A cost-savings methodology of panel enhancements
by Danna Gail Herbst

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial and Management Engineering
Montana State University

Abstract:
Many currently-operating, industrial plants were built without an emphasis upon human engineering. Incorporating human factors into the re-design of existing control panels requires a capital investment. However, the application of human engineering design principles to existing panel designs reduces human error., A methodology for conducting a cost-savings analysis of incorporating human factor design principles into existing panel designs is presented. The cost-savings methodology integrates several existing methods, models, and techniques to enhance acceptance and application by industry. These methods, models, and techniques include panel enhancement techniques, economic cost models, task analysis, fault tree analysis, and a method for cost-benefit analysis. In addition, the methodology contains a new application of a linear additive utility model and a new procedure for determining the efficiency of funding allocation.

The cost-savings methodology proposes human engineering enhancements to existing panel designs. Enhancement costs and potential human error reduction are estimated. Potential human error reduction is quantified in terms of monetary risk reduction. Monetary risk reduction benefits and enhancement costs provide the basis for a cost-savings analysis, which consists of a cost-benefit and a funding allocation analysis.

A COST-SAVINGS METHODOLOGY OF PANEL ENHANCEMENTS

by

Danna Gail Herbst

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Industrial and Management Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

September 1988

APPROVAL

of a thesis submitted by

Danna Gail Herbst

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

19 Sept '88 — Paul L. Schilling

Date — Chairperson, Graduate Committee

Approved for the Major Department

19 Sept '88 — David I. Gibson

Date — Head, Major Department

Approved for the College of Graduate Studies

September 29, 1988 — Henry L. Parsons

Date — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his/her absence, by the Dean of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Danna Gail Herbst

Date September 19, 1988

ACKNOWLEDGEMENTS

I gratefully acknowledge James R. Wilson as well as the managers and staff of the Operational Safety Analysis Section of Westinghouse Idaho Nuclear Company for suggesting this study. I wish to extend my appreciation to Les Mitchell, Jill Cox, and the managers and staff of the Quality Assurance Department at Westinghouse Idaho Nuclear Company for their support. In addition, I would like to thank my husband, Scott Herbst, for his patience, encouragement, and support during the completion of this thesis.

TABLE OF CONTENTS

TABLE OF CONTENTS-Continued

TABLE OF CONTENTS-Continued

LIST OF TABLES

LIST OF TABLES-Continued

LIST OF FIGURES

ABSTRACT

Many currently-operating, industrial plants were built without an emphasis upon human engineering. Incorporating human factors into the re-design of existing control panels requires a capital investment. However, the application of human engineering design principles to existing panel designs reduces human error.

A methodology for conducting a cost-savings analysis of incorporating human factor design principles into existing panel designs is presented. The cost-savings methodology integrates several existing methods, models, and techniques to enhance acceptance and application by industry. These methods, models, and techniques include panel enhancement techniques, economic cost models, task analysis, fault tree analysis, and a method for cost-benefit analysis. In addition, the methodology contains a new application of a linear additive utility model and a new procedure for determining the efficiency of funding allocation.

The cost-savings methodology proposes human engineering enhancements to existing panel designs. Enhancement costs and potential human error reduction are estimated. Potential human error reduction is quantified in terms of monetary risk reduction. Monetary risk reduction benefits and enhancement costs provide the basis for a cost-savings analysis, which consists of a cost-benefit and a funding allocation analysis.

INTRODUCTION

Background

Proper application of human engineering principles to design reduces human error and improves system reliability [6,14,18,22,27]. The importance of human factors in design was dramatically emphasized by the accident at Three Mile Island. Consequently, the application of human factors principles in the design of control panels has received increased attention in recent years [16]. However, most plants were built before this emphasis. To reduce human error and improve system reliability of currently operating plants, human engineering design principles must be applied to the re-design of existing control panels. The re-design of existing control panels has been termed retrofitting and backfitting [16,22].

Although retrofitting human factors into existing designs improves system reliability, it can be extremely expensive if hardware re-design is involved. Relocating instruments on a control panel is very expensive due to rewiring, drawing changes, engineering reviews, and safety reviews. However, human factor design principles can be applied to existing designs through surface enhancements. Surface enhancements are cosmetic additions, such as paint, tape, and labels applied according to information processing principles which reduce human error. The cost of retrofitting human factors via surface enhancements is substantially less than retrofitting via hardware re-design [22].

