IMPROVED PROBLEM FORMULATION
IN ENGINEERING SYSTEMS DESIGN

A Dissertation

by

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ABSTRACT

Improved Problem Formulation
In Engineering Systems Design. (May 1990)
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The objective of this work was to improve problem formulation in engineering systems design. Exploratory research investigated when, how and why information and knowledge are introduced into engineering systems design. The investigation employed surveys of practicing engineers and protocol analysis of expert designers in controlled task, free response experiments. Based on exploratory findings, a method to improve problem formulation was developed. The effectiveness of the method was validated with a controlled task, guided response experiment using a Multiple Attribute Value model for evaluation. Performance Identification and Performance Measurability were defined as two essential attributes for assessing improvements in problem formulation.

DEDICATION

To Beth

and

to my parents

ACKNOWLEDGEMENTS

I foremost thank Dr. Steven Gyeszly, my mentor and advisory committee chair, for his clear guidance and never ending support throughout this project. I thank the advisory committee collectively for providing their continual support and advice. Individually, I thank Dr. David Jansson for stimulating my interest in design methodology, Dr. Charles Samson for introducing me to the systems approach, and Dr. John English for his guidance on experimental design and analysis. I thank Dr. Philip Yasskin, the Graduate Council Representative, for his sincere interest and candid feedback. I am grateful to the United States Army for the opportunity to complete my studies. My deepest thanks goes to my wife, Beth, for her assistance and encouragement along the way.

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1 INTRODUCTION

Engineering systems design is a decision-making process through which an engineer creatively applies knowledge to information to develop a product or process that will satisfy performance objectives within a specified environment. The quality and efficiency with which an engineeering problem is solved is linked in part to its formulation [1,2]. Volkema [3] clearly describes the importance of problem formulation to planning and design:

> It is not difficult to make a cogent argument for more investigation into the problem formulation process. Because problem formulation often occurs in the early stages of planning and design, it has the potential for affecting the direction of all succeeding stages. This is due, at least in part, to the strong relationship that exists between the representation of a problem and the domain of solutions and ideas that the representation can produce.
>
> When a problem is first discovered, it is rich in solution possibilities. As the process continues, however, assumptions and constraints are added in an effort to bring manageability and closure to the problem. These limit the scope of the problem and the range of the possible solutions.
>
> Because the amount of information needed to change a decision is much greater than the amount needed to make it initially, reformulation of a problem becomes less likely once a particular formulation is selected and pursued. This places added pressure on decision makers to avoid premature closure and to select "optimal" problem statements. A problem that is defined with incorrect presumptions concerning needs and opportunities can result in significant monetary losses as well as problem solving ineffectiveness.

Journal model is <u>ASME Journal of Mechanical Design</u>.

1.1 Research Objective and Methods

The objective of this research project was to improve problem formulation in engineering systems design. Research was conducted in two phases.

Phase one investigated when, how and why information and knowledge are introduced into the design process by analyzing current practices in an engineering systems design environment. Data was collected using two techniques: surveys of practicing engineers and protocol analysis of a controlled task, free response experiment. Analysis of the survey data consisted of one-way and two-way contingency tables and graphic representations. Analysis of the protocols involved comparison of encoded events related to information acquisition for six experts solving three design problems. Phase one is discussed in Chapter 3.

Based on the findings from phase one, the objective of phase two was to develop and validate a method for improving problem formulation. The method, described in 4.1, uses five dimensions to assist in identifying boundary and performance criteria, and technical performance requirements as a means of expressing them. The method was tested in controlled task, guided response experiments, as discussed in 4.3. The results indicate that defining required performance and boundaries in measurable technical terms improved the problem statements from which solutions can be developed.

1.2 The Design Process and Systems Design

Design is "the decision-making process which...engineers use in the formulation of plans for the physical realization of machines, devices and systems." [4] The Accreditation Board of Engineering Technology (ABET) definition provides more focus in stating that:

> Engineering design is the process of devising . system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. [5]

The design process has been described in a variety of manners throughout its evolutionary history. The process has been divided into as few as three and as many as nine or more steps or phases by various authors [4,6,7,8,9,10,11]. Early approaches to design methodology attempted to force designers to follow rigid, lockstep procedures [6,7]. These models have given way to approaches which recognize a need for the method to adapt to the designer, not vice versa [12,13,14]. Second generation approaches emphasized design as a participatory or argumentative process without the need for rigid procedures [13,14]. A third generation conjectures a designerly way of thinking, recognizing the ill-defined nature of design problems and that the designer's activity oscillates between emerging requirement ideas and developing solution ideas [11,13,15]. Regardless of the number of steps or the degree of orderliness involved, design is a decision-making process which begins with some form of need identification which is translated into a problem statement and then progresses in a generally iterative or cyclic manner to generate alternatives and select a solution to the stated problem.

A system may be defined as "a set of resources--people, facilities, equipment, data and so on--organized to perform designated functions to achieve desired results." [8] A system is "assumed to be an entity separable from the rest of the universe (the environment of the system) by means of a physical or conceptual boundary." [16]

A systems approach to design recognizes that a product or process must be designed to operate within its intended environment. "The essence of what is considered to be the 'systems viewpoint' is to concern oneself with the operation of a complete system rather than the operation of the component parts." [16]

> Systems approaches emphasize looking at the problem beyond its existing framework; they search for what the purposes or problem ought to be. They challenge hidden assumptions and look for contextual purposes. The conventional approach's emphasis is on analysis, which is only a limited part of design.... [Systems approaches] increase the probability of working on the right problem. [17]

2 LITERATURE REVIEW

An investigation of information requirements and problem formulation in engineering systems design requires contributions from several disciplines, to include design methodology, systems methodology, and quality engineering. Each area will be addressed separately.

2.1 Design Methodology

Design methodology is the broad and general study of design principles, practices and procedures, with a focus on how design both "is" and "might be" conducted [18]. The majority of research on the design process "emphasizes data analysis, model building, selection, detailing and post-implementation analysis. Very little is stated about methods and techniques for the important steps of problem finding, formulation and redefinition." [19] Traditional texts on the engineering design process [4,6,20,21] typically devote between one paragraph and six pages to the transition from needs identification to problem statement.

As exceptions to the general emphasis on the later phases of the design process, Sakman [22] evaluated the effect of three explicit methods of problem formulation on the quality of general (nonengineering) problem statements developed by small groups. Nadler [19] evaluated the effect of three general methods of problem formulation on the quality of problem statements and on design performance in mechanical engineering design. Esterline, et. al. [23] applied protocol analysis to capture expertise in kinematic design. Their goal is a problem-formulation module for a knowledge-based expert system for mechanism design. Cross [24] offers the Objectives Tree Method for clarifying customer needs and the Function Analysis Method for describ what must be designed. McMahon [25] describes Structured Boundary Examination, a four-step process to redefine the problem, or needs statement, by equating parts of speech (verbs, nouns and modifiers) to aspects of design (process, results and specifications). Smith [26] evaluates case studies to show that understanding the real customer needs and associated performance requirements increases efficiency and effectiveness in creative product design.

2.2 Systems Methodology

AT&T Bell Laboratories developed a methodology for translating customer requirements into technical terms and then tracking technical requirements throughout the systems design process [27]. In computer systems development, Smith [28] demonstrates that early prototyping is being used as an effective tool in defining what the customer needs or wants.

2.3 Quality Sciences

Traditional approaches to quality emphasized product inspection or process control through statistical analysis [29]. Recently, quality has taken on new definitions and roles, with increasing emphasis on the planning and design stages of the product life cycle. Crosby defines quality as "conformance to requirements, not goodness." [30, p. 64] Juran [31, pp. 20-27] defines the Juran Trilogy, consisting of quality planning, quality control and quality improvement. Imbedded in quality planning are techniques for determining customer needs and translating customer needs into the producer's or supplier's language [31, pp. 94-108]. Quality Function Deployment (QFD) [32,33] offers a set of interlocking matrices that links customer needs or "Voice of the Customer" (VOC) to design and manufacturing requirements.

3 PRELIMINARY INVESTIGATIONS

The objective of the first phase of the research was to investigate when, how and why information and knowledge are introduced into the design process by analyzing current practices in engineering systems design. In order to use surveys and protocol analysis for data collection, an example of engineering systems design was selected to provide a sample space. Packaging systems design was selected for two primary reasons.

First, it is representative of systems design in that it involves the interaction of materials, machines, and people, both within the system and between the system and its environment. Packaging systems are the combination of the package, the equipment, and the operations required to facilitate distribution of a product from its point of production to its point of final use. Distribution may include packing, handling, loading, transporting, storing, displaying, and retailing the item. The primary purpose of packaging is to minimize the interaction between the product and its environment during distribution.

Second, packaging systems comprise a broad range of commonly understood concepts, so the results of the research can be easily understood and translated to other design domains. For example, the materials and processes used in packaging are similar to other engineering applications. The environmental conditions that must be examined (e.g., shock, vibration, electrostatic discharge) are familiar to engineers in several disciplines.

An ancillary reason for selecting packaging systems is the potential benefit that could result from any improvement in the ability of designers to efficiently use the resources involved, including both materials and manpower. Packaging is a major consumer of materials, especially glass, plastics, and paper products [34]. In addition, over one million people are involved in packaging operations, making it one of the largest industries in the United States [35]. Thus, any improvement in packaging system design could have broad impact on industry and consumers.

3.1 Survey of Practicing Engineers

Two sequential surveys were used to determine how practicing engineers identify and obtain the information and knowledge required in engineering systems design. The decision to use surveys in lieu of other information gathering techniques (e.g., observation or eyewitness accounts, performance tests, written tests, or review of existing documentation [36]) was based on efficiency and the type of information being sought. Surveys are effective in obtaining information that can be categorized as attitudes, beliefs, behaviors or attributes [37]. Information in each of the four categories, but primarily behaviors and attributes, was required for this research. Surveys are also efficient in obtaining information from a large population in a short time frame and at a reasonable expense.

Surveys may consist of questionnaires, telephone interviews, face-to-face interviews, or combinations thereof. The mailed, self-administered questionnaire was selected because of the large potential sample size and because it permits the participant to work at his or her desired pace. Questionnaires do not easily permit in-depth probes or follow-up questioning of individual participants. This was not considered to be a detriment to this research program since primarily behavioral and attribute data were sought.

3.1.1 Survey Development and Distribution

Numerous references offer guidelines for writing survey questions [38,39,40], administering surveys [36,38], and survey analysis [41,42,43,44]. For an overall approach to surveying, the Total Design Method (TDM) [37] was selected because it follows a philosophy similar to the systems approach to engineering design. TDM strives to maximize survey effectiveness by first identifying each aspect of the survey process that may affect either the quality or quantity of response, then developing a plan to minimize any negative effects. Instead of focusing inward on the details of survey preparation, TDM initially focuses outward on the environment in which the survey must be successful. Combining TDM philosophy with techniques of [36,38,40,43] resulted in a satisfactory 45% response rate to the initial survey and a 94% response rate to the follow-up survey.

Each survey was developed in a three-phase process. The first phase determined the survey objectives and the information required to support those objectives. The second phase was to determine the type of information being sought and write the individual questions in support of the survey objectives. The final phase was to arrange the questions into a logical format which encourages response and minimizes participant error.

The initial survey was a cross-sectional (i.e., administered only one time) design which sampled engineers selected from the 1989 membership roles of the Society of Packaging and Handling Engineers (SPHE). Forty-five replies were received from the mailing of one hundred initial surveys. From among those respondents who agreed to participate in the follow-up survey, 33 were selected as representative of engineers in corporations that develop packaging systems in support of their product lines. There are no uniform standards for determining sample size for surveys, but the general rule is that larger samples will provide higher levels of accuracy. When used in conjunction with literature reviews and other information sources, a sample of 20 to 50 respondents is considered appropriate during the early stages of research. The small sample size is adequate for developing hypotheses and procedures for testing them, since the primary purpose is to identify major problem areas and dimensions of the problem that the researcher may have ignored. In contrast, if the purpose of the survey was to draw conclusions that would have significant economic or social impact, an appropriate sample size could be two or three orders of magnitude larger [43, pp. 146-148].

3.1.2 Survey Objectives

The objectives of the initial survey were (1) to identify and collect background data on potential participants for follow-up research, and (2) to identify the range and modes of information and knowledge used. The information sought to support the objectives is listed in Table 1 and further detailed in Appendix A.1.

Initial survey responses helped formulate topics for the follow-up survey. The objectives of the follow-up survey were to (1) determine if engineers currently apply a systems approach to engineering design, and (2) determine what effect a systems approach has on the identification and acquisition of information and knowledge during the design process.

The information sought to support the objectives is listed in Table 2 and detailed in Appendix B.1.

Table 1. Information Sought During Initial Survey

A.	Identify categories of information topics used by packaging system designers.
B.	Identify categories of information sources used by packaging system designers.
C.	Identify categories of knowledge topics used by packaging system designers.
D.	Identify categories of knowledge sources used by packaging system designers.
E.	Identify respondent attributes, including experience, age, education and training, company size, organization and purpose.
F.	Identify what attributes engineers believe are important to performing their jobs successfully.

Table 2. Information Sought During Follow-up Survey

A.	Determine if the engineers responding use a systems approach to engineering design.
B.	Determine if the engineers responding use clearly defined technical performance requirements during the design process.
C.	Determine the relative difficulty of obtaining information inside and outside the engineer's immediate area of expertise.

3.1.3 Survey Analysis

Hypothesis testing is a fundamental tool in the analysis of statistically designed experiments [45,46]. However, in the analysis of surveys, hypothesis testing is rarely the sole or even dominant analysis technique. This is due in part to the uncontrolled nature of surveys, as contrasted with a highly controlled laboratory experiment. Rossi [43] offers three primary reasons for this argument. First, while survey data may support a hypothesis, it cannot prove the theory from which the hypothesis was postulated. The hypothesis may be consistent with theories other than the one under investigation. Second, strict hypothesis testing does not look for the existence of extraneous variables which may have influenced the data. Third, the survey may contain information supporting research ideas which could not be stated in clearly stated a priori hypothesis. This information can be extracted using techniques described as elaboration, the flow of analysis, the "pursuit of an idea", and other post factum interpretations of the data [43, pp. 201-239].

Survey analysis was conducted in three steps. First, the data was edited, encoded and recorded, [44, pp. 100-113] using a personal computer spread sheet, PlanPerfect. Second, preliminary analysis of the data included interpretation of one-way and two-way contingency tables, or graphs of frequency distributions. Finally, post factum analysis searched for information that could lead to further research topics.

The type of data solicited and the structure of the survey questions limited analysis in most cases to subjective evaluation of contingency tables or plots of frequency distributions for two reasons. First, in most questions the random variables belong to a nominal scale, where the only characteristic is that each variable is distinguishable from the others. The mode is the basic statistical measure for evaluating variables on a nominal scale [8, pp. 45-48], and no other statistic measures are applicable.

Second, in those cases where an ordinal or interval scale was used to measure a variable such as relative importance or relative difficulty, the majority of the survey questions required the respondent to rate all applicable topics. Not rating a topic indicated a response of "not applicable", which does not belong on a scale ranging from "not difficult" to "very difficult". Consequently, the sum of the probabilities for all possible values of the random variable along the scale does not equal one, a necessary condition in the definition of a discrete probability distribution.

3.1.3.1 Initial Survey Analysis

The initial survey with response data is Appendix A.2. The initial survey respondents represent a relatively narrow range of personal and professional attributes. The respondents can be categorized as predominantly engineers with between 2 and 10 years experience in packaging or packaging related positions. The modal respondent is between 26 and 35 years old with a bachelor degree or some graduate study. A 1988 salary survey of packaging professionals [47] sampled from a similar population describes the average packaging professional as 42 years old with a bachelor degree and 14.4 years of packaging experience. Over 20% of the respondents to the salary survey were managers of packaging, while 24% percent were packaging or project engineers. The larger proportion of managers, in contrast with the initial survey for this research, would tend to increase the average age and experience levels. Based on this comparison, the set of respondents to the initial survey is assumed to be representative of an average engineer in the packaging profession.

Almost exclusively, the respondents worked at division or corporate levels in a company employing more than 500 people. The companies manufactured a wide variety of products for consumer or industrial application and used packaging systems as part of the production and distribution process.

The areas in which information is required to develop new packaging systems were uniformly distributed among the eight topics offered in the questionnaire with three additional topics identified by respondents (Fig. 1). When arranged in order of decreasing difficulty in obtaining the required information, the top five were topics other than the packaging itself (Fig. 2). This indicates that information outside the engineer's immediate area of expertise is more difficult to identify and obtain. This topic was selected for follow-up investigation. Sources of information and their relative frequency of use were uniformly distributed among five of the topics listed (Fig. 3).

Categories of knowledge were distributed among nine topics, but only five of those ranked high in relative frequency of use (Fig. 4). Experience on the job and formal education were bimodal sources for acquiring knowledge. Analysis of this data offered no insights or patterns for follow-up questions.

Responses to questions about important aspects of an engineer's job indicated that interpersonal skills, especially the ability to communicate, were as important as technical skills. This topic was refined to focus on the need for effective communication in determining system requirements and selected for follow-up investigation.

