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ENGINE COMPONENT SIMPLICITY RATING

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ABSTRACT

This research report is the result of a NASA contract with the University of Alabama for a study to develop a system of Simplicity Ratings of components of rocket engines for the propulsion of space vehicles. In the award of this contract, the proposition was adopted, at least tacitly, that what is simpler is better.

There is included discussion of different facets of design simplicity, variations of the basic proposition, and ways to achieve less complex designs. One objective in the writing of the report is to give engineering supervisors confidence in deciding to adopt the system. The other goal is to aid working designers in making practical use of it in their daily work. For this latter purpose a chapter has been prepared in such a way that it may be made into a separate reprint to be used by each man as a text and a handbook. There is also provided an instructor's guide, (as an appendix), which should be of value at the time when the simplicity method is first being introduced, or when new employees are inducted.

Simplicity Engineering may be introduced as a valuable subdiscipline, or branch of engineering, and certain personnel assigned to see that it is kept in operation. In cases where it is desired to avoid changes in the organizational structure, as where a Value Analysis Division already exists, the methods and concepts of Simplicity Engineering may still be adopted as important auxilliary tools.

PREFACE

This is the report of a research project (known as NAS8-5262), done for the Propulsion and Vehicle Engineering Division of the National Aeronautics and Space Administration, George C. Marshall Space Flight Center. The liason between the University of Alabama and the Flight Center was assigned to Mr. R.G. Edwards, a Technical Supervisor. The complete title of the project is, "A Study to Establish a System for Rating Vehicle Propulsion Component Elements As To Absolute or Relative Simplicity."

The contract was dated March 30, 1963, and Professor S. K. Stimson, of the Mechanical Engineering Department of the University of Alabama was the first Project Director. Because of the difficulty of recruiting competent technical assistants, the work did not actually get started until June, 1963.

During the summer of 1963, Professor Stimson, assisted by three mechanical engineering graduate students made a search for books or articles dealing with simplicity, but they found very few references and most of those not really pertinent to the question of simplicity in manufactured parts. They also conducted seminars or brainstorming sessions on the topic, some of which were taped and transcribed. By September they had concluded that it might be fruitful to explore the possibility of rating components according to the costs of making them, in other words using the dollar as a common denominator.

Therefore, Professor Wyllys G. Stanton, of the Department of Industrial Engineering was invited to join the project as a Research Associate. In order to allow him to do so his department granted him released time from his teaching duties during the fall semester starting in September 1963 to the extent of one half of the hours normally devoted to classes. The role assigned to Professor Stanton was to prepare "synthetic time studies" and "route sheets" for the manufacture of engine components. To assist in this work the services of Professor Joe Newman, who teaches machine shop practice in the Industrial Engineering Department, were recruited.

During the next few months strenuous efforts were made, using the drawings of actual components of rocket engines, to determine their probable costs of manufacture. It was impossible to obtain the actual shop cost data from the civilian contractors who had made some of the parts because this is proprietary, competitive data, usually available only in "re-negotiation" cases in Defense Procurement and probably in NASA procurement also. The difficulty of finding the costs de novo was that there was no information, except speculation as to what machines and skills might be available in any particular shop undertaking to make the parts.

The one-year contract between NASA and the University of Alabama, expired at the end of March 1964. In the meantime, it had become apparent that there were more questions of an Industrial Engineering nature than those stemming from the Mechanical Engineering considerations.

On the recommendation of Professor Stimson, Project Director, Professor Stanton was named the new project director and the contract was extended until March 30, 1965. No additional funds were requested for this renewal. Professor Stimson thereafter continued from time to time as a Research Associate. Professor Stanton then encountered the same trouble that had been experienced by Professor Stimson in finding capable assistants, for the study.

Upon further examination of the records of the project and discussions with Mr. Edwards, at NASA, it became evident that a factor analysis approach was the only feasible way of achieving the desired rating system. Therefore the dollar approach was discontinued and work concentrated upon the factor analysis method . W ith this new viewpoint a further detailed analysis of the literature was undertaken because the original group of graduate students in Mechanical Engineering who had looked for material bearing upon simplicity ratins, had not been aware of the possibilities that might exist in an interdisciplinary approach.

During the course of the investigation it was inevitable that value analysis engineering would come to the fore as a possible method of rating. This possibility has been explored in some detail and the results of this examination reported. It happens that value analysis is very valuable for commercial companies, but it does not have equal application for a government organization such as NASA or for the military branches. Because of the fact that value analysis is widely used by companies contracting to do government work, and because Simplicity Engineering did not become available until the present time, many government establishments have value analysis divisions in their organization structures.

Simplicity Engineering is a technique developed by this writer as a superior means of obtaining the goals sought thru value analysis, with a number of advantages. One of these is that it is a system independent of price levels and inflation, another is that it can be applied prior to the making of a part, whereas value analysis is usually a post hoc procedure. This new technique may be adopted and organized as a structural element where the situation warrants, or it may be used by an existing value analysis division as another tool or method.

As in every case of writing a report,book, or article which draws upon information obtained from other persons, the writer is solely responsible for any misinterpretations, inadvertent misrepresentations, or other errors in reporting.

The writer wishes to express his deeply felt gratitude to all who participated in one way or another, and in varying degrees. For, without their help the work would have been impossible. Individual credits are not stated because of numbers.

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"The antiseptic presentation of fundamental theory in contemporary textbooks, where all of the rough edges have been trimmed away, too often yields a specious and deadening pseudo-clarity."

Max Black

CHAPTER I

INTRODUCTION

"The same problem assumes different facets of emphasis in different environments."

Wyllys G. Stanton

Attention will be concentrated in this report on the special problems associated with designing space vehicle hardware with particular emphasis on Rocket Engine Components. However, it will be evident to any readers except those with the narrowest possible viewpoints, that the rating system developed in this study has possibilities of application in many other fields of mechanical design. Also some of the points made can well be used in other fields, such as the design of systems of organization.

Therefore this is a report upon a study of possible methods of rating the simplicity of components entering into the construction and operation of propulsion systems for space vehicles. After consideration of a number of possible systems of rating, definite recommendations are made for a workable plan by which actual elements of engines may be rated according to their relative or absolute simplicity. Although this research was done specifically for, and under the aegis of the National Space and Aeronautics Administration, the results are applicable in all situations requiring the design of mechanical components for machinery or other systems. Moreover, the principles developed primarily for mechanical components will have wide application in all fields of design.

Typical Special Problems

Reliability of Components

The first of these special problems is no doubt the extreme reliability of components that is necessary. In this context reliability is used with the meaning that each component must perform its intended function without the least possibility of delay, partial performance, or other malfunction. All who have followed the news reports of space vehicle launchings realize that there have been instances in which missions have been aborted or millions of dollars worth of spacecraft and supporting efforts have been wasted because of the failure of some relatively insignificant component such as a valve or relay. What might be only a minor annoyance in the operation of an automobile, such as the engine refusing to run because a wire has broken off at the point of entry to the distributor contacts or the ignition coil can be a major catastrophe in the work of space exploration.

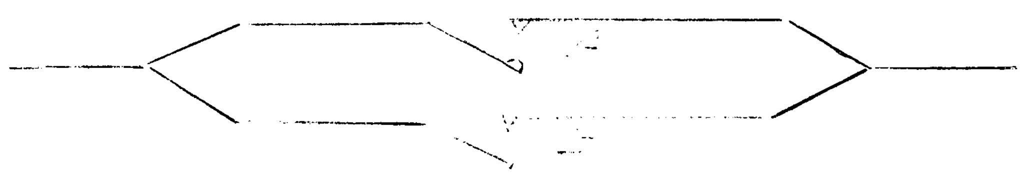
Weight Limitations

Another very important difference is that designers of space vehicle components must work under severe weight limitations. One generally used source to cope with reliability problems is redundancy, this is the duplication of a critical part so that the probability of successful function of a system which has a .9 probability of successful function becomes .99 when the element is duplicated. This system was used extensively on piston type aircraft engines in the provision of duplicate ignition systems with the bonus that the functioning of either of the ignition systems would cause the engine to continue to operate but the functioning of both of them simultaneously produced better performance characteristics.

Reliability by Redundancy

Paid for in Weight Costs

Two Relays in Parallel, each with P(Function)= .9



Possible Results:	Probabilities:
A and B both function	0.9 X 0.9 = 0.81
A functions, B fails	0.9 X 0.1 = 0.09
A fails, B functions	0.1 X 0.9 = 0.09
A and B both fail	0.1 X 0.1 = 0.01

Only the last result means complete failure of the redundant system, therefore its P(Function)= 0.99

Figure 1 - 1

Testing Requirements and Methods

Another problem of the designers of space hardware components is that which develops with respect to testing. It is true that many static tests can be performed so that the designers are not entirely dependent upon flight testing but it is also true that the final acid test is the manner in which a component performs during actual flight. Therefore, the static tests are not a complete or satisfactory substitute for flight tests, there is the possibility of interaction between the component of interest and the remainder of the system which leaves a considerable area of doubt as to the satisfactory characteristics of a component or the lack thereof until such time as the flight tests have been made. Because of the enormous effort and expense involved in the flight tests it is not practical for designers of component elements to depend upon "proving ground tests" as is practiced by automobile manufacturers and many other manufacturers of mechanical equipment.

It is also the case that simplicity contributes materially in the area of tests. It is obviously faster, less costly and more conclusive to test an element of simple design than another one that is a great deal more complex.

Effect of "State of the Art"

Another very important characteristic of the problem of designing space vehicle components is found in the rapid advances of the "state of the art." For example, one of the features of many drawings of valve elements and other engine components is a long list of engineering change orders and notes. These reflect the fact that the designs are in very much of a state of flux until "hardware" is actually delivered and even then the modifications continue so that successive pieces of components made to the same drawing may still be quite different from each other in important details. This situation presents an opportunity to the simplicity engineer or the designer who is practicing simplicity engineering techniques. In large mass production manufacturing when a design has been frozen and the drawing turned over to the production department there is little opportunity to make further modifications except in cases of extreme emergency. However, the designer of rocket engine components usually does not have to wait so long to incorporate any improvements, including simplification of designs that may have come to his attention.

Simplicity and Value Engineering

Simplicity is a term which describes a property that is recognized easily by most people and on which there is likely to be a good deal of agreement, but it is not so easily defined for a particular context. The new Webster Merriam International Dictionary defines simplicity as the quality or state of being simple, unmixed or uncompounded as the simplicity of metals or earths. A second definition given is, the state of not being complex or of consisting of few parts. The other words are taken in their usual dictionary meanings.

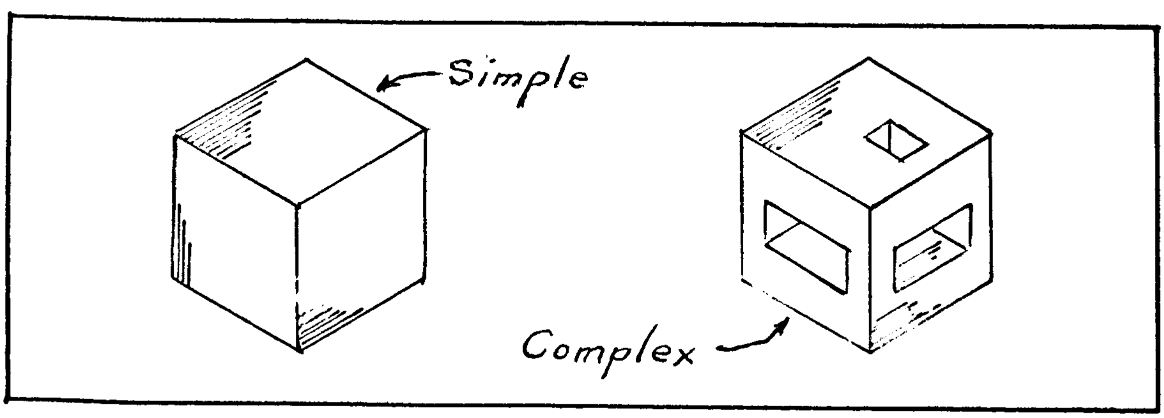


Figure 1-2

It is assumed that a logical objective in all design is simplicity with respect to various criteria. It is possible that a design might be very simple with respect to form but quite complex as to the material to be used or the processes necessary to obtain the desired form. Various other characteristics which define the frame of reference for the simplicity of the design of parts or mechanisms will be developed hereafter.

A basic premise of this study is that the paramount requirement at all times is reliability of function, designers will not hesitate to increase the complexity of their designs whenever and wherever it can be demonstrated that the increase in complexity improves the performance.

A much more complete discussion of the relationship between simplicity engineering and value analysis engineering will be found in Chapter VII however, it is important to note here that simplicity engineering is presented as an additional tool for value engineering work. This is in recognition of the historical fact that value analysis engineering which probably is an outgrowth of cost reduction effort has become very firmly established and there does not seem to be any logical reason for replacing these departments, divisions, or sections in the companies that are now using them. On the other hand, in those cases where the value analysis department has not been established, possibly because management did not feel that exclusive emphasis on cost analysis of engineering design is appropriate in their company, it may be that simplicity engineering work units can be utilized to good advantage.

Assumptions, Postulates, or Premises

It is desirable in a report such as this to establish certain definitions to avoid the possibility of a failure to communicate resulting entirely from semantic difficulties. No effort will be made at this point to develop absolute and final definitions, but only to lay down some broad guide lines leaving more detailed explanations of words as they are used herein to the places where they come up naturally in the text itself. The authority used is Webster's New International Dictionary (Merriam) Unabridged. However, some words are given double meanings in the dictionary and some words take on special significance in their uses in particular types of scientific investigations.

Assumption - The act of taking for granted, or supposing without proof that a thing is true. Alternatively it may be the thing which is supposed; a postulate or a proposition that has been assumed as the basis for further discussion.

Axiom - A proposition or principle to which people in general agree, an accepted maxim. It is also defined with reference to logic and mathematics as a self-consistent statement about undefinable objects which form the basis for discord. Such as the statement that there is one and only one straight line passing through two given points.

> Note: Assumption and axiom are very close in their meanings and often it is not necessary to distinguish between them. Moreover, it is often unimportant whether the assumption or axiom can be proved for it can still serve as a logical basis for a pattern of reasoning.

Concept - An idea as distinguished from a percept. In modern usage it is chiefly an idea that includes all that is characteristically associated with or suggested by, a term; also, a mental image of an action or thing.

Factor - According to the dictionary, this is something that actively contributes to the production of a result. As used herein it refers to a characteristic of something that can be taken as a separate element and considered independently. For example, in considering a rocket engine valve it may be quite important to examine its resistance to corrosive liquids and a ceramic material might be the best answer for the factor of corrosion resistance. However, another factor would be the attainment of precise size, and still another factor would be the capacity for resisting shock.

Heuristic - This word is used both as an adjective and as a noun, the latter being principally the abbreviation of a statement such as an heuristic argument and it is more likely to be encountered in the adjective form. An heuristic demonstration is one which serves to promote understanding without offering a logical proof. Heuristic teaching is a type in which the student is led into situations where he must find out answers for himself rather than having them offered to him ready-made.

Hypothesis - Here, this is any proposition, condition, or principle which is assumed, perhaps without belief, in order to develop the logical consequences that must follow if the hypothesis is true.

Percept - In modern usage this refers to the impression of any object obtained by use of the senses, therefore taking into account the existence of such things as optical illusions. There is no necessary connection between a percept and the true condition of the object observed.

Postulate - This is very closely akin to an axiom and it is also related to the heuristic method where the axiom may be something that is generally agreed upon as being true. A postulate may be simply a proposition or an hypothesis which is offered as the first premise in a chain of reasoning. Alternatively it may be taken to mean a condition or an essential prerequisite for that which follows and so again it may mean a proposition which is demonstrable and constitutes in fact part of the definition of the terms involved in it.

Premise - This also refers to a proposition supposed or proved as a basis of logical argument or inference. It occurs very often in the statement that no matter how clever the reasoning about a proposition may be if the premises are false then the result must likewise be false.

Example of Assumptions in This Study

The assumption is made that in order to obtain simplicity of design it is necessary to have this constantly in mind as an objective during the designing process. Without specific attention to the properties of simplicity, it is very probable that needless complexity will find its way into designs that are selected upon the basis of performance characteristics only. As a corollary it may be assumed that scientists and engineers concentrating their attention upon performance features of a component are likely in some cases to be unfamiliar with the problems of machining or otherwise fabricating a part. This is particularly likely to be the case when one considers the complexity of modern knowledge and the high degree of specialization necessary to understand and plan the operation of a rocket engine.

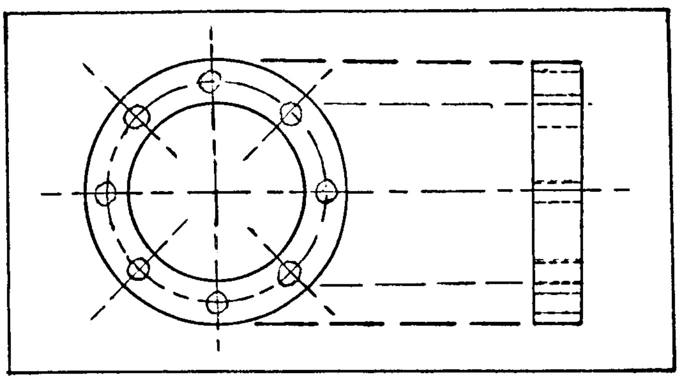


Figure 1-3

As an example, one part studied consists of a flat aluminum ring apparently intended to hold down a gasket; it has a thickness of .380 inches and outside diameter of approximately four inches and an inside diameter of approximately three inches with a number of equally spaced bolt holes around the circle. According to the drawing this is to be machined from a rolled aluminum blank. No detailed tolerance is specified on the .380 dimension, therefore, the general instructions for tolerance on such dimensions apply and this would be 1/16th of an inch or .0625 inches; therefore, it appears that it would be possible to make this part from a piece of 3/8 inch aluminum plate without machining the flat surface at all providing that the mill tolerances for rolled thickness is close enough and providing that the faces would be sufficiently parallel. It is possible that the .380 dimension, plus and minus its tolerance of .0625 inches, might result in some of the pieces being outside of the permissible tolerance limits. On the otherhand, there is nothing to suggest that a thickness of .375 inches would function any less effectively than that of .380 inches. It appears very much as if the face of this part, "fits the air," as a machinist would say, and if the rolled plate thickness and tolerances are satisfactory, there would be no need to machine the faces to obtain the .380 inch dimension and it is possible that the finish imparted to the plate in the rolling operation would be more suitable for the functioning of the part than a finish obtained by machining the flat surface.

A reasonable postulate for all design of parts such as those used in rocket engines is that all other considerations being equal, simple parts will function more effectively than complex parts. This proposition is, of course, not always true. It can be considered from two points of view, first, simply designed parts are easier to procure or manufacture, therefore, there is less chance of undetected deviations from the desired design, but secondly, it appears that a part which accomplishes its function in a simple manner is likely to perform the function more reliably than one that depends upon a complex approach to performance.

Finally as to premises, it is assumed that the quest for simplicity must be subordinated to the problems of obtaining useable solutions. The design of each part must be considered as a solution to the problem of obtaining the performance of the function for which that part is included in the overall design of the rocket engine and that it is therefore impossible to devote enough time to each individual part to attempt to make it a perfect solution. Perfection of design is, of course, like perfection in anything else, completely unobtainable and the solutions adopted must consist of sub-optimizations of the desired goal.

Even apart from the practical impossibility of achieving perfection of design, sub-optimization would still be necessary because of the fact that it is almost invariably impossible to completely optimize any one aspect of a system without reducing the degree of optimization of other closely related elements. In the case of the design of rocket engines there is so much at stake that undoubtedly more time and attention can be lavished upon each individual element than in the case of many other types of mechanical assemblies. However, the law of diminishing returns operates here just as it does in other design problems and regardless of willingness and ability to spend additional time and money on design problem solutions, it is impossible to escape the fact of interrelation and that engineering is essentially a series of compromises, that what is gained in one direction may cause a loss in some other direction.

Objectives of This Study

As charged in the basic contract, which caused this work to be undertaken, the objectives are:

a. Development of a system for rating propulsion system elements according to their simplicity of design, and

b. Application of the system devised to propulsion elements for the purpose of establishing a set of standards which may be used as a guide in new design work and in the revision of present designs.

These objectives briefly stated for the purpose of inclusion in a contract have been interpreted to mean the establishment of a system of simplicity rating broad enough to encompass all of the various aspects of simplicity which are pertinent to components of propulsion systems. It was quickly discovered that simplicity is in itself a complex concept and that it is impossible to develop any simple measure or rating number that can be assigned to describe the degree of simplicity inherent in a manufactured part. It was not apparent at the beginning of the study whether it would be possible to develop even a relatively complex rating system on an absolute scale or whether it would be necessary to settle for a purely relative scale analogous to the Mohr scale of hardness which arbitrarily chooses the diamond as the hardest material and assigns numbers to other materials to indicate their hardness in comparison with the diamond.

Since it was evident that no simple measure of simplicity will suffice, a first objective had to be that of establishing the various pertinent points of view needed to develop a composite scale of simplicity. For example a component might be extremely simple from the point of view of the technician required to assemble it with other components, because of a shape that can obviously be assembled in only one manner thus eliminating all possibility of confusion between right and left hand parts and all possibility of getting a part in place upside down. But this same part might be extremely complex from the point of view of the metallurgist who has to furnish the material or from the point of view of the machinist who has to form it to the desired contours.

Having given attention to the points of view that are properly to be considered in any such rating system as is desired here, new objectives immediately became evident, namely first to determine whether or not it is possible to combine a series of separate ratings to obtain a single meaningful rating number which could be applied to make a choice between two parts intended for the same function but differing in design. Having determined that it is possible to obtain a combined rating number, the second objective is that of actually devising the best possible system of combination of individual or elemental ratings.

The last and perhaps most important objective is that of putting the system into such form that it can be used by a design engineer or draftsman during the actual process of designing components. To a large extent this objective or requirement explains the present report which had to be sufficiently detailed and contain enough discussion of the methods used to arrive at the final result, to contain references to the authorities consulted, and otherwise be convincing to the executives who must approve the adoption of any system such as proposed here, while at the same time the end product must be simple and concise enough to meet the needs of those who will make daily use of it.

Methods of The Study

Again refering to the basic contract, we find it suggested that the study shall consider basic design elements for factors in a rating system including but not limited to the following list of items:

1. Number of dimensions
2. Manufacturing operations
3. Process operations
4. Assembly operations
5. Critical tolerances
6. Stress levels

Proceeding according to the method stated in the contract, devise a rating system based on these factors and any others that need to be added thereto, and then rate existing propulsion system elements to produce a set of standards for future use in achieving simplicity of design.

