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Department of Electrical Engineering

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NOTICE

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COMPUTER-AIDED DESIGN RELATED TO THE ENGINEERING DESIGN PROCESS

by

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(Mechanical Engineering Department)

8436-TM-5

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Approved by: ______________________

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ABSTRACT

The objective of the Computer-Aided Design Project is to evolve a man-machine system which will permit the human designer and the computer to work together on creative design problems. This document states the philosophy of approach of the design and graphics group of the project. A companion document 8436-TM-4 states the philosophy of the computer applications group.

The engineering design process is viewed as a stochastic iterative process in which a recognized human need leads to a preliminary tentative concept of a means for its achievement; subsequent analysis, evolution, and judgement leads to modification of the concept and even possibly to a modification of the original goal, until certain standards are met and the need is satisfied.

The manpower-time requirements for proceeding from the original design concept to its realization in a manufactured part, device, or system is investigated, with a view to determining where best to begin consideration of computer aids in the sequence. In general, the conclusion is drawn that for the present the computer can be most effective in replacing manpower in routine drafting, minor design decisions, engineering computation occurring in analyses, (particularly stress computations) and as an aid in the selection of standard parts.

PREFACE

The computer-aided design project at M. I. T. is a joint endeavor between the Computer Applications Group of the Electronic Systems Laboratory, Electrical Engineering Department, and the Design and Graphics Division of the Mechanical Engineering Department. Based upon their backgrounds in different disciplines, these groups are taking complementary approaches to the problem of how to use computers to assist humans in the design process. The long-term goal is automatic manufacture once the human-computer "design team" has established the features of a design. It is not contemplated that fully automatic design without human guidance and decision is a possibility for the foreseeable future. However, the possibility of having a computer be an active partner to the designer, to accept and analyze his sketches and perform all or a substantial amount of the necessary design calculations, does seem reasonable for the near future.

Based upon the first six months work, each group has made an initial formalization of its philosophy in approaching the problem, and these are published in two companion Electronic Systems Laboratory documents (of which this is one):

> "Computer-Aided Design: A Statement of Objectives," D. T. Ross, Technical Memorandum 8436-TM-4, September, 1960

> "Computer-Aided Design Related to the Engineering Design Process," S. A. Coons and R. W. Mann, Technical Memorandum 8436-TM-5, October, 1960

Details of the work conducted under these programs are contained in a series of Interim Reports beginning with 8436-IR-1, covering the period December 1, 1959 to May 30, 1960. Technical reports and memoranda are also issued on specific subjects where appropriate.

John E. Ward
December, 1960

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COMPUTER-AIDED DESIGN RELATED TO THE ENGINEERING DESIGN PROCESS

I. INTRODUCTION

The engineer's role is the creation of systems, devices, or processes sought by society and conducive to its welfare. The process by which these substantial goals of engineering are achieved we call engineering design. The Computer-Aided Design project (CAD) is devoted to reducing the elapsed time and resources expended in completing the design process by enlisting the special powers of modern data processing—prodigious, reliable, accessible storage of information and accurate, incredibly rapid manipulation of data.

In order to discuss effectively the role of the computer as an aid to design, it appears desirable to start by describing the engineering design process.

1.1 The Engineering Design Process

The process may be said to commence with the awareness and expression of some human want or need. Since the human want or need is usually couched in general terms, as a goal, the first obligation of the engineer is to develop more specific, quantitative information which defines the specifications of the task to be accomplished to satisfy the goal. Implicit here would be such matters as defining the scope of the problem, collecting pertinent information, questioning the source of the original request to make certain that the task specifications correspond to the end desired.

Subsequent to task specification is the development of a concept for the solution of the problem. At this stage, broad, qualitative, usually graphically expressed approaches to the problem are evolved.