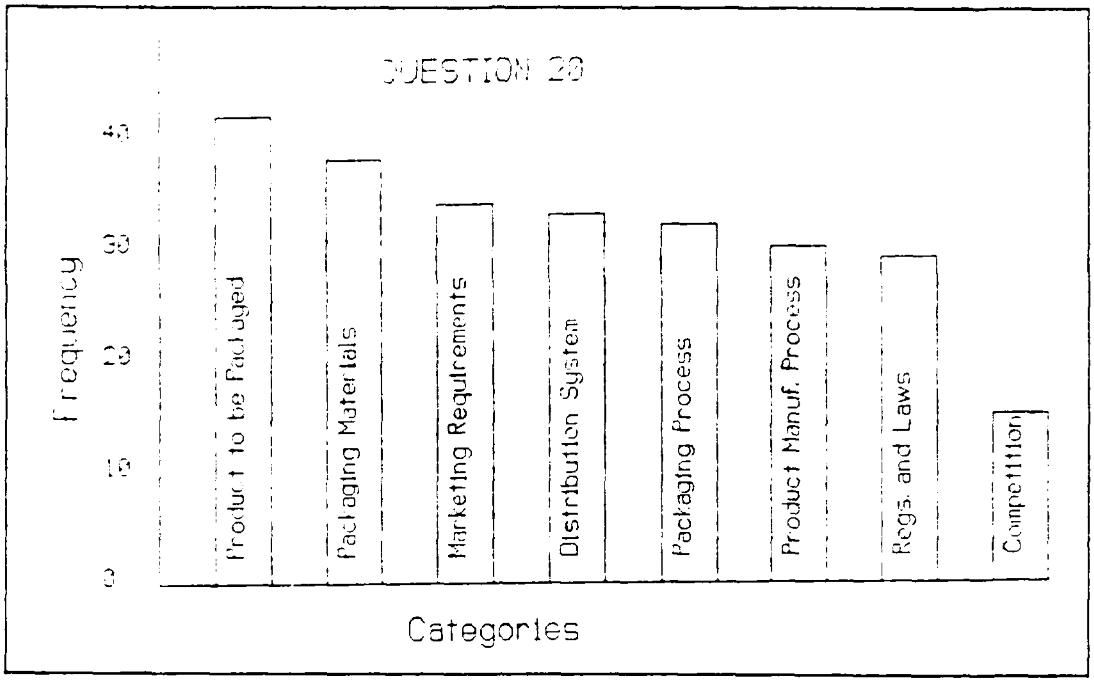

Figure 1. Topics for Which Information Needed

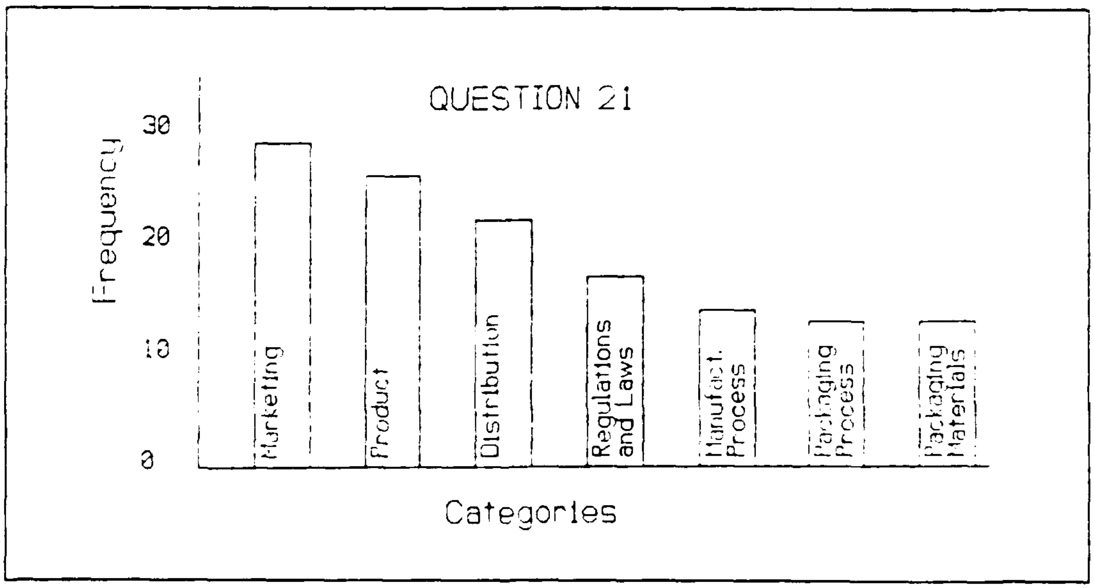

Figure 2. Information That is Most Difficult to Obtain

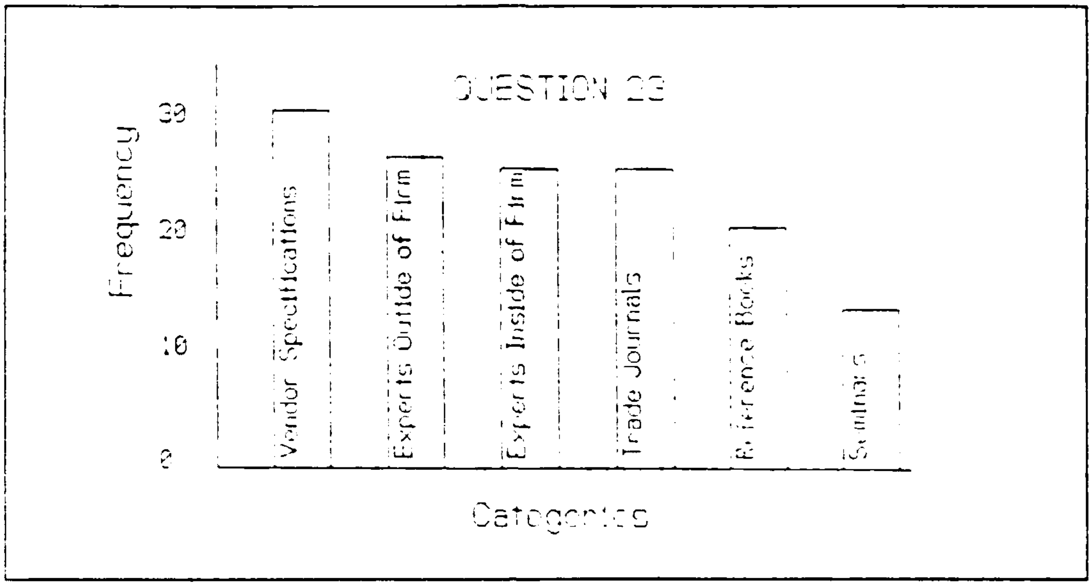

Figure 3. Sources of Information Most Often Used

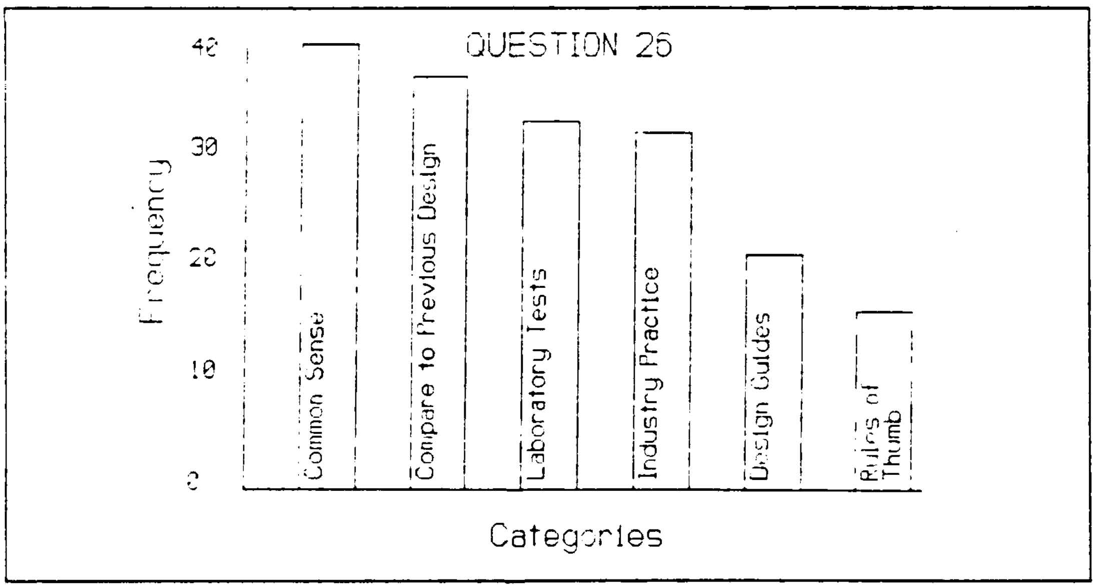

Figure 4. Forms of Knowledge Most Often Used

3.1.3.2 Follow-up Survey Analysis

The follow-up survey with response data is Appendix B.2. The detailed analysis of individual questions is Appendix B.3. One-way and two-way contingency tables and frequency distribution plots were the primary analysis tools. Correlating data between individual questions, three general conclusions were made:

1. The respondents do use a systems approach to solving packaging problems, although they may not formally recognize it as such.
2. Clearly stated technical performance requirements are not used as a deliberate part of the design process. Translation of requirements into technical terms appears to be a by-product of the design process.
3. Information and knowledge outside the immediate area of expertise are more difficult to obtain. Information about marketing is the one area which combines a high level of importance and high relative difficulty to obtain information.

3.1.4 Summary of Survey Results

The initial survey established the audience and provided two indicators of topics of importance which were pursued in the follow-up survey and subsequent experimentation. The first topic was the premise that information outside the engineer's immediate area of expertise is more difficult to identify and obtain. This was included in the follow-up survey. The second topic was the need for effective communication in determining system requirements. This was pursued in a design exercise focused on translating marketing needs into design requirements [48].

The follow-up survey provided indications that the respondents did apply a systems approach to developing solutions to packaging problems, confirming that the respondents were an appropriate sample for this research. It also supported the hypothesis that information outside the immediate area of expertise is more difficult to obtain. It failed to support the hypothesis that engineers deliberately translate performance requirements into technical terms during the design process.

3.2 Protocol Analysis of the Design Process

The design processes of several highly experienced and successful packaging systems engineers were documented and analyzed to search for commonalities which may be in part responsible for their success. Protocol analysis was used in controlled task, free response experiments to capture verbal reports as data. The experiments were focused on the phases of design, beginning with the identification of a need and concluding with the generation of design concepts for evaluation. Emphasis was placed on what information the engineer sought, and what influence that information had on the concepts generated.

3.2.1 Protocol Analysis

Protocol analysis is the best technique used in cognitive sciences to study complex behavioral processes, such as problem solving [49]. Subjects are required to "think aloud" as they solve problems. The recorded proceeding, or protocol, provides a detailed log of the subject's activities. The analysis of the protocol identifies the steps taken by the subject, and can provide insight for in-depth study of segments of the process [50]. Protocol analysis and other methods of acquiring verbal data about thought processes are generally accepted techniques for generating hypotheses and ideas for further exploration [51, pp. 2-4].

Protocol analysis offers advantages over two other approaches to examining the design process. <u>Retrospective analysis</u> requires the participant to reflect from memory what was done during an earlier design process. The disadvantages of retrospective analysis are (1) loss of some detail due to filtering by the participant, and (2) potential for biasing as the participant reports what he or she thinks was done or modifies actual behavior to reflect what he or she thinks should have been done. <u>Informal reporting</u> involves the observer taking notes and asking questions during the design process. It is the least disruptive but captures only data requested by the observer. Protocol analysis provides the most detailed and unbiased verbal data of the three common techniques One drawback of protocol analysis is that it tends to slow down the participant, but it is reported to not significantly affect the order or content of the design process [51,pp. 104-107,52].

Three major studies have used protocol analysis to study the design process. Adelson and Solway [53] studied software engineers in the design of an electronic mail system. Kant, Newell and Steier [54,55,56] studied graduate students developing algorithms for computational geometry. Ullman, Stauffer, Dietterich and McGinnis [57,58,59,50,60,61] studied six mechanical engineers involved in conceptual and detailed design of mechanical devices.

3.2.2 The Experiment

In controlled task, free response experiments, the participants are provided a fixed task but no guidance or rules on how to complete the task [62]. Appendix C describes the instructions provided and the experimental tasks. Three experimental tasks were developed to correspond with the areas of product expertise of the participants. The tasks were chosen to offer realistic technical and nontechnical challenges without being excessively complex in scope.

Six industry experts were selected, two each from three product areas. The participants ranged in experience from 15 to 43 years as packaging system developers. All had technical educational backgrounds ranging from two and a half years of college to master degrees. All were directors or managers of packaging functions, currently responsible for development of packaging systems within a corporate environment. Each participant was selected based on his or her professional reputation among colleagues, as well as level and breadth of experience.

The product areas were chosen as representative of different types of challenges facing a packaging system developer. The electronics area represents a high cost, low production rate item that is sensitive primarily to shock and vibration, but experiences little interaction with the surrounding environment. The food product is a moderate cost, moderate production rate item that is subject to interaction with the environment that must be controlled primarily to protect the product. The medical product represents a low cost, high production rate item where interaction must be controlled to protect both the product and the environment.

Each experiment was conducted at the subject's work location to allow access to normal references and design tools. The participant was provided general instructions describing how the exercise would proceed (Appendix C.1). After recording biographical information, the participant was provided the brief description of the product to be packaged (Appendix C.2). Verbal data was recorded on audio tape. All design notes and sketches were collected on sequential pages.

3.2.3 Analysis Procedure

The evaluation of the protocols consisted of three general phases: data transcription and editing, encoding, and analysis. Verbal data was transcribed verbatim, then edited to remove irrelevant comments and information identifying the participant or company involved. Irrelevant comments (e.g. "I need to take a break.") were removed to streamline the analysis. Identifying data was deleted to maintain confidentiality.

The protocols were reviewed to identify the introduction of information or knowledge into the design process. A coding scheme, shown in Table 3, was used to identify five characteristics about each occurrence. To reduce the possibility of biasing the data, each protocol was independently encoded by two mechanical engineering graduate students, each of whom was involved in research associated with the engineering design process. The two researchers agreed upon a composite set of coded occurrences to be used for analysis.

Appendix C.3 is a sample coded protocol. As shown in Table 4, the correlation of identifying the introduction of information and knowledge ranged from 45% to 65%, calculated by comparing the number of common occurrences before comparison to the number of occurrences by consensus. A majority of the discrepancies were in determining whether an occurrence was new information or the confirmation or restatement of previous information. For those occurrences that were commonly identified, the coding correlation ranged from 54% to 96%, generally improving with repetition of the process. Again, a consensus for each code was entered in the composite set.

Table 3. Codes for Information Occurrences

Classification	Focus	Level	Terminology	Concept
R,H.W	P,C,K,S,D,I,X	G,S	N,T	1
Requested data	Product	General	Non-technical	1 Concept Introduced
	Component	Specific	Technical	
Historical or assumed data	pacKage			
knoWledge to manipulate data	processS			
	Distribution			
	Environment			
	Internal			
	eXternal			

Table 4. Correlation of Coded Data

NUMBER OF OCCURRENCES	HDTV A	SWAB B	PIZZA C	PIZZA D	HDTV E	SWAB F
RESEARCHER A	73	91	46	32	36	26
RESEARCHER B	56	75	28	42	40	27
COMMON OCCURRENCES	38	51	26	25	26	15
FINAL CONCURRENCE	84	81	44	42	57	32
PERCENT CORRELATION	45	63	60	60	65	47

The analysis of the encoded data was both quantitative and substantive. The quantitative analysis compared the relative frequency distributions of the codes within the categories listed in Table 3. The substantive analysis studied the actual content of the information introduced at each occurrence to search for trends that would not be detected by quantitative means.

3.2.4 Findings

Four major findings extracted from analysis of the protocols are summarized below. The subsequent sections describe the motivation, the analysis procedure and the justification which lead to each finding.

<u>Finding 1</u>: Concept generation was influenced by information about system topics (e.g., distribution environment, production processes, user environment, corporate environment), as much as by information about the specific design task (i.e., package a product).

<u>Finding 2</u>: The focus of the information introduced was divided among three primary categories:

a. key performance parameter of the specific design task,

b. key performance parameter of the system,

c. other parameters defining the system boundaries.

<u>Finding 3</u>: Information acquisition is an integral part of the individual's design process, with two common characteristics:

a. <u>Methodical search vs. opportunistic behavior</u>: the design process may begin with a methodical search for information. However, once an initial concept was formulated, methodical searching ceased and opportunistic behavior was observed, interspersing concept generation and information seeking.

b. <u>Vertical thinking</u> [63, pp. 39-45]: pursuing single concepts and using information and knowledge to overcome obstacles to the success of that concept.

<u>Finding 4</u>: The distribution of topics of information introduced during the design process correlated to the distribution of topics identified as important and frequently needed in the survey of practicing engineers (page 17).

3.2.4.1 Finding 1

Concept generation was influenced by information about system topics (e.g., distribution environment, production processes, user environment, corporate environment) as much as by information about the specific design task (i.e., package a product). The motivation to investigate this topic came from the surveys. The surveys indicated that information about system topics was as important as information about the specific design task. This prompted investigation of whether that information was important for concept generation, or only for establishing the system boundaries.

The quantitative analysis required categorizing information introduced into the process as being focused on either the system or the design task. Systems information is that which was coded S,D,I or X (process, distribution, internal or external environment). Design task information is that which was coded P,C or K (product, component or package). The number of concepts introduced that are either concurrent with or immediately preceded by systems information were then tabulated. Concurrent occurrences of system information and concepts were low, ranging from 10% to 25%. Concepts preceded by systems information were high, ranging from 45% to 82%. Thus, the quantitative information is not conclusive, but indicates that systems information may have been influenced by concept generation as often as design task information.

For the substantive evaluation, the context of each occurrence where a concept was introduced was examined to determine what information may have influenced its generation. For examples:

> Expert A (HDTV), lines 10-14: "..with this high end product, I doubt that the dealer will order more than a couple at a time [HDGN System]. So with that, I will look to design packaging for this thing as an individually packaged unit [WKGN1 Task], as opposed to a bulk pack unit."

Assumed information about distribution contributed to the concept of individual packaging. Thus, the introduction of system information immediately preceding a concept was determined to have significant influence on that concept.

> Expert C (Pizza), lines 54-70: "Tomato based sauces come in cans [HCGN Task], but I would think in order to possibly keep this a simple package, one where you can package all the ingredients really easily together would be to put it in a flexible type package [HKGT1 Task].... Cheese could be the same way [HKGT1 Task]. This way the tomato paste and the cheese can be set on top of the crust in the package [WKGT1 Task] and take minimum amount of space. This would allow the sauce and cheese to be kept in the same general shape and put on top of the crust, which would allow it to be packaged fairly easily. If we go through the process now. We have a 5 x 6 inch piece of pizza crust, the tomato based sauce in a flexible package and the cheese in a flexible package. The crust can be put out on a continuous machine [HSST1 System] and the 5 X 6 slices cut out of it and then put on a piece of release paper [HKST1 System]."

Concepts for packaging the tomato sauce and cheese in flexible pouches were influenced primarily by historical information about package types, a design task specific topic. Concepts about the continuous machine and release paper were influenced by historical information about manufacturing processes, a system topic.

Among the six protocols, the percentage of concepts influenced by system information ranged from 33% to 60%, with a mean of 51% and a standard deviation of 11%. This evidence supports the finding that concept generation was influenced by information about system topics as much as by information about the specific design task.

3.4.1.2 Finding 2

The focus of the information introduced was divided among three primary categories:

a. key performance parameter of the specific design task,

b. key performance parameter of the system,

c. other parameters defining the system boundaries.

The motivation for this investigation was to determine what portion of the information introduced was focused on the critical design issues, and what portion was focused on keeping the design within a proper frame of reference.

The context of each coded occurrence was evaluated to determine if it could be classified into one of the three categories. Percentages shown in Table 5 are based on comparison to the total number of occurrences. The remaining occurrences, ranging from 16% to 40%, were divided among several topics. For the HDTV and pizza problems, approximately 10% to 15% of the information focused on refining the concept being developed (e.g., where to put graphics on a pizza carton or where to pack the HDTV remote control).

In five of six protocols, the focus of information was equally distributed among the three topics, indicating that keeping the design in perspective within the system boundaries is as important as satisfying performance requirements.

Table 5. Percentage of Occurrences by Focus

PRODUCT &EXPERT	KEY DESIGN PARAMETER	KEY SYSTEM PARAMETER	DEFINING BOUNDARIES
HDTV	PRODUCT FRAGILITY	DISTRIBUTION REQUIREMENTS	
A	35%	23%	27%
E	21%	16%	23%
PIZZA	PRODUCT DEGRADATION	PACKAGING PROCESS	
C	36%	25%	23%
D	24%	43%	7%
SWAB	LEAKAGE OR CONTAMINATION	PACKAGING SPEED/COST	
B	11%	32%	17%
F	22%	38%	16%

3.2.4.3 Finding 3

Information acquisition is an integral part of the individual's design process, with two common characteristics:

a. Methodical search vs. opportunistic behavior

b. Vertical thinking

The motivation for this investigation was to determine if common patterns existed among the six experts in their approaches to seeking information. If a common pattern existed, it could be the foundation for developing a method that could benefit other designers.

The analysis began with a search for sequential patterns by comparing coded occurrences for the total design effort and for quarterly periods. Referring to Table 3 (page 28), the frequency distributions of focus, level, class and terminology were compared. No discernable patterns were discovered. For example, there was no evidence of transition from general to specific information, from nontechnical to technical terminology, or from historical data to requested data. Information appeared to be integral to and initiated by events in each individual's process of design.

The next step of the analysis was to determine if information identification was deliberate or opportunistic. A pattern of progression from deliberate to opportunistic behavior was observed by Ullman, Stauffer and Dietterich [52] during protocol analysis of mechanical engineers involved in design of mechanisms. Expert A (HDTV), Expert B (Swab) and Expert D (Pizza) each began the design process with a deliberate search for information about the system, primarily focused on the key system performance parameter. Expert C (Pizza) and Expert E (HDTV) began with a deliberate search for information about the product, again focused on the key performance parameters. Expert F bypassed any deliberate questioning and began organizing thoughts leading toward the initial concept. In all six protocols, once a general concept was identified, no evidence of deliberate searches was observed. In terms of information identification, opportunistic behavior was observed in each experiment, where deliberate behavior was observed in five of the six protocols, but was confined to the early stages of the design process. Transition from deliberate searches to opportunistic behavior was observed in five of the six protocols, which is a pattern consistent with previous studies.

The third step in the analysis was to determine if individual experts applied vertical thinking, as evidenced by the pursuit of single concepts. Vertical thinking was also reported by Ullman, Stauffer and Dietterich [52, p. 13] in previous protocol analysis experiments. Four of the six experts pursued single concepts, incorporating information as it was required to overcome barriers. Two experts, both addressing the cotton swab, introduced more than one concept for portions of their design. Expert B was deliberate in writing down alternative approaches to overcome the two key performance requirements (i.e., no leakage and high production speed). This led to concepts of both flexible plastic and rigid glass packages. Once the glass concept was rejected, it was not reintroduced. Expert F pursued different production concepts (e.g., molded, blister pouch, or form, fill and seal) for the single package concept. In general, the experts followed a single concept through the entire design process, demonstrating a pattern of vertical thinking.

Based on these three analytical steps, it is concluded that the acquisition of information cannot be naturally separated from the individual design process. No common approach over time was observed, but evidence of a transition from methodical searching to opportunistic behavior and vertical thinking was observed.

3.2.4.4 Finding 4

The distribution of topics of information introduced during the design process correlated to the distribution of topics identified as important and frequently needed in the survey of practicing engineers (page 17).

The motivation for this investigation was to compare data from two distinct sources and two sample populations. Survey data is retrospective and subject to filtering by the respondent. Protocol analysis data captures a portion of the participant's thoughts at approximately the time they occur. Correlation of the two types and sources of data concerning the same question would increase credibility of the conclusions reached.

The relative frequency of the topics for which information was introduced is shown in Table 6. Component and product categories were combined to relate to the survey categories. The zero entries for distribution in both protocols addressing the cotton swab were further investigated. As discussed in section 3.2.3, some occurrences could have been coded more than one way, especially the focus code. The researcher must evaluate the primary focus of the information. For the cotton swab, occurrences discussing the number of swabs per carton could have been coded either as a package or a distribution focus. Because of the context in which they were entered, those occurrences appeared focused on the package. Secondly, cotton swabs are relatively insensitive to the distribution environment. During these short duration experiments, the experts appeared to direct their efforts toward the critical issues. Consequently, secondary issues may not have received the attention that would have been present in an actual design in a corporate environment.

Table 6. Relative Frequency of Information Topics

CATEGORY	HDTV A	HDTV E	PIZZA C	PIZZA D	SWAB B	SWAB F	AVERAGE
PRODUCT	28	26	25	15	35	9	23.0
PACKAGING	27	39	41	55	22	50	39.0
PROCESS	11	5	14	21	20	9	13.3
DISTRIBUTION	24	14	11	2	0	0	8.5
INTERNAL	6	7	0	5	9	19	7.7
EXTERNAL	5	9	9	2	15	13	8.3

Table 7 displays the top categories identified in two survey questions and in the protocols. Question 20, Survey 1, asked what areas of information were needed. Question 6, Survey 2, asked which topics were important. The terminology is different between the survey questions and the categories used during the protocols. For example, the protocol category "packaging" included both packaging materials and package features (e.g., zip-open carton for pizza, peel-top package for the cotton swab). Marketing requirements from the surveys would be divided among the categories of distribution, internal environment, and external environment in the protocols. Budget information, identified in question 6 of the follow-up survey, would be considered internal environment during the protocols.

Table 7. Comparison of Categories of Information

PRIORITY	QUESTION 20 SURVEY 1	QUESTION 6 SURVEY 2	PROTOCOL AVERAGES
1	Product	Product	Packaging
2	Packaging Materials	Distribution	Product
3	Distribution	Packaging Materials	Packaging Process
4	Marketing	Marketing	Distribution
5	Packaging Process	Budget	External Environment

Allowing for differences in terminology used in the surveys and the protocol, the lists are similar but not identical. The coding used on the protocols, the general and retrospective nature of the survey in contrast to the specific design problems of the protocols, and the suggested topics in the survey questions may have contributed to the difference.

4 A PROBLEM FORMULATION METHOD

Based on the preliminary research, it is hypothesized that deliberate identification of system boundaries and the key performance requirements of both the specific design task and the system parameters should occur during problem formulation and prior to concept generation. From the protocol analysis, the methodical search for information at the outset of the design process may be viewed as an attempt to "bring manageability and closure to the problem" [3] at the earliest possible stage by defining the conditions under which any solution can be viewed as complete. It is important to note that in establishing the system boundaries and the required levels of performance, the experts did not limit their ability to creatively develop concepts. They only defined the region within which to be creative, with hope of avoiding ineffectiveness and Errors of the Third Kind (i.e., solving the wrong problem or a "suboptimal" problem) [64]. MacCrimmon and Taylor [65] identify "determining the boundaries of a problem" as one of four strategies for reducing the complexities of problem formulation.

From both the surveys and the protocols, the consistency of categories for which information is required indicates that identification of key performance parameters about both the design task at hand and the environment within which the task must be solved are important to the process. The surveys provided no evidence that technical performance requirements were a deliberate part of the design process. The protocols provided evidence that the experts introduced technical performance requirements early in the design process, but stopped short of deliberately and explicitly stating them.

Therefore, the second phase of the research hypothesized and validated the effect of using a method which incorporates technical performance requirements on the quality of problem formulation in engineering systems design. A problem formulation method was developed, criteria and a model for evaluating the effect of the method were defined, and the method was experimentally validated.

Two goals guided the development of a problem formulation method. First, the method should assist in the identification of system boundaries and the key performance criteria of both the specific design task and the system parameters. Secondly, the method should encourage the use of technical performance requirements as a means of defining those boundaries and criteria.