When the study was actually begun, it became apparent that two basically different methods of study each have much potential value. One of these is to seek a common denominator which would apply to all manufactured parts and such a common denominator is to be found in the dollar. If it is possible to properly estimate the cost of manufacture of each item, then it becomes possible to say that the one that is lowest in cost is inherently the most simple because any change of material, size, method of manufacture, tolerances, or any other individual characteristic that increases the cost of the item, would also be a change that made the item more complex.

<u>Organization of The Report</u>

In the preparation of this report it has been kept in mind that there are at least two basic problems; first, to make the report complete enough to convince engineering design managers of the desirability of adopting the method; and secondly, to provide a guide that can be used by designers in the actual pursuance of their daily work. Therefore, Chapter V has been so written that it can be extracted from the report, duplicated, and distributed to all designers who have need of using this method. It is, of course, considered very desirable that the designers would also read the entire report so that they might have an understanding of how the points set forth in Chapter V were arrived at but this is not an absolutely necessary thing, therefore, a designer could start using the method before he has had time to study the entire report.

It is possible that managers of some design offices might wish to conduct training sessions for their designers in order that all of them may have the same understanding of the requirements of the system and apply it in the same way. Therefore, there has been included Appendix C, which consists of a discussion leader's guide and suggestions for the conducting of a training course. In this connection it will be desirable to have a number of sample components available so that the members of the training group may read each of them according to the several factors and compare their judgments with each other and with that of their supervisor.

Chapter IV is devoted to a discussion of the concept of simplicity and other concepts that are important with respect to a simplicity rating index. The interesting point is made that the universal acceptance of the idea that simplicity is a valuable thing which should be sought but that this is primarily on an intuitive basis. This leaves us with the necessity of accepting the virtues of simplicity as an axiomatic fact.

Chapter III is devoted to considering some of the various possible ways in which a simplicity index might be constructed. It shows that the problem here is very similar to problems which arise in job evaluation and in the rating of human intelligence as practiced by psychologists. The purpose of this chapter is to answer the question, sure to arise in the minds of some readers, as to why some other approach for example costs of manufacture is not recommended instead of the factor method developed. In Chapter V the actual factor method recommended is developed in considerable detail with attention to its weak points as well as its strength. The goal has been to produce a simplicity index which approaches the characteristic of a pure number such as π or e which has no units and is equally applicable in all systems of measurement. This goal cannot be attained but the simplicity index developed is free of units such as dollars per part and thus is less subject to the ravages of inflation, rising labor rates, or other constant sources of change. The reasons for the lack of complete purity are stated. Chapter V contains a number of examples of the application of the factor rating system. Chapter III has already been explained above. Chapter VI consists of the summarization of opinions obtained from practicing engineers and managers having responsibility for guiding design work and finally Chapter VII is a discussion of simplicity engineering which relates it to the already established value engineering specialty and the concept thereof.

The appendices include background material from the fields of job evaluation and intelligence measurement and the bibliography. There is also a guide for instructors which may be used by any company or group desiring to make an application of this factor analysis method of rating simplicity.

Recommendations

It is recommended that this report be circulated among engineering managers responsible for the control of component design efforts and possibly to some key design engineers. Each man should be requested to decide whether he feels that he can use the system as proposed or to raise questions and make suggestions so that modifications may be made in the system as needed.

The report has been so organized that the section which comprises the actual design simplification rating system may be separated from the discussion of how and why the system is recommended in this form. This will make it possible to use the "working section," as an operating manual to be duplicated and placed in the hands of design engineers who are in the position to make application of the system.

It is also recommended that copies of the complete report be available for any designers who may use the system in order that they may satisfy their intellectual curiosity and may gain more confidence in the validity and value of the system provided than would follow from working with the handbook or manual portion only. However, it is believed that the separate manual would be valuable as a daily-use-tool on the design board.

Even where it is believed that there may be some difficulty in the application of this system and where it is anticipated that the integrated value rating numbers may be somewhat inexact, it is still recommended that the system be used insofar as possible because it will draw attention to differences in the simplicity of different designs and suggest ways in which designs can be simplified and where they should be. Therefore it is recommended that realization of the subjective judgments involved in assigning degrees to different factors in the choice of the factors themselves and in the weights that are attached to them prevents the system from being absolutely accurate it should be applied because in spite of any lack of exactitude as between similar components it will put the spotlight on any glaring complexity in designs.

Chapter II

Concepts of Design Simplicity

"To be simple is to be great."
Ralph Waldo Emerson

What is simplicity? Is this design A more or less simple than this other design B? Why are we interested in the degree of simplicity or lack of it? Who, if anyone, will benefit from this design being made more simple? When we say that a design is simple per se, or that the design of A is more simple than the design B what is our frame of reference?

The questions stated above are only a few of those that might be raised concerning a concept or idea of simplicity and still others will be raised as we continue.

Again we will start with a definition from the Merriam Webster which says simply that simplicity is the state of being simple or uncompounded. The word simple itself has many definitions all running along the same line, for example, free from elaboration or figuration, plain, unadorned and one component of a complex to name a few. The synonyms given deal primarily with intelligence or human behavior and do not apply well to manufactured articles which concern us here. Thus we are forced to develop our own definition in terms that most readers will no doubt accept as a reasonable interpretation.

"Anything that exists at all exists in some quantity, and anything that exists in some quantity is capable of being measured."
E. L. Thorndike

The psychologists and perhaps some others make a distinction between measurement and evaluation, wherein measurement is a direct comparison with definite unit and evaluation is a subjective judgment. For the purposes of rating simplicity in the design room, it is not essential that this distinction be made. It will be seen that some of the factors require counting, some can be actually measured, and in some it is necessary to be content with subjective determinations.

To a large extent, the system proposed here is very similar to the method of paired comparison. L. L. Thurstone says, "For any attribute x about which a subject can say 'A' is x'er than 'B' ---" (A scale can be established.) The scale will not have a zero point, because, with simplicity as with intelligence, it is impossible to suppose something completely lacking the characteristic. Likewise it is impossible to postulate that which would represent the absolute limit of complexity, to establish the upper end of the scale. In Figure 2-1 is a graphic representation of the proposition that B is more complex than A, but there is no implication of degree, for there are no units on the scale line. Obviously A and B might be far apart or so close that there could be much disagreement between observers or raters as to which of them should really be placed to the right.

A	B
Simple ————————	Complex

Figure 2-1

To start with an intuitive approach to simplicity consider a picture puzzle made by mounting a picture on a cardboard or plywood background and then cutting it into small pieces with a series of curved jigsaw cuts. Some of these familiar puzzles are simple enough so that a small child may assemble them and recreate the picture after the separate pieces have been scrambled, while others are so complex that it may take an adult an hour or more to locate the various parts and fit them into their proper places. The simplicity of such a puzzle or the opposite pole complexity lies in two factors, if the cut lines are of simple waviness so that a number of the pieces are identical or practically so the problem becomes one of making the picture come out right so the second factor is obviously the nature of the picture. In a child's puzzle the picture is likely to be boldly covered with strong lines of demarcation between the figure and the background while in the difficult picture the scene may have areas of cloud or garden that are very similar to each other but not precisely matching.

Another intuitive approach to simplicity is implicit from other factors that observers instinctively take into account whether or not they are expressed.. Such ideas as the time required to produce the object being evaluated, the amount of skill necessary on the part of the person who produces it, the care that must be exercised in handling the object, and similar considerations influence one in deciding whether a given object is simple or complex. Some examples of this type of reasoning are the following, and it is interesting to note that in each case realization of the complexity of a thing depends upon the observer possessing some knowledge of the processes, the care, and the frustrations going into its manufacture. On being served a piece of cake a hungry boy is likely to evaluate it only on terms of whether it tastes good while his mother who has cooked cakes may note that this particular cake represents a very elaborate effort because it is made up of layers of three different colors of dough, is iced with two kinds of icing and has a topping of carefully placed nuts. Or again, a person looking at a beautifully made multicolored map may observe only that the colors are an aid in distinguishing between different states or countries but a skilled printer recognizing the necessity for a series of plates, one for each color, and the problem of obtaining good "register" sees it as a very complex undertaking compared with the simple black and white map. Numerous other examples of this type could be developed, the reader can no doubt furnish some from his own experiences.

Simplicity As A Characteristic

The preceding discussion raises a serious question as to whether or not there is really such a thing as a separate identifiable characteristic of simplicity or are we deluding ourselves by confusing value with simplicity? In the booklet entitled "Target-Value" published by the Rocketdyne division of North American Aviation, Incorporated and apparently written by Mr. W. M. Bayne, Chairman of value engineering in that company, we find value defined in five different ways when used in connection with product oriented activities. These consist of:

a. The actual amount paid for an item.

b. The minimum payment for which an item can be obtained under the most favorable real conditions.

c. The effectiveness of an item.

d. The desirability of, or esteem for, an item.

e. A comparative rating of the effectiveness of an item and its cost.

It is stated that each of these meanings has a special use in value engineering so other words are substituted for the first four meanings above and the word value is defined as the relationship of effectiveness to cost. The introduction of the term cost opens the door to a whole series of complexities but the basic idea of importance to simplicity engineering is the tacit recognition that more work, more skill, more esoteric materials and a number of other factors put into a thing tend to make it more complex and therefore less simple. Thus we find that the realization of the problem confronting us in considering simplicity brings with it its own remedy. If we can separate out those factors which tend to increase costs, such as more labor and, or, more investment so that they may be examined separately from their price tags we have a means of determining simplicity on a more or less scientific basis.

The Nature of Scientific Proof

Since the question of whether or not a theory or proposition has been proved scientifically is much debated by eminent scientists, no endeavor will be made to develop a rigorous proof of the merits of simplicity. On the other hand attention is called to the frequent references to simplicity found in the writings of prominent scientists. For example, Philipp G. Frank, in an article titled "The Variety of Reasons for the Acceptance of Scientific Theories" says:

> "If we restrict our attention to the two criterions (sic) that are called 'agreement with observations' and 'simplicity' we remain completely within the domain of activities that are cultivated and approved by the community of scientists."

Here Dr. Frank, who is a faculty lecturer in physics and the philosophy of science at Harvard, uses simplicity as one of the criteria upon which the approval of the community of scientists is based. He goes on to discuss the respective weights which should be attached to each of these criteria. He concludes that the choice of a theory is based on a compromise between both criteria and says "however when we try to specify the degree of 'simplicity' in different theories we soon notice that attempts of this kind lead us far beyond the limits of physical science."

Dr. Frank also recognizes the point made earlier that we cannot say that a thing is simple per se but we must take into account the observer for whose understanding the degree of simplicity is stated. He says "we note that even a purely mathematical estimation of simplicity depends upon the state of culture of a certain period. People who have grown up in a mathematical atmosphere-that is saturated with ideas about invariants-will find that Einstein's theory of gravity is of incredible beauty and simplicity; but to people for whom ordinary calculus is the center of interest, Einstein's theory will be of immense complexity, and this low degree of simplicity will not be compensated by a great number of observed facts."

Simplicity Ratings of Rocket Engines Parts

Rating the simplicity of parts carries a connotation of various degrees of simplicity, the idea that one item may be more or less simple than another. Furthermore, it contains the proposition that a rating system can be developed, having numbers or other symbols to stand as surrogates for the actual parts which they represent in a scale of simplicity. As a part may be described as being less or more simple than another, it is useful to have a term for the other end of the scale. This, of course, comes readily to mind as complexity. That which is not simple is obviously complex and vice versa.

Although it is relatively easy to establish the idea of a scale of values ranging from simple to complex, it is quite another problem to develop the actual scale. If, between two parts A and B it is possible to obtain agreement that A is the more complex, there is still no clue to the degree of separation between them. The difference between A and B may be so small that skilled observers may disagree and rate either one or the other as being more complex. On the other hand, in those cases where the differences are great and there is a strong consensus that B is a more simple object than A, there is also an intuitive impression the points representing these two objects on a linear scale should be large. Figure 2-2 serves to illustrate the effect of the differences developed in placing two objects on a scale of simplicity, according to their relative complexity or simplicity even when the scale has no units. And the ends have

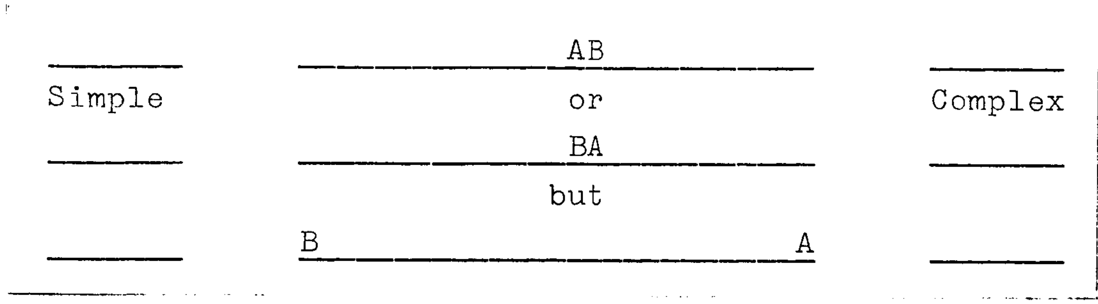


Figure 2-2

not been and may not be determinable.

In Figure 2-3 this problem is examined with reference to three objects A, B, and C. With three objects there are six possible permutations as to order of complexity and within each of these there are very large numbers (if not infinite) of possibilities as to the degrees of separation selected by various raters.

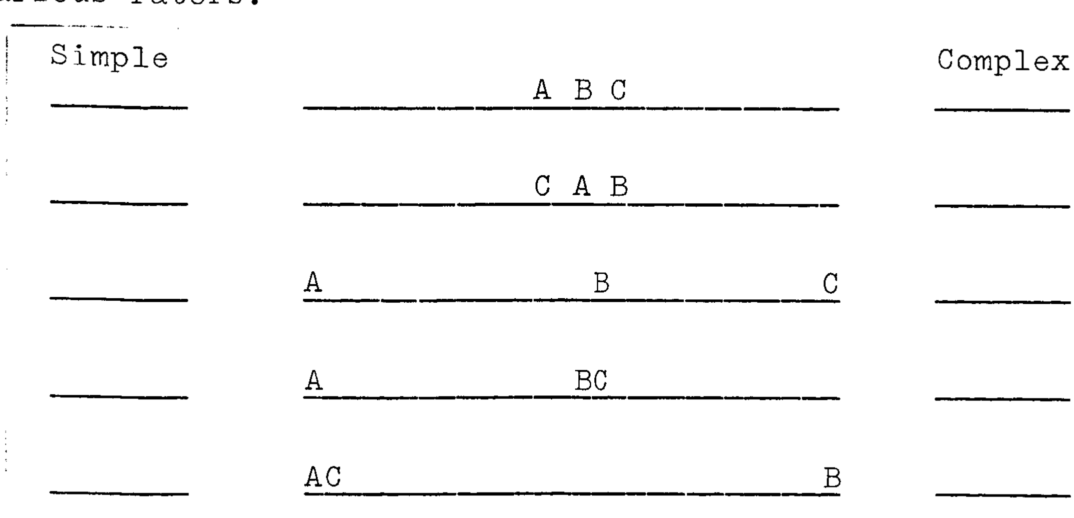


Figure 2-3

Various methods of rating more or less intangible characteristics used in disciplines other than design engineering are listed in Figure 2-4. Some of these have had more influence upon the Simplicity Rating Index, but they are mentioned and briefly described to show ideas previously available. If then

INTELLIGENCE RATING SYSTEMS
JOB EVALUATION SYSTEMS
VECTORS OF THE MIND
APTITUDE TESTING

Figure 2-4

a third object C is introduced to be rated with respect to A and B. the question arises at once as to the spacing of its point on the scale with respect to the two previously established points. Before going into the possible solutions of this problem, attention will be turned to similar problems wherein some progress has been made in other disciplines.

Antecedents of Simplicity Rating System

Intelligence Rating Systems

Intelligence testing and rating presents difficulties of the same type as those encountered in simplicity ratings. For present purposes a simple definition of intelligence will suffice; the capacity to apprehend facts and propositions and their relations and to reason about them. As in the case of rating objects from simple to complex, it is not too difficult to compare two individuals and decide that one is more intelligent than the other. Applying numbers to represent the degrees of the differences is much more of a problem. One solution has been an arbitrary statement of groups of facts, tasks, or acts which an individual should be able to perform or recognize at each age. One who meets these tests successfully is said to have attained the corresponding "mental age." A final number is obtained, as the intelligence quotient, commonly referred to as the IQ, by dividing the mental age by the chronological age and multiplying the fraction by 100.

Actually, the measurement and reporting of intelligence is far more complicated than would be inferred from this simple description. Different types of intelligence have been isolated and measured, at least to the satisfaction of the proponents of the particular methods reported. Efforts have been made to distinguish between "native" intelligence and that which is acquired by experience or learning, in recognition of which the well known Binet-Simon tests provide scales through the teen age years only. There are other systems of intelligence testing, such as the Wechsler Bellvue, and the Army Alpha which were designed to meet such problems as the testing of adults, illiterates and persons from non-English speaking cultures, but these are not as useful for this study as some other methods.

It is not claimed that the attention to psychology herein is original in any respect except its application to engineering design problems. One of the early forerunners is to be found in the work of a psychologist, L. L. Thurston, who wrote a book entitled "Vectors of the Mind." In his efforts to measure and compare intelligence Dr. Thurston quickly noticed that mentality apparently has a number of dimensions, a person may be extremely adept at dealing with mathematical concepts and at the same time may make very poor scores on tests of language ability. Much work has been done following Thurston by many other psychologists seeking to find how many dimensions of the mind may exist and the extent to which they overlap and reinforce each other. An interesting commentary is that on the whole the psychologists have not endeavored to find a single meaningful index of mentality but have instead developed the idea of a "profile" in which individual abilities are reported in each of a number of areas.

Job Evaluation Systems

Another area in which ratings of composite requirements or abilities has received a great deal of attention is found in job evaluation. Job evaluation is of great practical importance for the purpose of comparing different jobs in industry and other employment in order that wage scales may be adjusted to pay fairly for each job. The basic question is for example, which job is more difficult, more demanding, or more distasteful and therefore entitled to more wages when we compare the work of a carpenter and an electrician, and a lathe operator. It is important to note here that job evaluation work is directed at the job without regard to the particular incumbent at any given time. The fact that a job may be occupied by a college graduate does not automatically establish a college degree as one of the essential characteristics of that job, definition of the characteristics of an individual which may be used to decide whether he can fill a particular job is treated as a totally separate problem. Job evaluation has in common with the simplicity rating system developed here the characteristics of a job, but the job is rated individually in each of a number of factors prior to the actual consolidation thereof.

Job evaluation has the advantage of being more familiar to more people in industry than intelligence testing, (outside of the personnel department), and in that it includes a ready means for breaking up a problem of many facets into smaller elements. Moreover, job evaluation contains an automatic means of avoidance of the "halo effect," which is a tendency to rate a subject of analysis high in all parts because the rater has been very favorably impressed by the observation of one or more characteristics.

Because of the extensive use made of Job Evaluation models in developing the system of Simplicity Ratings presented here, Appendix A has been devoted to a more complete description of some of the Job Evaluation Systems.

A Practical Theory of Simplicity

Having recognized that simplicity as a concept is very complex and that conclusions about it depend upon the points of view of the interested persons, attention will now be turned to a practical theory of simplicity which can be useful to designers of mechanical parts and which will be based upon axioms and postulates which a large number of designers and engineers might be expected to accept. In this way a useful tool is developed and the ground work is laid for integration of the simplicity theory with the fine work already done in value analysis engineering. Of particular interest to the project of designing rocket engine components is the fact that the assumption of the common fund of knowledge on the part of all who may be engaged in such design work does not preclude frequent additions of specialized characteristics and capabilities of materials or processes. For example some of the drawings of parts carry a specification that they be "passivated" which means roughly that they are to be chemically treated so that they will not be subject to physical changes on being exposed to hydrogen peroxide. (This requirement may be obsolete with the discontinuance of the use of hydrogen peroxide as a liquid fuel element in engines. However if there should be a return to the use of this fuel the passivation technique would no doubt be revived.) Therefore we see that designers of rocket engine parts have to take into account characteristics that may be unknown to and of no interest to designers of parts for say a farm tractor. The rocket engine designer adjusts readily to special requirements when the information is supplied to him by physical metallurgists or other specialists who provide extraordinary materials, processes, or methods of manufacture.

The complete system of simplicity ratings proposed here is based upon 8 propositions as follows.

Simplicity Design Propositions

1. Component designs may vary from simple to to complex, and competent observers can compare designs to reach judgment as to which of any pair or group is most simple.

2. A design may be simple in some ways and quite complex in other ways depending upon the elements under consideration.

3. The elements of a component design which affect its degree of simplicity may be agreed upon by a number of designers and engineers and they may be defined and described for subsequent use.

4. That design which has a majority of its elements in the simple category is as a whole more simple than one which has many complex elements.

5. In order to facilitate the process of comparing designs, arbitrary degrees of simplicity may be assigned to each of the various elements agreed upon and designated by numbers.

6. The different elements rated as to their simplicity are unlikely to be of equal importance therefore arbitrary assignment of weights will serve to indicate the relative importance of each of the elements.

7. Numerical combinations of the different degrees of simplicity can be accomplished by matrix multiplication to establish a single over all degree of simplicity for any particular design so that it may be directly compared with alternative designs.

8. Design groups working with this system will acquire skill in its application. At the same time they will develop useful data for the refinement of the rating system itself.

Simplicity As A Design Objective

The concept of simplicity is very widely accepted as a desirable objective in many different fields. For example Professor Harold W. Martin, in the Journal of the Institution of Production Engineers in an article entitled, Investing In Simplification and Standardization, says that productivity is the key to increased earnings in an industrial economy. He goes on to discuss simplification of selling and says,

> "Simplification is the key to such cost reductions through increased productivity. Simplification of each product; simplification of the processes by which products are designed and manufactured; simplification of the range of products offered for sale; simplification of the distribution and selling processes."

While it is true that Professor Martin is concerned with commercial products primarily, no doubt, for consumer sales, some of the thoughts that he offers have a bearing on the concept of simplification in general and may point to a justification of concentration on simplicity as a goal in rocket engine components.