Having proceeded thus far, we hasten to point out that this necessarily sequential textual description and an associated two-dimensional space characterization of the process is not to be construed as an implication that the goal, the task specification, and the concept always appear in a simple sequential order. In fact, one characteristic of the design process is the seemingly random, unpredictable iterations between the various steps. We can suggest this stochastic character by drawing two-way connections between our various stages (Fig. 1), which implies that task specifications will influence the goal to be sought; concepts developed will, in turn, influence the task specifications; they may, in turn, change the goal; or, having defined a task and developed a concept which

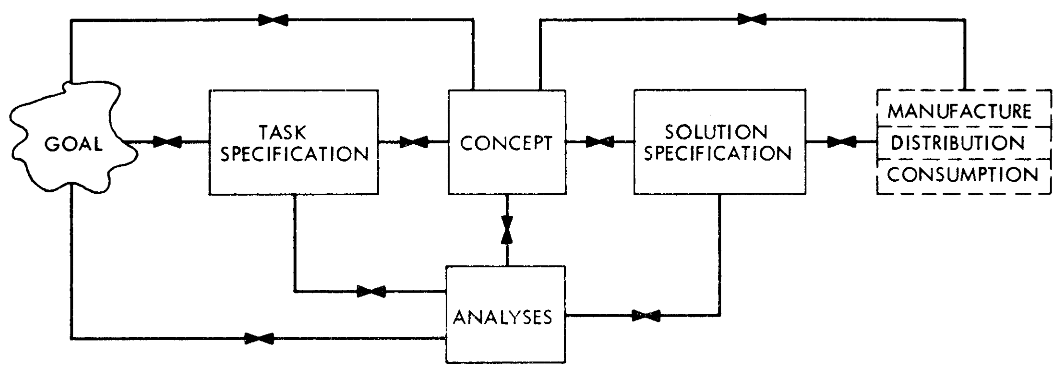

Fig. 1 The Engineering Design Process

might provide a solution to it, one might decide the goal sought is not the proper one and go back to the original statement of the goal and alter it.

The concepts are accompanied, sometimes followed by, sometimes preceded by, acts of evaluation, judgment, and decision making. This process of evaluation is sometimes intuitive and qualitative, but it is often mathematical, quantitative, careful, and precise. We call this phase "critical analysis." The iteration of concept and analysis invariably gives rise to a focusing and sharpening, possibly a complete change of the concept, and so following our two-way connections, we iterate between concept and analysis. Often we go back to task specification to change, in light of analysis conducted, our notion of what <u>can</u> be accomplished or what <u>might</u> be accomplished. We may, as we have seen, go back and change our goal. We may decide that we cannot do what we hoped to accomplish or that we could perhaps do something even more sophisticated or more useful than what we initially proposed.

The iteration of analysis and concept ultimately develops specific information which defines the solution to the problem, and so we have the solution specification flowing out of this interplay. Since techniques of fabrication must influence design, manufacturing considerations will be manifested in the solution and will also influence the conceptual and analytical stages. The substantive goal of any engineering project being a device, system, or process, the solution consists of drawings, specifications, parts lists, manufacturing information, etc.

Beyond the solution specification stage lies manufacture itself, with its vital considerations of volume of production, scheduling, quality control, etc., followed by distribution and consumption. A complete representation of the engineering process includes these latter stages, since they can be pivotally significant in many engineering situations, for example where economy of mass production or ease of maintenance are important considerations.

Having taken this broad look at the engineering design process, it will be to our advantage to scrutinize some of the relationships in more detail. Let us particularly explore the interactions between conceptualization and analysis. We can again resort to a graphical model, Fig. 2. On the left-hand side, as on the right, we have concept. Everything in between represents what we characterize as analysis.

Any physical situation of any degree of complexity cannot be analyzed in its entirety, owing to inadequate knowledge of the relevant

