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The report summarizes the results of a number of studies which have been performed in an attempt to develop a technology for using human resources data as criteria in engineering design studies. Eight investigations conducted during the period 1966-1975 are briefly described. The results of the eight studies are integrated around six topics of: feasibility and practicality of using human resources data as criteria in engineering design, methods for using the data in design studies, effect on the system of using the data as design criteria, types of human resources data most relevant for use as design criteria, methods for generating human resources data for use in design studies, and nature of the engineering design process. A 15-item bibliography is appended. (Author/BP)

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HUMAN RESOURCES AS ENGINEERING DESIGN CRITERIA

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March 1976

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Summarizes the results of a number of studies which have been performed in an attempt to develop a technology for using human resources data as criteria in engineering design studies. Eight investigations conducted during the period 1966 1975 are briefly described The results of the eight studies are integrated around six topics of feasibility and practicality of using human resources data as criteria in engineering design, methods for using the data in design studies, effect on the system of using the data as design criteria, types of human resources data most relevant for use as design criteria, methods for generating human resouces data for use in design studies, and nature of the engineering design process

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PREFACE

This report is a professional paper presented in the symposium entitled, "Human Resources and Engineering Design Criteria," which was chaired by Dr Harry L. Snyder, Chairman for Division 21, The Society of Engineering Psychologists, of the American Psychological Association The symposium was conducted during the 83rd Annual Convention, Chicago, Illinois, 30 August - 3 September 1975. Preparation of the paper was supported by the Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson AFB, Ohio This support was provided under Project 1124, Human Resources in Aerospace Development and Operations

TABLE OF CONTENTS

HUMAN RESOURCES AS ENGINEERING DESIGN CRITERIA

I. INTRODUCTION

The development of the human skills required to utilize the machines produced by man has been a problem throughout the history of technology. As long as technology was changing slowly, the problem was not serious. With the shift from craft experience to science as the basis for technology, the problem of matching skills required with skills available became significant (Singer, Holmyard, Hall, & Williams, 1958).

Reaction, Prediction, and Control

The importance of this problem has been recognized by the military services. Eckstrand, Askren, and Snyder (1967) traced the history of planning for human resources with respect to military weapon systems. Originally, skilled manpower for military systems were provided after the hardware was delivered to the military unit. Personnel selection and training was accomplished as a form of *reaction* to the demands of the equipment. Currently (1967, and still true in 1975) human resources planning is characterized by analyses which *predict* manpower needs early during system development. This early prediction allows the selection of personnel, and the planning for training to begin before the hardware is delivered to the operational unit.

Eckstrand et al. (1967), then postulated that the next phase of human resources planning will be a *controlling* or a *design interaction* phase, in which data on personnel and training factors will become design criteria, and influence the characteristics of the hardware of new systems. This new phase will follow, partly because control tends to follow prediction in science, and partly because of the need to restrain or reduce the rapidly increasing dollar costs of the human side of military systems.

Purpose of this Paper

This paper summarizes the results of a number of studies, by the author and his colleagues, which have been an attempt to develop a technology which could implement the design interaction phase of human resources planning. Eight studies are briefly described. The results are integrated to provide the beginning of a methodology for using human resources data as criteria in engineering design.

This work is part of a larger effort by the Air Force to develop methods, models, and data for using human resources and personnel cost factors in the development cycle of new systems. Examples of other efforts in this general area include studies by Lintz, Loy, Hopper, and Potempa (1973), and Maher and York (1974). Askren and Lintz (1975), and Potempa, Lintz, and Luckew (1975) also touch on the broader issue.

II. THE EIGHT STUDIES

Conceptualization of the design interaction phase began in 1966. The objectives and the first efforts at defining the elements of the problem were reported in Eckstrand et al. (1967). The first experimental study was performed shortly thereafter (Meister, Sullivan, & Askren, 1968).

First Study

The purpose of the first study was to determine the effect on system design of using manpower data as design constraints. A secondary objective was to determine under what conditions and in what form these data should be used to have maximum effect on design. Equipment data, manpower quantity and skill level data, and task information data which were produced during development of a ballistic missile subsystem were presented to six experienced design engineers. They were instructed to "design" the subsystem. The engineers were required to create schematics, equipment descriptions and drawings, control panel layouts, operation procedures, and bills of material.