Professor Martin says, for example, with reference to simplification in designing,

> "The process of product design and its related preparation of manufacturing specifications provides the greatest potential for increasing productivity through simplification and standardization. Simplification has two aspects: one represents a challenge to the designer, the other a challenge to design management." *** "If the designer creates a product design of higher complexity than is necessary for satisfactory performance, he lowers the productivity potential in its manufacture and thereby increases its manufacturing cost, which tends to increase the selling price and reduce the customer's willingness to buy."

Perhaps the greatest contribution in this paper to the problem of simplification in rocket engine components is Professor Martin's stressing of the desirability of interchangeability of standard parts and sub-assemblies which increases the productivity of both the design and manufacturing departments. For example, during the design process much time is saved if it is possible to specify a standard form or screw thread or other element of design which having once been determined can be reused in other components. Finally, in his summary he develops the fact that the rewards for simplification and standardization demand a management with the vision to recognize the need for planning simplification and insisting upon its achievement by all of the subordinate executives, designers, and engineers engaged in the manufacturing effort.

Turning to a totally different field for a view on simplicity, we find what is sometimes referred to as Morgan's Law of Parsimony. In general this rule or "Law" says that, in endeavoring to develop an hypothesis to explain behavior, one should always select the explanation that is adequate to explain the observed phenomena in the simplest manner possible. For example, if in the observations of the behavior of a dog, it is noticed that he can be taught to fetch a stick. A number of hypotheses might be formed to explain this behavior. One of these might be that the dog is believed to desire to please his master but a more simple hypothesis might be that the dog has learned that retrieving the stick leads to a reward in the form of a scrap of meat which he relishes and the simple theory, fetch stick - get meat, is adequate to explain his behavior in lieu of a more complicated hypothesis that the dog has developed affection for a master and reasons that if the master is pleased in some strange way by having a stick brought to him he, the dog, will bring the stick.

Another example of a well recognized acceptance of simplicity as a virtue is found in a branch of industrial engineering called work simplification. One of the chief exponents of this philosophy is Allan H. Mogensen, writing in the second edition of the Industrial Engineering Handbook. Mogensen not only accepts work simplification, that is the process or practice of finding a more simple way to do any job of work as an axiomatic good, but he offers a work simplification pattern which can be readily modified to produce a series of suggestions or rules to be applied to design simplification problems for rocket engine component designers and other designers. These rules will be discussed in more detail in a different chapter of this report so it suffices here to draw attention to the fact that this furnishes another example of a tacit acceptance of the value of simplification.

In summary of this part of the discussion, so far the search of the literature has not yielded any specific reports of studies of the value of simplicity but it appears that, the proposition that other considerations being equal, a simple solution is a better one for any problem is so widely accepted that no one has bothered to make a specific test or demonstration thereof.

Chapter III

Various Approaches To A Simplicity System

"It is past all controversy, that what cost dearest, is, and ought to be most valued."

Miguel de Cervantes

The quest for a simplicity rating index is like almost all problems capable of being approached from various viewpoints and by different methods. This report would not be complete without a review of some of the possible approaches, in addition to the one selected for development. It is not possible to claim that the following approaches considered constitute all possible approaches but it is believed that those most likely to occur to a majority of investigators have been touched upon here.

Approaches Considered

A number of approaches to simplicity rating have been considered including determination of the cost of each of the parts to be rated and the use of such costs as the index on the assumption that a part is more costly when it is made of materials that are more difficult to procure or prepare and that the cost is also increased when the part is more complex and, therefore, requires more man-hours to prepare. There are a large number of difficulties in the practical application of this method and these will be discussed in more detail later.

Search of The Literature

The most obvious starting point seems to be in a thorough study of all related literature, searching for three different things that might be helpful in developing a simplicity index. The first of these of course is the possibility that precisely the problem considered here has been previously attacked, solved, and reported upon by competent investigators.

Regardless of whether or not such precisely related reports are found it is also logical to search for discussions or solutions of similar problems in the hope that a model may be found which can be applied to the present problem with merely a substitution of terms. This is a more difficult phase of the literature search because it requires of the searcher more imagination and ability to translate ideas from one field of research to another, and since we are dealing in reports from other disciplines with unfamiliar concepts it is much less possible to obtain any certainty that some important work has not been overlooked.

The third and still more difficult type of literature search is one which looks for fragmentary solutions of problems either in the field of mechanical design of parts or in other disciplines with the aim of taking the various thoughts, adding to them original connective reasoning and thus developing a model that specifically fits the problems at hand.

As will be found in Appendix B Bibliography, an extensive search by each different participant in the project was made in a number of very adequate libraries. This search was supplemented by correspondence with editors of specialty journals dealing with design problems and with various men in industrial positions having responsibilities for engineering design. No actual solutions of the precise problem were found nor does it appear that much prior thought has been reported relating to the search for this solution. As will be found elsewhere in the report solutions of similar problems were found and fragments also were located and these have been combined so far as possible to arrive at the method recommended herein.

Methods of Psychology

Another approach might be based upon the work of psychologists in developing intelligence scales. The parallel here is that a scale is involved which has no zero point and no maximum value, neither does it have any units. This is because it is impossible to define a person completely lacking in intelligence unless this might be taken as the condition of a mongolian idiot when he is asleep. Likewise, it is also impossible to define the person who is 100 per cent intelligent. Consideration of the problems of the psychologists and the progress that they have made in solving this problem may have some clues for simplicity rating and it will be discussed more fully. This approach was mentioned in the preceding chapter but is included here for completeness and continuity.

A Speculative Approach

For a long time in the development of human thought the speculative approach was the only one used and in a general way it is the turn to experimentation for the purpose of confirming or refuting speculation that marks thought in the modern world. In fact the speculative approach is often referred to scornfully as "armchair philosophy" and references are made, derisively, to the "school men" of the late middle ages and early renaissance who are reported to have debated the number of angels who could dance on the point of a pin. Nevertheless, speculative thinking undoubtedly persists more in modern scientific laboratories than is usually realized or admitted.

Recognizing the value of pure speculation as an aid or possibly a point of departure seminars were held during the summer of 1962, attended by mechanical engineering professors and graduate students, which really amounted to roundtable discussions, or in the terms of modern writers such as von Fange and Barton, to creative thinking sessions. In these sessions questions such as, what is simplicity? What makes a thing simple or complex? and What are the relationships between simplicity and other necessary characteristics of a designed part, were discussed at some length. Tapes were made of some of these meetings and transcribed so that it is now possible to review some of the thinking that entered into the discussions. It is interesting to note that early in the speculative discussions the idea of considering one characteristic of a designed part at a time began to be important. Evidently this is a natural and instinctive development when considering simplicity.

A reasonable summary of the place of the speculative approach may be simply that the phases observable are excessive reliance upon speculation such that there ensued a period of attempts to completely reject the method and that we have now swung back to a position where speculation is used along with experimentation and statistical analyses as just another tool of the investigator. Certainly it is not possible to design an experiment and carry it to useful conclusions without some creative thinking about what the experiment should be designed to do, how the measurements should be made, and how many replications there should be. Finally in the interpretation of the experiment and the future planning as to additional experiments there is inevitably much speculative reasoning. We shall see later that much industrial design conducted by specialists such as Teague and van Doren contains a large proportion of speculative thinking.

Cost As A Common Denominator

A capitalistic economy depends upon the monetary unit as a common denominator by which comparisons may be made as to incomes, values of services, and allocations of resources. It is the basis of the mechanism of the market place which determines whether resources of material and labor shall be channeled into the production of bread or hula hoops and the relative amounts of each that shall be produced to meet the desires and demands of society. For this reason a dollar occurs to almost everyone who considers the problem of a simplicity index as a potent method for comparing alternative designs intended to accomplish the same purpose, therefore such an index could be expected to find ready acceptance on many fronts.

The basis of the argument for using cost as the measure of simplicity is superficially very simple. It is obvious to all that as we move from the simple to more complex characteristics in any design more labor is required, labor costs money, therefore the more complex design is more costly than a simple one. This argument applies not only to the work to be done in manufacturing a particular part but also to the materials from which it is made and the tests to which it must be subjected before final acceptance. (This statement is predicated upon the general realization that the finished product of one segment of industry such as the steel mill becomes the raw material of another segment such as the machine shop.) The real basis behind this proposition which may often be unrealized by persons making use of it is the classical economic theory that only labor can create value. A mineral ore undiscovered or unexploited in the ground has no value but the labor of men in digging it, transporting it, and finally refining it to a useful metal costs money and adds value.

In the face of such compelling arguments on behalf of the cost basis of simplicity many persons jump directly to the conclusion that ergo all that must be done to compare the relative simplicity of two component parts is to determine and compare the cost of each and then to proceed on the implicit assumption that the one which costs least is the most simple.

However the actual situation is not as simple as the preceding discussion would seem to imply. The application of this theory as a test of the simplicity of a design would require that the cost of each part must be determined and there are so many inherent difficulties in such cost determinations that questions concerning the real value of the approach become so important as to suggest that some other approach will be more fruitful. Some of the difficulties are:

Inherent Difficulties of Cost Comparisons

a. Quantity Effect,

Some designs are more affected as to their costs of production by the quantity made than others are. This is, of course, because some designs contain inherently more opportunity for the application of automation techniques. When the quantity of parts to be made according to any design is very small it is advantageous to carve out each one, so to speak, individually. On the other hand when the quantity increases beyond a certain point it becomes economical to devote much time to preparing a master copy, a jig, or a fixture to facilitate manufacture. There are many ramifications of the relationship between cost and quantity made but the foregoing will suffice to suggest the considerations involved.

b. Workers' Skills,

In the consideration of workers' skills and their effect upon cost it is necessary to distinguish between the degree of skill and the type of skill.

In any trade there are available workers utilizing the same tools and general methods but with great differences in the degree of skill with which these are applied, consequently some shops possessing a complement of highly skilled workmen in a given trade might be able to make a particular part at a much less cost than another somewhat similar shop. On the other hand the nature of the design of the part might be such that the highly skilled workman would not be required to bring to bear all of his available talent and a less skilled man at an adjoining bench might also be able to make it.

The type of skill enters in the fact that some designs are inherently easy for a machinist raised in the construction of machine tools while they might be extremely difficult for a railroad machinist and the converse is true.

c. Shop Equipment,

Another important difference lies in the equipment available in particular shops. Most designs of fabricated or machined metal parts can be made on different shop equipment, for example, plane surfaces may be achieved by use of a milling machine, planner, shaper, or surface grinder, or by combinations of these. Each production planning engineer will route a particular part according to the availability of the machines in the shop for which he is planning and the resultant costs may differ to a large degree.

d. Shop Customs,

Shop customs influence costs of production very strongly; in one shop the workman may be accustomed to "free hand" operations which are particularly advantageous in obtaining low costs on very small lots of parts. In other shops the mood and customs of the workmen may be such that they insist upon "tooling" even to fabricate a single part and obviously the costs would then be much higher.

e. Materials,

Materials specified is still another very important factor. In one shop there may be strong tradition and experience in the handling of stainless steels whereas in another very good shop there may be little or no experience in the behavior of such steels so that its costs could be considerably higher.

f. Overhead,

The costs to be used for comparing different designs as to their relative simplicity must necessarily be either the factory cost of the item or the direct material and labor cost the difference between the two of course being the overhead that is applied. Because of the different situations of different manufacturing shops it is quite likely that there would be material differences in the overhead or that some arbitrary adjustment for comparative purposes would need to be adopted. Obviously this introduces a great deal of complexity into the use of costs as the index of simplicity.

g. Labor Rates,

As previously indicated a large part of the costs of any fabricated design arises from the labor charge, however this is dependent upon the two elements, namely hours of time expended and the rates per hour paid. Therefore the comparisons of the relative simplicity of two or more parts would necessarily be dependent upon the assumption that both shops, in addition to meeting all of the other assumptions as to relative efficiency, experience, etc., would also have to meet the test of paying the same labor rates.

h. Inflationary Effect,

American experience, if not that of the entire free world, has been that for many decades we have experienced a steady decline in the value of the dollar. As a result even if it were possible to meet all of the problems enumerated above in determining the costs of fabricating a part of a given design, it would be necessary to pay serious attention to the date when the determination was made and to compare items associated with different dates it would be necessary to make careful and sometimes tricky adjustments on account of the changing value of the dollar.

Application of Costs Basis of Comparison

Before the numerous inherent difficulties of the cost method were fully comprehended serious efforts were made to use this approach in developing the simplicity index. It was evident that only two sub-approaches could be made at this point. One of these would be to obtain the actual costs of manufacture, if possible, from companies that have already made hardware according to a particular design. The difficulties here are that first this is proprietary information which the companies may not be obliged to furnish under the conditions of their contracts and secondly that if they did co-operate to this extent the information would only be historical as to the production of a particular design for a given batch of parts and would carry no large amount of information about the future costs of a repeat order of the same parts in the same shop or of an order placed in a different shop which might apply somewhat different methods. Not only did these difficulties exist with respect to designs that have already been fabricated but there is nothing in the situation to offer assistance with respect to new designs while they are still on the drawing board.

A number of tentative costs studies were made in the effort to test this approach. The propulsion engineering laboratory had made available a large number of drawings of various rocket engine components and these were studied in detail for at least a representative sample group. Since no historical costs were available it was necessary to approach the problem from the viewpoint of synthetic time studies and to prepare proposed route sheets. Professor Newman developed several ingenious methods to accelerate this phase of the work but he was handicapped in that he necessarily had to plan for a hypothetical typical shop rather than one actually in existence because no knowledge was available as to where the work might be done. In addition, the determination of the material costs would probably not have been too difficult but neither would it have been very precise, each drawing gives the specification of the materials to be used and the size of the blanks therefore application to the companies capable of supplying such materials should have obtained quotations which would provide some indication of the material costs involved. This material cost could not be precise however because no information was available as to the exact lot sizes under study, some approximation could be made because it is known that certain vehicles have multiple engine configurations and that certain numbers of parts are designated for static tests, replacements, and other needs. Finally, however, as mentioned above the difficulty remained that finding a cost index for a particular part whose design was already completed would not contribute much to setting simplicity indices for parts designed subsequently.

Industrial Designers' Approach

Another method might be called the industrial design approach, having in mind that there are a number of successful practitioners in this country who devote their effort to the review and analysis of designs of parts, machines, or almost anything that is made by manufacturers excluding, perhaps, for the purpose of this discussion, the design of fabrics. The goal of the industrial designer is usually to achieve a design that will meet with consumer acceptance and, therefore, be eligible for mass manufacture. This approach does not appear to be very fruitful for the objectives of simplicity in rating rocket engine components, but it also will be discussed below at greater length.

SUMMARY OF RESEARCH METHODS CONSIDERED
SEARCH OF THE LITERATURE
METHODS OF PSYCHOLOGY
SPECULATIVE APPROACH
COSTS OF THE PARTS DESIGNED
INDUSTRIAL DESIGN METHODS
QUEST FOR A COMMON DENOMINATOR
FACTORIAL ANALYSIS

Figure 3-1

The basic idea of using a single measure as an index of simplicity. that if costs of production is not practical for this purpose other common denominators are sought. For example in the 1940's Alford and Hannum proposed the use of a measure which they called the kilo-man-hour, which they proposed to apply to all sorts of variables in industry such as the sales, plant investment, accident statistics, and other matters of interest to management. However it quickly becomes evident that these are measures which can be incorporated in the factor analysis system of simplicity rating to be discussed below. The more one pursues the idea of a single common denominator the more evident it becomes that this is a will-o'-the-wisp which does not lead to any useful conclusions.

Therefore the only practical conclusion that can be accepted with respect to this thought is that simplicity is much too complex to be reduced to a simple common denominator of all of the considerations entering into the problem.

Value Analysis Engineering

Value analysis engineering is so important for a number of reasons that it will be discussed at greater length in Chapter VII Simplicity Engineering. Here it is important to consider value analysis engineering and all of the titles applied to engineering groups engaged in the work which is generally accepted as that of the value analysis engineer as merely another possible approach to the development of a simplicity rating system. It is desirable to recognize that the method of value analysis is very important and that it has much to offer to support simplicity engineering but that it is primarily designed and has its greatest utility in design for profit. One correspondent, a Manager of Engineering Services of a large, diversified American company in its Metal Products Division, offers a list of eight different specialties in engineering organizations which may deal with some of the same questions that are important in simplicity engineering. These are:

a. production engineering
b. quality assurance
c. reliability engineering
d. maintainability
e. cost reduction
f. value analysis engineering
g. standards engineering
h. simplicity engineering

This engineer then offers a list of ten points, or really questions which may be asked with respect to each design, and which may be of interest to at least some of the specialists implied in the list of eight engineering groups already enumerated.

Factorial Analysis of Simplicity

Finally we come to the method that has been selected as the recommendation for the simplicity rating of parts to be made by or for the rocket engine assemblies. This is patterned after the point system of job evaluation developed by industrial engineers, psychologists, and management authorities. In job evaluation the problem is to rate jobs in a factory or other commercial or industrial organization according to their ralative simplicity or complexity for the purposes of assigning proper pay rates. This method has been selected as a model for the method of simplicity rating as a result of this research and will be discussed fully during the remainder of the report.

Chapter IV

Introduction to Simplicity Factors

"Few people today are likely to argue that the acceptance of scientific theories, even by scientists themselves, depends entirely upon the logical evidence adduced in support of these theories."

Barrington Moore, Jr.

This chapter will be concerned with the development of and the rationale for the simplicity factors suggested and means for applying them to the design of rocket engine components. The detailed descriptions offered for purposes of comparison with existing or proposed designs will be reserved for Chapter V , which is intended to be separable from the remainder of the report.

Factors or Vectors

As mentioned earlier, Thurstone used the term "vector" for the different characteristics of mentality which he studied. It would also be proper to use the term Vectors of Simplicity in this discussion. However, the word "factor" has been used in almost every instance, because to many engineers vector suggests a geometrical representation of quantities by directed lines of lengths scaled to the magnitudes of forces, etc. These rating factors are vectors from an n-dimensional space, or spaces and to correspond to the vectors of matrix algebra, rather than to any specific geometry.

Factors of Simplicity

Since simplicity is a complex concept, it is necessary to rate components according to a number of different characteristics, for as indicated previously a part may be quite simple when regarded from one viewpoint and very complex from still another viewpoint. Accordingly different characteristics of simplicity or factors are to be considered, these are indicated in the diagram, Figure 1.

It is important to recognize what psychologists refer to as the "Halo Effect." The halo effect, very simply, is a tendency to attribute to a person or thing a general standard of excellence because of the influence of some one or two outstanding and desirable qualities. For example, in personality ratings it has become customary to require the rating of an individual on different characteristics such as diligence, appearance, intelligence, friendliness, etc., because if a person is merely asked for a general opinion of the individual he may be influenced unduly by a so-called, "pleasing personality," or particularly a pleasing manner of meeting people.

In considering the factors of simplicity, it will be seen shortly that some of these are purely subjective in nature while others offer possibilities of quantitative analysis resulting in objective ratings. The term factors is used because the elements of simplicity are not of equal importance and to develop a rating scale it was necessary to also develop a system of weighting of the factors.

Form 1. Component Simplicity Rating

Drawing No.__________ Person(s) Rating

____

Date Rated______________ ______________________

Project or Assembly No.______________________

Remarks______________________________

____

Factor	Relative Wt.	Degree and Weight Values					Rating of This Component
		1	2	3	4	5	
A	2	2	4 ✓	6	8	10	8
B	1	1	2	3	4 ✓	5	4
C	5	5 ✓	10	15	20	25	5
D	4	4 ✓	8	12	16	20	4
E	3	3	6	9 ✓	12	15	9
F	4	4	8	12	16	20 ✓	20
					Rating		46

Instructions: 1. Study component to be rated with respect to one degree at a time. If a group of components is being worked upon it is desirable to rate each of them on Factor A, then proceed to B, etc.

2. Compare the component with the manual descriptions, select the best fitting degree value and check the corresponding cell for the factor and degree.

3. Enter the cell values in the last column and sum the column when all factors have been rated.

Note: The values herein are merely arbitrary for illustrative purposes. See Page 82 for alternative form.

A number of factors or characteristics of components have been selected as the bases of comparison with respect to simplicity of design. These are such things as material, tolerances, stresses, form, etc. A degree scale has been prepared for each of the factors, with 1 representing the most simple condition or specification and 2, 3, ---n, representing more complex conditions.

Not all of the factors are of equal importance, therefore "weights" have been assigned to each of them. A weight of 1 indicates a factor of minimum importance and increasing numbers show the more important factors.

There are two ways to combine the degrees and weights to obtain an index of simplicity. Each component for which an index is desired is examined with respect to each factor and the appropriate degree number for that factor is recorded.

For each component the degrees assigned to each factor are put down in a row, in an arbitrary order which is maintained throughout the rating computations. This array then is a row vector of the factor degrees for the given part, or component. There is a column vector consisting of the weights assigned to each factor and in the same order as was used to arrange the row vectors of factor degrees for the components.

The row and column vectors described above are matrices and may be combined by matrix multiplication. The factors make a 1 X n matrix and the weights an n X 1 matrix. They may be represented by F and W respectively, then

$$F\,W = (f_1, f_2, \text{---} f_n) \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = f_1 w_1 + f_2 w_2 + \text{----} f_n w_n = \sum_{i=1}^{n} f_i w_i$$

The result of the above operation is a single number which may be used as the simplicity rating index of the component rated.

Attention is called to the fact that in a given rating system in use in the design activities of a particular organization the weights assigned to the factors are relatively constant. Therefore, it is feasible to print forms locally to expedite computation of the simplicity indices. Alternatively, if the number of factors, n, is not too large it would be convenient to prepare a table of values of $f_i w_i$, similar to those employed in some job evaluation applications. Figure 4-1 provides an example of the type of form that may be used is illustrated for a system which has only four factors. The degree of importance to be attached to each factor would be determined by reference to suitable charts. Here the maximum shown is three, but it may extend to any practical number of different steps. In some cases the managers of the design office may wish to assign permanent, (or nearly so.) weights to each of the factors. In other cases it may be found desirable to vary the weights used according to the location of a part in the final structure, or according to the function which it is to perform. These considerations would determine whether the weights are to be printed into the form, or blanks left for the rater to fill in. The form would also need to provide spaces for the part number, date, name of designer and/or rater, etc. A tentative working form is on page (54).