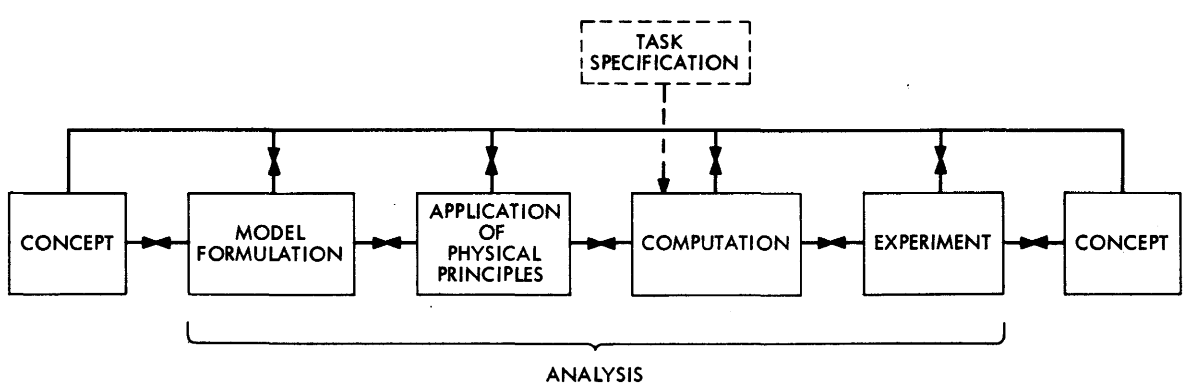

Fig. 2 The Role of Analysis

physical laws or inadequate time or facilities for the required mathematics or a combination of these shortcomings. For this reason, plus its inherent vagueness, the concept cannot be analyzed completely. Instead, one consciously or unconsciously develops simplified models upon which to perform the initial analysis. One then applies well-known principles and laws to describe the model in mathematical equations. The task specifications provide numerical values of parameters and one performs the requisite computational tasks. Since in challenging engineering situations the models on which the analysis is based cannot be confidently assumed to characterize completely all significant attributes of the ultimate physical system, or since in some cases one does not have physical knowledge of certain processes involved adequate to perform analysis, one usually takes recourse to experiment, the final arbiter in any physical study. Having satisfactorily demonstrated the adequacy of the analyzed concept, we have completed the concept-analysis loop.

Now in the same sense that in our initial broader picture there were all sorts of interconnections between the various stages, many and variable interactions exist here. For example, one defines a model based on the concept, recognizing existing physical knowledge about processes and phenomena involved, and anticipating the effort that will be involved in the reduction of the equations obtained to quantitative results. Or, with a critical part, or where one has inadequate physical knowledge, one might minimize computation and move rapidly to experiment, perhaps on an analog or scaled-down version of certain attributes of the concept to be evaluated. Thus, while in the general case the interrelationship of the stages is as indicated, in any particular instance of the design process there is much interaction and iteration between several stages.

1.2 The Hierarchy of Design Problems

This scheme of the engineering design process is quite general and can be applied to a wide variety of engineering situations, simple tasks and complex, small or large, short-range or far-reaching. Again for purposes of discussion and definition, we can tentatively establish a hierarchy of problem situations to which we can apply this scheme.

At one end of the spectrum we have systems engineering where the typical goal is a very broad, general, and ambitious one and the concept is concerned with the interrelationships of a variety of elements or components which, taken together, comprise a system to accomplish the desired goal.

At a different level in the problem hierarchy we can apply the same design process to the creation of a device which might be one component of the over-all system.

And at the detail end of this hierarchy we can apply this same block diagram to the engineering design of a single element of a component.

Let us try to illustrate this hierarchy by concrete examples. If the system is continental air defense, then a component in the system is a computer or radar transmitter-receiver or perhaps the output printer of the computer or the antennas of the radar set. Corresponding elements of these components would be detail parts, chassis, linkages, struts, gears, frames, etc. On the other hand, if the system is a high altitude, supersonic, long-range bomber, then a component might be the engine starter or landing flap, and the corresponding elements might be a turbine shaft, propellant grain breech or bell crank, gear, lock, etc.

Obviously, when one pursues the engineering design process to create one of these several elements, components, or systems, one exercises different phases of the process in different ways and in different degrees, depending on the particular problem at hand.