It was found that manpower quantity and personnel skill level constraint data impact the equipment configuration. The engineers were responsive primarily to the inputs that were framed as design requirements The results also indicate that if manpower and task data are to be incorporated into design, it is necessary to supply these inputs to the engineer as design requirements in his initial statement of work.

Second Study

The second study (Meister, Sullivan, Finley, & Askren, 1969a) was a further test of the effect on design of using manpower quantity and skill level data as design constraints. The study investigated whether the amount of data given to the engineer, and the timing of the data influenced design. Equipment and human resources data relevant to the development of the maintenance equipment of an air-to-ground missile were presented to eight experienced design engineers. The subjects were required to develop a conceptual design of the equipment. The experiment contrasted the simultaneous presentation of all human resources data inputs at the start of design with the same inputs presented incrementally throughout design. The investigation also contrasted manpower quantity constraints with skill level constraints.

It was found that the amount and timing of human resources data inputs do exercise some influence on the engineers' design The type of requirement imposed (skill level versus quantity constraints) made a difference to the engineers. Although the inputs are responded to by engineers primarily when those inputs are phrased as design requirements, informational data (task and time-line analyses) created an attitude of awareness in the engineers of personnel requirements. The engineers developed their designs quickly and resisted attempts to modify their designs. The results indicated, again, that if human resources data are to be incorporated in design, the data must be supplied at the start of design, and they must be phrased as design constraints.

Third Study

The third study (Meister, Sullivan, Finley, & Askren, 1969b) was conducted to investigate the design engineer's concept of the relationship between system characteristics and personnel skill. This was undertaken because the earlier studies had shown that personnel skill was a potentially powerful design constraint, yet engineers had little knowledge of the nature of skill, or how it should be translated into hardware characteristics. Fourteen paper and pencil tests, specifically developed to examine the relationships between skill and design, were administered to eight experienced design engineers.

It was found that certain design characteristics are significantly related to skill level. These are test points, internal components, checkout and troubleshooting procedures, type of test equipment required, and go/no go displays Individual design concepts such as *component repair* are related to the amount of training required. It was also found that engineers conceptualize maintenance skill in terms of knowledge, troubleshooting ability, and flexibility. A common denominator of the skill parameters appears to be troubleshooting ability Skill level appears not to be related, in the engineer's mind, to years of experience.

Transition

At this point it seemed as though enough research data were available to justify the recommendation that personnel quantity and skill level requirements be imposed on the engineer as a design goal. However, further analysis revealed a number of reasons why this approach would probably not be used. A major reason was the resistance by engineers and managers to the concept of manpower as a design goal. Manpower as a tiebreaker when all engineering factors are equal, yes, but manpower as a dominant design goal, no Another reason was technical. It was found that in order to impose this type of design constrain it would be necessary to predict the nature of the military work force which would be available at a da some 5 to 10 years in the future. No capability existed to make such predictions. Therefore, consideri these kinds of reasons it had to be concluded that it was not feasible to impose personnel factors as desig constraints

A new entry point to engineering design was required. Further investigations of the design process established that trade off studies were a significant part of design. The appealing part of trade off studies seemed to be that they could accept personnel and training data which compared the relative effect of several design alternatives, as opposed to requiring absolute statements about manpower design goals for a single design Design trade off studies appeared to be a good entry point for human resources data.

8

Fourth Study

The fourth study (Lintz, Askren, & Lott, 1971) investigated the engineering design trade study process to determine the feasibility of including human resources data in trade studies. This research also attempted to learn something about how engineers perform design trade studies. Sixty-one completed trade studies from actual aeronautical, missile, and command and control systems were analyzed to determine the characteristics of system design trade studies. Four simulated aircraft trade studies, containing engineering and human resources data, were constructed for experimental use. Seventy-two experienced design engineers performed the simulated trade studies.

It was found that engineers can and do use human resources data in system design trade studies. Personnel costs and manpower quantities were assigned more weight in the trade studies than skill types, skill levels, and availability of personnel. A detailed presentation of human resources data is given more weight than a condensed presentation. Human resources data should be presented to the engineer in quantitative units familiar to the engineer to be most useful. The four major sources of variability in trade study results were found to be choice of evaluation parameters, value weights for the parameters, methods of normalizing the parametric data, and methods of combining parametric data and weighting factors.