The cost of retrofitting human factors via surface enhancements represents a capital investment [16,22,31,32]. To justify a surface enhancement investment from an economic standpoint, monetary benefits of the human factor design inputs must outweigh the costs, and the investment must represent efficient allocation of available funds [10,33]. However, no systematic procedure exists at present to accomplish the complex integrative process necessary to quantify this type of human factor input to control panel design. The present study was initiated in an attempt to develop an economic analysis of panel enhancements that involves a cost-benefit analysis and a budget allocation analysis. The resulting methodology is entitled a Cost-Savings Analysis of Panel Enhancements (CSAPE). A CSAPE permits quantification of the benefits of surface enhancements in monetary terms, something human factors specialists are constantly under pressure from management to do.

Performing a cost-savings analysis of proposed panel enhancements will provide economic justification of the enhancement investment. Another advantage of conducting a CSAPE is the opportunity to evaluate the monetary benefits of panel enhancements before the enhancements are implemented. Both monetary benefits and reliability improvement benefits can be estimated.

A panel enhancement investment can be viewed as a safety investment. Methodologies that determine the cost-effectiveness of safety investments have been developed [2,3]. However, the previously developed methodologies evaluate cost versus a parameter, such as reliability, of a safety investment rather than cost versus monetary benefits [2,3,10,33]. These methodologies do not evaluate safety investments in terms of efficient budget allocation and do not deal with human factor design inputs [2,3]. A Cost-Savings Analysis of Panel Enhancements (CSAPE) evaluates safety investments in terms of cost versus monetary benefits, efficient budget allocation, and addresses human factor design inputs.

This study was conducted to develop a methodology for conducting a CSAPE. A CSAPE can be used to justify an investment in control panel enhancements and evaluate both the monetary and reliability improvement benefits of the investment. A CSAPE involves proposing surface enhancements for an existing panel design, quantifying the benefits of the enhancements in monetary terms, and performing a cost-saving analysis of the enhancements.

Objectives

The objective of this study was to integrate several established procedures into one methodology that would permit a Cost-Savings Analysis of Panel Enhancements (CSAPE). The CSAPE integrates established techniques of panel enhancements with economic cost models, task analysis, fault tree analysis, cost-benefit analysis, and a monetary risk definition [1,10,11,22,23,30,33]. Established procedures were used where possible to enhance acceptance and application by industry. However, the CSAPE also incorporates a new application of a linear additive utility model and a new approach to determine efficient funding allocation.

The Cost-Savings Analysis for Panel Enhancements (CSAPE) has been developed specifically for use in the chemical processing industry. However, with slight modifications, it could be used elsewhere as well.

Overview of the Methodology

The CSAPE involves proposing surface enhancements to an existing panel design, estimating the costs of implementing the enhancements, quantifying the benefits of the enhancements in monetary terms, and performing a cost-savings analysis of the enhancement investment.

The CSAPE begins with the identification of the control panel to be enhanced (see Figure 1). Surface enhancements are proposed for the existing design by using the surface enhancement process [22]. The costs for implementing the enhancements are identified and estimated using cost accounting and economic analysis principles [10,23,33].

The benefits of the proposed enhancements are quantified in monetary terms by calculating the risk reduction potential of the enhancements. The risk reduction potential is estimated by postulating an accident associated with the operation of the panel, and calculating the difference between the risk associated with the existing design and the enhanced design. Risk, as defined in the nuclear industry, is expressed in terms of expected cost of an accident. It is calculated by multiplying the economic consequences of the accident by the probability of the accident [1]. Consequently,