4.1 Method Development

To satisfy the first goal, Dimensional Analysis was applied to engineering systems design. Dimensional Analysis is an analytical technique designed to clarify and explore the dimensions and limits of general problems. Dimensional Analysis recognizes the five aspects of general problems as substantive, spatial, temporal, quantitative and qualitative [66, pp. 60-66]. Relating data from the surveys, five characteristic aspects of engineering systems problems were identified:

a. time (e.g., dates, duration, cycles, etc.)

b. dimensions (e.g., distance, areas, weights, etc.)

c. value (e.g., precision, cost, quality, reliability, etc.)

d. physical matter (e.g., materials, parts, machines, etc.)

e. people (e.g., user, manufacturer, organizations, etc.)

The five characteristic dimensions are not purported to be unique, universal, or inclusive. However, they are considered to be sufficiently representative and general to assist in the identification of system boundaries and the key performance criteria of both the specific design task and the system parameters.

To satisfy the second goal of method development, a concise description of technical performance requirements was formulated. Technical performance requirements describe in measurable or verifiable terms the levels of performance required for any solution to be considered acceptable and complete. Each technical performance requirement should include four elements:

Identification - a verbal description of the performance attribute (e.g., strength, speed, power, durability, weight)

Conditions - delineation of the environmental conditions under which the performance is required (e.g., temperature, moisture content, time, number of operators)

Target Value - the optimum performance value, that value which will minimize loss or maximize gain (e.g., 32 miles per gallon, 90 decibels, 63 hertz, $1200)

Allowable Variance - the permissible deviation from the target value (e.g., ± 2%, no more than, ± 6 hertz)

Concisely stated, the problem formulation method uses five dimensions to assist in identifying boundary and performance criteria, and technical performance requirements as a means of expressing them. The method can be conveyed using a guide, as shown in Figure 5.

Guide to Problem Formulation

During problem formulation, you should identify two elements: the boundaries of the problem and the key performance criteria. Describing these two elements will allow you to focus your creative efforts within the proper boundaries, and determine when your design is sufficient. Writing technical performance requirements will help you describe these elements. Technical performance requirements describe in measurable or verifiable terms the performance required for any solution to be considered acceptable. Each technical performance requirement should include four elements:

Identification - a verbal description of the performance attribute (e.g., strength, speed, cost, durability, weight)

Conditions - delineation of the environmental conditions under which the performance is required (e.g., temperature, moisture content, time, number of operators)

Target Value - the optimum performance value, that value which will minimize loss or maximize gain (e.g., 32 miles per gallon, 90 decibels, 63 Hertz)

Allowable Variance - the permissible deviation from the target value (e.g., ± 2%, no more than, ± 6 Hertz)

It is important that you describe **WHAT** performance you need, but not how to achieve it. You should not restrict the designer's creative ability, but should instead identify the boundaries within which to be creative. If you specify what levels of performance are required for any solution, the designer should be able to determine if a solution is within those boundaries and also when the solution is adequate enough to stop designing.

To help identify performance attributes, think and ask questions in terms of:

- **TIME** (dates, duration, cycles, etc.)
- **DIMENSIONS** (distance, areas, weights, etc.)
- **VALUE** (precision, cost, quality, reliability, etc.)
- **PHYSICAL MATTER** (materials, parts, machines, etc.)
- **PEOPLE** (user, manufacturer, organizations, etc.)

Use the answers to these questions to write as many technical performance requirements as you feel are necessary to adequately formulate the problem.

Figure 5. Problem Formulation Guide

4.2 Evaluation Criteria and Model

Evaluation criteria and an evaluation model were developed in order to validate the effectiveness of the problem formulation method. A Multiple Attribute Value model was selected as an appropriate evaluation tool.

Multiple Attribute Value models, also known as Weighted Criterion Function or Multiattribute Utility Function models, are appropriate for addressing value trade-offs among multiple objectives and uncertainty in complex problems [67]. The attributes should be independent of each other and each has its own utility scale. In addition, a relative weight is assigned to each attribute. For a given option (e.g., problem statement) a value may be subjectively assigned for each attribute. The weighted sum of values defines the utility of the option. In uncertainty situations, the option with the highest expected utility should be chosen. Problem solving can be viewed as an uncertainty situation in that the highest quality problem statement will not ensure the highest quality solution.

Sakman [22] used a panel of experts to develop a Multiple Attribute Value model to evaluate the quality of problem statements. Previous work had used the quality of solutions to indirectly indicate the quality of problem statements [3,68]. Sakman's five attributes and utility scales of quality for problem statements are:

<u>X0: Clarity</u> - The binary assessment of whether or not the problem is stated in a coherent way and in understandable, nonjargon terms sufficient to allow further evaluation of attributes.*

0	1
NOT-CLEAR	CLEAR
(Unacceptable)	(Acceptable)

<u>X1: Solution Implication</u> - The degree to which the statement suggests solutions or ways to achieve solutions to the problem. The more a statement does so, the less favorable it is (i.e., this dimension has a negative orientation).

0		100
SOLVES	LEADS	OPEN-ENDED
(Worst)	(Anchor)	(Best)

*Clarity was originally intended as a relative measure, but was ultimately used to eliminate problem statements which lacked sufficient clarity to permit evaluation of the remaining four attributes.

<u>X2: Structural Considerations</u> - The degree to which the statement reflects consideration for all relevant and unique aspects, parts, complexities and their interrelationships and intrarelationships to the extent that can be seen or verified at the stage of problem formulation.

0		100
NONE (Worst)	SOME (Anchor)	ALL (Best)

<u>X3: Stakeholders</u> - The degree to which the statement reflects considerations of the needs, interests and power of all stakeholders, i.e., parties that will affect or be affected, directly or indirectly, by the solution of the problem. Stakeholders may be tangible (e.g., an interest group) or intangible (e.g., the "unborn" generation), may have high salience (in the sense of being motivated, having high stake) or low salience, and may be vocal/outspoken or "invisible." (Note: It is assumed that all salient stakeholders are tangible, but not all tangible stakeholders are salient.)

0			100
NONE (Worst)	SALIENT (Anchor #1)	TANGIBLE (Anchor #2)	ALL (Best)

X4: Level of Focus - The degree to which the statement defines as high a level or as broad a problem as is possible and appropriate.

0			100
NARROW	SOMEWHAT NARROW	SOMEWHAT BROAD	BROAD
(Worst)	(Anchor #1)	(Anchor #2)	(Best)

Figure 6 illustrates the Multiple Attribute Value model used by Sakman to evaluate problem statements developed by small groups for general problems [22] and by Nadler to evaluate problem statements developed by individuals solving mechanical engineering problems [19]. Both research efforts compared the problem statements developed using problem definition methods selected from those available in the literature. In both research efforts, significant differences between methods were detected for individual attributes, but no significant difference was detected for overall problem statement quality.

ATTRIBUTE	WEIGHT	UTILITY SCALE	SCORE	UTILITY
CLARITY	1	0 1	S0	S0
SOLUTION IMPLICATION	W1=.28	0____100	S1	W1xS1
STRUCTURAL CONSIDERATION	W2=.31	0____100	S2	W2xS2
STAKEHOLDERS/ INTEREST GRPS	W3=.27	0____100	S3	W3xS3
LEVEL OF FOCUS	W4=.14	0____100	S4	W4xS4
		QUALITY=	S0 * Σ(Wi * Si) i=1,2,3,4	

Figure 6. Sakman's Multiple Attribute Value Model

Sakman's model was developed for general problems, and tested on both nonengineering and engineering problems. To reflect the importance of identifying and defining boundaries and performance criteria, two original attributes are introduced:

<u>Performance Identification</u> (X5) - The degree to which the statement defines what performance is required to satisfy the identified needs of the problem.

0		100
NOT DEFINED (Worst)	SOMEWHAT DEFINED (Anchor)	DEFINED (Best)

Performance Measurability (X6) - The degree to which the required performance can be measured or verified.

0		100
NOT MEASURABLE (Worst)	SOMEWHAT MEASURABLE (Anchor)	MEASURABLE (Best)

Structural Considerations (X2) and Stakeholders (X3) measure the degree to which the problem statement reflects consideration for aspects, parts, and complexities of the problem and for needs, interest and power of stakeholders. Performance Identification and Performance Measurability address similar aspects, parts, complexities and stakeholders, but from a more appropriate perspective. The purpose of engineering design is to develop systems, components or processes that perform in such a manner as to satisfy needs. Therefore it is more appropriate to identify and measure the performance required by a part or a stakeholder than it is to identify the existence of the part or stakeholder.

4.3 The Experiment

A controlled task, guided response experiment was used to evaluate the effect of the method on the quality of problem formulation. The test subjects were practicing mechanical engineers and graduate students in mechanical engineering. Two independent graders evaluated each statement for clarity

(X0) and along each of the six dimensions (X1 though X6) described in Section 4.2.

4.3.1 Experimental Task

General instructions to the test subjects are Appendix D.1. Each participant was provided the problem description shown in Appendix D.2 and tasked to formulate the problem. Half of the test subjects, selected at random, were asked to apply the problem formulation method by following the guidelines in Appendix D.3. The test administrator used the information in Appendix D.4 to answer specific questions from individual test subjects, as opposed to being made openly available to every test subject. All interaction between the test subject and the test administrator was done with handwritten questions and responses.

4.3.2 Experimental Design

The experiment was conducted as a 2^3 factorial design, signifying three factors or treatments, each at two levels. One factor was the approach used, either unstructured (control group) or the problem formulation method. The second factor was the classification of participants as either practicing engineers or graduate students. The third factor was the grader. The hypotheses evaluated the effect each of the three treatments on the attributes of quality (X1 through X6) and on the weighted aggregate value of quality. Clarity (X0) was used only to eliminate problem statements which lacked sufficient clarity for further evaluation. The Multiple Attribute Value model used for evaluation is Appendix D.5. Instructions to the graders are shown in Appendix D.6.

4.3.3 Sample Population

The sample population consisted of eight mechanical engineers and eight graduate students in mechanical engineering. Of the sixteen participants, two had earned doctoral degrees. Seven of the sixteen participants had earned Master of Science in Mechanical Engineering degrees, of whom four were studying towards doctoral degrees. The remaining seven participants had earned Bachelor of Science in Mechanical Engineering degrees, of whom three were studying toward advanced degrees.

The practicing engineers were currently employed as product design engineers, senior design engineers, or design and analysis engineers. Industry experience ranged from 8 months to 24 years. Participation in the experiment was voluntary, and both individual and corporate anonymity was assured. The engineers worked for one of two corporations in the Houston, Texas, metropolitan area. The corporations differed in their product and service areas, corporate size, and geographic span.

The graduate students were all enrolled at Texas A&M University in College Station, Texas. Each of the graduate students had received an undergraduate degree from an institution other than Texas A&M University. The four students pursuing their doctoral degrees received their master degrees from Texas A&M University. Four of the graduates students also had from 1 to 4 years of industry experience as mechanical engineers.

4.3.4 Graders

The independent graders were selected as representative of academic and industry perspectives of engineering systems design. Grader S is an associate professor of mechanical engineering in an ABET-accredited program. Grader S earned a Doctor of Philosophy degree in mechanical engineering and is a registered Professional Engineer. Grader S has taught courses covering the engineering design process, to include problem formulation and Multiple Attribute Value models.

Grader J currently directs the operational testing program for a military hardware system, verifying that the equipment and all supporting systems meet the user performance requirements prior to full-scale production. Grader J has over 10 years experience in research, development and testing of military hardware systems. Grader J earned a Master of Science degree in Operations Research.

4.4 Analysis Procedure

The handwritten problem statements were typed verbatim onto grading forms for consistent appearance (Appendix E.1). Each problem statement was evaluated by two independent graders, neither of whom were familiar with the experimental design or the focus of the research project. Results of the evaluations, coded for analysis, are shown in Appendix E.2. Analysis of variance (ANOVA) was used to determine the effect of the three factors (method, engineer/student, and grader) on the quality of the problem statement.

Analysis of variance is a procedure in which the total variation in a measured response is partitioned into components which can be attributed to identifiable sources of variation, called factors or treatments [69]. The objective of ANOVA is to make statistical inferences about the means of independent, random samples drawn from two or more populations. The null hypothesis to be tested is that all of the population means (μ_i) are equal, i.e.,

H_0: $\mu_1 = \mu_2 = \ldots = \mu_k$ for $\underline{k}$ treatments

H_1: $\mu_i \neq \mu_j$ for some $\underline{i}$ and $\underline{j}$.

The fundamental test is the comparison of the variance between treatments (SS_{Tr}, treatment sum of squares) to the variance within treatments (SS_E, residual or error sum of squares) by using an appropriate test statistic based on the *F* Distribution. The test statistic is the ratio of treatment mean square to error mean square, or MS_{Tr}/MS_E, where

$MS_{Tr} = SS_{Tr}/(k-1)$ for *k* treatments

$MS_E = SS_E/(N-k)$ for a sample population of size N.

If the null hypothesis is true, then the test statistic is expected to be close to 1; otherwise it is expected to be greater than one. If the null hypothesis is true, then the test statistic will follow an *F* Distribution with (k-1) and (N-1) degrees of freedom. The mechanics of ANOVA require the calculation of the appropriate test statistic from the experimental data, then comparison of that test statistic to the value in an *F* Distribution table for the appropriate degrees of freedom and appropriate limit for the probability of a Type I or Alpha (α) error. If the test statistic is larger than the *F* Distribution value, then the null hypothesis is rejected, with α probability that the treatment means were actually equal. Using SAS statistical analysis computer software, the ANOVA procedure calculates the probability of obtaining a test statistic greater than the value calculated if H_0 is true. If that value is less than an allowable significance level, then the null hypothesis is rejected.

Hypotheses were tested at an α=10% significance level, as was done by Sakman [22] and Nadler [19] in similar experiments. Ten percent is appropriate based on the amount of subjective evaluation required, the inability to identify and control all possible variables and the lack of preceding research [70]. At this level of significance, differences in the quality of the problem statements can be detected with 90% confidence that the difference actually exists and is not due to random error.

4.5 Results

The initial screening of the problem statements was to determine if they were sufficiently clear for further evaluation. Grader J determined that sample number 24 was unclear in accordance with attribute scale X0. Grader S evaluated number 24 but noted in the margin that it was almost eliminated as unclear. Therefore, sample number 24 was removed from the data set.

4.5.1 Validation of Assumptions

The assumptions underlying analysis of variance are:

1. The k samples (corresponding to <u>k</u> treatments) represent independent samples drawn from <u>k</u> specific populations with unknown means $\mu_1 = \mu_2 = \ldots = \mu_k$,

2. Each of the <u>k</u> populations is normally distributed, and

3. Each of the k populations have common variance [69, p. 456].

Independence of samples is assured by the experimental design. Each sample is assignable to an experimental unit, which is a unique combination of grader (GDR), control group or use of the problem formulation method (PFM), and classification as a practicing engineer or graduate student (WORK). No sample can belong to more than one experimental unit.

Normal distribution of the samples was verified using normal probability plots of the observed values. Hypothesis testing based on the F Distribution, as used in analysis of variance, is robust to moderate lack of normality [71, p. 86, 72, p. 737]. As shown in Appendix E.3, the populations plot along a generally straight line, indicating that the samples generally follow a normal distribution.

The assumption of equal variances between treatments was tested based on the F Distribution. For $\alpha = 0.10$, the F Distribution values for the confidence interval of a two-tailed test are $f_{0.05,14,14} = 2.48$ and $f_{0.95,14,14} = 0.402$. As shown in Table 8, three of the test statistics are outside of the confidence interval. For comparing means with unequal variances, the Smith-Satterthwaite approximation procedure was used [69, p. 307-308] and is annotated in appropriate tables in subsequent discussion.

Table 8. Test Statistics for Treatment Variances

	X1	X2	X3	X4	X5	X6	AGG
GDR	0.41	0.58	0.99	0.91	1.29	0.77	0.74
PFM	1.83	0.19*	0.74	3.71*	0.42	2.78*	0.61
WORK	0.54	1.60	2.05	0.47	1.17	1.58	1.40

* Indicates unequal variances at $\alpha = 0.10$

4.5.2 Testing Main Effects and Interactions

The effect of the three primary factors and all interactions was tested first. As shown in Appendix E.4, the three-factor and two-factor interactions had no significant effect on the quality of the problem statement.

The effect of the three primary factors on problem statement quality using the unweighted aggregate value was investigated. As shown in Table 9, the use of the method (PFM) and the grader (GDR) had a significant effect on the quality of the problem statement. Whether the subject was a practicing engineer or student (WORK) had no significant effect on the quality, eliminating that factor from subsequent models.

Table 9. Three-Factor ANOVA

Source	Degrees of Freedom	F Value	Probability of a Value ≥ F
PFM	1	5.33	0.03 *
GDR	1	16.22	<0.01 *
WORK	1	0.60	0.44

* Significant at $\alpha = 0.10$

The two-factor model with interaction shown in Table 10 indicated that there was no significant interaction between PFM and GDR. Therefore, all subsequent models evaluated only the effect of the two primary factors, PFM and GDR. The following sections will discuss the effect of each factor in detail.

Table 10. Two-Factor ANOVA with Interaction

Source	Degrees of Freedom	F Value	Probability of a Value ≥ F
PFM	1	16.55	<0.01 *
GDR	1	5.44	0.03 *
PFM*GDR	1	1.15	0.29

* Significant at $\alpha = 0.10$

4.5.3 The Effect of the Problem Formulation Method

The effect of using the problem formulation method (PFM) during problem formulation was investigated three ways:

a. The effect of PFM on each of the six attributes of problem statement quality,

b. The effect of PFM on problem statement quality as determined by the six-dimensional Multiple Attribute Value model as described in Appendix D.5, and

c. The effect on problem statement quality as determined by Sakman's four-dimensional Multiple Attribute Value model.

4.5.3.1 The Effect of PFM on Attributes of Quality

As shown in Table 11, test subjects who applied the problem formulation method were determined to have performed significantly better than test subjects in the control group with respect to four of the six attributes. The four attributes are Structural Considerations, Stakeholders, Performance Identification, and Performance Measurability. No significant difference was determined for the other two attributes, Solution Implication and Level of Focus. Figure 7 illustrates the differences in mean scores between the control group (CTL) and the treatment group (PFM) for each of the six attributes.

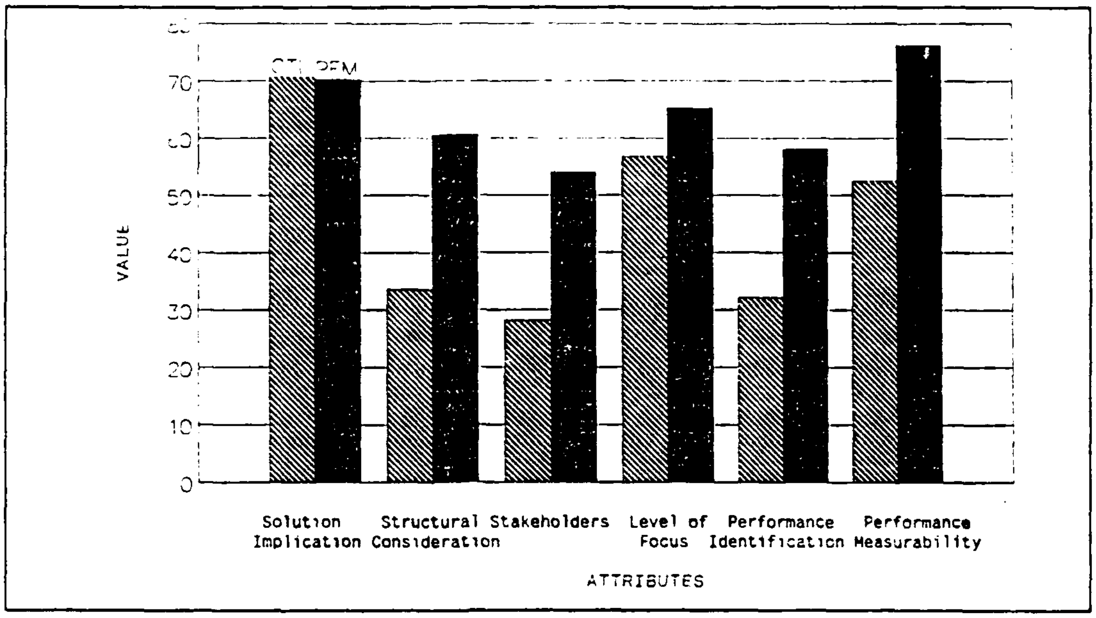

Figure 7. Effect of PFM on Mean Values for Six Attributes

Table 11. Effect of PFM on the Six Attributes

Source	Degrees of Freedom	F Value	Probability of a Value ≥ F
SOLUTION IMPLICATION	1	0.0	0.97
STRUCTURAL CONSIDERATIONS	1	3.8 **	<0.01 *
STAKEHOLDERS	1	24.3	<0.01 *
LEVEL OF FOCUS	1	1.0 **	0.31
PERFORMANCE IDENTIFICATION	1	12.8	<0.01 *
PERFORMANCE MEASURABILITY	1	2.8 **	<0.01 *

* Significant at $\alpha = 0.10$

** Calculated with unequal variances

4.5.3.2 The Effect of PFM on Aggregate Values of Quality

Test subjects who applied the problem formulation method were determined to have performed significantly better than test subjects in the control group when comparing weighted aggregate scores using the six-attribute model. To test sensitivity to the weighting factors, five aggregate models were evaluated. As shown in Table 12, an unweighted aggregate and four weighted aggregate models were compared. The weighting factors were based on Sakman's four-attribute model, which was derived from a panel of experts. The two additional factors (Performance Identification and Performance Measurability) were assigned weights ranging from the lowest to the highest value of the original four. The six-factor model was then normalized.

Table 12. Sensitivity of Aggregate Model to Weighting

ATTRIBUTES	WEIGHTING FACTORS AGG1	AGG2	AGG3	AGG4	AGG5
SOLUTION IMPLICATION	.167	.219	.187	.177	.173
STRUCTURAL CONSIDERATIONS	.167	.242	.207	.196	.191
STAKEHOLDERS	.167	.211	.180	.171	.167
LEVEL OF FOCUS	.167	.109	.093	.089	.086
PERFORMANCE IDENTIFICATION	.167	.109	.167	.184	.191
PERFORMANCE MEASURABILITY	.167	.109	.167	.184	.191
F VALUE	16.46	15.34	17.73	18.31	18.55
PROBABILITY OF A VALUE >F	<0.01	<0.01	<0.01	<0.01	<0.01

4.5.3.3 The Effect of PFM With the Four-Attribute Model

Test subjects who applied the problem formulation method were determined to have performed significantly better than test subjects in the control group when applying Sakman's four-attribute model. The mean score for test subjects using the problem formulation method was 62.2 out of 100 possible points. The mean score for the test subjects in the control group was 45.8 points. The test statistic value of 10.3 corresponds to a probability of less than 0.01 that the difference in means is due to random error. It is therefore concluded with greater than 90% confidence that the use of the problem formulation method resulted in higher problem statement quality.