1.3 The Time-Manpower Evolution of an Engineering Endeavor

Putting aside the diagram of the engineering design process, it is pertinent to discuss at some length the relationship of elapsed time and man hours in the evolution of an engineering design problem. Figure 3 plots elapsed time as the ordinate and effort as the abscissa. Proceeding from left to right in time sequence, we have the various stages in the evolution from inception through realization of the engineering design process. Task specifications and concept and analysis iteration is conducted by one or a few engineers in the early stages to establish the realizability of postulated forms of solution. As the design concept begins to become more specific and to take on more solidity, more and more

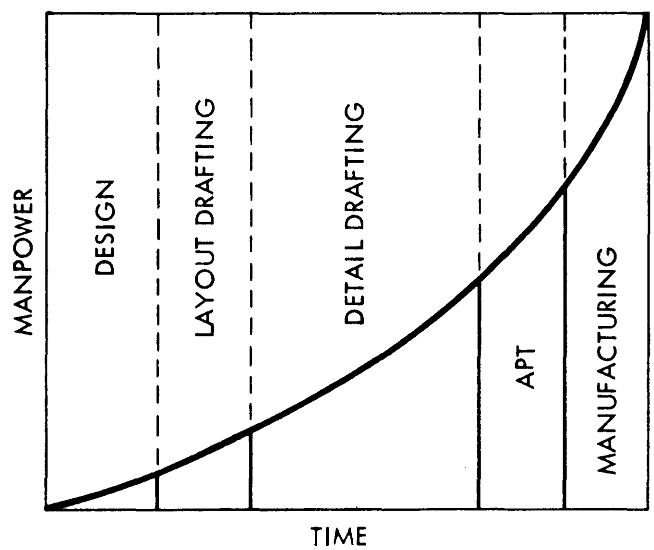

Fig. 3 Manpower Requirements

engineers, technicians, and draftsmen become involved in the project, and the process culminates, crescendo, in the solution specification—manufacturing drawings, manufacturing specifications, parts lists, etc. Where automated manufacturing techniques are warranted, some time is devoted to the transformation of graphic and numeric manufacturing information into a form decipherable by computers and machine tool directors. The APT program has its substantial impact in this area. Ultimately, the physical parts are realized in the manufacturing process.

But the important point is, with our present methods, as we have pointed out, and as the graph indicates qualitatively, more and more people are involved and more and more time elapses as one moves from the initial stage of conceptualization and analysis through the detailed design and fabrication processes to the culmination of an engineering endeavor.

The program we have conducted in the Computer-Aided Design project these past six months is based upon our awareness of and experience with the processes previously described, the engineering design process itself and the time-effort evolution of an engineering project.

II. PROPER AREAS FOR COMPUTER-AIDED DESIGN

When one speculates on the stages in the time-effort, Fig. 3, and considers the intellectual and manual processes at any particular stage according to the morphology of design, Figs. 1 and 2, one encompasses a spectrum which stretches from highly intellectual, creative acts of initial conception and critical analysis to mundane, largely manual, already machine-aided acts of manufacture. In shaping our Computer-Aided Design project we have to make some decisions as to where in this spectrum we will concentrate our effort.

2.1 Design Tests and Creativity

We have studied situations where creative approaches are possible by conducting "design tests" on a number of engineers of demonstrated ability. Their design approaches and subsequent discussion with them illuminates no common structure in the intellectual and decision processes they employed. Their solutions appear to come about as a result of stochastic free association of a wealth of simple concepts, evaluations, and judgments, and evaluations and judgments about evaluations and judgments. When, on the basis of direct experience, we extrapolate these findings to significant real investigations at, say, the systems or challenging component levels, where truly original work is necessary, we are at present unable to define any design methodology which has itself a structure susceptible of total mechanization. Furthermore, in actual problems, as suggested by Fig. 3, a very few very talented people make their contribution here, absorbing only a relatively small fraction of the total effort or elapsed time. Thus the creative end of the problem spectrum is not interesting from an economic or strategic point of view and is not assailable from the point of view of present knowledge.

While we have a pedagogic and scientific interest in the scrutiny of creative design and while we have devoted, and will continue to devote some of our effort to this study, we are convinced that the immediate, strategically significant area of computer-aided design is centered on those aspects of the design process which engineers know enough about to augment by means of the computer and which represent the predominant portion of the time and effort expended in an engineering endeavor.