Factor	No.	Deg.	Wt.	Product
Material	1	3	5	15
Tolerance	2	1	1	1
Finish	3	3	2	6
Ease of Assembly	4	2	3	6
Product Sam = Simp Index =				28

Figure 4-1

For those not familiar with matrix algebra, the validity of this method of combining degrees and weights may be seen readily by considering the anology of computing the cost of an order of groceries as is done daily in thousands of supermarkets. Let the factors be represented by Apples, Beans, and Cauliflower. Let the degrees correspond to the price of each in cents per pound, say 5 cents, 10 cents, and 10 cents. Then the weights are equivalent to the weights of the fruits and vegetables, say 10 lbs, 8 lbs, and 3 lbs.

The grocer would figure the cost of the order as:

Apples	10 lbs at 5 cents per lb.	=	$ .50
Beans	8 lbs at 10 cents " "	=	.80
Cauliflower	3 lbs at 10 cents " "	=	.30
	Total cost		$ 1.60

Changes in Factor List

It is not to be expected that any one list of factors will apply with equal validity to all kinds of design work. Neither is it to be expected that this first list of its kind is the best for rocket engine work. Therefore it is suggested that any organization which adopts the idea of simplicity rating indices by the factor/vector system should devote considerable effort to studying and improving the factor that they use in their work. Much will depend upon the manner and extent of the use of the system, whether it will be used within the confines of single organizations or becomes widely accepted as a standard system. Such general use may come about through the efforts of the Society of Value Engineers, or the American Institute of Industrial Engineers.

After a list of factors has been agreed upon in any particular situation, there may be need to make changes in it as time passes. For example, 50 or 60 years ago, if one were hiring a salesman, or deliveryman, and it was contemplated that he would travel by auto or motor truck, an important factor in the list of qualifications would have been the question of whether he knew how to drive a motor vehicle, but now this skill is so widely distributed that it is often assumed without the least question. It is more likely that changes in weights will be encountered and these will be considered next.

Factor Weights

Development of the single figure simplicity rating index . . .

requires, not only a list of factors with a series of numbers to indicate the degree of each of them, but also a series of weight numbers to be used with each of them. These numbers are expected to be more subject to change than the factors themselves. Designs requiring the utilization of new and unusual methods of fabrication, such as electron beam welding, will require the use of higher factor numbers for the factor degrees, plus higher weight numbers, when they are first introduced, than they will require after the method has become more or less commonplace.

These considerations will pose problems for design managers who adopt the Simplicity Engineering approach to analyze their work. However, it should not be thought that these changes will march so rapidly as to make the system unworkable. It is only when there is a genuine "breakthrough" or when a series of steady improvements have cumulated over a period of months, or even years, that changes in the system will be needed.

Value of the Factor System of Simplicity Index

Adoption of this system by a design group has great value because it directs attention to simplicity values while design work is still in progress. But the really great value is in the fact that it produces a "pure number" similar to Pi, e, or a trigonometric function which has no units associated with it. Even though this number will not have the thousands of years permanency of the mathematical constants, it will be much more useful over a reasonable span, than the cost comparisons obtainable by value analysis techniques without the aid of Simplicity Engineering.

Form As A Simplicity Factor

Consideration of this factor must be with respect to some of the other factors, it is impossible to completely separate out all of the characteristics but on this point the effort is to consider only the form of a component with a minimum of attention to other factors such as size, finishes and tolerances. It is also necessary to consider it with respect to the method of production, for example, a sphere may be considered to be one of the most simple forms that an object can take, only one dimension, the diameter, is necessary to specify the form of a sphere. However, from the standpoint of manufacture in the machine shop, the sphere is far from a simple object to manufacture and it is probable that the cylinder which requires two dimensions for its description, is the most simple machined part. This is because it is necessary in making a sphere first to devise an elaborate forming tool having a concave cutting surface of the radius of the sphere and even after this provision is made there is still a considerable problem in the finishing of the sphere because initially the work must be supported between centers and must be driven by a lathe dog or a chuck. The cylinder, on the other hand, may be supported between centers, turned to the proper diameter with a simple universal cutting tool and if the center holes at the ends are objectionable, they can easily be removed after the part is removed from the lathe by taking a milling machine cut on either end, holding the part in a angle jawed vise.

Another difficulty about the arbitrary rating of form as to simplicity, is a strong relationship to the quantity of a component that is required in any given situation. For example, an item to be made by a casting in a permanent mold or by die stamping, and there is a sufficient quantity to justify the cost of the preparatory work an apparently very complex component may, in fact, be quite simple as to form. In the present case of components for rocket engines to be made up in lots of five pieces because of the expectation of modification after tests, this particular consideration of form rating is not applicable at the moment. However, it suggests that in the redesign phase of these components whenever the performance characteristics are stablized and larger quantities of the components are made in each lot, it will be possible to re-examine the concept of form simplicity in the light of the opportunity to use different processes than are presently feasible. While it may be a long time before sufficient components are required to permit the use of mass pruduction methods such as die stamping, there are processes which are intermediate as to quantity for example, lost wax castings which might be substituted for the method used to make very small quantities of a component.

In accordance with the general proposition of endeavoring to move out of the subjective area to the qualitative or objective considerations in each of the factors of simplicity, it is important to consider those aspects of form which may be counted rather than merely rated by comparison or other methods. For example, in rating simplicity of form it might be possible to establish a subscale which is based upon counting the number of dimensions and possibly classifying these according to the closeness of the tolerances specified.

Another feature of form which lends itself to counting is the number of axes of rotation required to machine a component. Obviously any component which has only one axis of rotation from which all of the turned surfaces may be specified as a radius, is much less complex than another component having two or more axes of rotation with precise distances between them and possibly precise angular measurements of displacement.

Still another feature which greatly increases the form complexity of a component is the number of contoured surfaces. For example, components having only plane or cylindrical surfaces are relatively simple to obtain compared to those which have special curvatures and transitions from the plane or cylindrical surfaces to the contoured surfaces.

Simplicity of form is also affected by features which may be described as special characteristics such as the introduction of a third plane when two principle planes intersect as in chamfering or similarly the introduction of a curved surface at the intersection of two principle planes.

Use of Panels of Judges

After all of the elements of simplicity of form that can be dealt with by counting features as discussed above have been exhausted, it still may be necessary, in order to achieve a distinction in simplicity rating as between two components, to resort to subjective comparisons. For this purpose a series of illustrations will be developed and submitted to a panel of qualified judges who will be asked to rate them according to their relative simplicity as compared one to the other rather than by comparison with any abstract concept of simplicity existing in the mind of a particular judge. In this connection it was found useful to draw upon the experience and research of other fields of scientific thought and engineering, for example, the factor comparison method described by L. L. Thurstone, an eminent psychologist, and used in his field for the comparison of judgments of moral and esthetic values.

As mentioned earlier another fruitful source of guidance for methods in the comparison of judgments where no absolute units are available and where scale end points are difficult to determine is found in the field of industrial engineering where a fairly extensive literature has developed with respect to techniques of, "Job Evaluation" and, "Work Simplification." Rather than break the chain of development of simplicity factors at this point, these techniques are described in Appendix A and may be conveniently skipped by readers who are familiar with them or who do not care to devote sufficient time to make a thorough analysis thereof. It can be stated however that these principles have been applied insofar as feasible in determination of the simplicity rating scales for the simplicity factors.

It is impossible to develop any simple measure or rating number that can be assigned to describe the degree of simplicity inherent in a manufactured part. It was not apparent at the beginning of the study whether it would be possible to develop even a relatively complex rating system on an absolute scale or whether it would be necessary to settle for a purely relative scale analogous to the Mohr, Scale of Hardness, which arbitrarily chooses the diamond as the hardest material and assigns numbers to other materials to indicate their hardness in comparison with the diamond.

Since it was evident that no simple measure of simplicity will suffice, a first objective had to be that of establishing the various pertinent points of view entering into the development of a composite scale of simplicity. For example, a component which might be extremely simple from the point of view of the technician required to assemble it with other components, because of a shape that can obviously be assembled in only one manner thus eliminating all possibility of confusion between right and left hand parts and all possibility of getting a part in place upside down; but this same part might be extremely complex from the point of view of the metallurgist who has to furnish the material or from the point of view of the machinist who has to form it to the desired contours.

Having given attention to the points of view that are properly to be considered in any such rating system as is desired here, new objectives immediately became evident, namely, first to determine whether or not it is possible to combine a series of separate ratings to obtain a single meaningful rating number which could be applied to make a choice between two parts intended for the same function but differing in design. Having determined that it is possible to obtain a combined rating number, the second objective is that of actually devising the best possible system of combination of individual or elemental ratings.

The last and perhaps most important objective is that of putting the system into such form that it can be used in the design of components. To a large extent this objective or requirement explains the present report which had to be sufficiently detailed and contain enough discussion of the methods used to arrive at the final result; to contain references to the authorities consulted; and otherwise be convincing to the executives who must approve the adoption of any system such as proposed here while at the same time the end product must be simple and concise enough to meet the needs of those who will make daily use of it.

Material As A Simplicity Factor

By definition it is considered that a material used in the manufacture of a rocket motor component is simple when it is manufactured from commonly used material such as mild carbon steel or the aluminum alloys now widely used in the manufacture of air frames. These materials are obviously simple because many people have accumulated much experience in handling and fabricating them and they are also quite simple to procure.

At the other end of the scale are materials such as high carbon or alloy tool steels that are extremely difficult to work with because of the necessity for using special processes such as diamond grinding wheels, or spark process forming. Because these complex materials are more costly and less widely used, the fund of experience for fabricating them is much less distributed.

Still higher on the scale as we move from simple to complex materials are special alloys (or plastics or ceramics) which must be made up on special order and which may present difficult problems to the metallurgist in attempting to obtain a batch or heat with precise percentages of alloying elements with small tolerances as to these percentages. An example of this high complexity of material was found in the steel required to fabricate the caps of armor piercing projectiles for anti-tank weapons used during World War II.

In the consideration of the simplicity of materials it is necessary to recognize the fact that materials may at times be complex simply because of the state of the art at any given time. Materials which may be developed for the accomplishment of certain performance requirements of rocket engine components may be quite complex in the early stages of a development only to become commonplace at a later date. An example of this is found in aluminum which was, in spite of the great abundance of this element, a laboratory curiosity prior to the development of the Hall process for the reduction of oxides of aluminum.

In view of the foregoing, it may be stated as a proposition to guide designers seeking simplicity of components that they should use the most simple and abundant material that will permit them to achieve the performance requirements of the component which they are designing. Congruously they should not depend upon an expected future development of the state of the art unless it is absolutely necessary to do so.

Finally, the component designer should also keep in mind that some materials which literally meet the criteria of simplicity discussed above may, in certain instances, be quite complex in a particular application which they are considering because of process or fabricating problems when the particular material under study has not previously been used in the manner in which they propose to use it or any closely related manner.

Design Tolerances As A Simplicity Factor

The design tolerances shown on a component drawing are probably one of the most widely recognized sources of complexity in the fabrication of machined parts. A statement frequently heard in machine shops, design offices and production planning offices, is that cutting down the tolerance allowed on a dimension by 1/2 makes the part four times as difficult to fabricate as previously. It is accepted as a general proposition that as tolerances are reduced along an arithmetic scale, the cost and difficulty of production increases on an exponential scale. Whether or not this is literally true, it serves to spotlight the importance of tolerances as a measure of the simplicity of a machined part.

In spite of the general recognition of the importance of tolerances as a measure of simplicity or complexity, there are certain specific considerations which may apply particularly to rocket engine components such as the fact that parts for which dimensions are specified with extremely close tolerances should be assembled with other parts having close tolerances. In most cases it would seem to be foolish to machine one part to a tolerance of plus or minus one-one hundred thousandths of an inch and then to mate this part with another machined only to the closest one-one thousandths of an inch. Thus it is seen that the introduction of extremely close tolerances of dimensions perhaps beyond the actual need of the situation, tends to promote the use of very close tolerances throughout and that the tolerance of individual elements should not be considered separately from the problem of the tolerances required in the component as a whole.

Another important point on the subject of tolerances is that extremely close tolerances, or in fact any tolerance closer than standard practice in a particular shop involved, may severely limit capabilities of production. Some machines can easily produce parts to tolerances of one-one thousandth of an inch but are completely incapable of obtaining tolerances of one-one hundred thousandth with the result that special machines may have to be procured to execute the work or alternatively that the work may need to be sent to a specialty shop having the equipment necessary to cope with the extremely small tolerances.

With a special reference to the problems of designing and fabricating rocket engine components, is the question of the expected life of an element. This leads naturally into consideration of the question of purposes causing the specification of close tolerances. As an example, a component which is to control the flow of a gas may need to be made on the basis of a metal to metal seal because of the impossibility of finding any gasket material capable of effecting the required seal. This leads to the fact that in some cases simplicity may be achieved by a radically different approach. Instead of searching for methods of fabricating parts with tolerances adequate for the metal to metal seal the effort could be directed to a search for a better gasket material which would permit the use of parts with less stringent tolerance requirements.

This introduces a relationship to another simplicity factor, namely, reliability. However, reliability cannot be considered adequately without reference to the expected span of life or the number of cycles of functioning which may be required. In the case of a rocket engine the total life of a part may be measured in seconds or minutes whereas in the design of components for an automotive engine, close tolerances may be justified as a means of coping with the wear problem over a life of thousands or hundreds of thousands of miles of operation.

Finish Specification As A Simplicity Factor

In general it is expected that most persons knowledgeable in the field of design and fabrication of component parts of rocket or of other engines will accept the proposition that a part where the finish, "as machined" or "as cast" is acceptable, is much more simple than one which requires the performance of additional operations to achieve the specified finish. Similarly, it is expected that it would be agreed that a part is more simple when it has a "self finish" as contrasted with one which must be plated, anodized, passivated, or otherwise given a special finish apart from the fabrication operations. Thus, a part may be highly finished to a definite RMS value by lapping, honing, or grinding and still be more simple than one that requires chemical treatment. On the other hand there are many parts such as galvanized or cadmium plated parts where the purpose of the finish is to resist corrosion and where it is possible to apply the finish directly to the part as manufactured, thus it is possible to purchase a large range of standard bolts, nuts and screws which receive no machining beyond the rolling of the thread and are then cadmium plated for corrosion resistance.

The designer who has the above facts in mind as he progresses in the development of his design is not likely to complicate his parts unnecessarily by finish specifications.

<u>Size As A Simplicity Factor</u>

Size, per se, is not ordinarily considered as a factor of simplicity because of the large number of parts that come within a convenient range of sizes and therefore present no particular problems and because in most instances it is impossible to do any thing about a size requirement. For example, if a very small collar is to be held in place on its shaft by a set screw, this screw may be very tiny indeed and nothing can be done about it except a radical change of the method of applying the collar to the shaft.

Cases in which the size of a component part becomes a factor in determining its simplicity are those in which extremely small parts must be made and it is necessary to resort to the use of microscope or at least powerful magnifying glasses or jewelers loups and require special training of workers and provisions to prevent loss of the tiny parts. This is a condition which is now being experienced in some of the micro miniaturization of electronic parts.

At the other end of the scale, size becomes a factor complicating simplicity when parts become so large as to require unusually large machine tools and handling equipment capable of lifting the large weight of the parts involved. This probably will not apply to most rocket engine components although it may apply to the completely assembled engines because large power requires large units, however, that problem is outside of the scope of this investigation.

Ease of Assembly As A Simplicity Factor

This is one of the criteria or factors specifically mentioned in the Contract and properly so because a designer who gives careful thought to the assembly problems can alleviate them a number of ways. This attention will pay off not only in the original assembly of the device concerned but also in subsequent servicing activities.

Ease of assembly is closely related to tolerances because of the two or three different categories of assembly operations which are:

1. Random assembly - this is the situation when the tolerances of mating parts are selected so that the largest one of a group of internal parts which is within its tolerance will still mate with the smallest one of a group of external parts which are within their tolerance limits. Thus, the assembler can pick up any internal part at random and mate it with any external part also selected at random. This is the preferred method of assembly for mass produced machines, engines and similar items.

Loose tolerances have the effect of producing variations in the tightness of fit of mated parts from one assembly to another but engine manufacturers have been able to hold their tolerances close enough so that this variation is not as objectionable as the extra costs involved in other methods of assembly.

2. Selective assembly - in this case groups of parts to be mated are classified into sub-sets according to their actual dimension and the parts are selected for mating according to these groups. Although all of the parts may be within the tolerances, selective assembly permits closer control of the tightness of fit. Obviously, however, it is a much more costly method of operation. With the small number of rocket engine components to be manufactured and assembled and the high premium on the best possible performance, selective assembly is much more tolerable than it would be in automotive assemblies produced by

the millions. It is interesting to note in passing that some automotive manufacturers of fine engines have used selective assembly to achieve better balance by careful weight matching of pistons, connecting rods, and other moving parts.

3. The third class of assembly operations, now largely outmoded, is what may be called fitting assembly. This is the case in which the assembly workman is relied upon to make the parts fit by the use of files, scrapers, emery cloth, etc. There is very little to be said in favor of this type of design and it is obviously far from simple because the modification of mating parts to make them fit each other results in unknown tightness of fit and difficulty in reassembly when modification or repair of an assembled component is necessary.

There are other special assembly methods such as press fits and heat shrink part fits in which an internal part is cooled while the external part is heated to make it possible to place them together but these obviously reduce the simplicity of the components and should be avoided when possible. When a designer makes use of these methods, it should be done because no other satisfactory solution to the problem has been conceived.

Ease of assembly may also be achieved by the avoidance of right and left handed parts which can easily be confused with each other and by parts which can easily be inserted in the assembly in the wrong position - upside down or backwards for example. The use of fastening devices such as rivets, screws reduces the ease of assembly and the obvious solution is to make as many components as possible in integral or one piece designs. Here, however, there is a good deal of possibility of gaining in ease of assembly at considerable cost in the simplicity of fabrication of the part involved.

The ease of assembly factor of simplicity unlike some of the others needs to be weighed in its importance by the designer according to the use of the component. This is to say that a rocket engine being designed for tactical use which may have to be assembled or disassembled by soldiers or airmen under field conditions may justify more attention to ease of assembly than another rocket engine designed to be used at proving grounds or other scientific installations where they will be assembled or disassembled only by specially trained technicians.

The Simplicity Factor of Tests Required

The term "tests" is used in a generic sense to cover all types of quality control operations, such as measuring dimensions, angles, or other physical characteristics of a part, pressure tests, leakage tests, tests for chemical inertness or the presence of coatings or treatments specified in the design. Obviously a component which requires extensive testing is far less simple than one that is easily determined to have met its specifications. Because of the high performance requirements of rocket engine components, the designer may be constrained to specify numerous tests and simplicity of design with respect to this factor can only be obtained if the designer is thoroughly cognizant of the loss of simplicity entailed by specifying any test that can be avoided without loss of performance characteristics.

Special Treatments As A Simplicity Factor

Much of what has just been said about testing of components applies also to the specification of special treatments, such as, "passivating," anodizing, unusual plating operations, or any other treatments that are rarely used in an ordinary industrial production. Whenever these requirements can be designed out of the specifications of a component, a gain in simplicity has been achieved.

Methods of Production As A Simplicity Factor

This factor refers particularly to two of the items listed in the basic contract to be considered in the study of simplicity, manufacturing operations and process operations. Many points with respect to methods of production have already been touched upon in the discussions of other factors so it will suffice to say here that any method of production which is little known and seldom used constitutes a move in the direction of complexity of a component. This includes, of course, designs which require the invention or development of methods of production that have not previously been known. Such requirements may delay the production of a component and will almost certainly require extensive training of personnel to produce the components.

Within certain limitations it is the responsibility of the production engineer to select or devise the methods of production. however, it is a subject on which there should be close collaboration between the production engineer and the design engineer. If a design engineer proceeds merely to indicate the features of a component which he desires to accomplish a particular function without thought for the production problems that he may create and the production engineer takes such a design without question and proceeds to procure new machinery or operators of special skills, components may be produced that are lacking in simplicity. On the other hand, if the two engineers consult on the problem it may be possible in some cases to make design changes which do not impair function and performance in any way but greatly simplify the problems of production. Of course a design engineer who understands production problems and keeps them in mind as he designs, can greatly lessen the need for modification of designs at the behest of the production engineers.

Stress Levels and Simplicity

Stress levels are specifically mentioned in the contract as a factor to be studied with respect to simplicity and this is interpreted to refer to unit stresses imposed upon materials rather than total stresses on components. This interpretation is used because it is assumed that if a pressure vessel must be designed to withstand a certain internal pressure to obtain the thrust and other characteristics required of the rocket engine, little can be done to reduce this pressure level. This then leaves a designer with the choice of using a thick wall for the vessel wherein the unit stresses will be low relative to those that would be required in a vessel with a thinner wall. However, a compromise must be reached between the lowering of unit stresses by thickening the wall and the limitations of increase in weight and space occupied. It is probable that there is a general factor of loss in simplicity when a design moves to higher unit stresses of materials. The higher unit stresses are obtained by more sophisticated and rare alloys so that a designer who has simplicity in mind should specify high unit stresses of materials only in cases where performance and function dictate the necessity therefor.

Adherence to Recognized Standards

In all design work, unless there are compelling reasons to do otherwise, the designer should make use of existing and recognized standards of features such as material specifications, thread sizes, and dimensions. To anyone with design or shop experience this proposition is so obvious as to almost defeat discussion, nevertheless it is included here because of a desire to make the listing of factors as complete as possible.

The reference to standards must necessarily be considered with respect to the environment where the design is to be executed, for example if parts are to be made in United States machine shops it would be logical to specify a bolt 1/2 inch in diameter and if greater strength was needed the next choice should be 5/8ths. This would be true even though careful calculations indicated that the 9/16ths inch or 0.5625 inches diameter would supply just the required additional strength over and above that provided by a 1/2 inch bolt. Only in the event that weight of the parts or assembly is an over-riding consideration would any thought be given to using an odd size of bolt where by using a standard size (in the U.S.) problems of procurement would be greatly simplified and the bolts could probably be purchased from suppliers who keep stocks of the standard sizes made up in advance. On the other hand, if the work is being executed in France common sense would dictate that the size be chosen and specified in metric units in the standards available in that country.

The same considerations apply with equal if not greater force to specification of materials. Certain alloys and tempers of aluminum or steel bars, rods and sheets are readily available and therefore easily obtained whereas the specification of a different alloy requiring only a few percentage points of variation in the amounts of the chemical constituents of the alloy immediately creates a special problem which might make it extremely difficult to obtain the desired metal.