4.5.4 The Effect of Graders

Evaluating the problem statements was subjective within the guidelines provided in Appendix D.6. Consequently, each grader introduces a unique set of personal values into the evaluation process. The values may stem from experience, education or other uncontrolled sources which helped determine the grader's personal rating scheme. The mean scores awarded by each grader are shown in Table 13.

Figure 8 shows the mean values assigned by each grader for each of the six attributes. In general, Grader J awarded lower scores than Grader S. Despite the numerical differences between scores, the conclusions that were reached about the effect of PFM on each attribute were consistent between graders. It is therefore concluded that while the variable grader (GDR) had a statistically significant effect on the scores awarded, it did not have an effect on the conclusions that would be reached.

Table 13. Mean Scores Awarded by Grader

ATTRIBUTES	GRADER J CTL	GRADER J PFM	GRADER S CTL	GRADER S PFM
SOLUTION IMPLICATION	75	66	67	75
STRUCTURAL CONSIDERATIONS	37	55	30	66
STAKEHOLDERS	15	37	41	72
LEVEL OF FOCUS	61	62	53	69
PERFORMANCE IDENTIFICATION	30	56	34	60
PERFORMANCE MEASURABILITY	41	64	64	89

Neither grader awarded scores that resulted in a significant difference for attribute X1 (Solution Implication). However, Grader J rated PFM slightly below CTL, whereas Grader S rated PFM slightly higher than CTL. Even though no assignable cause can be determined, the reversed rankings illustrate that personal values can affect evaluation results.

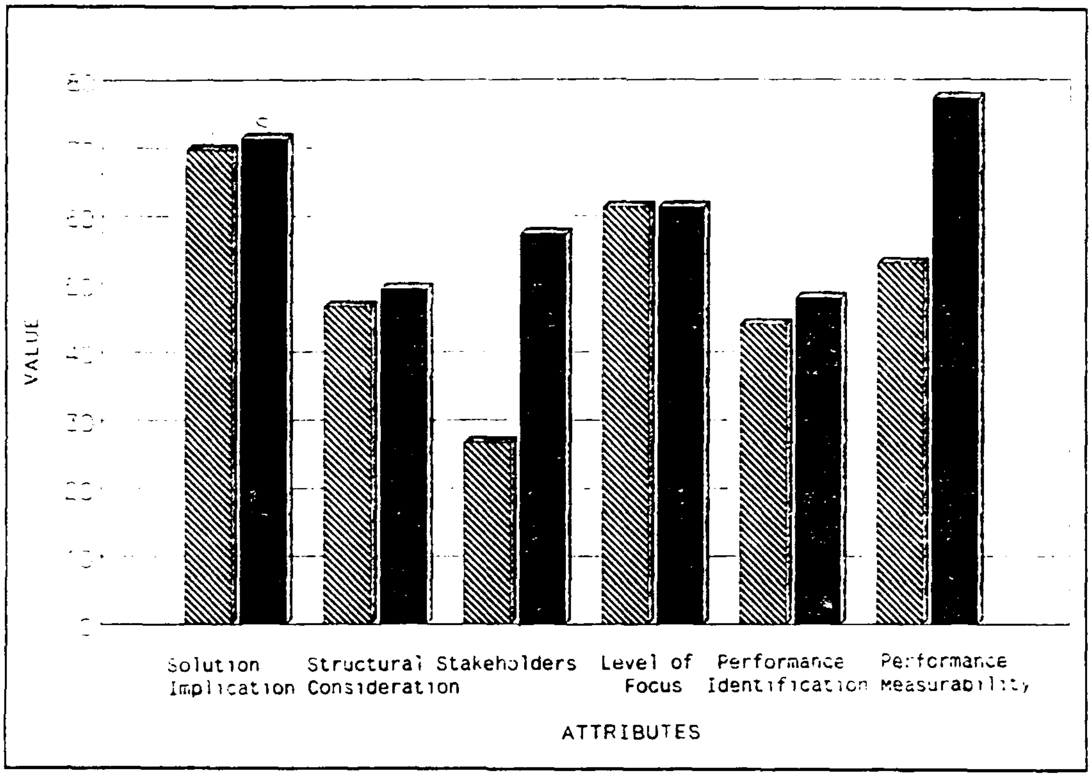

Figure 8. Mean Values by Grader for Six Attributes

4.5.5 Correlation Between Attributes

The correlation between scores for the six attributes for total sample population is shown in Table 14. A strong positive correlation exists between four of the attributes: Structural Consideration, Stakeholders, Performance Identification and Performance Measurability. Tables 15 and 16 display the correlation between the six attributes for the control group and PFM group respectively. In the control group, very low correlation exists between the four attributes. In the PFM group, the strong correlation remains.

Table 14. Correlation Coefficients Between Attributes

ATTRIBUTES		X1	X2	X3	X4	X5	X6
SOLUTION IMPLICATION	X1	1.00	0.19	-0.02	*0.69	-0.04	-0.05
STRUCTURAL CONSIDERATIONS	X2		1.00	*0.54	0.28	*0.83	*0.46
STAKEHOLDERS	X3			1.00	0.11	*0.58	*0.64
LEVEL OF FOCUS	X4				1.00	0.15	0.14
PERFORMANCE IDENTIFICATION	X5					1.00	*0.55
PERFORMANCE MEASURABILITY	X6						1.00

*Significant at $\alpha=0.10$

Table 15. Correlation Coefficients for Control Group

ATTRIBUTES		X1	X2	X3	X4	X5	X6
SOLUTION IMPLICATION	X1	1.00	-0.20	-0.19	*0.70	-0.33	-0.17
STRUCTURAL CONSIDERATIONS	X2		1.00	0.07	0.20	0.40	-0.01
STAKEHOLDERS	X3			1.00	-0.03	*0.50	0.39
LEVEL OF FOCUS	X4				1.00	0.07	0.04
PERFORMANCE IDENTIFICATION	X5					1.00	0.34
PERFORMANCE MEASURABILITY	X6						1.00

*Significant at $\alpha=0.10$

Table 16. Correlation Coefficients for PFM Group

ATTRIBUTES		X1	X2	X3	X4	X5	X6
SOLUTION IMPLICATION	X1	1.00	0.51	0.14	*0.74	0.17	0.20
STRUCTURAL CONSIDERATIONS	X2		1.00	0.45	0.32	*0.86	*0.54
STAKEHOLDERS	X3			1.00	0.06	0.34	*0.76
LEVEL OF FOCUS	X4				1.00	0.06	0.11
PERFORMANCE IDENTIFICATION	X5					1.00	*0.53
PERFORMANCE MEASURABILITY	X6						1.00

*Significant at $\alpha=0.10$

The strong correlation in the PFM group coupled with the significant improvement in the same four categories suggests that when the problem formulation method is used, the four attributes are not independent. This suggests that an improved four-dimensional model could be defined using Solution Implication, Level of Focus, Performance Identification and Performance Measurability. As discussed in 4.2, the latter two attributes would address the same concerns as Stakeholders and Structural Considerations, but from a more appropriate perspective. As shown in Table 17, aggregate scores using these four attributes support the same conclusions as either Sakman's model or the six-attribute model.

Table 17. Improved Four-Attribute Model

Source	Degrees of Freedom	F Value	Probability of a Value ≥ F
PFM	1	24.94	<0.01 *
GDR	1	13.84	<0.01 *

*Significant at α=0.10

5 CONCLUSIONS

The objective of this research was to improve problem formulation in engineering systems design. Several reasons attest to the importance of investigating improvements to problem formulation. Since problem formulation occurs in the early stages of the design process, it affects all succeeding phases of the process. Providing well defined and measurable boundaries and closure to a problem allows the designer to focus creative efforts within those areas with the highest probability of solving the need and to know when a project is complete. Improvements to problem formulation reduce the probability of solving the wrong or suboptimal problem. Design, including problem formulation, is a decision-making process. Generally, the amount of information required to change a decision is greater than the amount required to make an original decision. Therefore, improvements in problem formulation should improve overall design efficiency.

An original problem formulation method was developed based on needs identified during an investigation of when, how and why information and knowledge are introduced into the engineering systems design process. The method recommends searching along five directions (time, dimensions, value, physical matter, and people) to assist in identifying boundary and performance criteria, and technical performance requirements as a means of expressing them. The method was developed by combining an original manner of expressing requirements in measurable technical terms with an engineering adaptation of Dimensional Analysis. Dimensional Analysis is an established technique for general problem formulation. The method introduced by this work resulted in statistically significant improvements in the quality of problem statements when tested in a controlled task, guided response experiment using a Multiple Attribute Value model for evaluation.

Performance Identification and Performance Measurability were defined as two new essential attributes for assessing improvements in problem formulation. It is recommended that Performance Identification and Performance Measurability replace Structural Considerations and Stakeholders as two attributes of problem statement quality when addressing engineering systems problems. The newly defined attributes more precisely identify what performance is required to satisfy the identified need in engineering design problems.

The improved quality ratings were obtained without pre-training the test subjects. Previous work using the same evaluation method incorporated pre-training, yet failed to detect significant differences for overall problem statement quality between the general problem formulation methods.

The improved quality ratings were not sensitive to the weights assigned to individual attributes when combined in a Multiple Attribute Value model. This indicates that the improvements are sufficiently substantial to be tested under various models of problem statement quality.

The surveys identified reasons that information outside one's immediate area of expertise is more difficult to obtain, as discussed in Appendix B. Identification of perceived reasons is an important first step toward reducing the difficulty.

The surveys also identified industry specific categories and sources of information and knowledge that are important and frequently used in the design process. The identified sources could be useful in developing training programs for new engineers, or in determining appropriate mediums for disseminating information.

The sample populations of the surveys, the protocol experiments, and the problem formulation experiments were statistically adequate in size but limited in variety. Similar surveys, protocols and problem formulation experiments in other engineering disciplines and industries could be conducted to further generalize the findings. On the contrary, the general method could be tailored to specific disciplines or industries by expounding on the five directions for seeking information.

The problem formulation experiment was not preceded by any training to ensure that each participant had some baseline understanding of what constitutes a "good" problem statement. The diverse backgrounds of the test subjects, including education and experience, might justify pretraining to establish a common understanding of how to formulate problems and write problem statements. The variance within each treatment group was consistent, indicating that "poor" and "good" performers were randomly distributed between the control group and the problem formulation method group. Pretraining could reduce the variances within treatments, but its effect on treatment means cannot be speculated without further study.

The demonstrated improvement in problem statement quality does not ensure improvement in the ultimate solution to the problem or in design efficiency. Extending the evaluation procedure to include the remaining steps of the design process would be required to evaluate any correlation between the quality of problem formulation and either the quality of solutions or the efficiency of the design process.

The method was tested under controlled conditions. An extension of the research program should evaluate its effect under corporate conditions using either case studies or concurrent observation. This extension could address the effect of problem formulation on overall design efficiency by evaluating projects from inception to completion.

The findings suggest two additional topics for further research. First, the lack of significant difference in quality of the problem statements between the practicing engineers and the graduate students indicated in this study warrants further investigation. Second, the surveys of practicing engineers indicated that marketing information was both the most difficult to obtain and one of most critical categories. Interdisciplinary work could lead to the development of an approach that ensures that marketing requirements are properly reflected during engineering problem formulation.

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APPENDIX A

A.1 Initial Survey Objectives

A. Identify categories of information topics used by packaging systems designers. [Behavior]

A.1. Determine the areas in which information is required.

A.2. Determine which information is most difficult to obtain.

B. Identify categories of information sources used by packaging systems designers. [Behavior]

B.1. Determine which sources are used.

B.2. Determine which sources are used most often.

C. Identify categories of knowledge topics used by packaging systems designers. [Behavior]

C.1. Determine the types of knowledge most often used.

D. Identify categories of knowledge sources used by packaging systems designers. [Behavior]

D.1. Determine where knowledge is most often acquired.

E. Collect sufficient attributes about the respondents to test hypotheses about the effect of the following factors on their responses: [Attributes]

a. experience

b. age

c. education and training

d. company size and organization

e. company purpose

F. Determine what practicing engineers consider to be important to success: [Attitudes, Beliefs]

F.1. What do engineers believe are the attributes required to do their job successfully?

F.2. What aspects of the development process do engineers believe would lead to improvements?

G. Determine how computers are used in the development process. [Behavior]

NOTE: Types of information collected using surveys:

Attitudes - What people say they want

Beliefs - What people think is true

Behavior - What people do

Attributes - What people are

A.2 Initial Survey and Response Data

Note: Numbers indicate totals from all respondents

Control Number__________

SECTION I - GENERAL

The purpose of this section is to determine the range of professionals who are participating in the research. The data will be used to ensure that the research includes a broad range of participants, so that the results will not be slanted toward any segment of the industry.

1. How long have you worked in the packaging or packaging related positions?
   - 1 Less than two years
   - 10 Two to five years
   - 21 Five to ten years
   - 7 Ten to twenty years
   - 6 Over twenty years

2. What is your current position?
   - 36 Engineer
   - 1 Designer
   - 0 Technical Sales Representative
   - 4 Other (Please describe: consultant, owner)
   - 4 Management
   - 0 Marketing

3. What is the highest level of education you have achieved at this point in your career?
   - 0 High school graduate
   - 1 Some undergraduate college
   - 2 Two year college program
   - 25 Bachelor degree
   - 0 Other (Please describe:______________)
   - 11 Some graduate study
   - 4 Masters degree
   - 0 Doctoral Degree

4. What age bracket do you belong to:
   - 7 25 years and under
   - 24 26 to 35 years
   - 7 36 to 45 years
   - 5 46 to 55 years
   - 2 56 years and over

5. During your career, how much formal training directly related to packaging systems development would you estimate that you have received?
   - 7 less than 1 month
   - 11 1 to 6 months
   - 9 7 to 12 months
   - 18 over 12 months

6. How large is the firm in which you are currently employed?
   - 3 1 to 50 employees
   - 4 50 to 500 employees
   - 38 Over 500 employees

7. If your firm employs over 500 people, where is the group responsible for packaging systems development located?
   - 16 At corporate level
   - 19 At division level
   - 5 Other (Please describe: below division)

8. Approximately how many people in your firm are directly responsible for packaging system development? 7

9. Which one of the following classifications best describes the primary way in which your company is involved in packaging systems:
   - 3 Supplier
   - 37 User
   - 5 Other (Please describe: consultant, both supplier and user)

****
If your answer to question 9 identifies your company as a Supplier, please go to question number 15. If your answer to question 9 identifies your company as a User or Other, please continue with question 10.
****

10. Which of the following classifications describe the principle products of your company? You may indicate more than one.

- 5 Food and beverage
- 1 Pharmaceutical
- 6 Health and personal care
- 2 Chemicals and allied products
- 11 Electrical and electronic
- 4 Automotive
- 3 Paper and allied products
- 19 Other (Please describe: furniture(4), appliances(4), consulting(3), medical equipment (3), general merchandise(2), miscellaneous (3))

11. Which of the following categories best describe your primary customers? You may indicate more than one.

- 25 Consumer
- 20 Industrial
- 9 Military
- 7 Other (Please describe: medical, consulting)

12. Which of the following statements best describes your primary customers? You may indicate more than one.

- 37 Established or long term customers
- 19 New or short term customers

- 24 Large order quantities
- 28 Small order quantities

- 28 Continuous customer demand for the products
- 16 Highly fluctuating customer demand

- 32 Short order/ship lead time
- 12 Long order/ship lead time

13. Packaging design within your company is under the direct supervision of which of the following:

- 6 Product development (including R & D)
- 8 Manufacturing
- 3 Marketing
- 16 Engineering
- 9 Other (Please describe: quality, packaging)

14. Including the supervisor identified in question 13, how many levels of management are there between the leader of the packaging group and the company president? 4

****
If you answered questions 10 through 14, please go to question 20. If your company is a Supplier, please continue with question 15.
****

15. Which of the following best describes your company's products. You may indicate more than one.

_2 Packaging materials
_1 Primary containers
_0 Packaging components
_0 Other (Please describe: ______________________________)
_2 Shipping containers
_1 Packaging machinery

16. Which of the following best describes the primary materials used in your company product's? You may indicate more than one.

_2 Plastics
_0 Aluminum
_2 Paper, paperboard or corrugated board
_0 Other (Please describe: ______________________________)
_0 Glass
_1 Steel

17. Which of the following classifications describe the principle products of the customers you supply? You may indicate more than one.

_2 Food and beverage
_1 Pharmaceutical
_1 Health and personal care
_2 Chemicals and allied products
_1 Other (Please describe: medical supplies)
_2 Electrical and electronic
_2 Automotive
_2 Paper and allied products

18. Which of the following categories best describe how your customers use the packages you supply? You may indicate more than one.

_1 Consumer
_4 Industrial
_1 Military
_0 Other (Please describe: ______________________________)

19. Which of the following statements best describes your primary customers? You may indicate more than one.

_4 Established or long term customers
_0 New or short term customers

_3 Large order quantities
_1 Small order quantities

_4 Continuous customer demand for the products
_0 Highly fluctuating customer demand

_3 Short order/ship lead time
_2 Long order/ship lead time

Note: Numbers in questions 21, 24 and 27 indicate unweighted totals of all respondents.

SECTION II - INFORMATION AND KNOWLEDGE

The purpose of this section is to determine the range of categories of information and knowledge used in the packaging systems development. To reduce the amount of writing required for each question, several likely responses will be provided, followed by several blank lines. Please indicate each of the pre-printed responses you wish to include in your answer, then use the blank lines to print additional responses which apply to you and your company.

20. When you begin to develop a new packaging system, what are the areas in which you need information? Information may include data or assumptions from any source.

I need information about:

42 Product to be packaged
30 Product manufacturing process or equipment
32 Package manufacturing process or equipment
*2 Contractual
*2 Logistics
*6 Production rate/quantity
(* indicates write-in response)

33 Distribution system
34 Marketing requirements
15 Competition
38 Packaging materials
29 Regulations and laws

21. Which of the information listed in question 20 do you have the most difficulty obtaining? Rank up to five topics, beginning with the most difficult.

(1) Marketing (29)
(2) Product (26)
(3) Distribution (22)
(4) Regulations and laws (17)
(5) Product manuf. process (14)
(6) Package manuf. process (13)
(7) Package materials (13)

22. What is the most unusual piece of information you ever had to find in order to develop a workable packaging system? Anecdotal information

How did you obtain that unusual information?

23. Which sources do you routinely use to gather the information you need to develop a packaging system?

26 Trade journals
21 Reference books
31 Vendor specifications
8 Proprietary sources
6 Consultants
26 Experts inside of your firm
27 Experts outside of your firm
14 Seminars
7 Other (Please describe: regulatory sources, military specifications)

24. From question 23, rank the three information sources you use most often:

1. Vendor specifications (30)
2. Expert inside firm (20)
3. Trade journals (19)
4. Expert outside firm (16)
5. Reference books (14)

25. What is the most unusual information source you ever used?
Anecdotal information

26. Knowledge may be defined as the tools or methods which you use in conjunction with the information you have gathered in order to make decisions or develop your packaging system. Please list the types of knowledge you most often use in developing packaging systems.

40 Common sense
16 Rules of thumb
21 Design guides
14 Engineering equations
24 Standard procedures
32 Industry practice
*2 Consumer feedback
*2 Cost analysis
*1 Machine capability study
4 Graph
33 Laboratory testing
37 Comparison to previous packaging problems
13 Computer simulation
*1 Experience

* write-in response

27. From question 26, which forms of knowledge do you use the most often? List up to three, beginning with the most often used.

1. Laboratory testing (28)
2. Common sense (27)
3. Comparison to previous packaging problems (21)
4. Industry practice (18)
5. Design guides (10)

28. Select the one response which best describes where or how you acquired the knowledge that helps you do your job.

3 Seminars
1 Short courses
16 Formal education (including college or university)
28 Experience on the job
4 From a more experienced packaging professional
7 Learning on your own
0 Other (Please describe: ____________________)

SECTION III - THE PROFESSION

29. Assume that you are responsible for hiring a recent college graduate that will be trained to work as an engineer with responsibility for packaging systems development. What essential attributes would you look for in the candidates?

Technical education or skill	(20)
Communication skills	(15)
Ability to work with others	(13)
Cooperative or work experience	(10)
Common sense	(10)
Enthusiastic	(9)
Creativity	(8)

30. Assume you have just hired a new engineer to be trained for the position described in question 31. What professional advice would you offer during the first week of employment?

Ask questions	(13)
Meet people in the organization	(8)
Listen	(7)
Get involved quickly	(5)
Stay technically current	(5)

31. Assume that you have just been given responsibility for a new packaging system development project. What are the first three things you will do?

1. Obtain information aboput product, market and distribution

2. Establish schedule and budget

3. Organize a design team

32. What would make the process of packaging system development easier for you?

Clear and non-changing requirements	(9)
Computer aids	(9)
Getting involved earlier in the design process	(6)
More time	(5)
Product samples available earlier in development process	(5)
Clear Data	(4)
Formalized procedures	(3)
Feedback from the field	(3)

33. How often do you use a computer to assist you in developing packaging systems?

7 I use a computer constantly
22 I use a computer at least daily
8 I use a computer at least once a week
5 I rarely use a computer
2 I do not use a computer

34. If you do use a computer, what are the most common applications that you use in packaging system development? You may indicate more than one.

26 Word processing
26 Specifications
15 Access to data banks
27 Drafting or drawing
17 Simulations or calculations
8 Other (Please describe: Budgeting or scheduling)

SUMMARY

Thank you for participating in this initial phase of our research. A summary of the results will be provided to you in appreciation for your assistance. You should expect to receive the summary no later than the end of September 1989.

Based on the results of this initial phase of research, we will be seeking assistance in gathering more specific data about the information and knowledge used in the development of packaging systems. It is anticipated that this next phase will begin no later than September 1989 and will require approximately the same amount of time investment from the participants. Again, we will provide a summary of the results of the next phase to all interested participants.

The next phase may be distributed both in printed form and on a 5 1/4 inch diskette compatible for use on any personal computer using MS-DOS operating system. This should reduce the time required for participants as well as assisting in data analysis.

