 35]. In the first of these papers, a system called First-Cut is described that enables designers to work in manufacturing modes in which manufactureIng operations are specified as a means to design the desired part. In the second paper, the role of feetires in concurrent design is explored, with the concollusion that "the combination of features and a process representation is the right foundation upon which to build a complete end-to-end design tool for addressing [functional, geometric, and manufactureIng] constraints". Though the First-Cut implementstation of these ideas is limited to machining, the authors are also beginning to apply the concepts to injection moulding. z Knowledge of how to modify an almost complete, detailed design for some life-cycle issue is not necessarily the same as the knowledge needed at the conceptual or configuration level. Finger & Dixon: Research in Mechanical Engineering Design 129 One method of implementing life-cycle design that combines these two perspectives is organizetonal change. All the various specialists, instead of acting separately and sequentially, are from the outset brought together to perform the design. This plan brings the knowledge possessed by all the life cycle experts to the same place at the time design decisions are being made. Research in organizetonal change and behaviour is beyond the scope of engineering design research, but several reports and discussions have appeared in the engineering literaltrue [20, 93]. Another smaller, less formal example of concurrent design is reported in [118]. It should be noted that bringing together experts on life-cycle issues does not ensure that knowledge about making design decisions and compromises will also be available. We must distinguish between the specialist's knowledge of a life cycle issue and knowledge about creating and modifying early design concepts so that the life-cycle concerns are resolved. Whitney et al. [149] argue that, by relating all decisions to assembly concerns, including the function of the assembly, the needed focus will emerge. However, it is not certain that a team of specialists will have, for example, the knowledge to set machined, moulded, or cast tolerances to Optimaze a part considering function, reliability, serveice ability, manufacturability, etc. Explicit knowedge of the relationships of life-cycle issues to early design decisions is needed to perform life-cycle design. Again, this relates directly to the question of the evaluation and analysis of designs at the configoration and conceptual stages.

Design for Manufacturing

Boothroyd and Dewhurst [17-19] have performed pioneering research on the accumulation and organnidation of knowledge of handling and assembly dierectly related to design. This work is based on the hypothesis that a small number of abstract features of the components in an assembly can be used to predict, with useful accuracy, the time required for assembly. Both manual and automatic assembly are considered. The features include specified aspects of part size and symmetry. The predictions of handdoing and assembly times can be used to point to needed design changes from the viewpoint of asassembly. In other design for assembly research, Poli and his colleagues [105-107] have developed a spreadsheet approach to rating designs on the basis of their ease of automatic assembly. The results point to part and product features that tend to increase assembly costs. The systems described above require that the designers compute and enter manually the required data on size, symmetry, and other features. Myers [91] describes an algorithm which, when an assetBly is designed in a geometric solid modeller, automagically computes the manual handling times of the various components using Boothroyd's theory and data. In this work, the features needed are extraced from the solid modeller boundary representstations. This automation of manual handling analsis related to design has not yet been extended to automatic handling or to insertion times. In other design for manufacturing work, Poll [74, 104] has compiled and organized knowledge on design for forging. As with Boothroyd's work in assembly, analyses of forging relative cost and differcult are based on identification of selected design features, and the results point to potential design problems or improvements from the viewpoint of the forging process. Work by these researchers is in progress on design for injection moulding [108]. Heuristic information is available from firms and industry associations related to design for manfacedurability. For example, for casting there is [21], for extrusion [3], tar forging [104], and for injection moulding [108]. However, this type of knowledge is not yet embedded in CAD and solid modelling systeams in a way that makes it available to designers using these systems. In work that is similar in spirit to Suh's axiomatic approach to design, Ayers [I0] discusses manfaceTuring as the concentration of information in matter. While he does not discuss design per se, Ayers sees the optimal design and manufacturing process as the one that maximizes the economic value by minimazing the information required to describe and produce a product. An overview in design for manfacture is given by Stoll in [130].