2.2 Detail or Element Design

The design of elements of components of systems is such an area. We believe it to be the stage of the design process most conducive to machine assistance. To begin with, in most engineering projects, by far the greater portion of total manpower is involved in this stage, and the time lapsed in accomplishing this function is the major part of the total time from initial concept to realization. And secondly our current understanding of this portion of the design process suggests elements of generality which should be reducible to techniques applicable to machine computation and machine data processing.

The plausibility of devoting one's primary attention to design of elements is made even more apparent by reflecting upon the historical intrusion of machine-automated techniques into engineering design and manufacture. First we have the development of numerically controlled machines which make it possible to eliminate the set-up time and skills and the sustained surveillance of the machinist. Then the problem of converting information from the graphic numeric data of the manufacturing drawing and specification into a form digestible by the automated machine gave rise to such schemes as APT. We are in effect now concerned with the next move upstream against time in the engineering design and manufacture process.

2.3 Computer-Aided Design Activities

Having defined the sphere of primary activity in the Computer-Aided Design project we can now draw upon our morphology of the engineering design process, Figs. 1 and 2, to abstract those activities whose sufficient generality adapts them to machine-aided design. Applied to the detailed design of elements, the generalized stages might take the following specific forms. Consider as the goal the design of a bell crank for a wing flap linkage for a supersonic bomber. The bell crank must withstand certain predictable forces and torques and satisfy a certain mechanical advantage; it must move in relationship with other existing or to-be-designed parts; it must be related for support purposes to the main structure of the wing. Its weight must be minimized; its design should permit the simplest manufacturing techniques; it will probably involve the incorporation of some standard parts, ball bearings, fasteners, snap-rings, etc. These constitute the task specifications. The concept takes the form of a graphical sketch of a shape of the part in one or several views, as many as are necessary to describe adequately its physical form. Since the element must stand certain applied forces and torques, which give rise to time-varying combined stresses within prescribed margins of safety and with certain allowable deflections, the engineer-designer must apply the techniques of stress analysis. To conduct this study the engineer must reduce his complex graphical concept to models amenable to analysis, making appropriate simplifications where necessary or desirable. Appropriate physical equations are written for the model and numerical calculations carried out using data on the material to be used. He thus determines the deflections, stresses, etc., and revises his geometric design accordingly, iterating between geometry and stress analysis in order to establish, for example, an optimum or minimum weight for the part.

As the geometrical conception and stress analysis of the part proceeds, the incorporation of standard parts must be considered. The bell crank may rotate on a standard ball-bearing and it may accommodate standard fasteners and control cables. The geometry of the link must be such as to accommodate those fasteners and bearings which are themselves adequate to the applied forces and duty cycles. For such standard parts geometric information and theoretical and empirical data on operating characteristics exist. The designer must relate these data to the performance requirements and the evolving geometrical design and may have to proceed through several iterations of standard part choices. Ultimately, the geometrical restraints on the element and related parts are satisfied, stress considerations are satisfied, and standard parts to be incorporated are chosen. The results culminate in a manufacturing drawing of this element and whatever specifications are necessary for its manufacture and test.

III. PRIMARY AREAS OF CURRENT INVESTIGATION

Insights drawn from this scrutiny of the detail design process provide the basis for the primary areas of current investigation under the Computer-Aided Design project. These are:

1. A graphical input device and associated programming so as to enable the designer to introduce a geometrical shape description into the computer memory and process this data for ultimate use in manufacture;

2. A graphical output device (oscilloscipe, pantograph, etc.) to permit the designer to query the computer about the state of graphical information content;

3. A symbolic input device, perhaps a typewriter keyboard, by means of which both verbal and numerical inputs of data and instructions can be introduced;

4. Symbolic output devices, perhaps a printer, for program diagnosis, replies to queries from the designer, and publication of results of computations; signal lights to indicate the state of the computer;

5. A translating system for converting designer's language to machine language and the converse;

6. A shape description memory system;

7. A shape description computation system, consisting of a library of geometrical programs for computation, largely automatically selected and initiated by the geometrical inputs from the graphical and symbolic input devices.