Please indicate below if you are interested in receiving the research summary or if you are willing to participate in the next phase of the research.

__ Please send a copy of the research summary to me at the address shown below.

__ Yes, I am interested in participating in the next phase of research. I would prefer to complete the next phase of research using:

___ 5 1/4" diskette
___ Printed format

****

Please attach your business card or print the address information requested below.

Name:____

Company____

Address____

City_______________________State________Zip Code________

Telephone Number (   )______________FAX Number______________

APPENDIX B

B.1 Objectives of the Follow-up Survey

Purpose:

1. Determine if engineers currently apply a systems approach to engineering design.

2. Determine what effect a systems approach has on the identification and acquisition of information and knowledge during the design process.

Objectives: Within the survey population, determine the current state of three study topics by seeking answers to the questions listed below. Numbers in parentheses refer to the survey questions which provide indicators for answering each topic.

TOPIC A: The use of a systems approach to engineering design.

A.1. Do engineers believe they use a systems approach to engineering design? (Questions 1,2)

A.2. How well do engineers actually use a systems approach to engineering design? (Questions 4,5,6,7,8,9,12,13,14,16,21)

A.3. Does the information and knowledge sought by engineers indicate the use of a systems approach to engineering design? (Questions 6,7,8,9,12,13)

TOPIC B: The use of clearly stated technical performance requirements in the design process.

B.1. What do engineers consider to be requirements? (Questions 5,6,7,12,16,18,19)

B.2. Do engineers write technical performance requirements from marketing requirements? (Questions 3,5,8,9,10,13)

B.3. Who participates in writing and approving technical performance requirements? (Questions 14,15)

B.4. At what point in the design process are technical performance requirements written? (Questions 3,10)

B.5. What elements are included in technical performance requirement statements? (Question 16)

B.6. What internal and external marketing requirements are considered in writing technical performance requirements? (Questions 18,19)

B.7. How do engineers insure that requirements are satisfied during the design process? (Question 21)

B.8. What happens in the design process if all requirements cannot be satisfied? (Question 17)

B.9. After design is complete, do engineers use performance specifications or material property specifications to document manufacturing process and supplier requirements? (Question 20)

TOPIC C: The relative difficulty of obtaining information inside and outside the engineer's immediate area of expertise during the design process.

C.1. Is information outside of the immediate area of expertise more difficult to identify and obtain? (Question 11,22)

C.2. Is an increase in difficulty due to:
(Questions 4,5,6,7,8,9,1,22)

a. lack of subject knowledge, either background understanding or knowledge specific to the design project?

b. time and cost constraints of the design project?

c. lack of common language?

C.3. With whom do engineers most often communicate to obtain knowledge and information? (Question 9,11,13,14,22)

C.4. What information and knowledge is most important
(Questions 4,5,6,7,8,9,,12,16,18,19)

B.2 Follow-up Survey and Response Data

Control Number________

Packaging Systems Development
Research Survey

1. What do you design? Mark all applicable responses.

Sum	
29	Packages (primary, secondary, tertiary, etc.)
15	Packaging operations
14	Distribution (shipping, warehousing, handling)
15	Packaging systems
6	Packaging manufacturing equipment
10	Package manufacturing process
1	Other (Please specify:________________________)

2. String together terms from the following alphabetical list to describe your job <u>responsibilities.</u> (e.g. <design> <packaging> <containers>)

Sum		Sum		Sum	
7	a. Consult	2	i. Machinery	0	q. Scientist
3	b. Container	4	j. Manage	3	r. Supervise
25	c. Design	3	k. Manufacture(ing)	10	s. System
14	d. Develop	6	l. Materials	2	t. Technical
5	e. Direct	27	m. Package(ing)	1	u. Technology
2	f. Distribution	3	n. Prototype	15	v. Test(ing)
14	g. Engineer	4	o. Quality	2	w. Other________
3	h. Equipment	1	p. Science		

<__________> <__________> <__________> <__________> <__________>

3. In what relative sequence do the following occur in solving a packaging problem? Use "1" to indicate the first event, "2" the second, etc. Include all applicable items.

Sum	Ave	
98	3.4	Generate feasible solutions
91	3.2	Translate requirements into technical terms
34	1.2	Determine customer needs
62	2.1	Determine packaging requirements

4. How important are the following in the design process? Rate each topic that is applicable to your work.

0 ——— 1 ——— 2 ——— 3 ——— 4
Not Important ... Very Important

Sum	Ave	
118	3.9	Defining the problem
105	3.5	Analyzing possible solution
100	3.3	Generating possible solutions
55	2.0	Making assumptions
52	1.9	Management review of the design in progress
85	2.9	Obtaining input from other departments
96	3.2	Determining how your design problem affects and is affected by outside sources

5. Which of the following describe the design requirements from which you normally work in developing solutions to packaging problems? Mark all applicable responses.

Sum	
25	Derived from marketing requirements
21	Based on previous in-house packaging solutions
22	Include manufacturing process or equipment requirements
11	Written in technical terms
19	Specify permissible materials to be considered
13	Specify performance requirements, but not how to achieve them
15	Include ranges or tolerances for specified values
22	Based on in-house capabilities and limitations
21	Focused on what the customer needs
22	Include budget or cost limitations
8	Include personnel availability or limitations

6. From responses to the previous survey, listed below are the areas in which information is needed. How important is each area to your design work?

0 ———— 1 ———— 2 ———— 3 ———— 4

Not Important ... Very Important

Sum	Ave	
117	3.8	Product to be packaged
69	2.3	Product manufacturing process or equipmert
83	2.8	Package manufacturing process or equipment
99	3.2	Distribution system
88	3.0	Marketing requirements
53	1.9	What your competition is doing
98	3.2	Packaging materials
80	2.7	Regulations and laws
47	1.9	Contractual requirements
93	3.1	Rate or quantity of production
75	2.5	Logistical considerations
84	3.0	Project schedule
85	2.7	Project budget
3	3.0	Other(Please specify:__________)

7. Name or describe a product for which you might be expected to design packaging:__________

Write the first three questions about the design problem that you would like to have answered. Please respond spontaneously.

	Sum	Topic
(1)	(25)	Product
	(14)	Distribution System
(2)	(12)	Package
	(11)	Production Quantity
(3)	(11)	End Use Environment
	(9)	Product Process (6) Production Schedule

8. How important are the following in the design process? Rate each applicable topic.

0	1	2	3	4
Not Important				Very Important

Sum	Ave	
74	2.6	Verifying or challenging assumptions
114	3.8	Determining the design requirements
73	2.4	Communicating the problem and solution to non-engineers
100	3.4	Gathering information
83	2.9	Determining why the design problem must be solved (what is the purpose)
73	2.4	Obtaining approval for the design requirements
72	2.4	Translating qualitative requirements into quantitative technical terms

9. Which of the following are part of your design process? Mark all applicable responses.

Discuss the packaging requirements with:

Sum
- 19 Customer
- 24 Marketing
- 12 Sales
- 27 Product scientist or product engineer
- 17 Other engineers
- 29 Manufacturing
- 8 Financial planners
- 12 Regulatory advisors
- 8 Others (Please specify:____________________)

Document the packaging requirements:

Sum
- 5 formally, before you initiate solutions
- 18 as a routine part of developing solutions
- 5 formally as you develop solutions
- 18 once the solutions are developed

Attempt to quantify the packaging requirements

Sum
- 14 before you develop solutions
- 18 as you develop solutions

10. In what relative sequence do the following occur in solving a packaging problem? Use "1" to indicate the first event, "2" the second, etc. Include only those items which are applicable.

Sum
- 62 Determine packaging requirements
- 35 Collect information about the product
- 80 Collect information about available packaging equipment and processes
- 97 Translate requirements into technical terms

11. From the previous survey, the following seven areas were identified as the most difficult for obtaining information. Please indicate all the reasons you have difficulty obtaining information about:

Marketing of the product

Sum
10 a. Lack of time
6 b. Too costly
8 c. Knowing whom to ask
12 d. Asking the right questions
4 e. Understanding the answers
15 f. Information not available
6 g. Do not use the same terminology
9 h. Someone is uncooperative
1 i. Other (Please explain International Barriers)
6 j. Does not apply, information is easily obtained

Product to be packaged

Sum
10 a. Lack of time
4 b. Too costly
5 c. Knowing whom to ask
5 d. Asking the right questions
4 e. Understanding the answers
12 f. Information not available
6 g. Do not use the same terminology
5 h. Someone is uncooperative
1 i. Other (Please explain Prototype Not Available)
10 j. Does not apply, information is easily obtained

Distribution of the product

Sum
5 a. Lack of time
1 b. Too costly
11 c. Knowing whom to ask
9 d. Asking the right questions
4 e. Understanding the answers
11 f. Information not available
1 g. Do not use the same terminology
2 h. Someone is uncooperative
2 i. Other (Please explain People Do Not Know Answer)
10 j. Does not apply, information is easily obtained

Regulations and laws

Sum
5 a. Lack of time
0 b. Too costly
11 c. Knowing whom to ask
5 d. Asking the right questions
7 e. Understanding the answers
7 f. Information not available
4 g. Do not use the same terminology
0 h. Someone is uncooperative
0 i. Other (Please explain________________)
16 j. Does not apply, information is easily obtained

Product manufacturing process

Sum		
3	a.	Lack of time
1	b.	Too costly
4	c.	Knowing whom to ask
7	d.	Asking the right questions
5	e.	Understanding the answers
5	f.	Information not available
5	g.	Do not use the same terminology
2	h.	Someone is uncooperative
3	i.	Other (Please explain Process Has Not Been Determined.)
14	j.	Does not apply, information is easily obtained

Packaging materials

Sum		
8	a.	Lack of time
2	b.	Too costly
5	c.	Knowing whom to ask
8	d.	Asking the right questions
2	e.	Understanding the answers
5	f.	Information not available
1	g.	Do not use the same terminology
1	h.	Someone is uncooperative
3	i.	Other (Please explain Answers No Known, Interference)
14	j.	Does not apply, information is easily obtained

Packaging operations

Sum		
5	a.	Lack of time
3	b.	Too costly
4	c.	Knowing whom to ask
6	d.	Asking the right questions
6	e.	Understanding the answers
5	f.	Information not available
2	g.	Do not use the same terminology
5	h.	Someone is uncooperative
1	i.	Other (Please explain Poor Communications)
13	j.	Does not apply, information is easily obtained

12. How often do you need to seek information relating to a packaging system development project from the following?

0 (Never) — 1 — 2 — 3 — 4 (On Every Project)

Sum	Ave		Sum	Ave	
69	2.6	Marketing	61	2.4	Distribution
50	2.1	Customer	70	2.5	Management
96	3.3	Manufacturing or production	82	2.9	Manufacturing and process engineers
62	2.6	Quality Assurance	79	2.8	Vendors
29	1.4	Regulatory advisors	28	1.4	Financial planners
9	3.0	Others(Please specify:)			

13. At some point in a design project, quantitative values (e.g., allowable permeance, size limitations, probable drop height) are assigned to various packaging requirements. How often do you discuss the quantitative values of packaging requirements with each of the following?

0 — 1 — 2 — 3 — 4
Never ... On Every Project

Sum	Ave		Sum	Ave	
49	1.9	Marketing	65	2.4	Distribution
36	1.8	Customer	62	2.3	Management
63	2.3	Manufacturing or production	69	2.4	Manufacturing and process engineers
69	2.5	Quality Assurance	71	2.4	Vendors
23	1.1	Regulatory advisors	12	0.9	Financial planners
0	0	Others (Please describe ____)			

14. How much does each of the following contribute when you are developing packaging requirements?

0 — 1 — 2 — 3 — 4
Does not Contribute ... Contributes the most

Sum	Ave	
78	3.0	Design engineering
44	1.8	Customer
61	2.3	Marketing
28	1.2	Regulatory advisors
70	2.4	Process or equipment engineering
54	2.0	Quality assurance
43	1.5	Management
16	0.9	Financial planners
82	2.8	Manufacturing or production
2	2.0	Others(Please specify: Purchasing)

15. Are packaging requirements formalized and signed by approving authorities? (YES) (NO)
Sum 22 9

If yes, which of the following signatures would normally appear on the document? Select all applicable responses.

Sum	
12	Design engineering
2	Customer
7	Marketing
5	Regulatory advisors
3	Process or equipment engineering
11	Quality assurance
12	Management
1	Financial planners
7	Manufacturing or production
2	Others(Please specify: Packaging Engineer, Material Manager)

16. Which of the following elements are normally included in the packaging design requirements from which you generate solutions? Mark all applicable responses.

Sum
28 Available packaging materials
26 Available packaging equipment
12 Available personnel
23 Cost constraints
23 Time constraints
4 Existing patents
13 Reference to your competition
25 Level of protection required
7 List separating packaging characteristics into required and desired categories
12 Tolerances of performance
23 Conditions under which the product must be protected
22 Total quantity required
25 Production rate
1 Other(Please describe: Weights And Sizes)

17. Which one of the following best describes the action taken when one or more packaging requirements cannot be satisfied?

Sum
0 Terminate the development project
13 Use your engineering judgement to amend the packaging requirement
8 Notify the source of the original packaging requirements
19 Formally renegotiate the packaging requirements with their original source

18. Which of the following internal factors are normally considered when packaging requirements or constraints are developed? Mark all applicable answers.

Sum
27 Packaging equipment currently available in the company
13 Personnel currently employed
9 Company financial posture
21 Program budget
26 Previous solutions to similar problems
26 Packaging materials previously used
3 Other(Please describe: Materials, Special Promotions)

19. Which of the following external factors are normally considered when packaging requirements or constraints are developed? Mark all applicable answers.

Sum
26 Existing technology
16 What the competition is doing
6 Existing patents
26 Vendor recommended materials
22 Equipment available
12 Personnel available
4 Other(Please describe: International Materials, Legislation)

20. Which <u>one</u> of the following statements <u>best</u> describes the specifications you provide to your vendors?

Sum

25 Specifies the required physical properties (i.e., material and design specifications)

7 Specifies the required performance in technical terms (i.e., allowable permeance, compressive strength)

2 Specifies the required performance in non-technical terms (i.e., strong, leakproof, lightweight)

21. How do you insure that your packaging designs meet the needs of your customer?

Sum	Method
(14)	Customer Feedback
(12)	Testing
(8)	Customer Surveys
(8)	Audits

22. How difficult is it to obtain needed information for designs from the following? Rate each applicable response.

0 —— 1 —— 2 —— 3 —— 4

Not Difficult … Very Difficult

Sum	Ave		Sum	Ave	
56	2.1	Marketing	42	1.8	Distribution
52	2.5	Customer	56	2.2	Management
55	2.2	Manufacturing or production	35	1.4	Manufacturing and process engineers
27	1.2	Quality Assurance	34	1.3	Vendors
39	1.9	Regulatory advisors	28	2.0	Financial planners
4	4.0	Others(Please specify: Design Engineer)			

Thank you again for investing your time and sharing your expertise. I will mail you the research summary soon.

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B.3 Analysis of the Follow-up Survey

Analysis of individual questions is based on one-way or two-way contingency tables, or plots of frequency distributions or relative frequency distributions. The mode of the responses is the primary statistical tool used in evaluation. The essence of each question is provided in brackets.

TOPIC A: The use of a systems approach to engineering design.

A.1. Do engineers believe they use a systems approach to engineering design? (Questions 1,2)

Q1: **[What do you design?]**
Approximately 48% of the respondents indicated that they design packaging systems, packaging operations or distribution, whereas 94% indicated that they design packages.

Q2: **[What are your job responsibilities?]**
Less than one third of the respondents used the term "systems" in describing their job responsibilities.

Analysis: The respondents do not strongly refer to themselves as systems designers. However, the results are not significant enough to state that the respondents do not consider themselves systems designers.

A.2. How well do engineers actually use a systems approach to engineering design? (Questions 4,5,6,7,9,12,13,14,16)

Q4: **[How important are the following in the design process?]** "Defining the problem" was rated as the most important topic. "Determining how the design problem affects and is affected by outside sources" was rated by respondents as important as "generating solutions" and "analyzing solutions." This supports a systems approach.

Q5: **[How do you describe design requirements?]**
Q6: **[How important is information in various areas?]**
Q12: **[How frequently is information sought in various areas?]**
Q14: **[Who contributes to developing design requirements?]**
Relatively uniform distribution among topics and sources of information indicates use of a systems approach.

Q7: **[What information is sought first in a design problem?]** Information was sought about the distribution, end user environment and the product as often as it was sought about the package, indicating a systems approach.

Q9: **[With whom are design requirements discussed?]**

Q13: **[With whom are technical values of requirements discussed?]**

Discussing requirements with a wide range of departments supports a systems approach.

Q16: **[What elements are included in design requirements?]**

Wide range of information included in design requirements supports systems approach.

Analysis: Knowingly or unknowingly, the respondents indicate that a systems approach is used to solve packaging problems.

A.3. Do the information and knowledge sought by engineers indicate the use of a systems approach to engineering design? (Questions 6,7,9,12,13)

Analysis: As discussed in question A.2., a systems approach is indicated by the information sought.

Topic A Conclusion: The respondents do use a systems approach to solving packaging problems, although they may not formally recognize it as such.

TOPIC B: The use of clearly stated technical performance requirements in the design process.

B.1. What do engineers consider to be requirements? (Questions 5,16,18,19)

Q5: **[How do you describe design requirements?]**

Q16: **[What elements are included in design requirements?]**

Distribution of the responses indicates that design requirements include a broad spectrum of information but are not necessarily written in technical terms. Responses to both questions indicate that personnel availability is not a strong element in determining requirements.

Q18: **[What internal factors influence design requirements?]**

Q19: **[What external factors influence design requirements?]**

All areas listed, except personnel, company financial posture and existing patents, were used to develop packaging requirements.

Analysis: An appropriately broad range of performance and technical elements are considered in developing the packaging requirements.

B.2. Do engineers write technical performance requirements from marketing requirements? (Questions 5,8,13)

Q5: **[How do you describe design requirements?]**
The highest number of responses (81%) indicated that the design requirements were derived from marketing requirements. Six other topics had relative frequencies above 60%, indicating that "marketing requirements" is only one of several important considerations in developing design requirements.

Q8: **[How important are various activities in the design process?]**
"Translating requirements into technical terms" was one of the least important aspects of the design process, significantly below "determining design requirements" and "gathering information."

Q13: **[With whom are technical values of requirements discussed?]**
On a scale of 0 to 4, quantitative values for design requirements were discussed with marketing less often (average rating 1.9) than with management (2.3) or other technical functions (2.3 to 2.5).

Analysis: There is no strong indication that the respondents deliberately translate marketing requirements into technical terms, although marketing requirements are considered in developing technical design requirements.

B.3. Who participates in writing and approving technical performance requirements? (Questions 14,15)

Q14: **[Who contributes to developing design requirements?]** On a scale of 0 to 4, the level of contribution to developing design requirements was highest for design engineering (3.0), manufacturing (2.8), process or equipment engineering (2.4), marketing (2.3), quality assurance (2.0), and customer (1.8). The remaining categories ranged from 0.9 to 1.5.

Q15: **[Who approves formalized design requirements?]** Design Engineering (55%), Management (55%) and Quality Assurance (50%) were the highest three frequencies. Other categories ranged from 5% to 32% relative frequency.

Analysis: A wide range of participants contribute to the development of design requirements (Q14), but only design engineering, quality assurance and management were consistently listed as signatures on a formal requirements document. It appears that approval of technical requirements is kept primarily within the domain of technical people and management.

B.4. At what time in the design process are technical performance requirements written? (Questions 3,9,10)

Q3 & Q10: **[In what relative sequence do selected design activities occur?]**

The translation of requirements into technical terms was done very late in the design process. From question 3, an equal percentage (45%) of respondents indicated that the translation occurred just before or just after the generation of feasible solutions.

Q9: **[With whom are design requirements discussed?]**

Design requirements are developed either during or after, but seldom before the generation of feasible solutions. Sixty percent of the respondents attempt to quantify design requirements as they develop solutions, compared to forty-four percent attempting to quantify them before. Some respondents indicated both as appropriate answers.

Analysis: There is no evidence to indicate that technical performance requirements are developed prior to the generation of feasible solutions. There is no evidence to indicate that the translation of requirements into technical terms is a deliberate step in the design process.

B.5. What elements are included in technical performance requirement statements? (Question 16)

Q16: **[What elements are included in design requirements?]** Analysis: Respondents identified a relatively uniform distribution of categories related to packaging and production, to include cost, time constraints and quantities. Desired and required characteristics are not listed separately, and tolerances of performance are not a strong consideration.

B.6. What internal and external marketing requirements are considered in writing technical performance requirements? (Questions 18,19)

Q18: **[What internal factors influence design requirements?]** Equipment (87%), materials (84%), and previous solutions (84%) were considered most frequently, followed closely by the program budget (68%). Personnel (42%) and company financial posture (29%) were considered less frequently.

Q19: **[What external factors influence design requirements?]** Materials (84%), existing technology (84%) and equipment available (71%) were considered most frequently. Competition (52%), personnel (39%), and existing patents (19%) were considered less frequently.

Analysis: Emphasis is on the technical issues and on the specific packaging problem at hand. More indirect topics are not considered.

B.7. How do engineers insure that requirements are satisfied during the design process? (Question 21)

Q21: **[How do you insure that designs meet customer needs?]** Analysis: Customer feedback, formal and informal, and testing of the packaging and materials were the dominant methods, accounting for over 50% of the methods used. Testing did not indicate any assurance that the package met the needs, only that it did not fail to meet the design specifications. Customer surveys and internal company audits were also listed frequently. Customer satisfaction with varying degrees of formality appears to be the primary indicator of design adequacy.

B.8. What happens in the design process if all requirements cannot be satisfied? (Question 17)

Q17: **[What action is taken when a design requirement cannot be satisfied?]**

Analysis: Formal renegotiation was the primary method (61%), with engineering judgement a strong second (42%). Both indicate an active approach, as opposed to a defensive posture of terminating the project (0%) or only notifying the source (26%). Response indicates the desire to keep the design process in motion.

B.9. After design is complete, do engineers use performance specifications or material property specifications to document manufacturing process and supplier requirements? (Question 20)

Q20: **[What form of specifications are provided to vendors?]**

Analysis: Physical properties are the predominant method of writing specifications (81%). Performance specifications are used less than 20% of the time.

Topic B Conclusion: Clearly stated technical performance requirements are not used as a deliberate part of the design process. Translation of requirements into technical terms appears to be a byproduct of the design process.

TOPIC C: The relative difficulty of obtaining information inside and outside the engineer's immediate area of expertise during the design process.