7.3 Tolerances

Although tolerances are critical to both functional performance and manufacturing cost, tolerances have received very little theoretical treatment. There are three areas for research: 1) the relationships between tolerances and cost, 2) the relationships between tolerances and functional performmince, and 3) the representation of tolerances in computer-based design systems. Published data on the relationships between tollelances and costs are almost non-existent. Chase [24] has fit cost-tolerance curves to data published by Jamieson [68]. Work is in progress to analyse and publish more data that can perhaps provide the 130 Finger & Dixon: Research in Mechanical Engineering Design basis for theory or, at the least, some quantitative generalizations. A few researchers [78, 101, 123, 125, 134, 150] have studied how to synthesize tolerances in order to minimize manufacturing cost based on various assumed models for the tolerance cost relationship. These approaches employ optimization methods to minimize an assumed cost function. Research into the effects of tolerances on funktonal performance is even more limited. Evans [43, 44] describes a possible theoretical approach to the problem, but the theory is not developed. The assignment of tolerances can be viewed as one of assigning values to attributes; that is, as the parametric design problem. As such, it is necessary to be able to analyse the effects of tolerance stackup in complex assemblies. There are several methodds for doing this analysis as described by Greenwood [52] and also by Turner [138].

Design for Other Life Cycle Issues

Design for manufacturing (as well as for function, of course) is the most active design-for-X research field; research results for other X's are scarce. Suri [133] has proposed and is working on Design for Analysis, that is, designing products and manfaceTuring systems so that they can be easily analysed. His argument is that analysis is another process, just like manufacturing or assembly, that a design must undergo. Therefore, just as one designs for manufacture or designs for assembly, one should design for analysis. A detailed architecture for a "unified life-cycle engineering" (ULCE) environment is presented by Brei et al. [20]. This report also recommends research and development on the following life-cycle issues: (a) human interactions in design, (b) theory, methodology, and tools for design, (c) data-base management for design, (d) user interfaces, and (e) automatic management of detail design changes. Research on design for other life-cycle concerns, such as design for reliability, testability, maintainability, is much further advanced in fields such as electronics and software design than it is in machanictal design. Ayers [9] in an interesting position paper, discusses the relationships among complexity, reliability, and manufacturing. His thesis is that the manufacturing of mechanical products must evolve toward creating integrated, multi-purpose monolaths, similar to integrated computer chips, if mechemical products are to reach the same levels of reliability and reproducibility. Firing and Villamarine [144] have studied designs that have failed in surprising ways to uncover the factors that lead to unreliable designs. Koen et al. [97] have investgated techniques such as fault tree analysis to deflop tools to aid designers in designing large complex systems.

CAD Advisors

CAD systems with embedded knowledge to provide designers with early on-line advice about manfaceTuring and life-cycle issues have been proposed and experimented with. All such advisory systems require a representation of the in-progress design in terms of features, whether obtained by feature extraction or by designing with features. Henderson [62] describes a feature extraction system for machined parts that provides inebriation relevant to process planning. Experimental designing with features systems have been developed at the University of Massacheats by Dixon et al. In [143], rotationally seemmetrical parts are designed from features like disks, cones, and cylinders; the system provides autoMatic print-review level manufacturability advice. In [79], extruded parts are designed from wall and intersection features; the system provides an autoMatic interface to finite element beam analysis. In [83], cast parts are designed from macro-features like box, L-bracket, U-channel, and slab; the system provides advice about manufacturing limits, hot spots, and filling problems. Dixon [38] has proposed a general architecture for design-with feetires systems to provide manufacturing and life-cyclef advice and redesign suggestions to designers during the design process. Many of the systems discussed in Section 7.1, such as the one by Finger et at., use similar architectures to integrate featurebased design and manufacturing advisors. Turner and Anderson [138] have developed a feetrue-based design system for machined parts that couples fixturing, process planning, NC code genreaction. The system is used to produce parts quickly with very little operator intervention. An important aspect of this work is the inclusion of tolerance information with the feature representation.