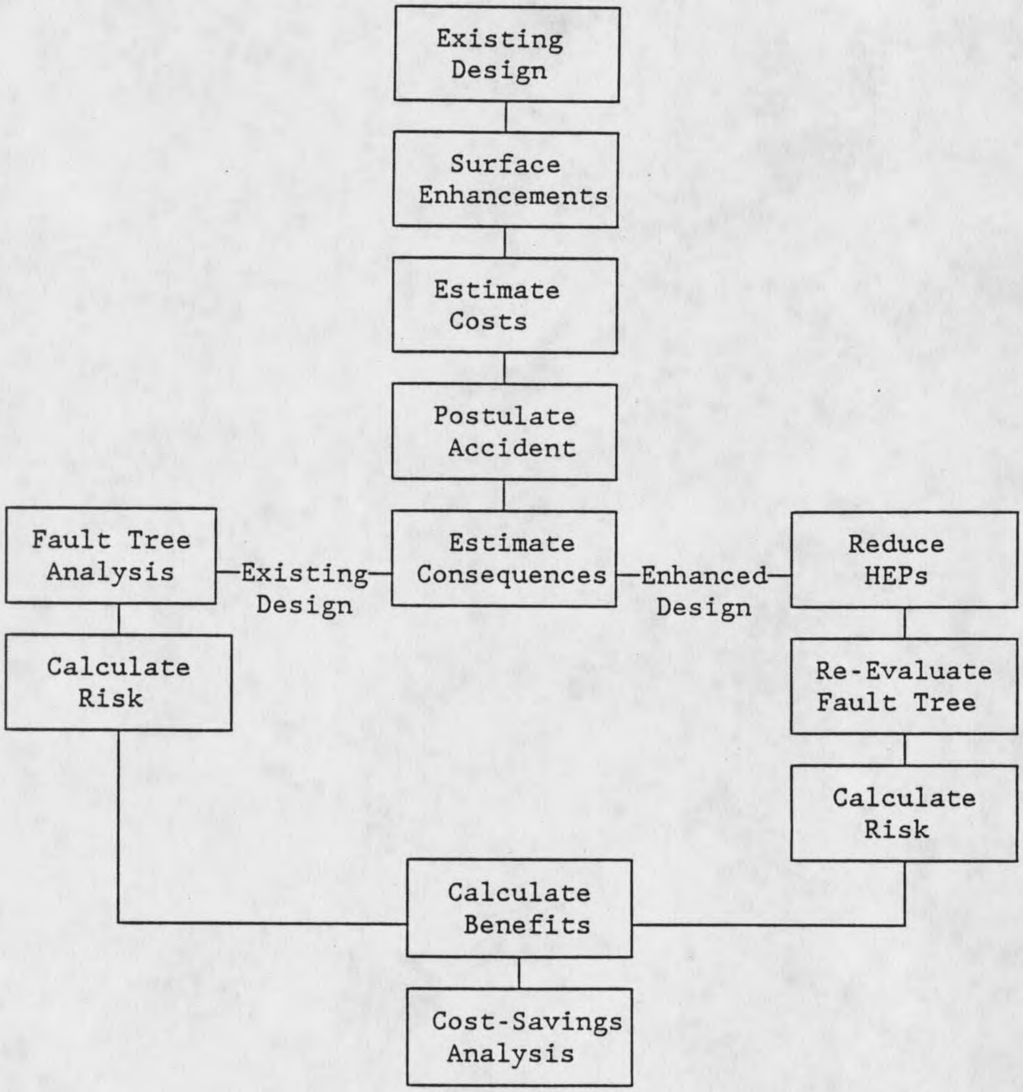


Figure 1. The methodology for a Cost-Savings Analysis of Panel Enhancements (CSAPE).

calculating the risk reduction potential requires estimating the financial consequences of the accident and estimating the probability of the accident with respect to both the existing and enhanced panel. The resulting risk reduction potential constitutes the monetary benefits of the proposed enhancements.

Estimating the probability of an accident with respect to the operation of the existing design involves conducting a fault tree analysis of the accident [11,17,28,30]. Fault tree analysis involves task analysis, fault tree construction, and fault tree evaluation. A task analysis of the operations involved in the accident provides the data base for the construction of the fault tree [27,30]. The quantitative evaluation of the fault tree provides the probability of the accident occurrence [11,17,28,30].

Estimating the probability of the accident with respect to the operation of the enhanced layout involves estimating the human error reduction potential of the enhancements and re-evaluating the fault tree. Surface enhancements reduce the human error probabilities (HEPs) associated with the accident [18,22,27]. A linear additive utility model is used to estimate the reducing factor for the human error probabilities (HEPs) [8,9,13,15,26]. The fault tree of the accident is re-evaluated using the reduced human error probabilities (HEPs) [7,11,30].

Risk reduction potential versus cost of the enhancements provide the basis for a CSAPE. The cost-savings analysis of the enhancement investment consists of a cost-benefit analysis and a funding allocation analysis. The benefit-cost ratio is used in the cost-benefit analysis [10,33]. The funding allocation analysis consists of determining the expected maximum yearly savings of the enhancement investment and using these savings to determine the efficiency of the funding allocation.

The CSAPE and an example illustrating its use are presented in subsequent sections.