C.1. Is information outside of the immediate area of expertise more difficult to identify and obtain?
(Questions 22,11)

Q22: **[How difficult is it to obtain information from different human sources?]**
On a scale of 0 to 4, customers (2.5), manufacturing (2.3), management (2.2),and marketing (2.1) were the top four cited in order of difficulty. Other engineers (1.4), vendors (1.3) and quality assurance (1.2), all relatively close to the area of expertise, were cited as the least difficult sources from which to obtain information.

Q11: **[Why is it difficult to obtain information on various topics?]**

Table 18 consolidates the raw scores of question 11. The topics listed across the top are arranged in general order of proximity to the area of expertise, with the closest topic on the left and the most distant topic on the right. Response "j" (does not apply, information is easily obtained) decreases from left to right, while the sums of responses "a" through "i" (all reasons for difficulty) increase. The only exception to the trend is the topic laws and regulations.

Analysis: Correlating questions 11 and 22, marketing information is the most difficult to obtain, followed closely by information about the product manufacturing process.

C.2. Is an increase in difficulty due to:

a. Lack of subject knowledge, either background understanding or knowledge specific to the design project?

b. Time and cost constraints of the design project?

c. Lack of common language?

(Question 11)

Q11: **[Why is it difficult to obtain information on various topics?]**

Analysis: Referring to Table 18, lack of time and nonavailability of information were cited as strong reasons for having difficulty obtaining information about both marketing and product. For marketing, two additional reasons were (1) knowing what to ask and (2) someone being uncooperative. Knowing whom to ask increased in difficulty for nontechnical issues (distribution, marketing and legal).

Table 18. Reasons for Difficulty in Obtaining Information

		CLOSE TO AREA OF EXPERTISE						FAR FROM AREA OF EXPERTISE
		TECHNICAL				NON-TECHNICAL		
	\ TOPICS REASONS \	Packaging Material	Packaging Operation	Product	Manufacturing Process	Distribution of Product	Marketing	Laws Regs
a	Lack of Time	8	5	10	3	5	10	5
b	Too Costly	2	3	4	1	1	6	0
c	Knowing Whom to Ask	5	4	5	4	11	8	11
d	Ask the Right Question	8	6	5	7	9	12	5
e	Understanding The Answer	2	7	4	5	4	4	7
f	Information Not Available	5	5	12	5	11	15	7
g	Do Not Use Same Language	1	2	6	5	1	6	4
h	Someone is Uncooperative	1	5	5	2	2	9	0
i	Other Reasons	3	1	1	3	2	1	0
Sum of Reasons For Difficulty		35	38	52	35	46	71	39
j	Not Difficult	14	13	10	14	10	6	16

C.3. With whom do engineers most often communicate to obtain knowledge and information? (Question 9,12,13,14)

Q9: **[With whom are design requirements discussed?]**

Q12: **[How frequently is information sought in various areas?]**

Q13: **[With whom are technical values of requirements discussed?]**

Q14: **[Who contributes to developing design requirements?]**

Analysis: Correlating responses to the four questions, the information is most often sought from production, product or manufacturing engineers, and marketing, in descending order.

C.4. What information and knowledge is most important? (Questions 6,7,12,16,18,19)

Q6: **[How important is information in various areas?]**

Q7: **[What information is sought first in a design problem?]**

Information about the product is most important, followed by distribution, the packaging materials, and production quantities. Marketing also received strong mention, ranked fifth in question 6, but not listed in question 7.

Q12: **[How frequently is information sought in various areas?]** Although a direct correlation of topics cannot be made, frequency of information sought supports the same five categories found in question 6.

Q16: **[What elements are included in design requirements?]**
Q18: **[What internal factors influence design requirements?]**
Q19: **[What external factors influence design requirements?]**
Information about the product, packaging, and production received strong mention as information needed to develop requirements. Marketing was not listed among the options for these three questions.

Analysis: Questions 12, 16, 18 and 19 correlate the findings of Questions 6 and 7. The most important information and knowledge is about the product, the packaging materials, product distribution, production rates or quantities, and product marketing.

Topic C Conclusion: Information and knowledge outside the immediate area of expertise is more difficult to obtain. Information about marketing is the one area which combines a high level of importance and high relative difficulty to obtain information.

APPENDIX C

C.1 Instructions for Participants

In this exercise, you will be presented a product that requires packaging. Your requirement is to begin the process that will lead to the development of feasible packaging concepts. You should work toward concepts that can be easily implemented in a timely manner under ordinary budget restrictions. You should proceed as normal, except that you should think aloud as you work. You should talk constantly from the time you receive the product until the exercise is completed. Do not plan out what you are going to say or attempt to explain your thoughts. Simply act as if you are talking aloud to yourself.

Use the paper and pens provided to sketch or make notes. The sheets of paper are numbered. Try to make your notes and sketches sequential from top to bottom on each page, but feel free to return to previous notes and sketches at any time.

There will be times when your thoughts are nonverbal. In those cases, just say something like "I am remembering..." or "I am visualizing...." You will not be interrupted, other than to be reminded to think aloud.

The main focus of this exercise is on **what** information you need **when**, and **where** you get it. You may use any references you desire, or you may just say aloud what you would do. If you would normally contact someone, just state who and for what purpose. If the information is known, I will provide it in response.

The emphasis is on your experienced approach and way of thinking, not on the resulting packaging concepts. Try to work as you normally would, but remember to **think aloud.**

C.2 Product Descriptions

Product Description

General: A sterile, disposable double-tipped cotton swab stick. One tip is saturated with a alcohol based antiseptic solution for cleaning an infected area. The other tip is dry for removing excess liquid after cleaning.

Available information (not provided to the participant):

1. User requirements:

   a. Maintain sterility of both tips.

   b. Confine liquid to saturated tip.

   c. Easy to open.

   d. User can expose each tip separately.

   e. Should be able to reclose the wetted tip prior to disposal.

   f. User can easily identify which tip has antiseptic solution before opening.

   g. Should be able to minimize exposure of a contaminated (e.g., bloodstained) swab to the environment during disposal.

2. Shaft

   a. Length: 5 ± 0.05 inches

   b. Diameter: 0.10 ± 0.01 inches

   c. Non-porous, non-absorbing fiber

   d. Flexible enough to withstand 180 degree bend when held at ends.

3. Tips

   a. Spun cotton

   b. Wrapped and clipped

   c. Volume: 0.25±0.02 inch diameter, 0.5±0.02 inch length

4. Solution

   a. Colorless antiseptic in 80% alcohol solution

   b. Sensitive to UV light

   c. Not sensitive to oxidation

   d. Initial volume 0.5±0.01 ml

   e. Allowable loss: 20% by weight in one year

5. Distribution system

   a. Desired shelf life: one year

   b. Method of transportation: common carrier truck

   c. Warehousing and storage: not controlled by company

   d. Storage conditions: worldwide climatic conditions, covered from direct exposure to weather

   e. Desired marketing container size

      (1) 10 per unit of issue

      (2) 24 units per carton

6. Production

   a. Rate of production: 300 per minute

   b. Swabs supplied in bulk from vendor

   c. Machine available for dipping swab into solution

   d. Space and funds are available to modify production line

PRODUCT DESCRIPTION

General: The product to be packaged is a single serving, microwavable, shelf-stable pizza. The product consists of a baked crust, a tomato based sauce and a processed cheese topping. Consumer must transfer shaped slice of cheese to crust, spread tomato sauce over the cheese and bake for 90-120 seconds in microwave on maximum power setting.

Available information (not provided to participant):

1. Crust
   - a. Size in square inches: 30
   - b. Weight: 6 oz (170g)
   - c. Ingredients: enriched wheat flour,partially hydrogenated vegetable oil shortening (soybean or cottonseed), water, yeast, dextrose, leavening (sodium aluminum phosphate and sodium bicarbonate), salt.
   - d. Preparation method: baked in radiant oven
   - e. Sensitive to
     - (1) moisture pickup and dehydration
       - (a) water content is 37%
       - (b) water content tolerance +/- 0.5%
     - (2) oxygen concentration must be less than 3%
     - (3) sensitive to UV light
     - (4) shock - not sensitive
     - (5) static load - cannot bear any load
     - (6) vibration - not critical

f. Mixed and baked at 425 degrees Fahrenheit for 12 minutes in-house

2. Tomato based sauce

a. Volume - 6 oz. (226g)

b. Ingredients - water, tomato paste, soybean oil, modified food starch, salt, oregano, natural flavorings

c. Prepared in-house

(1) tomatoes blanched

(2) food starch dissolved in cool water

(3) warm water added to tomatoes, then food starch and dry ingredients.

(4) mixture heated to 180 degrees Fahrenheit (maximum allowable temperature)

d. Viscosity (range is similar to molasses):

(1) 6000 centipoise at 70 degrees Fahrenheit

(2) 1800 centipoise at 100 degrees Fahrenheit

(3) 900 centipoise at 120 degrees Fahrenheit

(4) 300 centipoise at 150 degrees Fahrenheit

e. Sensitive to

(1) no oxygen permissible

(2) UV light sensitive

f. Water content: 68% (Solids: 32%)

3. Cheese topping

a. Volume - 1.25 oz (28g)

b. Processed and sliced

c. Shaped to fit crust so it can be transferred in one piece

d. Solid consistency

e. Sensitive to

(1) moisture

(a) water content: 32%

(b) water content tolerance: +/- 0.1%

(2) oxygen concentration must be less than 3%

f. Vendor supplied in size, shape and packaging specified

4. Distribution

a. Desired shelf life: 60 days from production

b. Method of transportation - common carrier truck

c. Intermediate and final warehousing

(1) geographic warehouses in major sales areas

(2) local warehousing in major metropolitan areas

d. Display requirements - maximum frontal exposure area

e. Desired marketing quantity per container - one dozen per sales carton

5. Production process and equipment

a. General process

(1) mixing vat and shaper for raw crust

(2) conveyer belt radiant oven to bake crust

(3) mixing and blanching vat for tomato sauce

b. Production rate - 600 per hour

c. Production volume - six month test market

6. Corporation

   a. Established national food distributor

   b. Six regional production facilities

   c. Willing to invest in equipment

PRODUCT DESCRIPTION

The product to be packaged is a high definition television (HDTV) with a 30 inch diagonal viewing screen. The television is portable (no console) with a wireless remote control. The product is a new introduction to the market. Manufacturer's Suggested Retail Price is $3700 including delivery and installation by the local retailer.

Available information (not provided to participant):

1. Product attributes

   a. Weight: 85 pounds

   b. Dimensions: 36" long x 32" high x 26" deep

   c. Electrical:

      (1) 120/240 volt, 50/60 Hz, 40 watts

      (2) 10 foot electrical cord wrapped on stakes on back side

      (3) all printed wiring assemblies mounted on rubber shock absorbers

   d. Remote control

      (1) 0.3 pounds

      (2) 2" x 6" x 0.5"

      (3) two size AAA 1.5 volt batteries included (not installed)

      (4) vendor supplied

   e. Known Sensitivities

      (1) shock limit: 40G in any primary direction

(2) temperature Limits: -35 to 135 degrees Fahrenheit

(3) moisture Limit: Relative humidity over 45% at 80 degrees Fahrenheit for 3 days

(4) compression load limits on television case:

(a) 250 pounds from top or bottom

(b) 150 pounds from left or right end

(c) 50 pounds from front or back

(5) critical natural frequencies:

(a) 7.5 Hz

(b) 47 Hz

(c) 354 Hz

(6) glass is sensitive to scratching

2. Production

a. Assembly line

(1) bench assembly

(2) variable rate handling system (Power/free capability)

(3) 36 stations including quality assurance

b. Production rate: 10 - 12 per hour

c. Production forecast: 50,000 - 75,000 units before first major modification

3. Distribution

a. International

b. Ship, rail, truck

c. Shipping time: 6+/-1 days domestic, 27+/-3 days international

d. Warehousing: controlled by shippers

e. Sales unit: individual

f. Package is not used for product display

g. One year on-site service contract included in sales price.

4. Corporation

a. No internal packaging department

b. Established name brand

c. One assembly plant for this product

d. Corporate goal of minimal equipment investments for next 24 months

C.3 Edited Protocol of Expert A

Note: **Bold typeface** indicates Researcher input. Normal typeface is test subject protocol.

At this point, the customer is not intimately involved with packaging, they don't pick it up from the store. The effect of using the package to communicate anything about the company or the product to the customer is not as big a factor as it would if it were a retail product and sat on a dealer shelf in some store location. So as far as that aspect of it, we don't have to worry about the box as far as it concerns any communication on the box. I am assuming that it'll be bulk packed to the dealer, but... as a lot of televisions are. But with this high end product, I doubt that the dealer will order more than a couple at a time. So with that, I will look to design packaging for this thing as an individually packaged unit, as opposed to a bulk packaged unit. Perhaps the first basic approach is that the package should allow the product to be shipped on its own to the environment. 30" diagonal screen--I have problems trying to imagine that dimension...I'd like to find out what the physical dimensions of the product are, dimensions and weight.

It's 36" long by 32" high, and 26" deep. And the television weighs 85 pounds.

I am off to get a tape measure so I can get some visualization. I would like to get a product. Is the product already into production where I can get a production unit?

Not yet. Still in the design stage.

Okay. Can I get a prototype unit?

Not this hour, but we could have one sent.

Okay, so we can't have a model or an actual unit. Is the mechanical design complete on this?

Yes.

What is first year sales expectations for this product?

The goal is between 50 and 75 thousand over the first year.

So, fairly low volume...[using tape measure to estimate size] Dimensioning the size and the weight, the package will have to be,.. it can't be handled by one person. Be either mechanically packaged, or packaged with mechanical handling, or by two-men carry. Since we're delivering it to retail locations, a lot of retailers do not have sophisticated mechanical delivery system, and they have commonly...Well, how many distributors or retailers will be...Will there be a lot of them or is there a select few that are...?

It's going to be distributed both domestic and international. So it's going to be quite a few distributors and retailers.

Okay. It's safer at this time not to make the assumption that the final recipient of the packaged product will not have, probably won't have any sophisticated means of mechanical handling of the product. Even, obviously a forklift. I doubt that would be usable. Maybe even a pallet jack, especially if it's being delivered to the customer. Now, is this going to be a home-used product?

Yes, a home-used product.

So I doubt that even that, maybe a dolly would be all he'd have. So I have to facilitate for at least a two-man carry. You said I can have a unit? Can I get three units?

What do you need them for?

For fragility testing.

That's been run on a prototype. We have some test data available.

Okay, what is fragility testing for shock and vibrations?

Shock has a 40g limit in any primary direction.

Okay. What about fragility in critical frequency?

Critical frequency, three were identified: 7.5 hertz, 47 hertz, and 354 hertz.

What are the amplitudes of those?

I don't have amplitudes on those. Those are the natural frequencies.

In the fragility testing, did the product damage when held at any of these frequencies?

Yes, they were damaged at all three of those frequencies,

if held there.

Okay. What input?

I don't have the input available.

We're going to assume an input of half a g. These are assumed to be sine. That was based on the sine sweep?

Yes

Whew, 7.5 hertz, that's awful low. You said 40g in any direction, that's a critical acceleration?

Yes, the limit.

Okay. Is that based on a square wave?

Impact loading drop test

Okay, but is that based on square weight testing, or a half sine? I'm trying to see whether or not it's...[sketched wave form of input]

Assume square wave.

Okay. So it is critical .... Based on the distribution cycle, what kind of distribution handling does it receive? .. would tell me what kind of qualification testing or drop testing...?

It's going to be shipped by combination of truck, rail and ship for international. And the warehousing is controlled by the shippers. We use common carriers, we don't control it, so we cannot anticipate what will happen in warehousing.

What was the critical velocity change in this fragility testing?

I'm sorry, they didn't give that to me.

What was the velocity change used in the fragility testing to achieve that 40g?

I don't have that either.

Okay, I'm going to make an assumption that it should have been done from something equivalent to about a 19" drop height, based on the product's weight and dimensions ...

[calculations made] ... so I am assuming it is 117 inches per second velocity change when that was done. You don't know what the amplitude of the vibration is at the 7.5 hertz, or any of these frequencies?

No.

It's just identified. I'm quite concerned about the 7.5 hertz natural frequency, because that's a very common frequency in the distribution environment, especially with trucks. Truck transportation and some ship transportation. I'm assuming that I get a fairly significant amplitude and say that I'm going to get about a 6g response at the 7.5 hertz, which it says it's given at displacement, whatever that is, it gives me some displacement, almost 2"? I wonder what that is. You don't know what breaks?

Internal parts, I don't have a breakdown of that.

I'm trying to think of inside a TV, something that way, it could be something on the processor board, could be a transformer on the processor board with a weak..[unintelligible]. Could be the mounting of the glass. This is a glass tube TV, is it?

That's correct.

[Long pause] I'm trying to visualize what might have been happening in vibration testing. One reason I focus a lot on the vibration testing is that in a distribution environment, shock is a probability function. Shock occurs when the vehicle hits a bump or the package shifts and drops, or someone picks up the package and drops it. And again, it's based on probability of these incidents occurring. Vibration is not a probability, it's 100% sure if it gets in a truck. I try to primarily look at that aspect, because that's what has a tendency to occur. I'm trying to figure out what kind of assumption here I'm going to make as far as what the 7.5 hertz situation is. This being delivered by the local retailer, it's possible that minor things could be done, and again, it depends on the company's policy. Our policy here is that we have a "plug in and play" philosophy. When a customer gets it, he should be able to plug it in and starts running it from there. Because of that, we do not do things like shipping plugs or reinforcement devices that could help the product in the distribution environment, but once it gets to the customer's location, it no longer needs any vibration-type devices on it, and it can be taken out and discarded by whoever installs it. That's why I'm trying to ponder what the assumption would be about what happens at 7.5 hertz. I'm having problems trying to switch from the way we currently design our products to making an assumption. Let's assume that it's a power supply and that there is an access door that whoever does the installation can reach inside and take a piece of corrugated block material that would support the power supply through shipment so that the 7.5 hertz is not a problem and that kind of damage is taken care of. That's how I'm going to address that issue, is that we'll use a shipment plug to brace the power supply and that can be discarded. And that it only adds minimal cost to the product. Maybe less than 20 cents to the packaging, rather than something expensive in redesigning the product. That's what I was pondering here. So the next frequency to deal with is 47 hertz, and then 354 hertz. The 47 hertz is also kind of an interesting range. There you need to do some uniqueness in choice of materials and designing the profile to attenuate that input at 47 hertz. With a range of materials that are used, a polyurethane foam material would attenuate or protect against 47 hertz very well. However, it is kind of cost effective, or not very cost effective. You also have--are these warehoused?

Yes, the company does not control warehousing.

Okay, so is there a consideration of flammability? If the company doesn't control warehousing, then they're automatically charged anyway. The very limitation on some countries such as in Europe, there's requirement for packaging material be of inflammable material. And with our situation, we don't address that issue. We've seen very little to be effected by it, and paying the penalty is automatically assumed. And for these quantities we assume that that's the same situation here. We're not going to regard the flammability issue to be a factor. In looking again at the 47 hertz, a styrene would be a very good,.. is a very common cushioning product for use in televisions set, especially the cheaper television sets. However, it has a big problem with vibration. It's very difficult to design for vibration. And it normally gives you a lot higher frequencies, normally to be able to get a good shock response in a design,.. common frequency responses for styrene is like around 80 to 70 Hertz which would put you up to have a problem with this 47 Hertz situation. Also, a secondary issue is that environmentally the consumers are getting educated to the point to where it's a product that primarily uses CFCs to expand and people that are environmentalists wouldn't want to support a kind of product that uses that. There are also landfill disposability issues to where dealers, especially the north-eastern United States who I have known to refuse to order a product based on the fact that it's packaged in styrene, because they are penalized by the volume and amount of cushioning or packaging that they have to throw away into the landfill. So, on that basis, I would kind of steer away from styrene. Based on those concerns. That puts me into the range of polyethylene or polypropylene foams. There's extruded polyethylene and molded polyethylene. Judging from the size of this product, there are some off-the-shelf cushioning that are premolded into corner blocks that can be bought, it doesn't require any special molding. So at this point, based on small quantity that this product has, it'll save me a lot of tooling costs, because molded tooling costs would run 20 to 30 thousand dollars. And I would prefer at this time to use some of the market off-the-shelf molded cushions made out of some kind of expanded polyethylene or expanded polypropylene beads. That would save a lot of design and engineering time. So that leaves me basically to determine how thick the cushion I will need, which will eventually tell me what size box I'll need. From the drop height of 18 inches, **[calculations being made]** requiring it to protect the product to 40g's using a cushion, just to be conservative, that's about 35% efficient in deflection. I would need 1.3 inches of cushion. Optimally I need 1.38. Hopefully, I can find, probably what's on the market are 1.5" or 2" cushions, corner cushions. That's what I'll try to design with. Now, you gave me the dimension on this thing, can we assume that this is a total rectangular TV, or is it sloped in the back?

The base is rectangular, except for the portion where the tube sticks out there.

Straight back like you drew it there, except in the middle of the back there's a slight projection where the tube comes out? How far out does that stick out?

Six inches.

You're making this challenging! Everything else is square, though?

That is correct, just all square.

Are there any weak areas within here that top and bottom where the plastic is awful weak. Can I assume that the corners and edges are the strong points?

There are no known weak areas.

No known weak areas. Again a 6" situation sticking out the back. That changes things. I'm going to have to ship it on its face.

Let's say we can get rid of that 6", just keep the problem straightforward.

Well, I think I'm going to ship it on its face anyway. That's the most stable orientation for a tube because of the cg. It gives you a very low cg. Okay, **[referring to sketch]** cg is right here. If you shipped it this way, you'd have a tendency to have to have somebody to have to pick it up and kind of rotate on them, okay? So, for all practical...it looks kind of weird, though, but since we're using a local store guy to deliver it to the customer, he should be able to... shouldn't have any problem with that, shipping it face down. Okay, I'm just trying to get an overview of, here again where I started from. I've been challenged here with a new product, a TV, fairly large, **[using tape measure]** about the size of this table, isn't it? Let's see, just slightly under the size of this table. Gives me a better visual...So if I load it face down, box is 32 by 36 **[sketching]**. So I put that face down and have a 1.5 inch cushion here...1.5 inch here, three inches overall, 39 inches to the top of the box. Are there any other accessories that go with this, or is it just one TV?

TV and a remote control.

Okay. No manuals or operating instructions?

Yes, the manual will be one pamphlet with operating instructions and warranty card.

Manuals and pamphlet, nothing like a [notebook] binder?