Formal Trade Study Limitation

While conducting the fourth study it was learned that only a small portion of design trade offs are made public via formal, documented trade studies. The high percentage of trade offs are informal comparisons of alternatives, and are not documented, except possibly in notes by the engineer for his own use. Consequently, the engineering psychologist is not likely to be aware of many of the design trade offs that are performed. Realizing the potential value of the design trade off as an input point for human resources data, an attempt was made to develop a method to identify, in advance, the numerous trade offs that would be made during design of a product. Such a method would enable the engineering psychologist to anticipate design trade offs, and to arrange for inclusion of human data in the more critical ones.

Fifth Study

The fifth study (Askren & Korkan, 1971, Askren & Korkan, 1974) was performed in response to this need. The result was development of the design option decision tree (DODT) method. The DODT is a graphic means of depicting the sequence of engineering decisions required for resolution of a design problem. The DODT also describes the design options available at each decision point.

In this study, the DODT concept was tested on aircraft propulsion and flight control subsystems. The resulting DODTs were evaluated by eight engineers experienced in designing these specialized areas of aerospace systems. It was found that the DODT is a feasible and valid method for anticipating and describing system design trade offs.

Sixth Study

The sixth study (Askren, Korkan & Watts, 1973) was conducted to explore the feasibility of developing design option decision trees to a level of detail which shows hardware involved in maintenance operations, and to measure the sensitivity of different types of human resources data to different design trade off problems depicted in these trees. This study also tested the feasibility of using psychometric scaling methods as a means of generating the data, which describe the impact of trade off alternatives on the human resource factors.

The approach included expanding a portion of the DODT developed for the aircraft jet engine in the fifth study, selecting trade off problems from the expanded tree for sensitivity analysis, and collecting psychometric data from experienced jet engine mechanics regarding this sensitivity. It was found that DODTs can be developed to the maintenance level of detail. It was also found that the factors of training and experience, amount of maintenance time, and ease of maintenance were most effected by choice of design options in the trade off problems. Complexity of tools, crew size, and job specialty were effected less. It was also found to be feasible to use experienced maintenance technicians as raters to make evaluations of the impact of design alternatives on the human resources factors.

Seventh Study

The seventh study (Askren, 1973) was conducted to determine the capability of engineering psychologists to respond in a timely manner and with realistic data to an actual design trade off problem. This study also explored further the use of psychometric scaling techniques as a means for generating the data which measure the effect of design alternatives on human resources.

The trade off problem concerned the selection of an electrical unit for a new aircraft undergoing development. Three design alternatives were evaluated as to impact on the number and kind of maintenance personnel required to inspect and repair the electrical unit, type and amount of training for these personnel, the time required to perform the maintenance work, and the dollar cost to provide these personnel for the life of the system. The data describing the impact of the three design alternatives upon the human resource factors were collected from experienced aircraft maintenance technicians using psychometric scaling techniques.

It was found that these types of human resources data could be generated for the three design alternatives in a timely fashion for engineering use. It was also found, again, that it is feasible to use experienced maintenance personnel as raters to make judgments about the impact of design alternatives on human resource factors. In addition, further developments were made in the psychometric procedures needed to collect the data.

Eighth Study

The eighth study (Whalen & Askren, 1974) was undertaken to accomplish two objectives. The first objective was to identify and classify the characteristics of conceptual design trade studies that have high potential impact on human resource requirements of Air Force weapon systems. The approach used was a case history review and analysis of 129 aircraft design trade studies. The analysis indicated that the avionics system has the greatest potential impact on human resources. It was also found that trade studies dealing with design alternatives that encompass widely different technologies have substantial impact on human resources. The types of human resources data (HRD) most influenced by alternative design options were maintenance task times and personnel costs. The second study objective was to determine the accuracy of using subjective estimates as a technique for deriving the HRD impact of trade study options. Using only engineering information for six avionics subsystems, from the conceptual design phase, Air Force maintenance technicians made subjective estimates of the impact of the designs on selected HRD items. It was found that technicians can make reasonably accurate estimates of the amount of time, the Air Force occupational specialty, the level of technical skill and the number of personnel needed to perform field maintenance tasks.