Multiple Use of Parts

This applies particularly with reference to assemblies. When a component consists of a number of different elements and when a number of similar components are needed which differ only in some specific characteristic, for example, the diameter of the orifice in a valve, it may be possible to use some of the identical elements in a whole series of valves. In some cases an assembly may require right and left handed parts but if it is possible to design these parts in a symmetrical fashion, it may be that the same part can be used on both the right and left hand side by merely turning it over. Because of the small quantity of rocket engine parts to be manufactured, opportunities for the use of this factor of simplification may be limited, nevertheless it is desirable that the design engineer be aware of the importance of this characteristic and make use of it whenever possible. Multiple use of parts may serve to increase quantities to be manufactured and the value of increased quantities is discussed in the next section.

Quantity As A Simplification Factor

As previously indicated in the general discussion of simplicity, quantity may have a strong influence on simplicity. Therefore, even in dealing with components such as rocket engine parts where the total quantity must be limited it is still worth while to keep this factor in mind and to strive for the largest possible quantities or more particularly to anticipate the time when larger numbers of components may be needed and when it will be possible to obtain the contribution that quantity makes to simplicity by having had it in mind from the beginning of the design consideration.

At the other end of the scale, that is mass production, there is the paradox that complicated methods of production may result in simple solutions. This is to say that the complex operation of manufacturing a stamping die and the fairly large cost resulting from such die manufacture are spread over so many thousands of pieces that the simplicity of the situation wherein a part is produced with a single stroke of the press is vastly different from the complex process of making one, two, or a dozen pieces by the laborious method of hand sawing and filing parts when no die manufacture and press set up can possibly be justified.

Summary

The simplicity factors have been discussed here to explain the theory behind their use. In Chapter V detailed descriptions are given to permit designers to match their selections of form, materials, methods, etc. to suggested degree levels.

The discussion of the assignment of weights to different factors will also be found there, together with the actual application of this method of simplicity rating.

Chapter V

Designers' Guide

"Simplicity is the most deceitful mistress that ever betrayed man."

Henry Brooks Adams

As previously indicated in Chapter I this chapter is offered as a separable part of the report which may be duplicated and distributed to working designers, therefore, the remainder of the chapter is designated under the title of "Designers' Guide."

It is well understood among engineers and scientists engaged in all branches of investigation and design that for any given problem the best solution is usually the most simple solution. Although it is true that there are some exceptions to this statement it is desirable that any changes in a design which cause it to move from simple to complex are made deliberately and knowingly for sufficient reasons. The justifications for these statements in part at least, are to be found in the remainder of the report from which this is an abstract. The following then, is a check list which contains the essential ideas of simplicity rating so that they may be used by a working designer while he is engaged in the actual design of mechanical parts, systems, or other elements where it is very important to achieve simplicity.

Check List of

Simplicity Rating Factors

No.	Factor	Degree	Weight	Product
1.	Adherence to Standards			
2.	Ease of Assembly			
	a. Fits and Fasteners			
	b. Putting the Parts Together			
3.	Finish Specifications			
4.	Form			
5.	Material			
6.	Methods of Production			
7.	Multiple use of Parts			
8.	Number of Dimensions			
9.	Quantity			
10.	Size			
11.	Special Treatments			
12.	Stress Levels			
13.	Tests Required			
14.	Tolerances			
15.	Weight			
			Total	

Figure 5-1

Elements of Simplicity

First. it is important to recognize that when we ask the question whether a design is simple or complex the question and answer are meaningless unless we also state simple with respect to what frame of reference.

The first step in becoming familiar with this system of simplicity evaluation which represents an advanced form of value analysis engineering, is to become familiar with the various factors of simplicity. As stated in Chapter IV of the main report it is not expected that these particular factors, or more especially the values assigned to them here and now will always apply. Nevertheless the currently stated factors and values constitute a good basis for departure and for improvement of the system and for its adaptation to particular circumstances that may develop in future design problems.

The first step then is to become familiar with the following design evaluation form which not only lists the various criteria of simplicity but also indicates the weights that have been assigned to each of them. The weights shown represent the opinions of the type to be obtained as the consensus of the criteria of simplicity, chosen by groups of experienced production men. For examples consider the two characteristics of form and material. Every experienced production man knows that a form which includes different diameters of turning of various areas requiring milling, and changes of axes of turning is quite complex from the form point of view. He also knows that in going from one material to another the changes involved often or usually are only changes in the choice of cutting tool material or changes in feeds and speeds. The changes of feeds and speeds may result in the part being in the machining process longer but this may be of small importance with respect to the complex problem of preparing separate tooling, jigs, and fixtures for radical increases in complexity of form.

With this introduction the simplicity rating form should be useful. Sufficient copies of the form can be made available so that each part may be easily rated according to its own inherent simplicity, or lack of it.

Use of The Simplicity Factors

It will be noted that the simplicity factors in the preceding check list were arranged in alphabetical order under the titles used in that list. Each of these factors could probably be renamed by the use of synomyms without changing the basic meaning. However, such changes would change the alphabetical order but this is not an important consideration.

In the following pages each factor is listed with a number of different degrees ranging from three to thirteen in number. A design engineer wishing to evaluate a given design as to its simplicity or lack thereof should consider each of the factors individually comparing his design with the description given under the different degrees to select a degree number which he considers to be applicable to the design being evaluated. It is to be expected that there will be instances in which a design under consideration does not seem to agree exactly with any of the descriptive paragraphs under a particular factor. In this event the evaluator should simply select that degree number whose description seems to follow most closely the design under consideration.

The selections of degree numbers as made should be entered on the evaluation form. It will be noted that in every case the most simple description of a factor is given degree number one and there are no zero degrees, thus every factor must be rated but if it turns out that each factor for a given part is rated in degree number one, the final simplicity score will become merely a sum of the weights assigned to the various factors. Some factors have a greater number of degrees than others have simply because the nature of the characteristic being evaluated is such as to permit finer degrees of differences such as in the case of ease of assembly referring to fits or tolerances and the factor of design tolerance. Some other factors are more difficult to break down and specify by description of different degrees of simplicity to complexity but the system of adding the products of the factor degrees and weights to obtain a final rating of simplicity for a part makes it possible to use different numbers of degrees for different factors without impairing the usefulness of the system in any way.

Note: It is desirable that a relatively large number of rating forms should be available, perhaps in a ratio of four or five times as many as the number of designers taking the rating course.

Factor Degrees and Descriptions

Factor: Adherence to Standards (1)

Degree	Description
1	All elements of the design conform to recognized standards such as those published by the American Standards Association, The American Society of Automotive Engineers, and similar groups. Materials, methods of manufacture, and fasteners are all selected from standard practice.
2	Most but not all aspects of the design conform to recognized standards as described in degree number one above.
3	A design which is mostly non-standard but does have some few elements which are specified according to standard practice as in degree one. This permits the manufacture of the parts to benefit from the use of some standard items or practices even though there is much that is non-standard included in the design.
4	This is the case of a design which has no standard elements.

Factors: Ease of Assembly - Fits and Fasteners (2a)

Degree	Description
1	Loose fit (class 1) - large allowance. This fit provides for considerable freedom and embraces certain fits where accuracy is not essential. It allows random assembly.
2	Free fit (class 2) - liberal allowance. For running fits with speeds of 600 rpm or over and journal pressures of 600 lb per sq. in. or over. It allows random assembly.
3	Medium fit (class 3) - medium allowance. For running fits under 600 rpm and with journal pressures less than 600 lb per sq. in. Also for sliding fits. It allows random assembly.
4	Snug fit (class 4) - zero allowance. This is the closest fit that can be assembled by hand and necessitates work of considerable precision. It should be used where no perceptible shake is permissible and where moving parts are not intended to move freely under a load.
5	Wringing fit (class 5) - zero to negative allowance. This is also known as a "tunking fit" and it is practically metal to metal. Assembly is usually selective and not interchangeable.
6	Tight fit (class 6) - slight negative allowance. Light pressure is required to assemble these fits, and the parts are more or less permanently assembled. These fits are used for drive fits in thin sections or extremely long fits in other sections and also for shrink fits on very light sections.

[1] These degrees are derived from the ASA classification of fits. See French, Thomas E. and Vierck, Charles J. Engineering Drawing, New York, McGraw-Hill, 1953.

Factors: Ease of Assembly (2a.) Cont'd.

Degree	Description
7	Medium force fit (class 7) - negative allowance. Considerable pressure is required to assemble these fits, and the parts are considered permanently assembled. They are also used for shrink fits on medium sections or for long fits. These fits are the tightest which are recommended for cast iron to its elastic limit.
8	Heavy force and shrink fit (class 8) - considerable negative allowance. These fits are used for steel holes where the metal can be highly stressed without exceeding its elastic limit. These fits cause excessive stress for cast iron holes.

Factor: Ease of Assembly - Putting the Parts Together (2b)

Degree	Description
1	A design that has very few subcomponents which may be attached to each other easily and where there is little or no possibility of confusion or of putting things together in a wrong way.
2	A part design that is more difficult to assemble because it has more subcomponents or elements to be put together.
3	The parts are more intricate and require more skill and attention to put them together correctly than is the case in degree one.
4.	Subcomponents are not identical with each other but are so nearly identical that much care must be emphasized to avoid confusing one element with another, or confusing right hand and left hand parts.
5.	A case in which special fixtures or instruments are required to put the parts together correctly such as, delicate torque wrenches or other agencies to insure that the assembly will work correctly.

Factor: <u>Finish Specifications</u> (3)

Degree	Description of Finish Specification
1	The simplest finish - no finish.
2	A less simple finish, such as, abrasive blasting, belt sanding, wire brushing, barrel tumbling, buffing.
3	An average finish, such as, painting, hot-dip galvanizing, terne coating, phosphate coating, blackening by conversion coating.
4	A moderately complex finish, such as, electroplating, anodizing.
5	A complex finish, such as, metalizing.

Factor: <u>Form</u> (4)

Degree	
1	The simplest geometric forms, such as, cylinders, hexahedrons, tetrahedrons.[1]
2	Less simple forms, such as, prisms, pyramids, and cones.[1]
3	Average forms, such as, spheres, tori, and ellipsoids.[1]
4	Moderately complex forms, such as, paraboloids, hyperboloids, serpentines, dodecahedrons, and icosahedrons.
5	Complex forms, such as, hyperbolic paraboloid, clyindroid, helicoid, hyperboloid.

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[1] Pictures of these forms will be found in Thomas E. French, <u>Engineering Drawing</u>, McGraw-Hill, New York, 1953, p. 90.

Factors: Material (5)

Degree	Description of Material
1	A simple, easily procured material, such as, low carbon steel, standard aluminum alloys, or brasses.
2	A less simple material, such as, cast iron, copper alloys, lead alloys.
3	An average material, such as, wood, plastic, ceramics, glass, cast steel, magnesium alloy, rubber, nickel,
4	A moderately complex material, such as, titanium, cadmium, chromium, wilver, tantalum, tin, tungsten, cobalt.
5	A complex material, expensive and difficult to work with, such as, tool steel, gold, palladium, platinum.

Factor: Methods of Production (6)

Degree	Description of Method of Production
1	The simplest method, such as, machining, press brake forming.
2	A less simple method, such as, welding, explosive forming.
3	An average method, such as, sand casting, extrusion, stretch forming, rubber forming (Guerin process).
4	A moderately complex method, such as, shell casting, permanent mold casting, centrifugal casting, investment casting, forging, drawing.
5	A complex method, such as, die casting, powder metallurgy, piercing and blanking die work.

Factor: Multiple Use of Parts (7)

Degree	Descript on
1	Where a design consists of a number of subcomponents or elements but they are identical with each other either in their entirety or perhaps half are of one type and the other half is a different type.
2	A design which has some parts that are used on a multiple basis and some which are entirely different from any other parts in this design or other designs.
3	Parts designs which have no identical parts within the design but where the parts are identical with those used, in part at least in another rocket engine component.
4	A design in which the parts are all different from each other and are not known to be identical or very similar to any parts used in other rocket engine components.

Factor: Number of Dimensions (8)

Degree	Description of Number of Dimensions
1	An object having simple linear dimensions and not more than three or four of these.
2	An object having six or eight dimensions or less and still limited to linear dimensions.
3	An object having a number of linear dimensions as in the previous degrees but also having angular dimensions expressed in degrees and radii expressed in inches or centimeters.
4	An object having the characteristics of the previously described degrees but with the additional complexity that the point of origin of some of the linear dimensions or angular dimensions are dependent upon surfaces that will not become available to measure from until after the object is partly fabricated.

Factor: Quantity (9)

Degree	Description
1	Parts that must be made on a strictly one of a kind basis only one unit is used in each rocket engine component and only one component is called for at the time of the designer's work.
2	Parts that are required to be made in lots of five to ten units thus permitting some advance on the learning curve.
3	Parts that must be made in quantities of forty to one hundred because a given rocket engine may be duplicated on the vehicle several times and because each engine contains several of the parts under question, thereby permitting the use of jigs and fixtures and an approach to mass manufacture techniques.

Factor: Size (10)

Degree	Description of Size
1	Small - greatest dimension of part from 0 to 1 inch.
2	Medium - greatest dimension of part from 1 to 12 inches.
3	Large - greatest dimension of part from 12 to 72 inches.
4	Very large - greatest dimension of part from 72 inches and over.

Factor: <u>Special Treatments</u> (11)

Degree	Description
1	A component which has absolutely no special treatment required.
2	Parts which require some special treatment during manufacture or fabricating but such treatment is not so unusual as to present great problems. Example: The sintering of pressed green shapes in the powdered metal forming process.
3	Cases of where the operations required to fabricate a part are very new or unusual such that specially trained personnel and, or, it is likely that a number of experimental pieces will be required before successful fabrication of a satisfactory unit. Example: Parts requiring assembly by the electron beam welding process.

Factor: <u>Stress Levels</u> (12)

Degree	Description of Stress Level[1]
1	0-60,000 psi tensile strength, such as listed for cast iron, structural steel, aluminum, copper, and magnesium alloys.
2	60-120,000 psi tensile strength, such as listed for cold rolled steel, stainless steel 18-8, some brasses, and monel metal.
3	120-180,000 psi tensile strength, such as listed for steel SAE 1300 quenched and drawn 1000° F, certain steel castings, heat treated, and some phosphor bronze.
4	180-240,000 psi tensile strength, such as listed for steel SAE 1300 quenched and drawn 700° F.
5	240-300,000 psi tensile strength, such as listed for steel SAE 4340 quenched and drawn 400° F.

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[1] Values taken from Marks, Lionel S., *Mechanical Engineers' Handbook*, McGraw-Hill, New York, 1952, p. 397.

Factor: Tests Required (13)

Degree	Description of Test Method
1	The simplest tests using simple instruments and procedures, such as, steel rules, calipers, combination sets, radius gages, stress coat.
2	Less simple tests using micrometers, vernier gages, mechanical hardness testers.
3	Average tests using plug, ring and snap gages, angle gages, thread gages, microscopes, optical flats.
4	Moderately complex tests using comparators, magnaflux, zyglo.
5	Complex tests using precision gage blocks and dial indicators, ultrasonic methods, X-rays magnetic.

Factor: Design Tolerance[1] (14)

Degree	Description
1	$\pm$ 1/8 Smallest tolerance possible for forgings from 10 to 60 lb weight.
2	$\pm$ 1/16 Smallest tolerance possible for forgings from 1 to 10 lb weight. Also for dimensions having no effect on the function of the part on parts 18 in and larger and for medium size sand castings.
3	$\pm$ 1/32 Smallest tolerance possible for forgings from 0 to 1 lb and for small sand castings. Also for dimensions having no effect on the function of the part on parts 6 to 18 in.
4	$\pm$ 1/64 Smallest tolerance that can be held on small and medium size die castings and plastic moldings. Also for dimensions having no effect on the function of the part for sizes 0 to 6 in.
5	$^{+.015}_{-.000}$ Smallest tolerance that can be held on drilled holes from 1 to 2 in. in diameter, on lathe rough turning of diameter of 2 in. or larger.
6	$^{+.010}_{-.000}$ Smallest tolerance that can be held on drilled holes from 3/4 to 1 in. in diameter, on lathe rough turning of diameter from 1 to 2 in.
7	$^{+.008}_{-.000}$ Smallest tolerance that can be held on drilled holes from 1/2 to 3/4 in. in diameter, on lathe rough turning from 1/2 to 1 in. diameter and finish turning of 2 in. or larger diameter.

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[1] This section is derived from French, Thomas A. and Vierck, Charles J., Engineering Drawing, New York, McGraw-Hill, 1953, p. 377.

Factor: Design Tolerance (14) Cont'd.

Degree	Description
8	+.005 -.000 Smallest tolerance that can be held on drilled holes from 1/4 to 1/2 in. diameter, on lathe rough turning from 1/4 to 1/2 in. diameter, finish turning of 1 to 2 in. diameter, on most milling work.
9	+.004 -.000 Smallest tolerance that can be held on drilled holes from No. 1 to No. 29.
10	+.003 -.000 Smallest tolerance that can be held on finish lathe turning of 1/2 to 1 in. diameter, on milling single surfaces, on broaching of surfaces 1 to 4 in. apart and 2 to 4 in. diameter.
11	+.002 -.000 Smallest tolerance that can be held on drilled holes from No. 30 to No. 60, on finished lathe turning of 1/4 to 1/2 in. diameter, on broaching of surfaces up to 1 in. apart and diameters 1 to 2 in.
12	+.001 -.000 Smallest tolerance that can be held on broaching of diameters up to 1 in., on reaming of diameters from 1/2 to 1 in., on broaching of diameters up to 1 in.
13	+.0005 -.0000 Smallest tolerance that can be held on reaming of diameters up to 1/2 in. and on both cylindrical and surface grinding.

Factor: Weight (15)

Degree	Description
1	0.5 to 3.0 pounds.
2	0.1 to 0.499 pounds and 3.01 to 15.0 pounds.
3	15.0 to 40.0 pounds.
4	41.1 to 100.0 pounds.
5	100.1 to 1000.0 pounds.
6	0.01 to 0.099 pounds.
7	0.5 to 2.0 tons.
8	2.1 to 20.0 tons.
9	20.1 to 100.0 tons.
10	Excess of 100 tons.

The Assignment of Factor Weights

Two possibilities exist in the application of weights to the simplicity factors. In one case the supervision of any given design operation might determine a set of weights which are believed to apply to the factor degrees for all kinds of designs. In such a case as mentioned elsewhere it would be possible to print the weights on the evaluation form, however it is now believed that a better result will be obtained if the weights as well as the degrees are made variable. To some extent the weight assigned might be influenced by the degree assigned for a particular design and factor.

An example of the foregoing might be taken from the experience of the Western Electric Company. The design of a switch to be sealed inside a glass tube and to be actuated by a magnetic field created by a coil applied to the exterior of the tube required a very special magnetic alloy for the fabrication of the moveable reed to be placed inside of the tube. The metallurgical laboratory of the Bell labs experimented until it had designed a suitable magnetic alloy but the material could not be obtained from any commercial source. The Bell System, that is the Western Electric Company, had one of the specialty steel manu facturers to prepare a small heat of the metal and to pour an 800 pound ingot.

This was then rolled into strip forms suitable for the manufacture of the special switch leaves. As a result the first few thousand switches to be made were very costly, but it was anticipated that as production proceded the special difficulties would dimenish and the project would become economical. In evaluating the design in such an instance as this both the factors material and the weight of that factor would necessarily carry large numbers and regardless of the degree and weights assigned to other factors the design would come out with a relatively high total number on the simplicity index, reflecting correctly the fact that this was by no means a simple design. Parenthetically it might be added that experience in the fabrication of the switch reeds developed the fact that the material was characterized by a large "spring back" which was also variable in nature so that the item was far from simple with reference to the fabrication aspect as it was difficult to design a die to "over bend" enough to compensate for the large variable spring back.

It is important to note that in commercial production such as this the simplicity rating of the design will no doubt change to a lower number when the development stage is completed. The part will then be scheduled in lots of tens or hundreds of thousands. In general some designs may tend to progress toward lower simplicity rating indices, as the parts progress from the exotic to the commonplace. Other parts, e.g., those that require exceedingly precise work on small pieces in a "white room" may always retain complexity.

Discussion and Study of System

As soon as the simplicity rating forms are distributed to the group of working designers in training, it is to be expected that there will be numerous complaints, criticism, or even statements of rejection of the concept. This is a natural reaction because of the innate human tendency exhibited in various degrees by all persons to be distrustful of anything new or different from the practice that they have been accustomed to.

If you find yourself having difficulty in accepting the idea of factor ratings of simplicity the best thing to do is enter into a discussion with some of the other trainees. The following list of probable questions or objections and useful answers to them may be helpful. It is suggested that there not only be an effort to find answers to these questions and objections but also to consider whether they have any self-validity (since the questions are being provided here in the manual you do not have the embarrassment potential of criticizing a question proposed by a good friend or a superior.) It is also suggested that the discussion be directed to considering whether the suggested answers given here are valid, unique, or in general the best ways of dealing with the questions. It is suggested that early in the period of study of the rating system it would be helpful if each member of the training group would read sections from "Professional Creativities" by Eugene K. Von Fange of the General Electric Company which was published by Prentice-Hall in 1959.

The Appendix II on page 235 by Paul R. Lawrence is particularly interesting with respect to the question of changing methods.

Discussion Questions on Rating System

QUES. 1. There is no need for a system of simplicity rating any good designer can review his designs and see points wherein they might be simplified.

ANS. 1 Experience of large manufacturing companies and of industrial engineers over the decades does not bear out this contention. For example Rocketdyne, a division of North American Aviation, Incorporated, publishes a "Handbook for Design Review." Although this particular handbook is prepared by the "Reliability Design Review" section at the Canoga Park California plant and deals primarily with reliability much of the discussion pertains equally well to both simplicity review and value analysis review. An important feature of this handbook is the presentation of numerous check lists for example the check list for functional parameters dealing with such aspects as, mechanical, electrical, and environmental contains more than seven and one half pages of questions to be answered with respect to a particular part design.

Quotation from the introduction "Because reliability must be inherent in the design and can only be improved by design changes improvement must be made early. Certainly it is axiomatic that the design engineer has the primary responsibility for the design and, hence, the reliability of the end of product. However the rapidly changing state of the art, the many and varied engines being produced by Rocketdyne, the long lines of communication and the continued influx of new designers lacking extensive experience make the services of the Design Review Board invaluable."

Another booklet with a different approach but directed toward the same end is that put out by the Lockheed Corporation Missle Systems Division entitled "Designing for Electronics Maintainability." Although this booklet is somewhat humorous with numerous cartoons it asks many pertinent questions and calls the attention of designers to some aspects of the problem of maintaining electronic gear in field service which should be considered by the design engineer as the equipment is planned.