No.

Where's the manufacturing location?

The manufacturer is going to be located in Oklahoma.

Because of the size of the box and the size of the product, and considering the,...right now I'm just kind of considering how it would be placed and how it would be cushioned. But one of the primary things is how the customer, or whoever has to get the product out of the box and at the same time be able to ship it in transportation. It sometimes becomes a problem when the packaging is so tight that when it gets to the other end, the customer can't get the product out, it makes it very frustrating. And once you start getting feedback, that means that people are refusing to buy the product because of the packaging, and that's not what packaging is for. And that's happened, I've seen that happen. **[Took a break]** The concept I'm developing here is, I'm trying to make it where it's easy from the distribution, when it moves through the distribution. I'm trying to understand the material handling systems that might be available where this thing is going. It needs to be able to accommodate those. A lot of freight forwarding places would prefer to have something that they can pick up with a forklift. But they do accommodate to be able to have these things where they can just run it through the conveyer system. This type of product with its size, I doubt that it will go through any kind conveyer system or any kind of distribution environment. So, what I've done here **[sketch]** is made a base made out of multi-layered corrugated, structurally corrugated, probably triple walled, with some kind of skids on it that would allow a forklift to go under. They make these again as a standard off-the-shelf product that can be purchased in preset quantities. This, again, would limit a lot of engineering time in designing these pallets. That, with minimal modification, could be done. What this would do is give you a little cap right here, and then you can glue these corner blocks down on the pallet where you put the unit in. The top part is a sleeve that fits down over the unit. And, to close the box, we're going to use bands, plastic bands that are friction welded. Now the reason for that is to make it easier on the other end as far as opening it. Friction-welded bands require no tooling, just flip it over and peel it, but it holds very well. And it also holds as well as metal bands, without doing a lot of cutting. Probably some corner boards down here. We're going to put hand holds right here so it allows for manual carry for those situations, in places where you don't have mechanized systems to go do that. But when it gets to the other end, to unpack it all you basically do is take the top cover and the unit is exposed, and then you can just tilt it from that and move it into location. Okay, and then at the top, if it's just a pamphlet, I'll probably tape the manual to the side of the container with a non-residue plastic pouch. Encase the product in a plastic bag to prevent any dust from entering into the system. Basically just to protect it from dust, not cosmetic aspect. Okay, next thing I do is to go test this basic concept....

APPENDIX D

D.1 Instructions to All Participants

You will be given a description of what I need. Write a problem statement from which a solution could be developed. Do **not** solve the problem. Write your statement as if you will give it to another qualified mechanical engineer for developing a solution. Write the statement on the titled page.

If you want any information, write down your question on the blank pages and I will write a response. You do not have to form complete sentences. Please number your questions (Q1, Q2, etc.) and I will number the responses (A1, A2, etc).

Control Number______

Problem Statement

D.2 Problem Description

PROBLEM DESCRIPTION

I make small devices which require two coil compression springs with equal performance. I need a good way to determine if any two coil springs selected at random from a large inventory are a compatible pair.

Each individual spring in the inventory meets manufacturing tolerances. Most pairs of springs are compatible, so I need to detect the infrequent pairs that are not.

D.3 Guidelines for Treatment Group

Guide to Problem Formulation

In writing your problem statement, I want to challenge you to make it more descriptive of both the problem and the environment within which the problem must be solved. Your statement should include as many Technical Performance Requirements as you can identify at this point in the design process.

Technical Performance Requirements describe in measurable or verifiable terms the performance required for any solution to be considered acceptable. Each Technical Performance Requirement includes four elements:

Identification - a verbal description of the performance attribute (e.g., strength, speed, cost, durability, weight)

Conditions - delineation of the environmental conditions under which the performance is required (e.g., temperature, moisture content, time, number of operators)

Target Value - the optimum performance value, that value which will minimize loss or maximize gain (e.g., 32 miles per gallon, 90 decibels, 63 Hertz)

Allowable Variance - the permissible deviation from the target value (e.g., ± 2%, no more than, ± 6 Hertz)

It is important that you describe **WHAT** performance you need, but not how to achieve it. You should not restrict the designer's creative ability, but should instead identify the boundaries within which to be creative. If you specify what levels of performance are required for any solution, the designer should be able to determine if a solution is within those boundaries and also when the solution is adequate enough to stop designing.

To help identify performance attributes, think and ask questions in terms of:

- **TIME** (dates, duration, cycles, etc.)
- **DIMENSIONS** (distance, areas, weights, etc.)
- **VALUE** (precision, cost, quality, reliability, etc.)
- **PHYSICAL MATTER** (materials, parts, machines, etc.)
- **PEOPLE** (user, manufacturer, organizations, etc.)

Once you gather your information, write your problem statement to include the Technical Performance Requirements you have identified.

D.4 Available Information

Spring specifications in the inventory:
1. Free length: range: (4.9, 5.1);
   normally distributed: N(5, 0.03)
2. Spring rates: range (lb/in): (0.98, 1.02);
   normally distributed: N(1.0, .065)
3. Spring diameters: 3 inches (nominal) ± 0.1 inch
4. Material: Music wire, uncoated
5. Wire diameter: 10 gauge nominal (0.1 in.)
6. Number of turns: 15
7. Total deflection: 3 inches (nominal)
8. Weight: 4 ounces (nominal) ± 0.1 ounce

Allowable differences for a pair of springs:
1. Difference in free length: 0.1 in
2. Difference in spring rate: 0.02 lb/in
3. 98% probability of detecting incompatibility (Alpha=0.02)
4. 5% probability of falsely determining a compatible pair to be incompatible (Beta = 0.5)

System information:
1. Load range: 0 - 3 pounds, static loading, non-cyclic, no impact loading.
2. Efficiency requirement: less than 15 seconds to test
3. Weight limit for tester: 8 pounds
4. Cost limit for tester: $50
5. Historically, only 6% of pairs tested are rejected as not compatible.
6. Number of testers required: 5
7. Training time should be less than 15 minutes.
8. Tester should be portable, requiring no fixed installation.
9. No records of individual test are required.
10. Must be available for use in 4 months.
11. Male and female assembly line operators.
12. 500 - 700 pairs of springs must be tested per day
13. Life requirement of device is one year.
14. Device assembly is manual operation.
15. Operating environment is 70 - 100 °F, normal atmospheric conditions.

D.5 Multiple Attribute Value Model

ATTRIBUTE	WEIGHT	UTILITY SCALE	SCORE	UTILITY
CLARITY	1	0 1	S1	S1
SOLUTION IMPLICATION	W2	0__________100	S2	W2xS2
STRUCTURAL CONSIDERATION	W3	0__________100	S3	W3xS3
STAKEHOLDERS	W4	0__________100	S4	W4xS4
LEVEL OF FOCUS	W5	0__________100	S5	W5xS5
PERFORMANCE IDENTIFICATION	W6	0__________100	S6	W6xS6
PERFORMANCE MEASURABILITY	W7	0__________100	S7	W7xS7
		QUALITY=	S1 * {Σ Wi*Si} i=2,3,4,5,6,7	

Legend:

W_i Relative weight of the i^{th} attribute

S_i Graders score of the problem statement with respect to the i^{th} attribute

D.6 Instructions for Rating Problem Statements

You are asked to rate a collection of problem statements, each of which was developed by individuals based on the situation described below:

> I make small devices which require two coil compression springs. I need a good way to determine if any two coil springs selected at random from a large inventory are a compatible pair.
>
> Each individual spring in the inventory meets manufacturing specifications. Most pairs of springs are compatible, so I need to detect the infrequent pairs that are not.

Additional information pertinent to the situation is listed on the next page. This additional information was not provided to the participant, but was used to respond to specific questions asked as the participant developed the problem statement.

Each statement will first be assessed to determine if it is written with sufficient clarity to allow you to evaluate it. If the statement is unacceptable due to lack of clarity, no further evaluation is required.

Each acceptable statement will be given a rating between 0 and 100 along six dimensions:

- Structural Considerations
- Stakeholders
- Solution Implication
- Level of Focus
- Performance Identification
- Performance Measurability

Definitions and rating scales for the six dimensions are provided on subsequent pages. Please read the definitions, then reflect on what these dimensions mean to the specific situation described above. It may be helpful to note your reflections about each dimension on the appropriate definition page. At this time, you are establishing your personal rating scheme that you will consistently apply in evaluating each statement.

The six dimensions are independent. You should rate the entire set of statements along one dimension without consideration for how you will rate it along the other five dimensions. Each scale should be considered a continuum. You should rate each statement using the end points and anchors as guides, but you are free to assign any value between 0 and 100.

Once you have established your rating scheme, please follow this sequence:

1. Read each statement for clarity. If a statement is unacceptable due to lack of clarity, mark it as such and remove it from the set of statements.

2. Shuffle the remaining statements. Randomly select one dimension (out of the six) for evaluation. Examine the scale for that dimension, then rate each statement along that dimension.

3. Repeat step 2 until each acceptable statement has been rated along each of the six dimensions.

Do not reward or penalize statements based on length, sentence structure and grammar, choice of words, or format. As long as minimum clarity standards have been met, try to evaluate the statements solely along the six dimensions.

Available Information

Spring specifications in the inventory:

1. Free length: range: (4.9, 5.1);

   normally distributed: N(5, 0.03)
2. Spring rates: range (lb/in): (0.98, 1.02);

   normally distributed: N(1.0, .065)
3. Spring diameters: 3 inches (nominal) ± 0.1 inch
4. Material: Music wire, uncoated
5. Wire diameter: 10 gauge nominal (0.1 in.)
6. Number of turns: 15
7. Total deflection: 3 inches (nominal)
8. Weight: 4 ounces (nominal) ± 0.1 ounce

Allowable differences for a pair of springs:

1. Difference in free length: 0.1 in
2. Difference in spring rate: 0.02 lb/in
3. 98% probability of detecting incompatibility (Alpha=0.02)
4. 5% probability of falsely determining a compatible pair to be incompatible (Beta = 0.5)

System information:

1. Load range: 0 - 3 pounds, static loading, non-cyclic, no impact loading.
2. Efficiency requirement: less than 15 seconds to test
3. Weight limit for tester: 8 pounds
4. Cost limit for tester: $50

5. Historically, only 6% of pairs tested are rejected as not compatible.

6. Number of testers required: 5

7. Training time should be less than 15 minutes.

8. Tester should be portable, requiring no fixed installation.

9. No records of individual test are required.

10. Must be available for use in 4 months.

11. Male and female assembly line operators.

12. 500 - 700 pairs of springs must be tested per day

13. Life requirement of device is one year.

14. Device assembly is manual operation.

15. Operating environment is 70 - 100 $^{\circ}$F, normal atmospheric conditions.

Clarity - The binary assessment of whether or not the problem is stated in a coherent way and in understandable, non-jargon terms sufficient to allow further evaluation of attributes.

0 NOT-CLEAR (Unacceptable)	1 CLEAR (Acceptable)

Solution Implication - The degree to which the statement suggests solutions or ways to achieve solutions to the problem. The more a statement does so, the less favorable it is (i.e., this dimension has a negative orientation).

0		100
SOLVES	LEADS	OPEN-ENDED
(Worst)	(Anchor)	(Best)

SOLVES: The problem statement explicitly states a solution or a set (class) of solutions.

LEADS: The problem statement suggest or leads to a (set of) solution(s) or a way of arriving at one.

OPEN-ENDED: The problem statement suggests no solutions or ways of arriving at solutions; it merely states the problem.

Structural Considerations - The degree to which the statement reflects consideration for all relevant and unique aspects, parts, complexities and their interrelationships and intrarelationships to the extent that can be seen or verified at the stage of problem formulation.

0		100
NONE (Worst)	SOME (Anchor)	ALL (Best)

NONE: The problem statement reflects no consideration of the structure.

SOME: The problem statement reflects some consideration of the structure.

ALL: The problem statement reflects full consideration of the structure.

Stakeholders - The degree to which the statement reflects considerations of the needs, interests and power of all stakeholders, i.e., parties that will affect or be affected, directly or indirectly, by the solution of the problem. Stakeholders may be tangible (e.g., an interest group) or intangible (e.g., the "unborn" generation), may have high salience (in the sense of being motivated, having high stake) or low salience, and may be vocal/outspoken or "invisible". (Note: It is assumed that all salient stakeholders are tangible, but not all tangible stakeholders are salient.)

0			100
NONE	SALIENT	TANGIBLE	ALL
(Worst)	(Anchor #1)	(Anchor #2)	(Best)

NONE: The problem statement reflects that no stakeholder has received adequate consideration.

SALIENT: The problem statement reflects consideration of stakeholders of high salience, as defined above.

TANGIBLE: The problem statement reflects consideration of stakeholders that are tangible, as defined above.

ALL: The problem statement reflects that all stakehold ers have received adequate consideration.

<u>Level of Focus</u> - The degree to which the statement defines as high a level or as broad a problem as possible.

0			100
NARROW	SOMEWHAT NARROW	SOMEWHAT BROAD	BROAD
(Worst)	(Anchor #1)	(Anchor #2)	(Best)

NARROW: The problem is too narrowly defined.

SOMEWHAT NARROW: The problem is somewhat narrowly defined.

SOMEWHAT BROAD: The problem is somewhat broadly defined.

BROAD: The problem is defined as broadly as is possible and appropriate.

<u>Performance Identification</u> - The degree to which the statement defines what performance is required to satisfy the identified needs of the problem.

0		100
NOT DEFINED (Worst)	SOMEWHAT DEFINED (Anchor)	DEFINED (Best)

NOT DEFINED: Required performance is not defined.

SOMEWHAT DEFINED: Some required performance is defined.

DEFINED: All required performance is adequately defined.

<u>Performance Measurability</u> - The degree to which required performance can be measured or verified.

0		100
NOT MEASURABLE (Worst)	SOMEWHAT MEASURABLE (Anchor)	MEASURABLE (Best)

NOT MEASURABLE: Required performance cannot be measured or verified.

SOMEWHAT MEASURABLE: Some required performance can be measured or verified with difficulty.*

MEASURABLE: Required performance can be measured or verified using existing standards.

* Difficulty could be due to technical, cost, time, lack of standards, or other reasons.

APPENDIX E

E.1 Problem Statements from Sample Population

Design a test method or an equipment that can be used to determine if two compression springs are compatible with each other.

The test method or equipment <u>must</u>:

a) measure the tolerance between the springs

$l_o \leq \pm 0.1$ in (free length)

$k \leq \pm 0.02$ lb/in (spring constant)

e.g.	spring 1	spring 2		spring 1	spring 2	
l	4.9	5.1		4.9	5.0	
			unacceptable			acceptable
	1.0	1.0		1.0	1.02	

b) - detect incompatible springs 98% of the time

- not falsely detect a compatible pair as incompatible more than 5% of the time

c) be done in less than 15 mins.

d) cost less than $50

Choice of test method is unlimited. Test method or equipment must be easy to use (user friendly) and reliable and should not change the property or performance of the springs.

CONTROL #_23_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Design a inexpensive ($\leq$\$50) device and/or process that will be ready for use in less than 4 months and requires less than 15 minutes training, to determine if two coil springs are of equal length and stiffness. Springs considered equal in length are $\leq$ .1 in. different in length and springs considered equal in stiffness are $\leq$ 02 lb/in different in stiffness. The procedure and/or device must require less than 15 sec. to make this determination, and must detect an unequal pair of springs 98% of the time and must not declare an equal pair of springs unequal more than 5% of the time. All springs will have a nominal weight of 10 ga, Diam of 3 inch and be made of music wire. The maximum and minimum length of the springs encountered is 5.01 and 4.99 inches respectively and the maximum and minimum stiffness of the springs encountered is 1.02 lb/in and .98 lb/in respectively.

CONTROL #_31_ GRADER _____	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Pairs of springs are to be tested to detect differences in both free lengths and spring constants. The free lengths of the springs range from 4.9 to 5.1 inches (mean = 5.0 inch) and spring constant ranges from 0.98 to 1.02 lbf/in (mean = 1.0 lbf/in). Two springs are considered to be incompatible if the free lengths differ by more than 0.1 inch or if the two spring constants differ by more than 0.02 lbf/in or both free lengths and spring constants differ by the above amounts.

Develop the conceptual methodology for detecting incompatible pairs of springs selected at random from a large inventory. The methodology is to be implemented into either a manual process or an automated machine which tests the springs. Automation is preferred, and the mechanical design of the machinery or equipment needed is needed also.

CONTROL #_25_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

a) Require a process to select two springs with equal spring constant 'k'. Could check by applying equal force (compression) on each spring and noting deflection
b) Increase tolerance of manufacturing process (don't know if this is problem statement)

CONTROL #_24_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Project: We require a testing facility that will assist a worker in inspecting free spring lengths and stiffness by visual inspection. The testing device must be quick and reliable within the specifications below. Testing time should be minimized. Hint damping in the facility for determining spring stiffness.

Spring Dimensions: Free length: l=5" l_{min}=4.9" l_{max}=5.1"

$\triangle$ l between springs $\leq$ 0.1"

Stiffness: k_{norm}=1.0 lb/in k_{min}=0.98 lb/in

k_{max}=1.02 lb/in

$k_{spring1} - k_{spring2} \leq$ 0.02 lbs/in

Particulars: Diameter: 3.0" and Weight: 4 oz (light)

Testing Time: Total time 15 s. Suggest distribution:

$t_{inspection}$= 5 s

$t_{compression}$= 10 s

Testing Conditions: Dry and room temp.

Cost $\leq$ $50 + $5.00

CONTROL #_32_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

The compression springs which are made of music wire are in small devices. In order to determine if the springs are acceptable for application a compatibility check is required to be made. The compatibility check is to determine if any two coil springs selected at random from the inventory are a compatible pair. Wire diameter is 0.10 inch (nominal), coil diameter is 3 inches (nominal), free length varies from 4.9 to 5.1 inches with a mean value of 5.0 inches. The vendor has assured a spring constant of 0.98 - 1.02 lb/in with a mean value of 1.00 lb/inch. Measuring instruments and load applying facilities for the springs are provided in the shop.

CONTROL #_26_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

There is a large inventory of springs. A performance test needs to be run to measure the compressive resistance of each spring. Springs with identical compressive strengths (stiffness) need to be paired together. The dimensions of the springs is given below.

Spring: Compressive coil spring 3 in. Dia x 5.0 Length Nom.
Material: Music wire
Manuf. Stiffness: 1.0 lb/in. mean

Any spring that is unable to be paired with another (stiffness does not match any other spring) is to be set aside.

Please contact me if there are any questions regarding this matter.

CONTROL #_28_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKFHOLDERS	PERFORMANCE VERIFIABILITY

A device is required which will test 2 springs selected randomly from inventory to insure compatibility and equal performance in our product.

The test will be done prior to spring installation into the product. The device shall indicate a pass/fail response when two springs are tested. When 2 springs indicate a pass response, the 2 springs will be kept together. If 2 springs indicate a fail response, the springs shall be returned to inventory.

Pass/fail criteria:

- Spring free lengths shall not differ by more than .01"
- Spring constants must not differ by more than .02 lb/in

CONTROL #_30_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Identification:
Design a device that will quickly compare the free length and spring constant of two helical compression springs.

Conditions:
The device must be used under assembly line conditions and must be capable of performing the required task within approximately 15 seconds using any of a number of assembly line workers.

Target value and acceptable variance:
The two springs compared shall have a free length that is 5" with a manufacturing tolerance of ±.1 but the two springs must have a free length within 0.1" of each other. Also the two springs shall have a spring rate of 1.0 lb/in with a manufacturing tolerance of 0.02 lb/in but the rate of the two springs must be within 0.02 of each other.

CONTROL #_33_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

A method and/or design is required to determine if two coil compression springs, chosen at random from a large inventory, are compatible enough to work as a pair.

Compatibility is a function of two manufacturing variables: free length and spring rate. The difference in free length between two springs in a pair must not exceed 0.1 inch. The difference in spring rate between two springs in a pair must not exceed 0.02 lb/in.

The parameters of the springs as manufactured are as follows:

Free lengths: 5.0 inch ± 0.1 inch
Spring rate: 1.0 lb/in ± 0.02 inch
Outside diameter: 3.0 in ± 0.1 in
Inside diameter: 2.8 in ± 0.1 in
Weight: 4 oz ± 0.1 oz
Stroke (working deflection): 0 to 3 inches

The operating conditions for the springs is 70 to 100 °F, normal atmospheric conditions.

CONTROL #_34_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Two coil springs made of 10 gage music wire are to be selected from a large inventory. All springs are known to have 4.9 - 5.1 in. free length and stiffness k = .98 - 1.C2 lb/in. Springs are made to exercise st^tic compression loads, (0 - 3 lbf).

Need a device that will do the following:

1. Allow to pick two springs (not more than .1" difference in free length), & (not more than .02 lb/in difference between their stiffness).
2. Device is to be manually driven (for both males and females).
3. Device is expected to live for 1 year & to perform 500-700 times a day in an environment of 70 - 90 °F. Atmospheric conditions apply. The time of using (operating) the device each time should not exceed 15 sec.
4. Device should be less than 8 lbs & should not cost more than $50 to produce it.
5. Device should work 98% of the time. It also can fail to test that two compatible springs are incompatible less than 5% of the time.
6. Device should be ready in 4 months.

CONTROL #_35_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

For any pair of randomly selected springs, design (devise) a procedure which tests the difference in free length and stiffness. If the difference in free length is greater than 0.1 inches or if the difference in stiffness is greater than 0.02 lb/in, they are deemed incompatible.

The above can also be stated for any randomly selected pair of springs, devise a method which tests the diff in free length and stiffness between them. If the diff in either is greater than 1/2 the tolerable deviation from the mean (5.0 on, 1.0 lb/in), the springs are deemed incompatible.

CONTROL #_21_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Two coil springs are required for a device which I manufacture. It is desired that each pair of springs be compatible. The springs need to be 5 inches long, the coil needs to be 3 inches in diameter and the spring constant should be 1.0 lb/in. The manufacturing tolerances of the springs are that the length is given as % inches ± 0.1 inch, the diameter is given as 3 inches ± 0.1 inch and the spring constant is given as 1 lb/in ± 0.2 lb/in. For a pair of springs to be compatible, their lengths should be within 0.1 inch and the spring constants should be within 0.02 lb/in. The diameter of the coil is not critical. The given manufacturing tolerances are such that most pairs of springs will be compatible. The objective of the test is to find those that are not compatible.