III. INTEGRATION OF RESULTS AND CONCLUSIONS

The findings from the research reported above are organized around six topics: feasibility and practicality of using human resources data as criteria in engineering design; methods for using the data in design studies; effect on the system of using the data as design criteria; types of human resources data most relevant to use as design criteria; methods for generating human resources data for use in design studies; and nature of the engineering design process. These integrated results are given in the following sections.

Feasibility of Human Resources Data as Design Criteria

The overriding finding throughout all of the research has been the feasibility and practicality of using human resources data as criteria in engineering design studies. Quantification of the data is possible. Engineers accept the data. Input points to the design process are available. And the quality of the human data is often as good as the quality of the engineering data, especially in early conceptual design studies.

Methods for Using Human Resources Data in Design Studies

Human resources data may be incorporated in the design process by at least two means: as design constraints, and as decision parameters in design trade offs. The trade off use of human resources data has

10

the greatest probability of successful application at this time. In the future, given better techniques for predicting the nature of manpower forces to be available, the design constraint method could be a powerful means of influencing the characteristics of equipment.

Effect on the System of Human Resources as Design Criteria

Based on the studies reported above, it is anticipated that the effect of human resources design criteria on the system would range from moderate for a large per cent of design studies in which the data are used, to great effect in a small per cent of design studies. As found in the fourth study, it is probable that human resource criteria data will have their greatest effect when acting in combination with other engineering and operational requirements data, rather than as a single controlling factor.

Types of Human Resources Data Relevant to Design Studies

A wide variety of human resources data were found to be useful as criteria in design studies. This included such factors as manpower quantity, technician skill level, technician job specialty, personnel dollar cost, type and amount of training, task performance time, job difficulty, and personnel turnover rate. The sixth study found that the type of data relevant to a particular design problem is a function of the nature of the design problem. All human resources data do not apply to all design studies. It is critical to provide the engineer with data that is most relevant.

Methods for Generating Human Resources Criteria Data

Three methods for generating human resources data for use as criteria in design studies were examined during the course of the research. These methods were. (a) mathematical and computer simulation models which predict the effect of design on human resources, (b) historical, documented data which show relations between design characteristics and human resources, and (c) the use of psychometric scaling techniques and subject matter experts to give ratings of the impact of designs on the human resource factors. When consideration was given to the use of data during early, conceptual design studies, generation of the data on a timely basis, and low cost in developing the data, the psychometric scaling technique was selected for more intensive investigation. This was found to be a viable method. Three studies attest to its feasibility and validity. It was found that the judges respond to the rating task in a serious manner, that they are able to make judgments for a wide spectrum of human resource factors, and the validity of their ratings appears adequate for use in design studies.

Nature of the Engineering Design Process

Two views of the design process have emerged from this research. One view describes design as an artistic rendering, in which the engineer receives a design problem, acknowledges constraints, and then, drawing on his own personal experiences, works very quickly to develop a concept. The other view describes design as a human decision process in which the engineer methodically makes a series of design choices. He follows a path from design problem to design product. Along the path he makes judgments about the characteristics of the product he is designing. Many times he will face choice points with options to choose between.

Which process will a given engineer follow for a given design problem? The answer seems dependent on a number of factors such as the training of the engineer, his personal style, the nature of the design problem, time available to complete the design task, and company and management design philosophy. It is hoped to address this question in future research.

Conclusions

It is feasible to include human resources data as criteria in engineering design, and it is expected that the data will affect the design product. Human resources data may be incorporated in the design process as constraints, or as decision parameters in trade offs. The trade off method is preferred at this time. The trade offs to be performed during the design of a new system can be anticipated, using the design option decision tree method, and the more critical trade offs identified. A variety of human resources data are useful in design studies, with the nature of the design problem dictating the particular data. Valid data can be generated in a timely manner using psychometric scaling techniques and judgments of subject matter experts. The engineering design process itself is amenable to study, with beneficial results to both improved use of human data and greater knowledge of the nature of design.

What next for this area of research? The need is for an effort which puts all the findings together into a single technological package, followed by a demonstration of their practicality, acceptability and value in an ongoing engineering design program. It is hoped to perform such a test in the near future.

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