When Frederick W. Taylor introduced the idea late in the nineteenth century of having shop planners to designate machines to be used, tool formations and feeds and speeds there were many who decried the idea saying that any good machinist should know all these things and should be able to do his own production planning as he went along. Today, however, there are few large shops that do not operate on the basis of route sheets which schedule particular jobs to certain machines and prescribe the tooling and other details of production.

QUES. 2. How do we know that the list of simplicity rating factors given in this system is the correct one? Are there not too many different items listed? Is it not true that some of the factors chosen overlap or imply some others in the list, for example number four form, and number eight, number of dimensions seems to represent a redundant situation?

ANS. 2 (a) It is desirable to keep the number of rating factors in any system such as this as small as possible. Psychologists use similar rating systems for such things as personality ratings and experiments have demonstrated that it is as possible to obtain good results from a small number of factors as from a larger number. However, it is logical to use the factors specified herein and their presence on the rating form serves as a check list so that none of them will be overlooked.

(b) There is no contention that this particular list of factors is the best one that could possibly be developed, it is even anticipated that in application of this rating system some design groups might develop different lists either by using different names for the qualities suggested here or by considering totally different qualities. The important thing is that for any design group working with an agreed list of factors, it is the utilization of a system of factors, that is more important than the particular factors used.

QUES. 3. Why are different factors assigned different weights?

ANS. 3 Some of the factors are much more critical in determining the simplicity of the design than others are moreover the same factor may have different weights for different degrees. For example, the factor size may be relatively unimportant except when a part becomes so large as to require extensive special handling facilities or when it becomes so tiny that microscopes must be provided for working with it.

QUES. 4. How can a design group develop a reasonable amount of uniformity in ratings made by different designers?

ANS. 4 One good way would be to select several different designs and have each of the members of the group to rate it individually using the rating form provided and working without consultation or discussion with other designers.

At the end of this operation the designs can be exchanged and each member of the group asked to either concur or criticize the ratings made by his colleagues. This activity would naturally lead to round-table discussions in which the reasons for assigning particular degrees and weights for each factor.

QUES. 5. Should a simplicity index determined in one design group agree with that arrived at by a different group?

ANS. 5. This is a matter to be settled by the managers of each organization. It is probably impossible to expect to achieve complete uniformity of practice, and doubtless of little value to do so. If the design groups being compared are within a given larger organization, as in the parts of a large governmental agency operating at different locations, or parts of a multi-plant company, agreement of indices may have real value.

As indicated in the discussion of factor degrees and weights, what is simple for one shop may be quite complex in another. An example is to be found in Factor 10, Size. At the time of rating a particular design for production in that shop where material handling facilities are limited, a large weight may be given to a degree of 4.

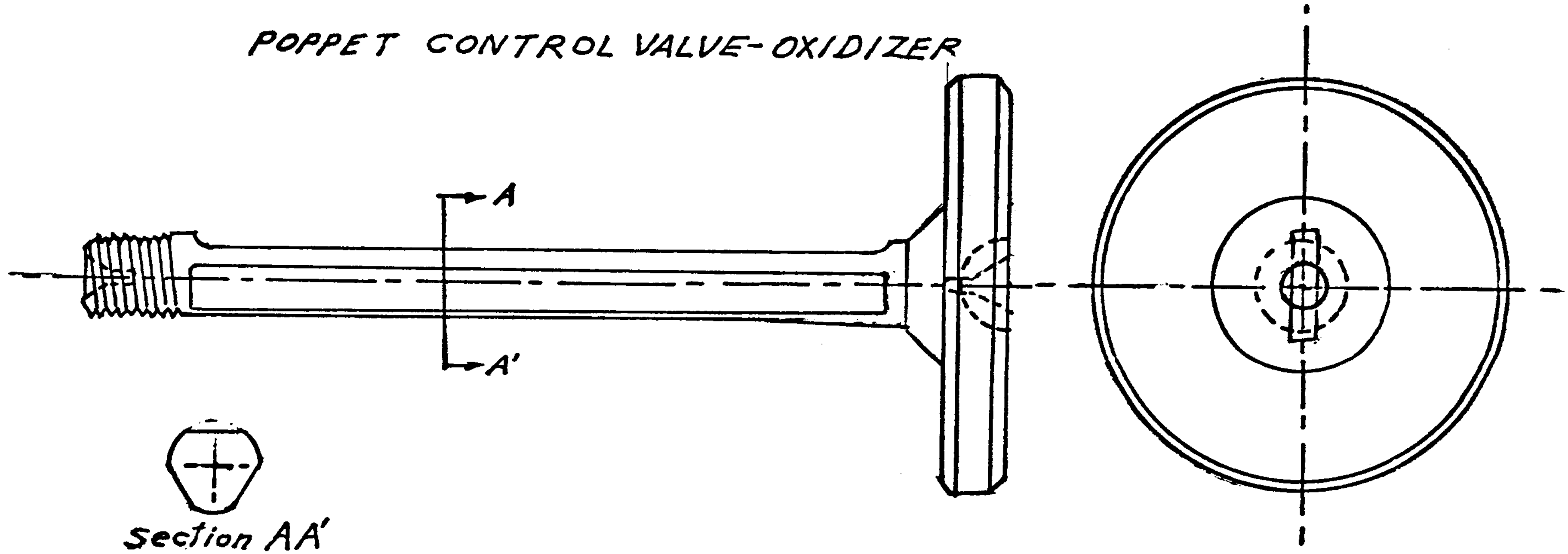
In another shop which has specialized equipment for large pieces, the weight assigned would be much lower. Also, the shop for which a part was rated high because of Factor 10, might have the rating reduced after the installation of adequate equipment.

QUES. 6. If a simplicity index can vary from shop to shop and from time to time as described above, of what value is it?

ANS. 6. Application of the simplicity engineering concepts during the process of developing designs, or as a review procedure, directs attention to those points which may be unnecessarily complicated. It can cause a considered decision on a design feature which vitally affects simplicity and therefore cost and availability, in place of a situation allowed to drift by chance because of divided responsibilities.

QUES. 7. What is an actual example of the application of the Simplicity Engineering principles described here, to a particular part design?

ANS. 7. As a basis of discussion, we will use, Poppet, Control Valve-Oxidizer, Gas Gen. Ass'y, of which is taken from one of the drawings supplied by the Propulsion Division of NASA. This is a relatively simple example, and the use of it here is not intended in any way to be a criticism of the design. It is used only to show how a designer might apply Simplicity Engineering Concepts in the course of his daily design work. In Figure 5-2 it is seen that this at first glance appears to be a rather simple poppet valve, similar in many respects to the valves in millions of automobile engines. Closer scrutiny, however, reveals the presence of a "key slot" in the outside flat surface of the head, flats on the sides of the stem and a threaded portion on the small end of the stem opposite the slotted head, plus a slot on this stem end. Obviously, all of these features make it much more complex than an automobile engine intake or exhaust valve. There is no intention here to criticize these features; as mentioned above, it is used only as an illustration of the ways in



Scale Double Actual Size

Drawing Number Illegible On Copy Supplied

Figure 5-2

which a working designer can ask himself questions to improve the designs that he turns out.

Any Engineering Draftsman, who has not served time in a machine shop or a tool-room, has a serious dis-advantage which will always plague him whether or not he is interested in Simplicity Engineering. One way to reveal the complexity of a part like this one is to review a hypothetical "Route Sheet" for the manufacture of this item. As mentioned in other parts of this report, it must be recalled that there are different ways of doing many tasks, so that this suggested solution of the machining problem may not be that exact one which would be selected by knowledgeable readers.

Routing Instructions for Poppet Valve

1.0 Engine lathe or (small turret lathe) with collet for 1 1/4" Round Bar Stock.

1.1 Feed bar through collet to expose 3.25" and clamp. (Collet is at workman's left hand.)

1.2 Face exposed end of bar. (On second and successive pieces the facing operation is already done by the cut-off tool on the preceding piece.)

1.3 Mount taper shanked No. 3 Center Hole tool in tail stock and advance to make center hole. (On turret lathe index turret to bring center tool into position.)

1.4 Replace Centering tool with Live Center, (Ball-bearing type) and advance to support work.

1.5 Advance turning tool in cross slide, starting at faced end, turn to a diameter of 1.09" for a distance of 2.90" toward the collet.

1.6 Starting 1.60" to left of faced end, turn down to a diameter of 0.480 for a distance of 2.74" to the left.

1.7 Starting 0.317 to left of faced end, turn down to a diameter of 0.263 for a distance of 2.583" to the left.

1.8 Use forming tool "X" to make thickness of valve head 0.156" and recess back of head to diameter 0.240" ± 0.010" with 45 degree chamfers, as shown.

1.9 Use other side of forming tool "X" to chamfer 45 degree on faced end, reducing diameter of flat portion to 0.962".

1.10 Use forming tool "Y" in cross slide holder, feeding toward right to make recess on stem side of valve head.

1.11 Use forming tool "Z" to turn diameter of stem to 0.2490 + 0.0000 - 0.0050.

1.12 Use threading tool to cut 1/4-28 UNF-3A thread on end of stem, minimum 0.535 full thread. Pitch diameter of 0.2258.

1.13 Use cut-off tool to obtain overall length of valve at 2.763" and at the same time facing bar for next piece.

2.0 Milling Machine, (any small but accurate machine, even a 'hand-miller' will do.) Place valve, head up, in box fixture "H" which has previously 'located' on table.

2.1 Raise table to cut 0.31" radius circular slot in head 0.094" wide, centered on the axis of the valve, to a depth of 014".

* * *

It becomes very tedious to recite all of the many operations necessary to fabricate a simple (?) part like this valve. There are twelve more operations on the milling machine, involving the use of a second box fixture, and then the piece must be put on a sensitive drill press for two more operations. It is possible that a very expert machinest might dispense with the fixtures, using only a vise with "V" slots, but the indexing of the stem by exactly 120 degrees to cut the flats could cause him trouble.

QUES. 8. This system is too complicated with all of these factors, different degrees in each, and on top of that the weights.

ANS. 8. Personnel people have been coping with similar situations for a long time. Just looking at the fact that there are 15 or more factors which may be examined with reference to the simplicity, or lack of it, in a mechanical design, may well lead to the thought that this is a very complex approach, but considering the old Chinese proverb that a journey of 1000 miles begins with a single step, observe that only one characteristic need be examined at one time.

It is precisely because of the difficulty of trying to view all aspects of a problem at the same time, and to reduce the "Halo Effect," that the practice of considering only one, more or less narrow item at a time was introduced. No matter how complicated a situation is, it may be simplified by the method of concentration upon one element or area of the problem at a time. This is the method by which the developers of Job Evaluation techniques were able to cope with very complicated jobs and make them comparable.

It is also important to realize that many techniques which may appear to be very complicated and difficult when first introduced, turn out to be simple after a little experience in working with them has been developed.

As previously mentioned, it is impossible, from this point of view to criticize the design because the drawing gives no information about the reasons for the various chamfers, flats and slots. However, it should be obvious that just a few simple lines on a drawing may easily double the time required for manufacture. Unless there is a compelling reason for each feature, it should be omitted. In the case of this poppet valve, the drawing specifies as material, a section of "bar stock" large enough to carve away about 85 to 90% of the metal purchased to leave the desired shape of the valve. In the circumstances this is possibly the only practical way to make the valve, but in an auto engine, where millions or at least hundreds of thousands would be needed, the possibility of forging the stem and head on an Acme Upsetter or similar machine would certainly be investigated.

It should be noted that most companies have printed forms for their route sheets showing in specified spaces, the drawing number, parts number, numbers of the machine to be used, quantity and tool numbers, for each job. In a case such as this where the part will be worked on a lathe, milling machine and a drill press, there would be three separate route sheets to correspond with the different machine tools.

Because of the lack of much information that would be available to the designer of this part, no further attempt will be made to select the degrees and assign weights. Consideration of the necessary operations for manufacture indicate that the degrees will vary, and that the actual designer could readily determine the total simplicity number.

CHAPTER VI

Industry Views of Simplicity

"To laugh at men of sense is the privilege of fools."

Jean de la Bruyere

To determine what is being done in industry with respect to simplicity of designs, letters were sent to companies expected to have experience and interest in such a line of inquiry. This was done because it is likely that some engineers doing important work in the area of design review and many other busy men in industry do not take time to write articles for the journals or to prepare books. The letter was sent to 150 companies selected from a list of the 500 largest manufacturing companies published by Fortune magazine each year. Only those companies believed to be engaged in metal goods manufacturing were selected and textile or trading companies were deliberately excluded excepting some very diversified organizations. There is of course no reason to believe that only the largest companies may have developed research in simplicity engineering, in fact some much smaller companies may have made notable progress in this direction, on the other hand it was reasoned that the probability of finding such research in the large companies was equally as good as among smaller companies, and further that the larger companies would have the interest and resources to carry on correspondence on this subject. As stated elsewhere in the report an extensive search of the literature was also made to determine if there had been any previous studies or investigations of simplicity engineering. However, it was found that very few references deal directly with simplicity of mechanical design.

The response was rather astonishing and a summary of the correspondence experience is given in Table 6 - 1 below.

Summary of Correspondence		
	Numbers	%
Letters mailed	150	100
Replies received	58	39
No answers received	92	61
Useful replies	43	29
Replied, but no contribution	15	10

Table 6 - 1

No specific questionnaire was sent out because it was felt that this would be too restrictive upon the statements of those who chose to respond to the query, instead the brief on rating simplicity which is appended to the end of this chapter was sent.

Analysis of the 58 letters (or approximately 40%) received in reply to the query resulted in classifying 43 (or 28%) of them as useful and 15 as nonresponsive. The nonresponsive category was defined to include those replies which wished us well in the study and regretted that they did not feel in a position to make any positive contribution at this time, although a number to them requested that they be permitted to see the results of the study when it is completed.

Careful analysis of the 43 letters that were considered useful, led to the indentification of 63 different statements or questions in response to the idea of simplicity engineering. In addition to the letters per se (some of which ran to three pages of discussion,) a number of companies sent in supplementary literature, such as pamphlets developed for intercompany circulation, instructional memoranda and other documents bearing on the topic.

Although a number of companies did write and offer permission to quote their comments the time available for this phase of the inquiry did not permit contacting all of the companies whose statements might have been quoted and it was therefore decided not to make any specific quotes, at this time, of company statements. Rather some of them which were particularly penetrating and pertinent to the study have been paraphrased and included herein as anonymous statements.

It does not necessarily hold true that the largest companies are most likely to be engaged in a related research program, or to have developed something of value for this work. However, many of them are in a position to benefit from a system of orderly appraisal of mechanical designs. Also, they have the resources to permit them to follow up on promising lines of investigation.

The chief officers of each selected company were looked up in Moody's Directory of Corporations, and the letters were addressed to individuals, asking them to put the matter in the hands of the proper persons, in their organizations. As might be expected in any such broadside attack as this, some of the inquiries fell into the hands of men who wrote back that they were not engaged in any phase of rocket engine work and therefore could not offer any help. Such replies were more than offset by many others who grasped the ideas involved and wrote two and three page letters.

In some instances the director of this project wrote back to the companies for clarification of certain points and further correspondence resulted. On the other hand, it is also important to note that most of the replies received were from vice-presidents, chief engineers or other responsible executives of the respective companies and that the answering of this query had, for the most part, not been assigned to some less experienced employee.

It was possible to find a great deal of agreement in the ideas expressed by the respondents, when the letters were analyzed in detail. For example 20 respondents expressed a belief that a simplicity index rating, and the development of doctrine of simplicity engineering to determine such ratings has much potential value. At the same time, 16 said they were already making use of the techniques of value analysis, and thought it to be an adequate substitute. There was some difference in the exact terminology used, i.e., Value Analysis Engineering, Value Engineering, Value Analysis Studies, etc., but there is little doubt as to the meanings intended in their statements. Moreover, 9 indicated that they felt that value analysis, by one of its several names, provided them with all of the design audit that they need.

Altogether, 43 correspondents expressed a total of 206 comments, or an average of 4.8 specific comments per letter. These have been carefully tabulated and the results are summarized in Table 6 - 2. It will be noted that there were just 14 different points or questions which were mentioned by five or more respondents. Thus, there were 49 other ideas expressed four or less times each. The fact that a particular thought seemed important enough to four or less people, or occurred to four or less persons, for mention in their replies does not, of course, supply a complete measure of its importance. Therefore, the following pages will contain quotations, or paraphrases of a number of items that would not turn up in a review of the letters that was limited entirely to a statistical report.

It is obvious that an analysis of a group of letters such as is reported here contains a very large subjective element. Another competent observer reading the same group of letters might very well come up with a different set of comments. On the other hand the lack of complete objectivity is not as serious as it might at first appear to be. If a total of 16 companies, out of 43 respondents include such phrases as, "We depend upon our Value Analysis Group for the type of service you have described," or "We have referred your letter to our Value Analysis supervisor," the fact that 37% of the companies responding have value analysis activities of one type or another is quite objective. While it is true that some of these may have larger, better organized Value Analysis groups than others, this is beside the point.

Relations With Responding Companies

In the letter of inquiry the companies were assured that there was no desire to obtain information about any proprietary procedures which they might be using for competetive advantage and that they would not be quoted specifically without their permission. All of the companies with which ideas were exchanged were told that none of their comments or information would be quoted in this report without obtaining their specific permission to do so. As stated above, it is not the fault of any of the companies who were so generous in their cooperation that correspondence with them was not pursued more vigorously. Seven of the companies, or 16% sent valuable documentary material concerning their methods of handling value analysis and design review problems. One company wrote a later letter approving, carte blanche, quotations from their correspondence and the extensive documentary contributions that they had made.

Some of the engineering vice-presidents and other supervisors were so enthusiastic about the possibilities opened in this line of research that it is planned to correspond further with them after the preparation of this report has been completed. For the men who may chance to see a copy of the report when it is published, before there is time to write them again; a most hearty thank you is expressed here. Ten of the respondents requested that copies of the report be sent to them, and it is planned that this will be done.

Since this report can cover only the first or introductory phase of simplicity rating, or simplicity engineering, it is expected that the industry contacts and interest will be a good deal more valuable in follow-on work than at present. An example of this situation is that no matter how successfully the development of an initial list of factors of simplicity is completed, there will be opportunities to improve it by the collective wisdom of groups of working designers. Of course the same comment also applies to the descriptive phrases assigned to each level of the factors used and the weights allocated to each factor.

As was indicated above, some of the respondents failed to see any distinction between simplicity engineering and value analysis (as identified under several different titles), and some of these expressed a belief that their value analysis activities would supply all the answers that they might need. Figure 16-2 contains a summarization of 14 different points which were repeated many times in the replies received. It is significant that 20 of the 43 respondents stated that they recognized the value of simplicity engineering even though they might go on in the remainder of their letters to point out numerous difficulties in putting it into practical application. It is also interesting to note that a number of the respondents confused simplicity engineering with reliability engineering or that they thought a good reliabiltiy engineering program might make it unnecessary to consider such a thing as simplicity engineering.

A most interesting reaction obtained from six of the companies was to deplore the idea of introducing a new discipline. Obviously these writers are very conscious of the organization structures of their companies and visualize the complication thereof by the introduction of a new branch of engineering under the title of simplicity engineering. Some of them seemed prepared to dismiss the whole idea on account of this fancied difficulty while others recognized that simplicity engineering could be a tool used in the value analysis department or section, where they already had one in their organization structure, and would not necessitate the employment of additional engineers and engineering supervisors.

On the whole, the keen perception of the importance of the simplicity concept exhibited by many of the respondents was very gratifying and on the basis of this small sampling it can be stated that the operations of these large organizations contacted are being guided by very astute thinkers. It is further believed that in those cases where a response appeared to miss the point of inquiry completely, it was very likely due to semantic differences rather than a real difference in basic thinking.

To the extent that it was possible, the reactions of men concerned with design problems were sought out in personal interviews, and are reported with the letter responses, because the ideas expressed by the respondents to the requests for reactions provided the basis for leading questions in the interviews. For example, Captain William J. Firoentino, U. S. Army, Ballistic Missile Command, Redstone Arsenal, pointed out that the question of simplicity of a system is just about inextricable from the functional requirements. He used the automobile as his example, as in the early days of auto travel, exposure and discomfort were expected by those who traveled in this manner. Today, however, it is expected to provide controlled temperature, or at least protection from rain and dust. Thus, with the demand for increased functional capability, no amount of design improvement can possibly make the modern auto as simple as the old model "T" recalled so fondly by those who conveniently forget its shortcomings, such as the lack of the windshield wipers. This same general point was expressed in a variety of ways by a number of the engineers who answered the letter query.

The importance of care to avoid being enmeshed in semantic problems is illustrated in the remarks of one writer who states that his company is engaged in a simplification program. However, he goes on to explain that their endeavor deals with the fact that over the years they have had such a proliferation of products and sizes in their production line that they must reduce it to manageable proportions. Fortunately, he recognized at once that this is quite a different thing from finding an index of simplicity of designs, and commended our effort.

Still another correspondent discusses design simplicity in very narrow terms, excluding the selection of a material, or the methods of fabrication from the responsibilities of the designer. However, he was alone in this approach as others clearly indicated their agreement with the proposition that it is the job of the designer to decide all of the pertinent questions about the shape, size, material, etc., of the parts assigned to him, and that product design engineers and production engineers must work closely together and concur in all changes made.

Further Analysis of Comments

In line with the policy of not sending out a specific questionnaire, no advance effort was made to prepare a list of points or questions to be watched for in reading the replies. Instead, as the letters were read, the points made by the correspondents were jotted down on scratch pads, and an effort was made to match up those that were expressing the same ideas even though they did not use precisely the same words to do so. Ordinarily, in reporting an investigation such as this one, it would be sufficient to state that X number of companies were contacted and the tenor of their replies was ---. In this case, however, it is felt that the reader is entitled to a more complete revelation of the actual responses received, in order that he may make his own judgements as to the acceptance or rejection of the basic thesis. Therefore, the actual comments, questions, or points raised in the letters of response are summarized in Table 6-2, which contains a generalized or paraphrased statement of the correspondents wordings in their letters, together with the frequency of each.