The spring is made of music wire and its operating conditions are temperature = 70 to 100 °F, standard atmospheric pressure, current relative humidity. The spring does not operate in a corrosive environment. The test conditions should be the same as the operating conditions. The springs are loaded slowly, without cyclic or impact loads, and the typical deflection ranges from 0 - 3 inches for loads of 0 - 3 pounds. Again, the springs should be tested using compressive deflections 0 - 3 inches (preferably 3 inches). Also the springs are restricted to weigh 4 oz. Again, the testing conditions should simulate the operating conditions.

The restrictions on the test and test device are as follows:

(a) test must take less than 15 secs.

(b) the tester device must cost $50 or less.

(c) the tester should be ready in 4 months.

(d) tester is restricted to weigh 8 lbs.

-MORE-

So, concluding, I need a tester device which weighs 8 lbs or less, cost $50 or less and can provide test results in 15 secs or less to determine compatibility of a pair of springs and I need this device in 4 months. Also, those springs which are not compatible should be returned to the inventory since they may be compatible with other springs in the inventory. Historically only 6% of springs are incompatible.

CONTROL #_22_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

Develop a testing procedure to determine if any two coil springs selected at random from inventory have equal performance.

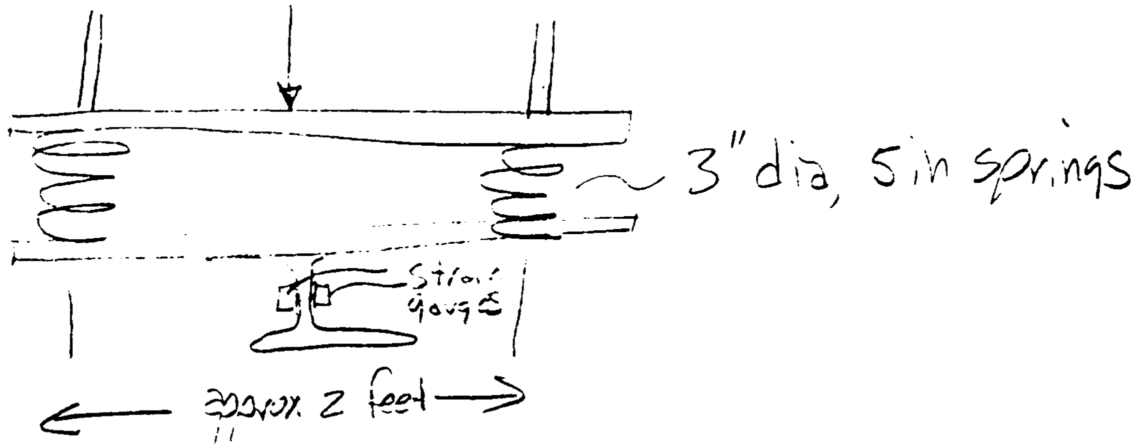
The springs are 4.9 - 5.1 inch long with 3 inch diameter. Equal is defined as the difference of free length of less than or equal 0.1 inch and spring constants' <u>difference</u> less than or equal to 0.02 lb/in.

The procedure should allow for testing 500 - 700 pairs of springs per day. No record is required.

The procedure should be an optimized balance of lowest cost considering both machine and labor cost, and must satisfy all government safety regulations.

CONTROL #_27_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

I need a spring tester built and calibrated. If successful, 5 will be built. The test bench will look as follows:



Design criteria:

1. Bench to have capability to evenly load both springs (ie, top of spring press must be made to travel only vertically without any rotation)
2. Bottom of spring press to have some means to locate spring in same location for every test (recesses?)
3. Pivot supporting bottom shelf to be designed thin enough so slight rotations of bottom shelf can be detected thru strain gauges on sides.
4. Make/Break on rotation: one spring must not be stiffer than other by .02 lb/in, or have difference in free height of .01 inch.
5. Design method of easily comparing strains on either gauge for quick readout (perhaps light on/off?)
6. Total cost of bench $50

CONTROL #_29_ GRADER ______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

A testing device to evaluate the performance of pairs of coil compression springs is required. The springs are to be used in a device that requires static loads from the springs. The springs meet all material and dimensional tolerances for the intended use. The detecting device will determine whether a selected pair is equal in performance. The performance compatibility will be the compressive stiffness of the coils. The stiffness must be 1.0 lb/inch and both springs must not vary by more than ±0.02 lb/inch. The testing device must be designed to provide a compressive load of up to 10.0 lbs force with a stroke of not more than 5.0 inches. The machine cost cannot exceed $50.00. The testing operation will be performed in an assembly line environment and must not exceed 15 seconds to evaluate a pair of springs.

CONTROL #_36_ GRADER _______	SOLUTION IMPLICATION	LEVEL OF FOCUS	PERFORMANCE IDENTIFICATION
CLARITY Acceptable__ Unacceptable__	STRUCTURAL CONSIDERATION	STAKEHOLDERS	PERFORMANCE VERIFIABILITY

E.2 Experimental Data

CTL	WORK	TPR	GDR	X1	X2	X3	X4	X5	X6
21	0	0	0	95	30	0	90	40	60
25	0	0	0	65	50	10	80	30	50
26	0	0	0	85	30	5	65	0	5
22	0	1	0	25	50	30	50	65	70
23	0	1	0	90	55	40	70	65	75
31	0	1	0	100	95	20	90	85	75
32	0	1	0	50	20	30	60	40	50
27	1	0	0	80	40	50	85	50	60
28	1	0	0	95	45	15	50	15	20
29	1	0	0	10	35	15	5	45	40
30	1	0	0	90	30	10	50	30	50
33	1	1	0	80	50	45	55	30	55
34	1	1	0	85	40	20	65	30	50
35	1	1	0	45	40	40	65	40	45
36	1	1	0	50	90	70	40	95	90
21	0	0	1	70	30	30	30	30	90
25	0	0	1	80	30	50	70	30	90
26	0	0	1	70	20	30	50	30	10
22	0	1	1	80	90	70	60	70	90
23	0	1	1	90	80	80	80	70	90
31	0	1	1	90	90	90	80	80	90
32	0	1	1	50	50	80	50	60	90
27	1	0	1	80	50	60	80	60	40
28	1	0	1	90	10	40	40	20	50
29	1	0	1	0	40	50	10	40	80
30	1	0	1	80	30	30	90	30	90
33	1	1	1	80	60	60	70	50	80
34	1	1	1	80	50	70	90	30	90
35	1	1	1	80	90	70	70	90	90
36	1	1	1	50	20	50	50	30	90

LEGEND:

CTL: Control number

WORK: Graduate Student (0) or Practicing Engineer (1)

TPR: Control Group (0) or Technical Performance Requirements Treatment Group (1)

GDR: Grader S (0) or Grader J (1)

E.3 Normal Probability Plots

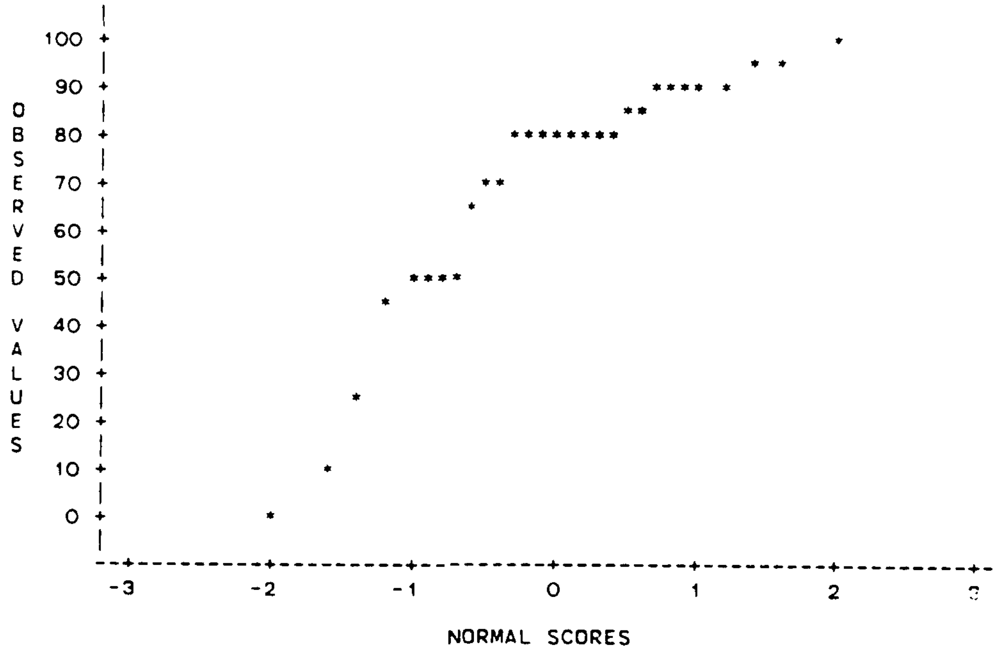


Figure 9. Normal Probability Plot for Attribute X1

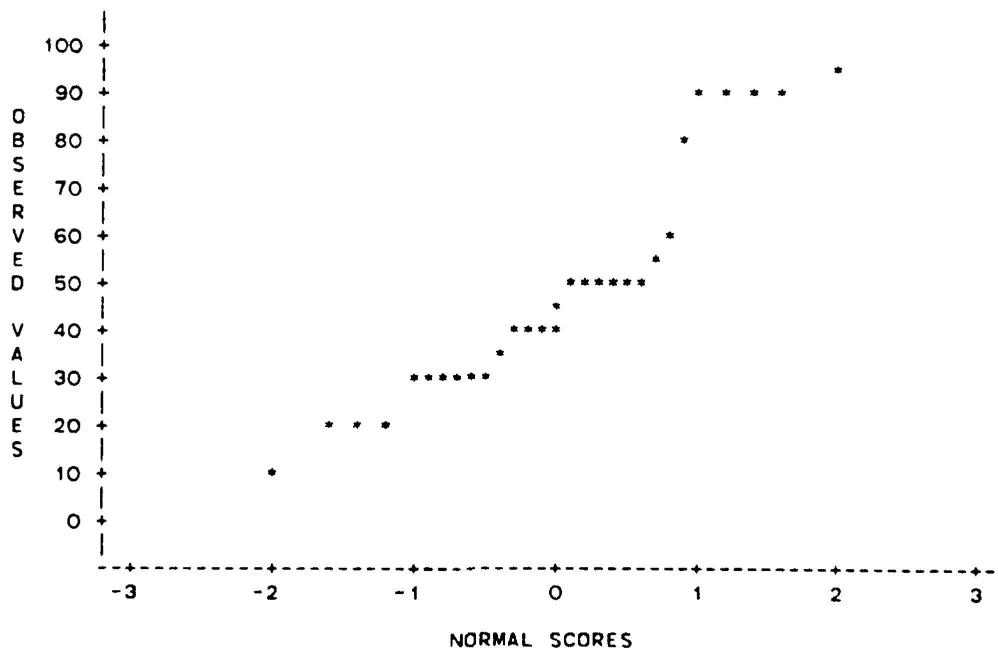


Figure 10. Normal Probability Plot for Attribute X2

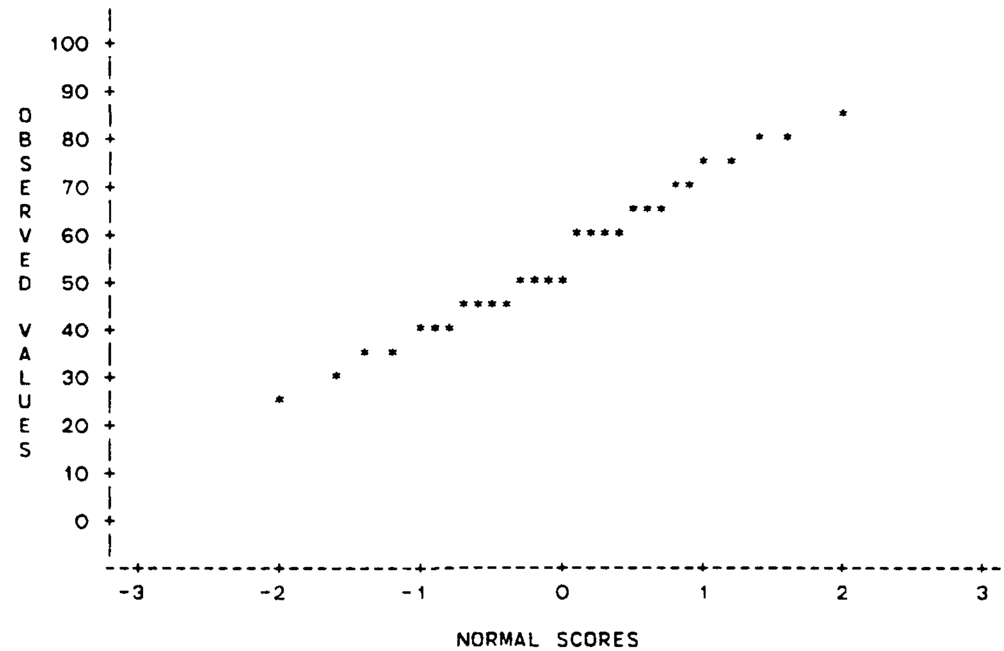


Figure 11. Normal Probability Plot for Attribute X3

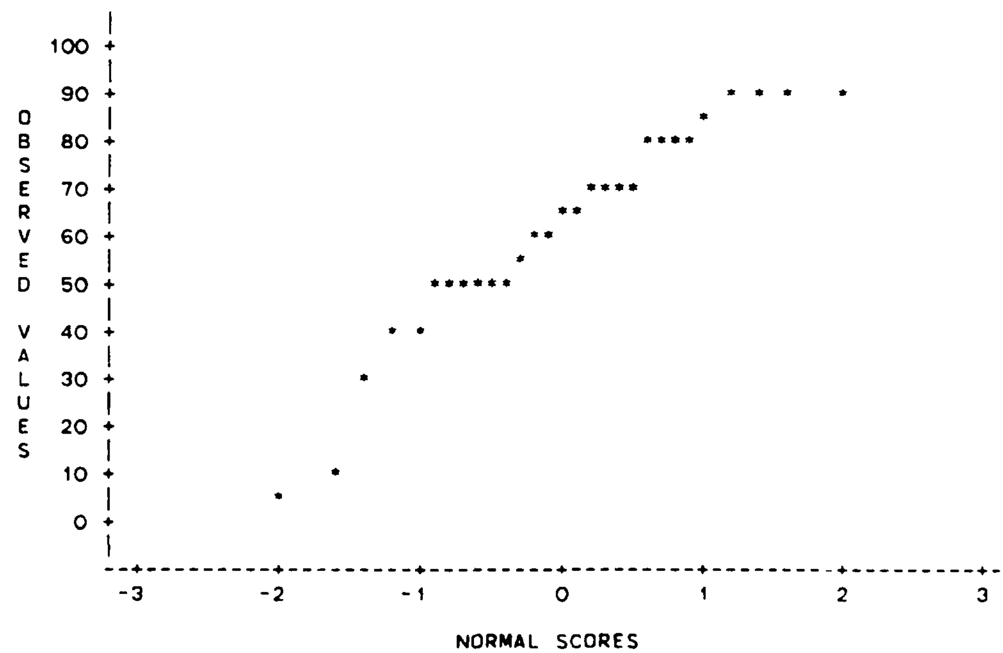


Figure 12. Normal Probability Plot for Attribute X4

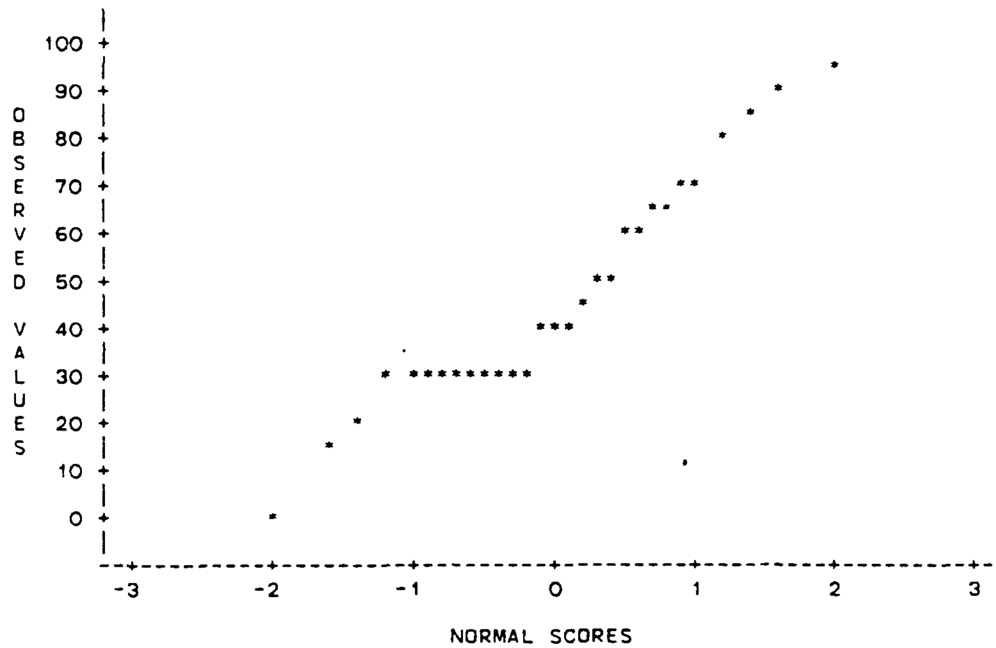


Figure 13. Normal Probability Plot for Attribute X5

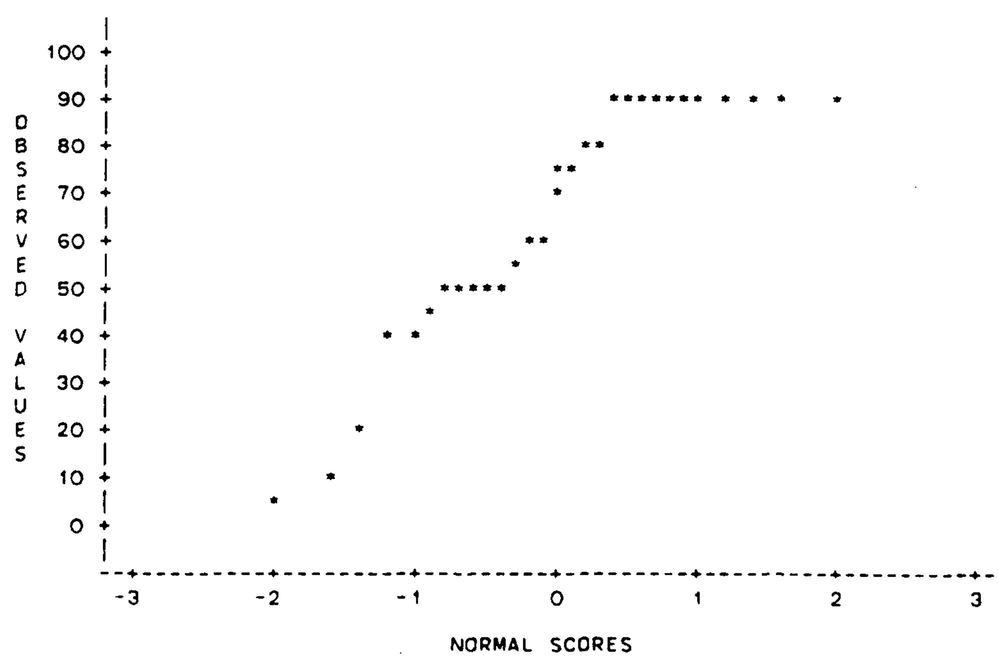


Figure 14. Normal Probability Plot for Attribute X6

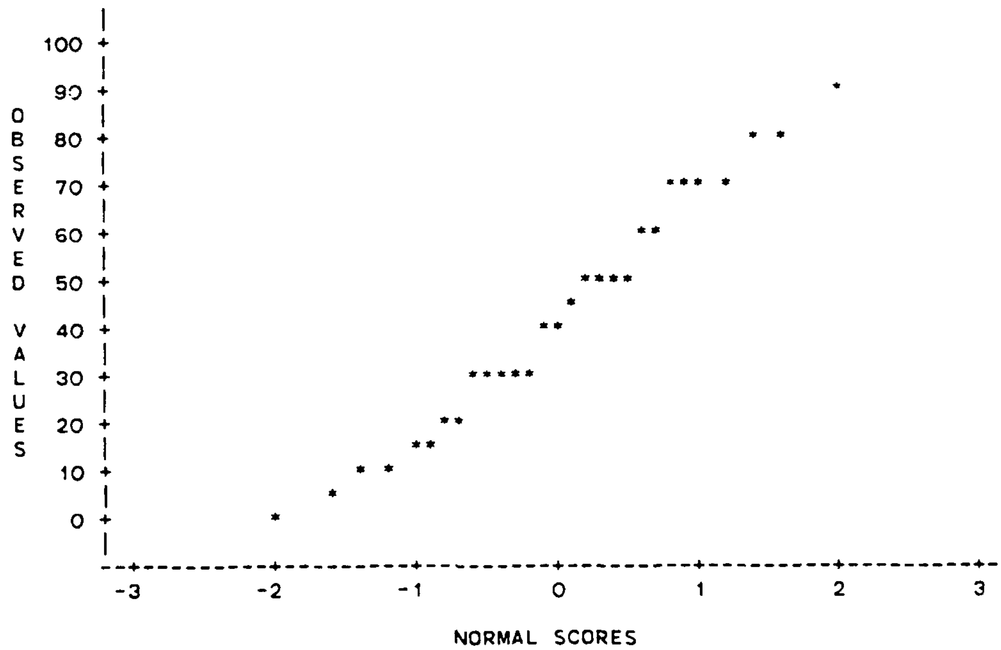


Figure 15. Normal Probability Plot for Aggregate Value

E.4 Three-Factor ANOVA With Interactions

Table 19. ANOVA With Two and Three-Factor Interactions

Source	Degrees of Freedom	F Value	Probability of a Value $\geq$ F
PFM	1	15.06	<0.01*
GDR	1	4.95	0.04*
WORK	1	0.56	0.46
PFM*GDR	1	1.02	0.32
PFM*WORK	1	0.67	0.42
GDR*WORK	1	0.07	0.79
PFM*GDR*WORK	1	0.38	0.54

*Significant at $\alpha = 0.10$

Table 20. ANOVA With Two-Factor Interactions

Source	Degrees of Freedom	F Value	Probability of a Value $\geq$ F
PFM	1	15.47	<0.01*
GDR	1	5.08	0.03*
WORK	1	0.57	0.46
PFM*GDR	1	1.04	0.32
PFM*WORK	1	0.69	0.41
GDR*WORK	1	0.07	0.79

*Significant at $\alpha = 0.10$

VITA

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