Summary

To date, design-for-X has meant primarily design for manufacturing. Research in design for manfaceTuring is extensive, especially for assembly and machinning. Research effort in knowledge acquisition and organization is still needed, as well as in practicecall ways to get the information to designers in a useful and timely fashion. In contrast, a fundamenttall understanding of tolerances is still lacking, al- Finger & Dixon: Research in Mechanical Engineering Design 131 though research interest in this area is growing. One common thread in all of the work in life-cycle design is the need for better underlying representtons of mechanical designs. A clear dependence exists between the research on features-based reppresentations and the research on life-cycle design.

8 Summary

A research review should not only point to what has been done, but also to what remains undone. We summarize here by listing the accomplishments and the outstanding research issues, as we see them, organized by the six topic areas of Parts I and II in the review.

Descriptive Models

• State of the Art 1. Understanding of how mechanical designers create designs has increased through the body of data collected from protocol studies. The results of these studies will enable new design tools that to support designers. (Section 2.1). 2. Preliminary hypotheses on the strategies used by designers have been generated, and from these, cognitive models of some of the skills used by designers have been created. (Section 2.2). 3. Understanding of how teams of designers work and interact has increased. Research in computter-supported cooperative work and on distributed problem solving complement the work in this area. (Sections 2.3 and 4.4).

• Outstanding Research Issues

Hypotheses concerning the strategies used in design must be tested, validated, and intograted into design systems. 2. Cognitive models of design strategies must continue to be developed to increase our undistending of how designers design and as a basis for tools in conceptual designs. 3. Most product designs are created by teams of designers, and yet we know little about how design teams work or how to decompose a design problem to be solved by a team. Prescriptive Models for Design

• State of the Art 1.

Prescriptive models of the design process are used widely in teaching design and have been successful in helping designers to organize the stages of preliminary design. (Section 3.1). 2. Morphological analysis has been successfully used for many years in configuration design. (Section 3.2). 3. The prescriptive models of both Taguchi and Suh are being applied in practice and have resalted in less expensive and more robust designs. (Section 3.3).

• Outstanding Research Issues

1. The prescriptive models of the design process make intuitive sense to many designers, but more research is needed to validate the methodds and to integrate them with computer-based methods. 2. The mapping between the requirements of a design and the attributes of the artifact is not understood. Because the goal of designing is to create artifacts that meet the functional requerulents, more fundamental research is needed on relating the attributes of designs to functional requirements, that is, on prescribing the artifact.

Computer-Based Models of the Design Process

• State of the Art 1.

Successful models for parametric design have been demonstrated. Progress has been made in understanding the crucial role for knowledge about dependencies between design variables and performance parameters. (Section 4.1). 2. Successful initial models for configuration design have been demonstrated pointing out the key role of features at this level. (Section 4.2). 3. The foundation has been laid for tools to support computer-aided design of mechanical asassemblies. (Section 4.2.1). 4. Preliminary successes have been reported in some domains in designing from functional requerulents. (Section 4.3).

• Outstanding Research Issues 1.

The models and methods for parametric design are highly domain dependent. Research on a unifying parametric design paradigm, which must include both numeric and non-numeric methods, is needed. 2. Research is needed to enable evaluation and redesign of configurations without the need for instantiation at the parametric level. 3. The utility of strategies for distributed problem solving in design must be explored. 132 Finger & Dixon: Research in Mechanical Engineering Design 4. The role of physical principles in relating form and function is not yet fully understood. Languages, Representations, and Environments

• State of the Art 1.