Statement	Company Statements Frequency
1. Our company is now using the value analysis method.	16
2. We believe that value analysis techniques are all that we need for our designers.	9
3. We are committed to the importance of individual ingenuity in machine design.	1
4. It seems to us that other methods that are now in use can do the same job as you propose for simplicity engineering.	5
5. The references listed herein may help you.	7
6. There is enclosed booklets, (memos, directives, drawings, etc.) which you may find useful.	7

7.	There is no doubt a great deal of potential value in the Simplicity Engineering concept and we hope that you will work it through.	20
8.	Because of the different possible approaches to simplicity you may need to develop a two component system.	5
9.	The simplicity analysis must be related to the skills and knowledge of the individuals concerned.	2
10	We wish you well in this endeavor and we would like to arrange to see the results of the study.	20
11.	We are preparing a package of material which we believe to be pertinent to your studies and which we will forward soon.	4
12.	As we see it, simplicity is a relative term, and perhaps cannot be quantified.	2
14.	The facilities required to obtain specific results at a minimum cost are often very complex.	1
15.	Factor analysis methods require weightings of the points.	6
16.	Creativity cannot be standardized or optimized.	1
17.	Simplicity must be determined on a case by case basis. (This is what we propose, but he failed to note this point.)	1
18.	However desirable it may be, we doubt that it will be possible to develop an index of simplicity.	1
19.	Our I.E. operations are based upon an application of common sense, and, therefore, will do what your Simplicity Engineering method would do.	1
20.	Work Simplification is the "Touchstone" and a good application of this technique makes it needless for us to master a new approach such as your Simplicity Engineering is not needed.	1
21.	Simplicity is not an end in and of itself.	2

22.	In our organization, design engineers, production engineers, and quality control engineers, are all aware of the importance of simplicity, so we have nothing to be concerned about in this area.	2
23.	Our value engineers include the simplicity of a design in their reviews, as a prime factor.	1
24.	Simplicity is like value in that it is not defined in an absolute sense.	1
25.	We are already using a reliability program.	7
26.	We already have a maintainability program.	2
27.	We now have a product safety program.	5
28.	Simplicity is an important goal in our operations, as all our engineers agree, but how to define it is the problem.	5
29.	We agree with the factor approach in analysis of simplicity, but a very large number of factors will be required.	1
30.	We believe that the dollar is the best common denominator to compare designs.	3
32.	We will be pleased to assist you, particularly in reference to the following aspects of the problem, ----.	7
35.	We consider that your problem of simplicity can be solved if you can get the customers to adopt realistic specifications.	2
36.	We obtain simplicity by attention to functions and reliability of components.	4
37.	To us, simplicity is but a facet of value assurance.	4
38.	We find that the way to get simplicity, value, reliability, and good engineering is by hiring competent people.	4
40.	We have had committees working to simplify our designs on a case by case basis.	3

41.	It is up to the design supervisor to instill simplicity ideas in his men.	2
42.	The time pressures on getting out designs are too heavy to permit attention to simplicity.	3
45.	We have to design to produce a product within cost limits.	2
47.	The idea of simplicity designing is very interesting to us, we will want to learn more about it.	3
48.	We fail to see how this approach can be generalized to cover items other than rocket engines.	2
49.	Here is a list of the factors we would use in simplicity analysis.	2
50.	We find that a general engineering approach is best and that it is unfortunate to have proposals to introduce new disciplines within engineering.	6

Table 5-2, Statements Paraphrased from Company Letters.

There is some overlap between that table and the more complete statements in the text, because some of the points merit reiteration or elaboration. A manager of a military contracting department of a large machinery manufacturer says that his company has long had regular and continuous programs on quite a formal basis, dealing with Reliability Engineering and Value Engineering. However he does not entirely approve of these, in fact seems to be a little scornful, because they are for the purpose of getting people to foster an attitude of doing things that people have been, or should have been doing all along.

He goes on to say that long before the terms Value assurance, Reliability Engineering, or Quality Control came into vogue, the principles were being applied by good engineers in their day to day operations. Of course, he is wrong to the extent that the application of Sampling Theory and Frequency Distributions such as the Normal and the Weibull, and the use of mathematics in general in these areas did not arrive until Fisher, Feller, Shewhart, Duncan and other "School Men" had shown the way. In a similar fashion it is easy to say that there is nothing new about simplicity, that is what we have been doing all the while. However, just a little investigation reveals that the use of Job Evaluation methods for the comparison of designs was never used by production engineers and designers, who had never heard of Job Evaluation.

This same letter contains one of the most definite statements encountered, with reference to the value of simplicity in design. It is said that they strive toward simplified designs because they believe that the best design is the simplest, and if the three elements of definition of value are met; function, reliability, and lowest cost, we can be sure that we have attained the simplest design. Although the last statement is not completely accurate, there is a good deal of truth in it, and the most important point is the strong recognition of the value of simplicity.

Statements of other commentators back up this line of thought by stressing a difference between commercial and military or government design. Commercial designers are constantly subjected to the disciplines of the market place, good (simple) designs survive while poor (complex) designs are rejected by potential purchasers. When an organization is at once the vendor and the customer and there is little or no alternative way of obtaining a needed item, there is no competition to help sharpen thinking.

To make complete this report of the efforts, (and success) of collecting industry views about simplicity, there now follow the letter which was addressed personally to the president or other important officer in the large companies contacted. The brief which was appended to show more fully the nature of the undertaking also follows because it was an attachment to each of the letters.

August 24, 1964

Dear ------------,

This is addressed to you in the hope that you will refer it to the division or individual in your organization who may be interested in corresponding on ideas in the field of Simplicity Ratings.

The University of Alabama has a research contract with the National Aeronautics and Space Administration, (hereinafter NASA) to devise a System of Simplicity Ratings. This system is to be applied by NASA to the design and redesign of components of rocket engines for space vehicles.

It is our belief that there are many men in leading industrial companies who can make important contributions to the project in criticism, ideas, and experience, if we can contact them. No trade secrets or proprietary data are sought. The results of the completed work will no doubt be in the public domain, available for use by your company, or any other, obtaining research reports of NASA and other government agencies.

The enclosed document is a brief for the detailed consideration of the executive, scientist, or engineer who may be willing to give us the benefit of his thoughts on the topic. It is not a questionnaire, because none could fit between the varied interests of the men from whom we seek reactions, and the so far, loosely defined concepts of Simplicity Engineering.

Cooperation by you and members of your organization will be gratefully received. What we hope to receive are letters of comment and suggestions, reprints or articles, (or references to them), or samples of training and conference materials,

Sincerely,

Wyllys G. Stanton, P.E.
Project Director
Professor of Industrial Engr.

WGS:ga
Enclosure

Brief on Rating Simplicity of the Designs of Mechanical Components

by

Wyllys G. Stanton, P. E.
Project Director

Introduction

Assignment: This work is being done by and under the direction of the University of Alabama according to the terms of a research contract with NASA.

Objectives: To develop or devise a system for rating rocket engine components as to simplicity of design. Attention is to be given, but not limited to, stresses, materials, methods of manufacture, etc. Also to apply the system to a large array of existing components for redesign.

Methods of Study Used

Search of Literature: An exhaustive search is being made in various indices of technical journals and books, for articles or mentions of the subject of simplicity of manufactured components.

Correspondence with Interested Persons: A number of editors of technical publications, and engineers in industry have already contributed ideas, manuals and seminar notes. It is hoped that more support can be obtained of this type.

Cost Analysis: One approach has been based upon the proposition that more complex items tend to require more man-hours and perhaps more costly materials. Although not completely abandoned, this method is not currently being pursued.

Factor Analysis: This method requires the analysis of each component to assign it on a degree scale for each of 14 or 15 factors of simplicity. Each factor has an assigned "weight" and vector multiplication results in a number which is the index of simplicity for the component. Investigation is being devoted to reducing the number of factors by finding out which are dependent or highly correlated to others. Some of the factors being considered are; form, material, number of dimensions, tolerances, finishes, and similar concepts.

Simplicity Engineering

It seems likely that the simplicity rating system being developed under this contract may lead to a new specialty in the field of industrial engineering useful in all manufacturing. Simplicity engineering is similar to, but not exactly the same as, the specialties of production design, quality control, reliability engineering, and value analysis engineering.

Simplicity in designs must be always subordinated to requirements of function and reliability. The most simple design possible after these requirements have been met, usually results in ease of maintenance, ease of procurement, ease of assembly, lower cost, and contributes to the characteristic of reliable functioning which is the initial limiting factor.

The Simplicity Engineer may have a separate job in some cases, particularly in large organizations, in others he may be a production designer, reliability engineer, a product designer, etc., who has for the moment, "put on a different hat". The really important point is that he has acquired and is applying the skills and viewpoints pertinent to simplicity.

Just as it has been found that in spite of their close relationship and some overlap of activities there is need for both quality control men and reliability engineers, there is also a need for "simplicity" engineers. Their function is to do simplicity ratings or promotion, but more especially to teach or demonstrate how simplicity of designs can be increased without loss of other design requirements.

Chapter VII

Value Analysis and Simplicity Engineering

> "Just what is engineering? What is an engineering problem? How is divided engineering effort to be organized and coordinated in an industrial enterprise? Is engineering something that can be departmentalized into a department of an enterprise?"
>
> Everett Laitala

Judging from the replies received from 58 large corporations which were kind enough to answer the queries about their reactions to the proposal to develop a simplicity rating factor, it is evident that Value Analysis has become very widespread and in fact proprietary interests are beginning to cloud the issued. That is, the person who has obtained a position as head of a value analysis section or division is not likely to look favorably upon proposals to introduce another approach.

Running through these letters, there appears to be considerable agreement on the absolute value of simplicity. The engineering vice-president of one large company says, for example, "The designer is aware of the fact that a simple design is the best one, everything else being equal, and therefore tries to keep his design simple."

The designers' supervisor is aware of the same fact and, therefore checks the designs for simplicity among other factors. The principal difference here seems to be that many companies have committed themselves to value analysis activities to such an extent that there would be many costs in switching to any other system of attaining the same ends. As always, historical experiences and developments may operate to curtail the freedom of managers in adopting new methods.

Particularly in the case of companies that are dedicated to the goal of making profits, the values analyses directed specifically at the reduction of costs, and therefore to the increase of profits is most attractive. The very word 'value' carries a strong connotation of dollars. There are two possible ways in which simplicity engineering may be attractive to such companies. One of these is that the direct assault on costs of manufacture made by the value analysis approach may miss some important angle which would be uncovered by the simplicity engineering approach. This is especially true because the latter is designed to consider an entire situation and to be aware of the need for the sub-optimization of some elements, to obtain greater degrees of optimization in other parts of the total system.

The other way in which simplicity engineering may be of immediate interest to profit oriented companies, is that many of them deal with governmental organizations. Although the government may express an interest in the cutting of costs, sometimes expressed picturesquely in such terms as, "More bang for the buck," the hard core interest is in accomplishment. Even though simplicity engineering may often reduce costs, it may also increase the effectiveness of designs and assure the success of the mission without having any effect upon costs. It is quite true, as will be shown later, that some defense establishments have their own value analysis groups, but this may be a result of the historical accident of value analysis having been well started before simplicity engineering was thought about. When dealing with an organization such as the Atomic Energy Commission, or the Space Administration, where there is a specific goal like that of putting a man on the moon, costs may be subordinated and it may be more impressive for the company making a presentation, to show that there has been a careful application of the principles of simplicity engineering, than it is to show that value analysis has been used to cut costs. This will be, of course, more likely when there has been time for more people in the engineering business to learn about the existence and availability of simplicity engineering.

Value analysis is a review and correction procedure which has proven to be of very great value in a great many manufacturing organizations. However, except in some local situations, or in papers presented at some of the gatherings of value analysis personnel, it does not seem to embody any particular method or protocol. It is in essence, a fresh look at things, such as may happen when there is an independent design review by different personnel, or even by the original designers when it is possible to set aside a piece of work long enough to allow it "cool off" and then look at it again with a new perspective. This type of value analysis or design review is probably as old as design itself, and no doubt this attitude occurs spontaneously whenever anyone designs or makes something. Therefore an effort is made here to turn attention to more formalized and publicized aspects of value analysis. This is what is found in company groups dignified by a place in the organization structure such as a Group, Section, Division or whatever sub-units, are there employed.

There is a great variety of terminology applied to elements in organizations structures which engage in value analysis work. These include such names as: Value Analysis Department (or Division), Value Engineering Group, Design Review Board, etc., but no effort will be made to identify all of them because they are for the most part self explanatory, and there should be no difficulty in identifying them. What is more important is, as suggested earlier, that persons engaged in this type of work have come to develop a proprietary interest in their jobs that may cloud their judgements in considering a new approach such as simplicity engineering.

Not only are individuals likely to fear a new system which they believe may upset their snug berths, but the company managers are always likely to be aware that any change in the organization structure is a probable source of added costs, both overt and hidden. Moreover, when organizational changes are made, the costs are almost always immediate, while offsetting benefits, although larger in size, do not come into view until sometime later. The fears of the persons now engaged in value analysis and who instinctively think that simplicty engineering will hurt them, because they hear of it before they hear what it is, can be overcome by education. The concern of the managers is also groundless, when it is considered that simplicity engineering techniques do not necessarily call for organizational changes. It is simply an advanced form of value analysis that can be adopted and put into practice by any existing value analysis group that is doing successful work, just as such a group can adapt to the use of any other new tools that may come to its attention.

Values Analysis Engineering

The discussion of value analysis has been introduced in this report because of a number of misunderstandings that have already been noted, such as:

1. Some have indicated that they thought that value analysis and simplicity engineering were really the same thing under two different names.
2. Others have thought that the two methods would duplicate each other, so that if one is being used there is no need for the other. (Although it is true that simplicity engineering can and will do all that value analysis will do, the reverse proposition is by no means true.)
3. Still another belief has been that value analysis will do all that simplicity engineering will do so that those who are using value analysis have no need for the new technique.

It is intended to give a further account of value analysis related to the present state of that art, so that it may not be said that the desirability of simplicity engineering has been extolled by ignoring the many creditable things about value analysis. The discussion is based to a considerable degree on information very kindly supplied by Mr. Frank J. Johnson, Manager, Value Analysis Engineering Department of the Lockheed Georgia Company, Marietta, Georgia. The discussion has two other important purposes, first to describe value analysis as understood by one outstanding practitioner of the art, and secondly to develop the differences between value analysis and simplicity engineering. As previously indicated, these two activities do have a close relationship and some similarities, but there are definite differences.

The Lockheed Georgia Company definition is, "Value analysis engineering is an important tool in searching for unnecessary cost and developing lower cost alternatives." According to a booklet prepared by the company for the guidance of their personnel, value analysis engineering began in about 1947 in the General Electric Company under Mr. Harry Erlicher, Vice-President of Purchasing, and Mr. Larry Miles who was assigned to pursue the newly developed concept that substitutions of materials resulted frequently not only in being able to manufacture articles that could not have been otherwise made, but also in producing lower costs and improvement in the final product. In 1954 the U. S. Navy Bureau of Ships learned of the General Electric program and arranged for training of Navy personnel in this new field which they called value engineering. In the Lockheed Georgia Division of the Lockheed Aircraft Corporation, the term 'value engineering' has been broadened and the department now includes five groups, namely; production design, metallic materials, finishes and processes, standards engineering, and value analysis. The company has conducted a number of seminars and has published manuals to guide their personnel, both in and out of the value engineering department.

Another specific definition of value analysis engineering appearing in the Lockheed manual is, "A systematic, creative approach to insure that the essential function of a product, process, or administrative procedure is provided at minimum overall cost." The manual provides a listing of some twenty-one steps or operations involved in the value analysis engineering job plan and techniques. A number of other definitions of terms such as value analysis engineering study, functional divisions into primary and basic and secondary are also given. The twenty-one steps are rather well summarized in a condensed listing of five phases, which are; the information phase, the speculation phase, the analysis phase, the planning and decision phase, and the summary and conclusion phase. With the exception of some discussion in the cost analysis, the approach appears to be largely qualitative, even though the ultimate result is better components at lower costs.

An important concept is introduced as the balance of the different elements of a design so that they are reasonably related to one another. This is illustrated by an account of a certain Navy landing craft which was originally provided with copper-nickel trapezoidal shaped fuel tanks. These were replaced by two standard steel drums which were sprayed on the insides with a corrosion resisting plastic. This change reduced the cost of the fuel tanks to one eighth of what it had previously been. An objection to the proposed change was made on the ground that the steel drums would not last as long as the copper-nickel tanks. However, when the rebuttal was made that the boats themselves were made of plywood with a life expectancy of some eight years, the discrepancy in balance of design became apparent, because the original tanks would have outlasted the hulls many times, if not sooner lost in combat or by accident. Even the steel barrels would outlast the hulls, although they would not last so long as the copper-nickel tanks.

Much emphasis is placed upon the use of creative thinking as approached by variations of "brainstorming" and, of course, the idea of overcoming roadblocks, that is, putting aside preconceived ideas which might inhibit the development of better ideas for design which can be obtained from the value analysis engineering technique.

To summarize, there is very much in the value analysis technique which has assisted in the development of the concepts for simplicity engineering and the design of the simplicity rating system in this report. One of the most important points is the emphasis on the desirability of radical innovation. Progress in designs may be made in two ways, by mincing steps that yield a few percentage points of improvement each year, or by bold breakthroughs, to things as they have never been done before. An example of the latter was the action of Frederick W. Taylor in turning a water hose on a lathe cutting tool and obtaining a large increase in cutting capacity, rather than the disintegration of the tool predicted by the critics. The suggestion is made that instead of merely refining design to achieve improvements on the order of five to ten percent per review, in the improvement of function or the reduction of cost, the approach should be to consider totally different solutions to the problem the design is proposed to solve, with a goal of achieving improvements on the order of fifty, seventy-five, or one hundred percent.

Other manuals and other company uses of value analysis could be reported, but these reports would become repetitious, the idea is so useful that it has gained wide acceptance. It seems to have gained an especially strong foothold in the areas of space exploration and the aircraft industry and missile manufacture. On 18 and 19 November 1964 an Army value engineering symposium on advancement in the state of the art was held at the Army Missile Command at Redstone Arsenal. As stated by General Zehrt in his welcoming address, this was not the first symposium on value engineering as there had been one there for the first time in November of 1960. For the 1964 meeting, 44 engineers, mathematicians, and other interested persons prepared a total of 41 technical papers dealing with various aspects of value engineering, although it was impossible to deliver this large number of papers in the two-day symposium, they were printed in a 450 page report and thus made available to all who are interested in this relatively new development in manufacturing and management engineering.

The Characteristics of Simplicity Engineering

In its barest essentials, simplicity engineering consists simply of a recognition of the value of simplicity and a constant effort to achieve simplicity in all mechanical designs, procedures, and other planning. Although the technique can be easily extended to cover operating methods, record keeping, and many other aspects of organizational work, the discussion here will be confined to its use in the improvement of mechanical designs. Thus, simplicity engineering may be said to be a frame of mind or attitude more than it is any specific operational approach, and that it can and should be applied during a designing process rather than as a review after the design has been completed.

This point of developing the simplicity engineering phases of a design which is in progress, rather than as an after thought as value analysis is so often applied, has great psychological impact. Most persons, including engineers and draftsmen are human enough to have much pride in their brain children. Pride of authorship is very strong and only the most resolute individuals can cast it out, in fact many persons may be strongly motivated by it without the least realization that it is present. Obviously, when questions of the simplicity or lack of it, of different elements of a design are reviewed in the different factors, step by step, as the design grows, there is so much less danger of the designer becoming committed to a given plan of action so that it blocks his consideration of alternatives.

It has been pointed out that value analysis is largely a qualitative way of operating, and that in its elemental form, the same thing is true of simplicity engineering. But quantitative knowledge is almost always superior and there is a way to make simplicity engineering a matter of numerical elements which insure that no important points will be overlooked. The use of a set of factors does not interfere with that approach of taking a fresh look or applying creative thinking so much stressed by devotees of value analysis. It is rather a change of emphasis from cost reduction to concentrating upon functional capability and reliability in the design of space vehicle components.

It is proposed, as is explained in more detail in other sections of the report that for each component design there shall be separate attention focused sequentially upon a series of factors, or attributes of the part. The very existence of such a set of factors will constantly keep alive the question of whether the factors in the rating sheet are all of those that should be considered, and whether or not they are defined in the best way. Each design organization has the option at all times of making meaningful modifications, after proper discussions.

A principle advantage of the simplicity engineering approach to value analysis or cost reduction or reliability improvement, is in the provision of an orderly method of examining all facets of a design in a critical manner. The usual operation in some value analysis activities is to take something that has been made in a certain way, and to brood over it, ask one's self questions such as, "Why was it made in this way, instead of this other way?" or "Why is it made of this material, instead of that one?" etc., and the results have been extraordinarily worthwhile. However, in most cases these results have been obtained by a special class of men, with strong creative powers and a large amount of skepticism. It is easy to see that their efforts may have been even more effective when coupled with a procedural tool which enables less gifted men to accomplish very good results, and before any hardware has been made. It is interesting to note that in military and civilian flying, very expert pilots make use of check lists to cover each possible defect before takeoff.

Where various valid local reasons cause an organization to plan to continue use of a value analysis section, it will still pay to have the designers trained in simplicity engineering methods so that they can apply them during the process of designing or redesigning components and thus possibly minimize the amount of work remaining to be done by the value analysis specialists. It is possible that if simplicity engineering is adopted as a recognized technique and applied in the design room, it may ultimately be absorbed into value analysis or vice versa. However, in view of the fact that value analysis has been practiced for almost twenty years, it is more likely that simplicity engineering will become one of the tools of the value analysis engineer in those organizations which have value analysis activity.

This point is really unimportant except as a matter of semantics because either development will lead to designing better components and to making the improvements early instead of late. A valuable difference is that there may develop the application of simplicity engineering at the initial stage of designing instead of having to throw out hardware that could have been made better in the beginning.

A second and more important difference is that simplicity engineering provides a design evaluation system which is independent of dollar costs of material, labor, and overhead. This is obviously important in situations wherein competition is not available to force costs down, or where the costs of malfunction are so very great in relation to the cost of the component, that value analysis does not provide a realistic base for the studies.

Organizational Structure Considerations

All learned professions are plagued with problems of organization, and it is not limited to problems of placing engineering effort within a commercial or governmental organization structure, but also with the organization of engineering knowledge itself. In the beginning, there was only one type of engineering, military, which evolved into civil engineering because it was found that the skills of the engineer are quite useful to civilian needs. Subsequently as the field of scientific knowledge expanded, the field of engineering which is devoted to the application of such knowledge, inevitably expanded also until we now have many different branches of engineering.

A natural consequence of the expansion of engineering activity and knowledge is specialization with a proliferation of names of different kinds of engineering disciplines or sub-disciplines. For example, within the field of civil engineering, which is definitely recognized as a major branch, we have also sanitary engineers, structural engineers, and others.