PROPOSING ENHANCEMENTS

The methodology for a Cost-Savings Analysis of Panel Enhancements (CSAPE) begins with the identification of the panel to be enhanced and the surface enhancement process. A panel that needs to be enhanced can be identified once a distinction is made between a properly designed layout and a poorly designed layout. A panel layout survey is conducted to identify deviations in a layout from properly designed layouts. The surface enhancement process is then used to enhance poorly designed layouts [22].

Panel Layouts

There are several differences between proper panel designs and poor panel designs. A properly designed layout reduces display selection errors and unintentional control activation. Proper panel design aids an operator in locating, identifying, and selecting instruments quickly and accurately [22,27].

A properly designed layout will conform to the NUREG-0700 Guidelines [29]. The NUREG-0700 Guidelines recommend grouping displays and controls on a panel according to the principles of "task sequence" and "system function". The principle of task sequence groups instruments in order to minimize operator movement during task performance. Grouping displays and controls by system function refers to functional groups of instruments relating to system structure.

Further, groups of displays and controls should be assigned to panel locations according to their importance and frequency of use. Important and frequently used groups should be placed in the center visual area of the panel. Since it may be impossible to apply all of these design principles, design trade-offs will have to be made in allocating panel positions to instruments and groups of instruments [21,35]. Population stereotypes should be followed in arranging controls and displays within the groups as long as they do not conflict with the principle of task sequence. If a standard arrangement of components has been established, it should be maintained on other panels or sections of a panel. However, panel sections should not be mirror imaged. Control or display groups should be separated from one another using spacing or demarcation lines. If large groups of instruments are necessary, labeled coordinate axes should be used to facilitate the identification of an instrument within a grid. Control separation distances should be sufficient to allow for access and simultaneous activation of adjacent controls while preventing inadvertent activation. Color coding may be used to enhance the recognition and identification of displays, controls, or groups of instruments [29]. The above mentioned recommendations from the NUREG-0700 guidelines represent examples of areas that deal with a properly designed layout and are samples of what is meant by surface enhancement [22,29].

A panel layout survey should be conducted to identify deviations in the design from these guidelines. Table 1 illustrates a generic checklist that may be used in conducting such a survey [29].

Table 1. A checklist used in a panel layout survey.

	N/A	Complies With Guidelines	Does Not Comply With Guidelines	Comments
Panel Feature				

If a panel design deviates in major ways from these guidelines especially in terms of instrument location, it may be impossible to backfit recommendations by relocating instruments on the panel. Fire protection requirements may prohibit the separation of cables in order to relocate instruments. New cable or conduit installation is extremely expensive because of the requirements for engineering and seismic analyses, fire loading, safety reviews, and drawing changes [22]. However, improvements in the layout can be made through the use of surface enhancement techniques [22,31,32].

The Surface Enhancement Process

The surface enhancement process of proposing changes in panel layouts involves identifying the organizational structure of the panel, enhancing the organization structure, and verifying the enhancements [22].

Identifying the Organizational Structure

The organizational structure of an existing layout must be identified because the structure will govern the nature of design improvements possible. Existing panel designs may be based upon a number of organization structures or combinations thereof. The location of displays and controls on a panel may correspond to the functional relationships of plant subsystems and equipment. For example, a panel layout may be a mimic of the plant process, or the panel may be organized according to the relationships of plant support functions to major plant systems.

Components on a panel may be arranged according to the common activation and operation of equipment. Or, panel designs may be based on the functional relationships among the controls and displays. For example, instruments may be located on a panel to facilitate their simultaneous or sequential operation. Panel designs could also be based on the geographical relationships of the equipment.

The purpose of surface enhancement is to reduce inconsistencies and conflicts of the organizational structure in order to enhance the operability within the design. Careful attention should also be given to the manner in which operators mentally organize the panel in order to successfully enhance the design [22].

Enhancing the Organizational Structure

Enhancing the organizational structure involves making decisions concerning the surface enhancement techniques to be employed, component group formation, and elements of the component groups. Recommendations regarding these decisions should be obtained from the operating personnel [22].

Verifying the Enhancements

The proposed enhancements must be verified! Inappropriate changes in panel design may in fact degrade the man-machine interface. For example, the enhancements may violate existing design conventions, lead to negative transfer of learning, and may be inconsistent with the existing design. Therefore, modifications of an existing design must be thoroughly evaluated through the use of models and mock-ups. Three-dimensional models provide the most effective way of evaluating alternative designs in terms of colors, textures, color schemes, equipment arrangement, and operability. However, drawings may be adequate for the preliminary analyses.