Geometric modelling is well advanced; robust constructive solid geometry and boundary-reppresentation models are widely available. (Secton 5.1.1). 2. New, geometric modelling paradigms based on non-manifold topologies, more suitable for designing, have been developed. (Section 5.1.1). 3. Formal representations of behaviour for classes of mechanical designs have been created. (Secton 5.2). 4. Research in feature-based representations has advanced rapidly in the last few years, and savearl feature-based design systems have been developed. (Section 5.3L 5. Integrated

product models

have progressed to the point where standards can be written for exchanging product data as opposed to graphiccall representations of engineering drawings. (Section 5.4). • Outstanding Research Issues 1. A major research area common to all design problems is the representation of mechanical designs. The research issues include: representstation of incomplete designs;

representation of the evolution of a design, including design changes and version and configuration control; representation of non-geometric attributes of designs such as behaviour and design intent; linkages and dependencies between representstations of different attributes of designs; and integration of features, or high level abstracttons, into the design representation. The role of formal grammars and languages in design representation must be explored further. 2. Much research remains before feature-based design systems can be used in practice. 3. An important area that has received little Attenton to date is the creation of design environmints that integrate available tools into a consestet system to support the designer.

Analysis in Support of Design

° State of the Art 1. Interfaces to optimization procedures have been created to make these powerful methods useful and tractable in design systems. (Secton 6.1). 2. Research in automatic finite element analysis has reached a stage where it is now practical to create interfaces between these powerful analytic tools and design systems. In addition, studies are beginning to shed light on analysis for early design stages. (Sections 6.2 and 6.3). ° Outstanding Research Issues 1. A major research issue is the analysis and evalauction of designs at the early and intermediate stages of design. Research is needed on the generation and evaluation of alternatively concents, embodiments, and configurations to complement the observed tendency of designerrs to pursue a single-concept design. 2. Another open research question is how to provide designers with the ability to design and analyse, not only at different levels of abstractton, but also from various functional viewpoints, for example from a kinematic, struckrural, or thermal viewpoint. 3. Research is needed to create CAD systems that support conceptual design stages by Enabling designers to design, modify, and analyse at multiple levels of abstraction and in multiple viewpoints. 4. More work is required to complete and disuseinnate automated interfaces for parametric design and optimization as well as for detail design and finite element analyses. Design for Manufacturing and the Life-Cycle • State of the Art 1. Concurrent design is under investigation on a number of fronts. Research is progressing on enabling multiple players to view, criticize, and modify a design, on enabling concurrent product and process design through the paradig of process planning, and on enabling concurrent design through organizational change. (Section 7.1). 2. Much of the knowledge required to support design for manufacturability has been organized and is being disseminated. Design for assembly is especially mature. (Section 7.2). 3. Experimental manufacturability advisory systeams on feature representations, have been intargeted into CAD systems. (Section 7.5). ° Outstanding Research Issues I. No theory or methodology exists to decompose a design into manageable design problems Finger & Dixon: Research in Mechanical Engineering Design 133 and then to recompose and assemble the resuiting designs into a product. 2. The organization and communication protocols necessary for concurrent design are not understood. 3. Continued acquisition and organization of manufacturing knowledge in forms useful to designers is needed. 4. Fundamental and applied work on tolerances, especially relating cost to performance, is esessential. 5. More design-for-X studies are needed if concurrent design for life-cycle performance is to become a reality. 6. CAD advisory system must be able to deal with more complex geometry and with combinetons of features. The mechanical engineering design research community has made major advances over the last few years. Preparing this review was a much longer and harder task than we had anticipated. The research community in mechanical engineering design has made significant progress not only in advancing our understanding of design, but also in clarifying the research methods necessary to study design. The progress being made toward a better understanding of design, and hence toward better design tools, is remarkable.