There are many who deplore this multiple designation of types of engineers, but administrative convenience, particularly in commercial and industrial or governmental organizations in which many engineers are employed, seems to make it necessary to have such designations. Regardless of the views or wishes of engineers themselves, administrators continue to create new branches or sub-branches of engineering at the stroke of a pen whenever it seems expedient to them to do so.

Vested interests and organizational inertia produce tendencies to preserve and maintain designations or titles, whether or not they have any continuing value from an analytical point of view. As indicated earlier in this chapter, many individuals may look upon any changes in organizational structures as inimical to their personal security. To be specific, a man who has achieved the title of "Chief, Value Analysis Engineering Branch," and the administrator to whom he reports, both look with disfavor on proposals to introduce a new sub-branch designated simplicity engineering. Nevertheless there is a real need to recognize simplicity engineering as a subject to study, a method, or a sub-branch of design engineering because of its similarity to and differences from value analysis engineering as presently practiced.

For the comfort of value analysis personnel who may see in this proposal a threat to their security and for the comfort of the administrators who may see in it the multiplication of their areas of responsibility, it is proposed that in those cases where it is desired to do so, simplicity engineering may be looked upon as a strictly intellectual approach or method which may be used in connection with value analysis engineering effort as an assisting element for engineers and their supervisors. It is again emphasized that the use or application of simplicity engineering thinking does not necessarily involve the creation of a department or a position title, although there may be some instances in which the present and past organizational structure of a company or governmental agency may make it desirable to convert a value analysis engineering group into a simplicity engineering effort where none previously.

CHAPTER VIII

LITERATURE SEARCH

"Any group that does not appreciate and acknowledge its debt to its past leaders is not worthy to make further progress."

- Wyllys G. Stanton

Every serious research effort should include a search of the literature pertaining to the subject, for the purposes listed below:

1. To avoid duplication of efforts. There is so much research that needs to be done, that once a certain piece of work has been done, later investigators should take advantage of previous efforts and avoid repetition. The writer once heard the Vice-President in charge of Engineering and Research of the General Electric Company say that one of his big problems was to keep his men from reinventing the wheel. He explained that they had so many different research staffs engaged in different basic problems at different locations that often facets of the problems would overlap and days would be spent in solving some minor aspect that others in the company had already encountered and solved.

2. To obtain leads for further study. It often happens that prior workers on a particular problem may have encountered and put aside, some aspect of a problem which may be more germane to the present work than it was to their objective. Sometimes, in such cases, mention is made of the abandoned line of investigation, and sometimes not. If it was an important finding, it is likely to be reported, even though for the time being they may have dismissed it. Even though dismissed from immediate consideration, some such ideas are noted with the thought of their being worthwhile to take up later.

3. To find clues to other references. It may well happen that nothing can be found in the card catalogs, or the Engineering Index, but the bibliography of some book or article that is only slightly related to the problem being researched may contain leads to other sources.
4. To find authoritative statements to back up the claims made or propositions offered in the write-up of the subject being researched. This is particularly true when new areas of thought are being explored. The information located may be used for direct quotations, or it may merely suggest a new line of reasoning which is not so closely related as to require quoting.

In the case of simplicity engineering, a search for prior investigations, if any, on this topic or those that may be closely related, assumes more importance than may be the case in some other investigations.

The reason why this is the case is simply because the subject matter, or at least the present way of considering it is so new that very little has been published about it. Value analysis under its various pseudonyms has been the subject of a number of articles, and this is the field most closely related to simplicity engineering, but as explained in other parts of this paper, there are very important differences.

The concepts of simplicity engineering, as developed in this report, cut across several intellectual disciplines to find ideas or facts that can be adapted to the exposition of this subject. Some of the references read or examined and listed in the bibliography may seem to be very remote in their relationship, if any, to this subject, yet such a reference may serve as a catalyst to start a chain reaction of thoughts quite pertinent to simplicity engineering, or whatever topic is being examined. This is the sort of thing which is said to happen in brainstorming sessions wherein an otherwise useless comment by one participant have the effect of starting a line of discussion which leads to a desirable solution of the problem at hand.

No specific footnotes are included in the text because some of the references are, as indicated previously, only slightly connected to the detailed questions of simplicity engineering. Moreover, some of the references are in books or journals dealing with psychology, education, and management which may not be readily available to engineers.

The search was made in the libraries of the University of Alabama, the University of Pittsburgh, and in the Ohio State University library. Time did not permit a search in the United Engineering Societies library in New York, and it was considered that it would be too difficult to prepare a statment of the subject of the search to ask the permanent personnel of that library to make a search for the project. The search for pertinent books and articles could have been much extended to other libraries and private collections, but there comes a time when one must say, "In spite of the fact that more time in research in the literature might pay off with useful references, it is necessary to call a halt to this phase of the work or there will never be a report made."

The usual methods of library search were employed, such as the library catalogs, the Engineering Index, the Readers' Guide to Periodical Literature, and one of the most fruitful source of leads, the bibliographies of books previously consulted. In addition to these, there is now available a new listing of engineering keywords, and a permutation of engineering titles.

In order to conduct the widespread search that was desired, it was necessary to ask all of the Research Associates and Research Assistants, who were employed at any time on the project, to assist in the search for references. Some of these men worked for only brief periods, and it is somewhat doubtful if some of them ever grasped the ideas behind the project. To complicate things still more, there was the change of approach from purely speculative consideration to the use of the dollar as a denominator, and at last, the factors analysis. As a result, the early expenditure of time in a literature search had little impact on the final results.

Recognizing the variety of levels of research experience and backgrounds of the various persons engaged in the library search, an outline, "Notes on Literature Search," was prepared and distributed to the associates and assistants. This consisted partly of explanation of why certain things were to be done, and a series of adjurations as to the correct ways of doing them. A copy of this outline is included at the end of this chapter, therefore, it will not be discussed in detail.

In addition to the formal library search described, an effort was made to uncover other sources. The writer wrote to a number of friends who are editors of technical journals and magazines, describing the problem and asking about as yet unpublished articles. It was also requested that he be put in touch with other engineers or writers who may have displayed similar interests, whether or not the particular journal found the subject to be suitable to appear in its pages. Similar letters were sent to a number of personal friends who are engineers, production managers, or others who might be interested in the subject. It has happened so often in the past that two different investigators have solved the same problem independently, each unaware of the interests of the other, e.g., Bessemer and Kelly, or Leibnitz and Newton. Some very useful suggestions were obtained from these editors and engineers.

Related Areas Search

It is possible that the search for references in the available scientific literature may be more important in this research than in some other types. At least this was the consensus in discussions held by those working on the project. The reasons for these opinions seem to be that so little was found directly relating to simplicity, that it became apparent very early that it would be necessary to extend the search into the literature of other disciplines whether or not there was any immediately visible relationship to the primary objective. As noted in the instructions for searchers mentioned supra, this decision at once presented the special problem of using searchers capable of dealing with two different technical vocabularies.

For example, in the discipline of psychology, a chief tenet is the doctrine of parsimony, i.e., explanations offered to deal with sets of observations should be as concise as possible. No hypothesis is acceptable, in a given situation, if it contains more than a bare minimum of ideas adequate to explain what has been noted. Although the word 'simplicity' has been avoided, (albeit with difficulty) that is precisely what the psychologist is talking about. Although a discussion or book on parsimony in hypothesis may be exactly what is needed by a writer on simplicity engineering, an average library assistant, requested to find all that is available on the subject of simplicity, would be very unlikely to come up with the volume about parsimony. Even more troublesome is the fact that the same word may have very different meanings as used in the various areas of study, so a person not aware of such variations might be led to believe that something had been found pertinent to the current field of investigation when actually there is no relationship.

Bibliography

The bibliography given in Appendix B is simply a listing of all of the books and articles examined by the various persons who participated in the literature search. Therefore it is of limited value, for some of the entries refer to sources that were very important and helpful, while others represent only leads that were tracked down, and often very quickly discarded. With this negative recommendation, the reader very naturally wonders why such entries are made at all. The reason is simply that the location of these titles represents many hours of work and there was not time enough for them to be reviewed by the project director or a senior research associate.

It would be highly desirable in this case, and in other serious research, to present a classified and annotated bibliography. Without disturbing the convenient alphabetical ordering of the items, it would be possible to classify them by prefix symbols which would categorize them in various ways, such as their utility to simplicity engineering, the field of learning from which they are drawn, and the level of authority of the author. Such refinement will have to be postponed, at least until the next edition of the report.

NAS8-5262 6 July '64

Notes on Literature Search

by

Wyllys G. Stanton
Project Director

1. Responsibility of every research engineer and scientist to pertinent literature.
    - 1.1. Gain ideas (good or bad).
    - 1.2. Avoid duplication of previous research. (Problem to avoid "re-invention of the wheel").
    - 1.3. Aid subsequent researchers by recording fruitless searches that sounded promising at start.

2. Problem of inter-disciplinary subjects.
    - 2.1. Some topics do not fit neatly into any single heading.
        - 2.1.1. Solution may depend upon knowledge borrowed from a number of fields of study.
        - 2.1.2. Reference may be only a paragraph in an article on a seemingly un-related topic.
    - 2.2. Vocabularies of different groups of specialists may differ greatly.
        - 2.2.1. Certain technical terms often have different exact meaning in different specialties. This can cause both checking into useless references and overlooking some good sources.
        - 2.2.2. Some especially capable engineers or scientists write in more than one interest.
    - 2.3. Indices must be used carefully-
        - 2.3.1. No index better than capabilities of the editors or librarians who prepare them.
        - 2.3.2. No matter how intelligent an indexer is, he is usually not trained in the specialty of the writer.
        - 2.3.3. Example: U. S. Dept. of Commerce, Office of Technical Services is now publishing, <u>Key Words Index to U. S. Gov't. Tech. Reports,</u> this is a permuted title index. Recognizing that articles may be overlooked because of use of first word of title in a subject index, the key words of titles are rearranged.

3. Methods of Search
    - 3.1. Look for subject titles of books and articles.

3.1.1. Use imagination as guide to related subjects. e.g. , Simplicity, see also Complexity avoidance of.

3.1.2. Make lists of synonyms and antonyms. Also list all related subjects.

3.2. Make copious notes showing books and journals or indicies referred to, etc.

3.2.1. Even if a source tried seems useless, a record should be made to show why and to avoid wasting time on it on this or future projects. Record should include enough information to reveal type of reference because during a project there may be changes of viewpoint and interest. Ideas that seemed useless at one point during the research may prove to be very valuable at a later time.

3.2.2. List of indices or journals may be very useful if point of view changes.

3.2.3. When referring to articles, etc., look at the bibliography, if any, and note its presence or absence and comment on its probable value as source of further references.

3.2.4. List names, authors, reviewers, critics and others in connection with articles. When a man has published on a given topic he may do so again. Include in this group companies, colleges, or research institutes, they may have other members interested in the subject. Also if any address information, company, or institutional connections, etc., are given, put them down - it is always possible to write to an author and ask him what he really meant or what he has found out since - if you can find him.

4. When a reference is found which seems to be pertinent and useful-

4.1. Brief abstract notes may be made to indicate what it is and why it appears valuable, (and of course, instructions to locate it again).

4.2. Time permitting, complete notes with any suitable quotations may be made so reference can be used. (Of course source data is still needed).

4.3. If reference seems worth the trouble, and facilities are available, a Xerox, (or other type copy) may be made. This permits handing reference around the team or discussing in conference.

5. Do not pass up references merely because in a foreign language.

5.1. Various indices and abstracts or reviews often give enough information in English to permit a first judgement of value.

5.2 If a valuable item is available only in French, German or Russian, etc. translations may be procured.

6. Watch for sub-headings, e.g., in the Engineering Index, September 1963, Vol. 1, there is mention of article on Short Run Production with Miniature Dies.

   6.1 This article indexed under dies.

   6.2 Same volume.. It is listed under Rockets, Missiles and Materials - see Beryllium.

7. Make notes of any ideas developmed about ways to improve literature search or similar topics.

Note: It is strongly recommended that the two forms illustrated below be used to record the results of your search for references.

CLASSIFIED SUBJECT: | | | PROJECT NUMBER | FILE NUMBER

AUTHOR:

TITLE:

EDITION:

PLACE PUBLISHED: PUBLISHER:

DATE: VOL.: PAGES:

PUB. DESIGNATION AND SERIAL NO.: CALL NO.: AVAILABLE AT:

LIST PRICE: REVIEWED IN:

AUTHOR'S POSITION:

ABSTRACT:

DATE EXAMINED: BY: PURPOSE OF SEARCH: CONT'D.

FORM 5301 ABSTRACT BLANK FOR BOOKS, BULLETINS, ADVERTISING BOOKLETS, ETC.

DEPARTMENT OF INDUSTRIAL ENGINEERING
THE UNIVERSITY OF ALABAMA

DEPARTMENT OF INDUSTRIAL ENGINEERING
THE UNIVERSITY OF ALABAMA

CLASSIFIED SUBJECT:			PROJECT NUMBER	FILE NUMBER

AUTHOR:

TITLE:

ORIG. REFS.:	VOL.	NO.	PAGES	DATE
ABSTR. REF.:				

ABSTRACT:

CONT'D.:

DATE EXAMINED: BY: PURPOSE OF SEARCH:

FORM 5300

ABSTRACT BLANK FOR PERIODICALS AND REGULARLY ISSUED PROCEEDINGS

B-1

APPENDIX A

NOTES ON JOB EVALUATION[1]

The note is intended only to show the similarities between the problem of job evaluation in a group of employees in a factory or other type of company and the simplicity rating index problem which has been accepted.

Modern job evaluation may be said to have started in 1909 as a result of requirements of the Civil Service Commission of the city of Chicago. Very soon thereafter the Commonwealth Edison Company, also of Chicago, pioneered in this field on behalf of private employers. In 1924 Merrill R. Lott developed a formal job evaluation system making use of 15 factors or work characteristics and thus laid a foundation for various systems in use at this time. An outstanding characteristic of Lott's chart is that 5 general characteristics are presented with subdivisions under each.

The purpose or ultimate goal of all job evaluation systems is an effort to produce equity in wage payment scales. This may mean simply an effort to insure that the wages paid to a carpenter and an electrician or plumber working in the same plant will properly reflect the amount of labor that each must put into his job in actual physical effort and all other characteristics of the job which may tend to make one job more valuable to the company or more costly to the individual and thus justify differentials, if any, between the wages which they receive. A good job evaluation system not only takes into account the effort expended on the average, from day to day, but also such important factors as the hazards to which the workman is exposed, the amount of formal education and training which he must bring to the job, the period of apprenticeship which he must have undergone, and

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[1]Based upon the book Patton and Smith, Job Evaluation, Irwin, Inc., Homewood, Illinois, 1955.

the responsibilities which he must assume for his own safety, the safety of others and for the protection and preservation of the assets of the company.

It is generally found prior to the introduction of job evaluation plans in a group of employees that there are serious discrepancies between the wages paid on different jobs. These discrepancies result from a variety of causes including personal aggressiveness in demanding increases on the part of certain individual employees, historical accidents of wage rates at the time of employment, aggressiveness on the part of foreman in obtaining increases for the men under them, and often a lack of knowledge on the part of management of what a given job actually entails. In no case can a job evaluation system determine, on any absolute scale, just what amount should be paid for a particular job but a system that is carefully selected to fit the circumstances where it is applied and introduced after reasonable study, can assure that a skilled workman who may receive an hourly wage of 200% of that of the lowest paid employee in the group is justified by the characteristics of the job.

SYSTEMS OF JOB EVALUATION

As might be expected in the case of a technique which has been developing for more than half a century, a number of different plans or systems of job evaluation have been developed, experimented upon, and refined. At this time, any company desiring to improve its wage and salary administration can readily find a variety of plans to consider and a host of practioners offering their services as consultant to assist in selecting and installing plans. Each plan has some merits to justify its choice for a particular situation, that is with respect to the size of the employee group, the formality or lack of it in handling supervisory problems, the presence or lack of a union or other characteristics which dictate relations between a group of employees and the company for whom they work. There are, in general, four methods of job evaluation:

1. Predetermined grading or classification
2. Job ranking
3. Factor comparison
4. Point rating

Each of these methods will be described briefly and it will be seen that the point method is the one most like the simplicity rating index system proposed.

Predetermined Grading Method

In using this method arbitrarily established job levels or classifications are determined and all jobs are analyzed and the broad job characteristics identified following which classifications are made and each job is placed in a particular classification. This method has been used by the Westinghouse Electric Corporation for grading salaried employees into seven levels ranging from office boy up to and including senior elected policy making officers in the seventh or top grade. The method is also used by the United States Civil Service Commission and many State Civil Service bodies and it can be used in conjunction with a point rating system to reduce the number of jobs that must be evaluated. The method has the advantage of simplicity and speed of application and can be explained to employees readily, therefore, the problem of selling the plan is simple. However, in the opinion of Patton and Smith, the disadvantages of the method outweigh the advantages, too many blanket judgements are passed on jobs and errors in slotting jobs into particular grades may cause trouble.

Job Ranking Method

In using this method, an individual or committee ranks all of the jobs in the order of their relative worth. The first step is to select a group of key job duties and responsibilities of which are well known and whose rates of pay are in substantial agreement with those of similar jobs in the community. An effort is made to reduce the subjective element by having members of the committee rank the jobs at intervals and averaging the ranks which they assign by placing the rankings on cards, it is possible to sort them into different rank orders and thus to facilitate the job of consolidating the several opinions entering into the application of the system.

While the job ranking method may be desirable in small employee groups, it probably does not work too well in large companies because of the difficulty of finding sufficient key personnel acquainted with all of the jobs to form a suitable committee. The method is also subject to errors caused by the "halo effect" because no provision is made for looking at different elements of a job separately from others.

Factor Comparison Method

This method was originated in 1926 by Eugene J. Benge and it is one that approaches the point system. It consists of selecting representative key jobs just as in the job ranking method, but it also includes the selection of a group of critical factors and the ranking of the selected jobs with respect to each different factor rather than by looking at each job as a whole. The method also differs from the others in that money rates are introduced into the evaluation system. The use of representative key jobs makes it possible to handle a larger volume of jobs to be evaluated by the simple system of interpellating the remaining jobs among those that have been evaluated.

Point Rating

This system consists fundamentally of developing a set of standards or definitions to apply to different characteristics of a job and awarding points to each particular job according to the presence of these characteristics in different degrees. For example, a man working high tension electric wires "hot" on high pole lines might be defined as possessing the highest degree of personal hazard and would also possess high degrees of responsibility for the safety of others. Whereas another man working as a switcher in a tower or control room which he did not have to leave during the course of his work would probably be rated very low on the hazard scale. There has been a general tendency for large companies to develop their own original point rating job evaluation plans rather than to adopt any standard plan which may be available, such as that of the National Metal Trades Association. Patton and Smith list five basic steps in developing a point rating plan as follows:

1. A study of jobs to determine characteristics to be used in measuring.
2. Consideration of the maximum and minimum possible degree of presence of each characteristic in order that all jobs to be considered will fall inside of the boundaries of the system.
3. The writing of suitable definitions for the characteristics or factors and for the degrees of each.
4. Agreement on the weights to be assigned to each factor and degree and the assignment of a specific number of points to each degree of each factor.
5. Selecting key jobs and evaluating them according to the plan thus developed.

Summary

From the descriptions above, it is evident that the point rating system is the more sophisticated and it is also the one which serves best as a model for the problem of evaluating the simplicity of mechanical designs. It will be found well worth the time devoted to it for anyone concerned with the simplicity rating application to read additional portions of the Patton and Smith text.

APPENDIX B

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APPENDIX C

INSTRUCTION GUIDE

Part of the material that pertains to the instruction of designers in the use of simplicity engineering concepts has been included in Chapter V so that in those cases in which the separable chapter is duplicated for distribution to each designer, it will be at all times available to them.

Nevertheless, it will be highly desirable to conduct a number of instruction meetings when the program is started. This plan will have the following beneficial results:

a. It will indicate to the men involved that management is behind the program and wants to have the system used.

b. It will assure that every person concerned has gone through the instructions, at least once or twice, instead of tossing it on the back of his desk to be examined later.

c. Some individuals learn best "by doing" and an actual drill on real or hypothetical designs in practice sessions, will benefit them greatly.

d. In cases where special design problems make it desirable to develop modifications of the factors and degrees proposed in this report, the changes can be worked out in group discussions.

e. Individuals who participate in a development of plans become committed and will cooperate more fully.

The exact plan for the instruction sessions will, of course, depend upon the details of the situation in the particular design group involved. It is strongly recommended that the meetings be conducted on "company time" because otherwise it will be difficult to demonstrate that this is something that management really believes in. If the group has a supervisor who regularly works with them, circulating in the design room for impromptu conferences, it is logical and effective for him to be the discussion leader. If on the other hand the supervisor is burdened with other duties, and thus is more distant from his men, it may be desirable to designate one of the senior designers as instruction leader.

In any case, it is highly desirable that the leader shall spend enough time in preparation to thoroughly study the entire report, formulate additional questions, and think out the answers. If in a particular point he does not agree with the statements in the report, or does not understand them, he should make notes and prepare to discuss them with the entire group. An instructor does not lose dignity or confidence when he admits to a class that there are some things that he does not know. What does hurt him badly is an attempt to bluff, for he is sure to be found out, especially in an adult class.

It will no doubt always be best to handle the instruction on a discussion basis. This is particularly true when the person functioning as the leader has doubts about his abilities as a teacher. Another advantage is that the material to be covered can be divided up into as many segments as there are persons in the group, and assigned to the various designers for presentation.

Visual aids will assist a great deal in "getting across" the ideas of simplicity engineering. These may consist of actual pieces of "hardware" from past work, to models and drawings or photographs. When such materials are used, they should be kept under control, that is, the person responsible for them should bring them out at the appropriate time and exhibit them or even pass them around the group. However, they should not be permitted to stay on the table to distract after the discusssion has moved on beyond the part to which the exhibits were pertinent.

The knowledge which a successful designer should have is so vast that the discussion of simplicity engineering can be used as a means of bringing to their attention new materials, fasteners, finishes, production methods, and other things that are constantly being announced in trade publications.

If the organization contains a value analysis group, it would be very profitable to have the supervisor of that group talk to the designers. Simplicity engineering may be thought of as the practice of value analysis before hardware has been made rather than being a post hoc operation to find out how parts may be redesigned to lower the cost or to increase reliability and effectiveness.