Control panel mock-ups also allow for the safe testing of operator-equipment interfaces. In addition, they can be used as training tools after a design has been tested and approved. Models and mock-ups should be reviewed by operators, supervisors, engineers, and human factor specialists in order to disclose problem areas and provide direction for design trade-offs [22].

Surface Enhancement Techniques

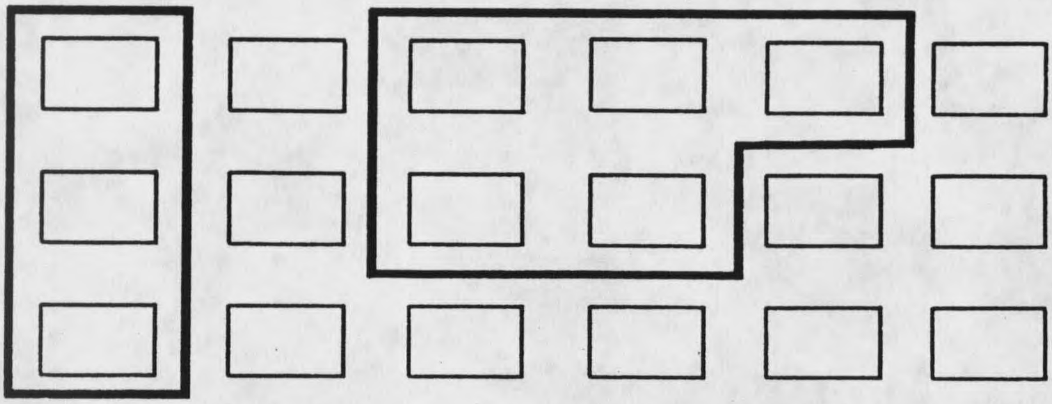
Surface enhancement involves the application of location aids. Location aids include demarcation, color shading, color coding, and mimic lines. These location aids are employed to enhance the perceptual organization of a panel's content. Surface enhancement techniques are based upon perceptual organization principles to provide an operator with visual location aids. The principles of perceptual organization include association, closure, dominance, and uniqueness. Implementation enhancement techniques must also include a concern for color selection and hierarchical labeling [22].

Association

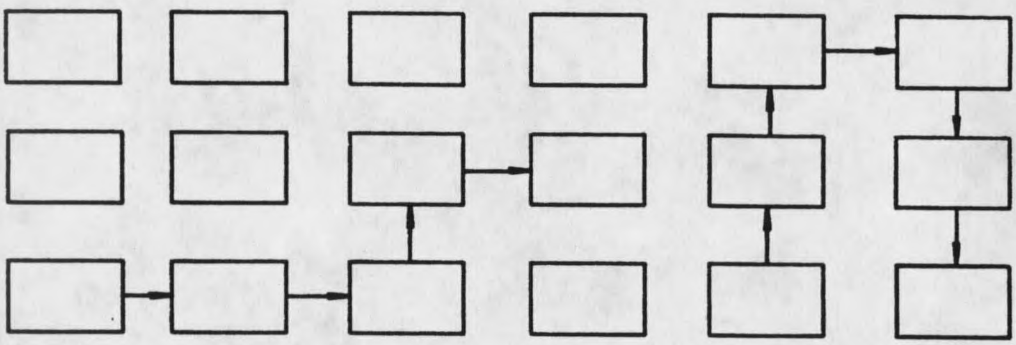
Association of displays and controls can be conveyed through the use of shape, color, and lines. For example, components with similar knob shapes or instrument cases can be perceived as forming a group. Color can convey association between physically separated components. In order to avoid a patchwork effect when using this technique, neutral color tones should be selected. Neutral color tones, such as greys and pastels, are more effective in conveying association. Strong colors can produce a conflicting organization principles of dominance. Strong colors also contribute to visual fatigue, clutter, and reduce contrast which leads to poor label readability [21,22,35].

A group of components can be associated by enclosing them with a line. Lines that enclose components groups are demarcation lines (see Figure 2). Demarcation lines with rounded or beveled corners tend to form stronger groups than ones with square corners. Demarcation lines should never cross and the lines should contrast well with the panel background color.