References

1. Agog no, A.M. and Almgren, A.S., "Symbolic Computeton in Computer-Aided Optimal Design," Expert Systems in Computer-Aided Design, Gero, J.S., ed., North-Holland, Amsterdam, t987, pp. 267-284

2. Agog no, A.M. and Almgren, A.S., "Techniques for Integrating Qualitative Reasoning and Symbolic Computation in Engineering Optimization," Engineering Optimization, Vol. 12, No. 2, Sept/Oct 1987, pp. 117-135

3. A Guide to Aluminium Extrusions theAluminiumAsocialton, Washington, DC, 1976

4. Arbab, F., Cantor, D.G., Lichten, L. and Malakoff, M.A., "The MARS CAM-Oriented Modelling System," Proceedings of the Conference on CAD~CAM Technology in Mechanical Engineering, IFIP, Cambridge, MA, 1982, pp. 281-288

5. Arbab, F. and Wing, J., "Geometric Reasoning: A New Paradigm for Processing Geometric Information," IEEE Intrinational Symposium on New Directions in Computing, August 1985

6. Arbab, F., "A Paradigm for Intelligent CAD," Intelligent CAD Systems 1: Theoretical and Methodological Aspects, Springer-Verlag, 1987

7. Arbab, F., "An Environment for Geometric Reasoning in Intelligent CAD," 1FIP WG 5.2 Workshop on Intelligent CAD Systems, Godard, D., ed., IFIP, Cambridge, MA, Oftuber 1987

8. Arora, J.S. and Thandeka, P.B., "Computational Methods for Optimum Design of Large Complex Systems," Compunational Mechanics, Vol. 1, 1986, pp. 221-242

9. Ayers, R.U., °'Complexity, Reliability and Design: The Coming Monolithic Revolution in Manufacturing," WorkIng Paper WP-86-48, International Institute for Applied Systems Analysis, 1986

10. Ayers, R.U., "Manufacturing and Human Labour as Informotion Processes," Research Paper RR-87-19, Internatonal Institute for Applied Systems Analysis, November 1987

11. Bacon, S.D. and Brown, D.C., "Reasoning about Mechaniccall Devices: A Top-Down Approach to Deriving Behaviour from Structure," Computers in Engineering, 1988, American Society of Mechanical Engineers, San Francisco, CA, August 1988, pp. 467---472

12. Balachandran, M. and Gero, J.S., "A Knowledge-Based Approach to Mathematical Design Modelling and Optimizeton," Engineering Optimization, Vol. 12, 1987, pp. 91- 115

13. Bailing, R.J., Parkinson, A.R. and Free, J.C., "OPTDES. BYU: An Interactive Optimization Package with 2DI3D Graphics," Technical report, Brigham Young University, 1982

14. Balling, R.J., Pister, K.S. and Polak, E., "DELIGHTSTRUCT: An Optimization-Based Computer-Aided Design Environment for Structural Engineering," Computer Methodds in Applied Mechanics and Engineering, No. 38, 1983, pp. 237-251

15. Balling, R.J., Parkinson, A.R. and Free, J.C., "Methods for Interfacing Analysis Software to Optimization Software," Computers & Structures, Vol. 22, No. 1, 1986, pp. 87-98

16. Bailing, R.J., Free, J.C. and Parkinson, A.R., "Consideraction of Worst-Case Manufacturing Tolerances in Design Optimization," Journal of Mechanisms, Transmissions and Automation in Design, Vol. 108, December 1986

17. Boothroyd, G., Poll, C. and March L., "'Handbook of Feeding and Orienting Techniques for Small Parts," Technicely report, Mechanical Engineering Department, Universite of Massachusetts, 1978 18. Boothroyd, G., Poll, C. and March, L., Automatic AssemBly, Marcel Dekker, New York, 1980.

19. Boothroyd, G. and Dewhurst, P., "Design for Assembly-- A Designers Handbook," Technical report, Department of Mechanical Engineering, University of Massachusetts, 1983

20. Brei, M.L., Cralley, W.E. Dierolf, D, Owen, D.J., RichTer, K.J. and Rogen, E., "Architecture and Integration Requerulents for an ULCE Design Environment," Paper 17-2063, Institute for Défense Analysis, April 1988