8. Programs for strength of materials calculations, to be selected and initiated by the designer, with parameters introduced both externally and by interconnections with the shape memory when needed;

9. A catalog of standard parts, including descriptive specifications, strength data, and duty cycle data; this memory system to be accessible through the symbolic input system.

The first Interim Report 8436-IR-1, outlines in some detail our present course of action in these areas. One chapter discusses several possible approaches to the problem of graphical input-output equipment.

In the category of information storage and retrieval, other chapters discuss (1) the standard parts selection problem and (2) stress analysis problem in which is explored two possible approaches, one based on the existing fund of analytic and experimental formulae describing the performance of relatively simple geometries and the second a scheme where possibly the speed of the computer could be enlisted to generalize somewhat the stress analysis problem.

Although under stress analysis we concentrate on that body of scientific knowledge characterized by applied and solid mechanics, the techniques for computer handling of these physical laws ought to be equally applicable in other fields of engineering science, to wit, fluid mechanics, thermodynamics, thus the study of stress analysis ought to be generalizable to design problems which involve these other engineering fields.

Finally, since the realization of some of these concepts of graphical storage and manipulation and information storage and retrieval make ever increasing demands upon the storage capability of the computer we are endeavoring to devise schemes to organize data stored in the computer so as to reduce the memory capacity necessary. A chapter in the report discusses a possible arithmetic, algebraic manipulative scheme.

IV. SUMMARY

By way of summary then, we have endeavored to define the engineering design process and to describe the progression of an engineering project from initial conception to realization, commenting on the time lapse and ever-increasing manpower involved, and have used both these examples to define the area of the design process in which we feel activity can be most profitably concentrated.

We will not study the more prosaic element design field to the complete exclusion of continued interest and scrutiny of the over-all design process. But whatever may evolve from long-range investigation of the rationale of creative design, the facilities of graphical communication and information storage and retrieval now under study are certainly sufficiently general as to be relevant to broad as well as the more restricted design situations and will, in fact, be essential to a computer-aided design facility of any magnitude.

Finally we tend always to move from the known into the unknown and as we move from the present design practices to their automation, by data-processing techniques, we are on safer and more productive ground exercising first our automation of those processes which we understand relatively well. We use this as experience in preparation for venturing into the design process for which we and others have as yet no satisfactory conceptual model.

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5001 KEARNEY VILLA ROAD
SAN DIEGO 11 CALIF

CONVAIR DIV GEN DYN CORP
ATTN THOM E PIPER EXEC STF
ASST GENERAL OFFICE
SAN DIEGO 12 CALIFORNIA

CONVAIR PL 1
DIV OF GEN DYN CORP
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SAN DIEGO CALIF

CONVAIR DIV OF GEN DYN CORP
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DEPT 6-1
AEROPHYSICS COMP LAB
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3855 LAKEWOOD BLVD
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LONG BEACH CALIF

DOUGLAS AIRCRAFT COMPANY
C.C. NANCE, A2-260 COMPUTING
3000 OCEAN PARK BLVD.
SANTA MONICA, CALIFORNIA

DOUGLAS AIRCRAFT CO
MR JOSEPH P IVASKA A260
MISSILES ENG DEPT
3000 OCEAN PARK BLVD
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DOUGLAS AIRCRAFT CO INC
ATTN N H SHAPPELL WORKS MGR
SANTA MONICA DIV
SANTA MONICA CALIF

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IND SALES DIV
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30 ROCKEFELLER PLAZA
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DIR COMPUTING CTR
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CINCINNATI 15 OHIO

GENERAL ELECTRIC CO
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CINCINNATI 15 OHIO

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MGR ROOM 6472
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PHILADELPHIA 4 PA

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3628 W PIERCE ST
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FOND DU LAC WISC

GLENN L MARTIN CO INC
ATTN VINCE M WERBACH A-66
P O BOX 179
DENVER COLORADO

GLEN L MARTIN CO INC
ATTN R A BENNETT
P O BOX 179
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ATTN G BENDER
SR MFG ENGR
MAIL 666
BALTIMORE 3 MD