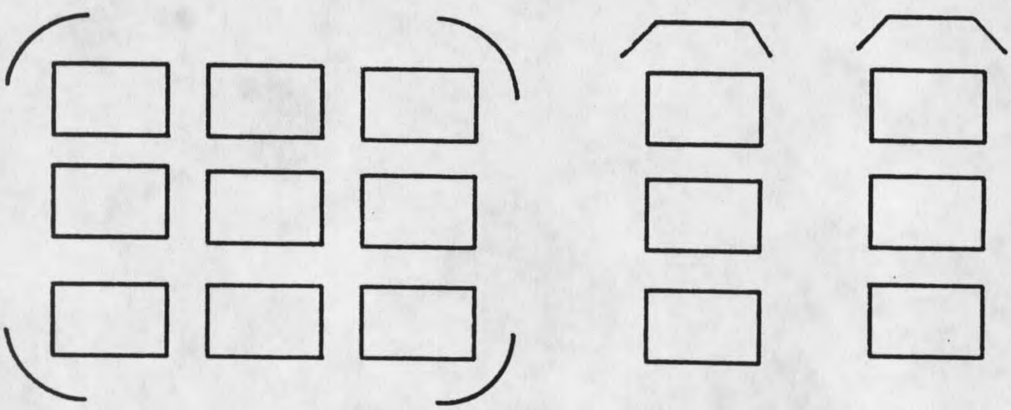
Instruments can also be visually linked by connecting them with a single line where the line indicates a task sequence or the process flow. Single lines that indicate task sequence or process flow are mimic lines. Mimic lines should never cross and arrows should indicate the direction of flow. A prerequisite of mimic line use is



Demarcation lines indicate association.



Mimic lines indicate association.



Rounded corners and brackets indicate closure.

Figure 2. Illustration of the perceptual organization principles of association and closure.

the appropriate physical arrangement of instruments to allow flow paths to be reflected (see Figure 2) [22].

Closure

The principle of closure is based upon the normal human perceptual tendency to visually extrapolate closure from existing graphic cues. For example, groups of instruments can be formed through the use of brackets or corners (see Figure 2). This bracket technique is only successful if the brackets are placed at the top of a group [22].

Dominance

Functional importance of components can be conveyed through the use of line width, contrast, or color. For example, wider demarcation lines convey a major group while narrower demarcation lines indicate subgroups (see Figure 3). Color can also convey dominance or importance when it is brighter or visually stronger than surrounding colors. However, care should be taken in applying color to denote dominance because strong or bright colors visually clutter the layout and reduce label contrast [22].

Uniqueness

The uniqueness or perceptual distinctiveness of an instrument can be conveyed through shape or color. A component with a different shaped knob or color than the surrounding components will appear unique (see Figure 3). A technique for making demarcation lines unique is using filled-in, rounded, or cut-off corners. Color can also be used to create mimic line uniqueness. However, this technique can be overused and the uniqueness lost. Uniqueness of mimic lines can also be lost by using too many mimic lines. Color shading may be used to make a group of instruments more distinctive. However, using too many colors can result in a "Christmas tree" effect [22].