GOODYEAR AIRCRAFT CORP
ATTN R C ABBOTT
ERUIPMENT ENGINEER
1210 MASSILLON
AKRON 15 OHIO

GOODYEAR AIRCRAFT CORP
ATTN A D SHAPR
MGR ENG EQUIP & SERV
AKRON OHIO

GOODYEAR AIRCRAFT CORP
ATTN S F TINGLEY
COMPUTING LAB
PLANT C
AKRON 15 OHIO

GRUMMAN AIRCRAFT ENG CORP
ATTN G D FOGEL
AUTOMATIC COMPUTING GRP
PLANT 5
BETHPAGE NEW YORK

GRUMMAN AIRCRAFT ENG CORP
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V P OF MFG
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GRUMMAN AIRCRAFT ENG CORP
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HILLER HELICOPTER
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CHIEF TOOL ENG
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1707 CLOVERFIELD BLVD
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DIR DIGITAL SYSTEMS GROUP
CAMBRIDGE MASS

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1933 W WISCONSIN AVE
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BLDG 63-1
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LOCKHEED AIRCRAFT CORP
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7701 WOODLEY AVE
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MARQUARDT AIRCRAFT CO
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DEPT 3140
1000 W 33RD ST
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BOX 670
OGDEN UTAH

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MFG ENGINEER
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T6032 DIGITAL UNIT
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805 SO FERNANDO BLVD
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315 FOURTH AVE
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STAFF DIR IND ENG
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CLEVELAND 7 OHIO

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DIR OF RSCH & DEVELOPMENT
5701 CARNEGIE AVE
CLEVELAND 3 OHIO

Reports Published on this Project

"Papers on the APT Language," Douglas T. Ross and Clarence G. Feldmann, Technical Memorandum 8436-TM-1, Electronic Systems Laboratory, June 1960.

"Method for Computer Visualization," Albert F. Smith, Technical Memorandum 8436-TM-2, Electronic Systems Laboratory, September 1960.

"A Digital Computer Representation of the Linear, Constant-Parameter Electric Network," Charles Shelly Meyer, Technical Memorandum 8436-TM-3, Electronic Systems Laboratory, August 1960.

"Computer-Aided Design: A Statement of Objectives," Douglas T. Ross, Technical Memorandum 8436-TM-4, Electronic Systems Laboratory, September 1960.

"Computer-Aided Design Related to the Engineering Design Process," S. A. Coons and R. S. Mann, Technical Memorandum 8436-TM-5, Electronic Systems Laboratory, October 1960.

"Investigations in Computer-Aided Design," Project Staff, Interim Report 8436-IR-1 for period December 1, 1960 to May 30, 1960.

"Automatic Feedrate Setting in Numerically Controlled Contour Milling," J. D. Welch, Report 8436-R-1, Electronic Systems Laboratory, December 1960.

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Electronic Systems Laboratory
Massachusetts Institute of Technology
Cambridge 39, Massachusetts
COMPUTER-AIDED DESIGN RELATED TO THE ENGINEERING DESIGN PROCESS by S. A. Coons and R. W. Mann, dated October 1960. 13 pages including illustrations and references. Technical Memorandum 8436-TM-5. Contract AF-33(600)-40604. (Unclassified Report)

The objective of the Computer-Aided Design Project is to evolve a man-machine system which will permit the human designer and the computer to work together on creative design problems. This document states the philosophy of approach of the design and graphics group of the project. A companion document, 8436-TM-4, states the philosophy of the computer applications group.

The engineering design process is viewed as a stochastic iterative process in which a recognized human need leads to a preliminary tentative concept of a means for its achievement; subsequent analysis, evolution, and judgement leads to modification of the concept and even possibly

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to a modification of the original goal, until certain standards are met and the need is satisfied.

The manpower-time requirements for proceeding from the original design concept to its realization in a manufactured part, device, or system is investigated with a view to determining where best to begin consideration of computer aids in the sequence. In general, the conclusion is drawn that for the present the computer can be most effective in replacing man-power in routine drafting, minor design decisions, engineering computation occurring in analyses, (particularly stress computations) and as an aid in the selection of standard parts.

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