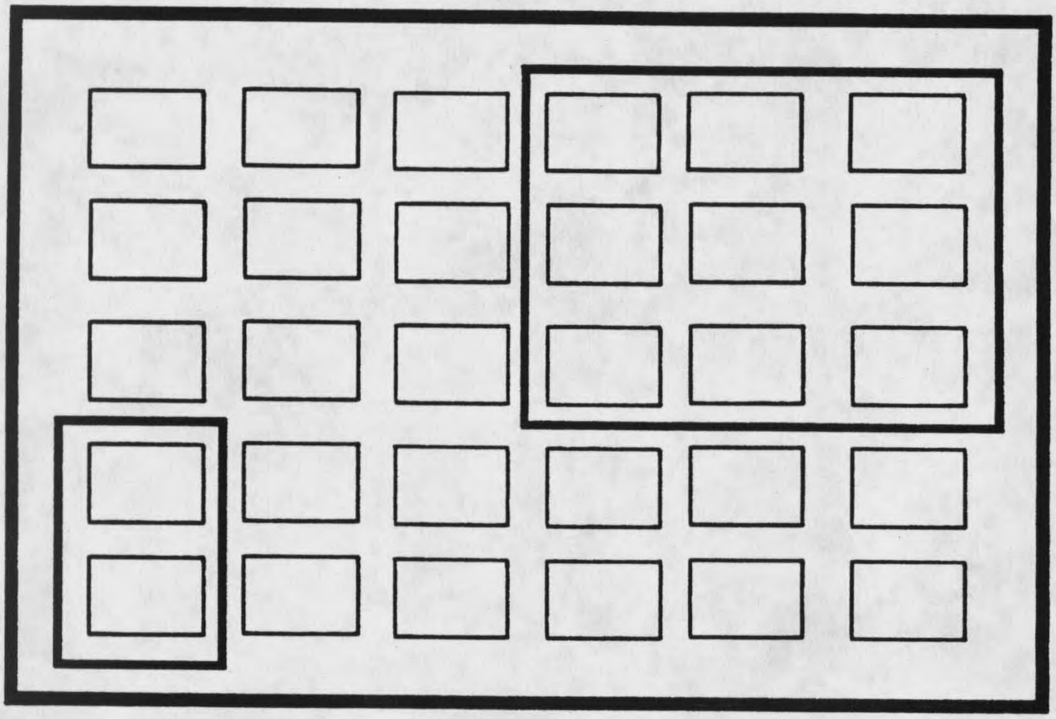
Color Selection

Color selection should be based on the type of hardware on the panel, panel board background color, and the colors of indicator lamps, CRT displays, and annunciators. Generally, large component groups require neutral tints while contrasting colors are used for smaller groups [22]. Light gull grey and dark gull grey are recommended for large and small component groups respectively [21,35].

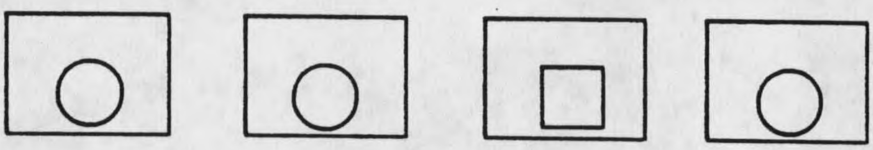
Hierarchical Labeling

Hierarchical labeling must be complementary to demarcation and color shading. The purpose of hierarchical labeling is to simplify and highlight the presentation of information in a manner that relates and integrates functionally similar component groups. Using a hierarchial labeling scheme, functionally related components are identified by general group labels. This reduces the verbiage on individual labels and consequently, reduces reading time [22].

Two important factors in the design of a hierarchical labeling scheme are levels of the hierarchy and letter size degradation. The four levels of a hierarchical labeling scheme are major, subordinate, component, and position identifier levels. A major level refers to a major system or work station while a subordinate level refers to subsystems or functional groups of instruments. The component and



Wide demarcation lines indicate dominance.



Shape indicates uniqueness.

Figure 3. Illustration of the perceptual organization principles of dominance and uniqueness.

position identifier levels refer to instrument labels and control selection labels, respectively. Appropriate letter size of the hierarchy must be determined from the appropriate letter size of the component label since the letter size increases 25% for each level of the scheme. Appropriate letter size for instrument labels depend upon the viewing distance and illumination levels. Larger character size is required for greater viewing distances and lower levels of ambient light. The guidelines of NUREG-0700 should be followed when selecting the letter size [22,29].

Other considerations in the design of a hierarchical labeling scheme include information of the major, subordinate, and component elements conveyed, and the nomenclature selection. The labels should not present redundant information and should only be used if unrelated components do not intrude into the area. Major labels should be located in the center, top edge of a panel, while the subordinate labels should be centered above the demarcation lines or shaded areas. Component labels should be located above the instruments to complete the top-down phenomenon created by the hierarchy. The NUREG-0700 guidelines regarding the placement, mounting, spatial orientation, visibility, information content, word selection, consistency, readability, and style should be applied to the labels [22,29].

ESTIMATING ENHANCEMENT COSTS

A cost-savings analysis of control panel enhancements requires the estimation of the enhancement costs. The total cost of implementing surface enhancements consists of several components. The cost components are initial costs, lost production costs, and incremental costs of operation and maintenance [2,10,23,33]. The cost components cannot simply be aggregated to arrive at a total cost estimate due to the difference in the timing of the cash flows. Money has a time value because of interest and inflationary effects [10,33]. Hence, only the value of the cash flows at the time of surface enhancement incorporation will be considered in the analysis. The time value used in the analysis will be denoted present worth. Once the cash flows or cost components have been converted to a present worth value, they can be aggregated to arrive at a total cost estimate. Consequently, each cost component will be analyzed in terms of a present worth value. A total cost estimate can be determined by summing the results [10,23,33].

Initial Costs

The initial costs of surface enhancements will consist of direct material, direct labor, and any overhead costs relating to the enhancements, mock-ups and models [23,33]. The overhead costs consist of administrative costs. Direct materials consist of paint, tape, and labels for the enhancements as well as the materials for the mock-ups or models [22]. The direct labor cost is composed of the labor cost necessary to implement surface enhancements and to construct the testing devices [22,23,33]. Since the timing of most of the cash flows is concurrent with implementation of surface enhancements, the cash flows are denoted as present worth values. Thus, the present worth value of the initial cost component is the sum of direct material, direct labor and any overhead costs related to the enhancements and testing devices [22,33].

Lost Production Costs

Another cost that may be incurred when implementing surface enhancements is lost production costs or costs due to plant downtime while incorporating the surface enhancements. Since it will be assumed that surface enhancements can be implemented in less than one year and end-of-year cash flows will be used in the analysis, the downtime costs can be aggregated and represented as a present worth, single sum value [10,33]. The estimate of lost production costs can be added directly to the initial cost component.

Although the lost production cost component is considered in the analysis, it could be avoided. Surface enhancement incorporation could be scheduled simultaneously with routine maintenance. Thus, surface enhancements could be incorporated while the plant was shut down for regularly scheduled maintenance. Eliminating the lost production costs would reduce the total cost of a surface enhancement investment, therefore, making the investment more attractive.

Incremental Operating and Maintenance Costs

The final cost component considered in the total cost of the surface enhancement investment is the incremental costs in maintenance and operation [2]. Additional costs might be incurred in the maintenance and operation of the plant due to surface enhancements. The incremental operation and maintenance costs may consist of the costs to revise written operating procedures due to the changes and the costs to refurbish the surfaces of the panel [22]. Such costs would be incurred throughout the remaining lifetime of the plant. For the purpose of this study, the average lifetime of an industrial plant will be assumed to be 40 years [4]. Thus, the incremental cash flows will be incurred over 40 minus n years, where n is the number of years the plant has been in operation. The incremental maintenance and operation costs will be modeled as discrete, end-of-year, cash flows (see Figure 4).

Since the timing of the incremental operating and maintenance cash flows is not concurrent with the incorporation of the surface enhancements, they must be converted to a present worth, single sum value. The present worth value, using then-current dollars, will be used in order to compensate for inflation and interest [4,33].

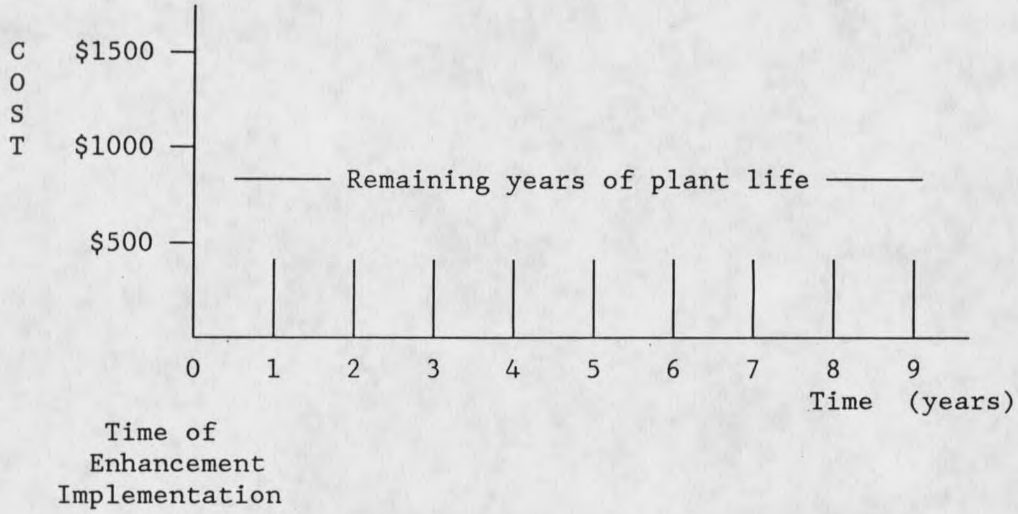


Figure 4. Cash flow profile of incremental operating and maintenance costs.

The present worth value using then-current dollars can be calculated as follows [4,33]:

$$P_i = \sum_{n=0}^{k} C_n(1 + i_r + j + i_r \cdot j)^{-n} \qquad (1)$$

where P_i = present worth value of the incremental costs
C_n = incremental cash flow in year n
i_r = interest or discount rate
j = inflation or escalation rate
n = year from year of enhancement completion
k = remaining years of plant lifetime

After all of the cost components have been estimated, a total cost estimate for the surface enhancement investment can be determined by summing the results [23].