Proceedings of DETC'02
ASME 2002 Design Engineering Technical Conferences
and Computer and Information in Engineering Conference
Montreal, Canada, September 29-October 2, 2002

DETC2002/DAC-34144

EVALUATION OF CONCEPTUAL DESIGNS AND MAINTAINABILITY INCORPORATING UNCERTAINTY

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ABSTRACT

This paper presents a method for carrying out a quantitative evaluation of design concepts with incomplete assessment information. When evaluating design solutions, in addition to consideration of product functionality, quality and cost, product life cycle performance such as maintainability should also be evaluated. Product maintainability issues are one of the more difficult design aspects to evaluate in early design stage. This paper describes specific maintainability metrics for evaluating product maintenance of conceptual design alternatives. Because of the uncertainty associated in early stage design evaluation, the varying degree of customer expectation must be incorporated into the evaluation system. Non-traditional fuzzy sets are used to represent expectations of the customer and compare them to design solution parameters. A case study is presented to illustrate the design method.

1. INTRODUCTION

1.1 Background

Design evaluation incorporating life cycle performances such as maintainability at various product development stages is critically important for developing successful products that meet customers' needs. In conceptual design stage, the evaluation based on various criteria is more difficult as product design data and life cycle information are incomplete with uncertainty, and reliable and comprehensive design evaluation methods are not readily available. However, the incomplete information must still be used to make the decisions which allow the design to progress. To accomplish effective evaluations, uncertain information is used in conjunction with fuzzy set concepts to evaluate designs based upon the voice of the customer. The use of fuzzy sets allows the system to use a variety of information types for evaluation. Evaluation of the design indicates the level of quality of each design and estimates the risk that this rating may not be achieved. These measures allow the most promising designs to be selected for further development.

To select a successful design concept, evaluations should be conducted based upon compliance of the design to the customers' needs. Paul and Beitz [1] developed a hierarchy of evaluation criteria beginning with the needs for a product. A weighted sum reveals the value of the design, which can be indexed by comparing it to an ideal concept from both economical and technical perspectives. Rodgers et al [2] discuss the development of design attributes that can be used to measure a customer's perceived performance in the development of a conceptual model of the evaluation process. Thurston [3] and Thurston and Locascio [4] modified this approach using a multi-attribute utility analysis wherein the designer determines tradeoff levels or importance of each attribute to be used in the evaluation. This method allows for the nonlinear effect of an attribute level on the evaluation of a design.

Each of the evaluation methods discussed above can be divided into two components. The first component is the type of information to be used as the evaluation criteria. The second component is the method used to combine and compare information so that the designs can be evaluated. Decisions are then made based on these evaluations. A taxonomy to describe the structure of design problems was established to review some of these techniques [5].

Maintainability is usually assessed late in the design by estimating the failure rates of components and then applying parts costs, labour costs and assembly times as well as other factors to compute an expected repair cost [6]. There are research publications available for evaluating maintainability after the products are design and manufactured. However, little work has been done to assess maintainability early in the design when the designer is still able to make significant improvements. In 1989 a review of life-cycle issues by Finger and Dixon [7] showed that very little work had been done in this area for mechanical design at that time. Kusiak [8] applied concurrent engineering concepts to evaluate design candidates for life-cycle issues. Sing and Gu[9] tallied life-cycle service costs to develop a serviceability index for products. Electricité de France [10] has begun to take maintainability into account in the early conceptual design stage by building upon a Failure Modes Effects and Criticality Analysis (FMECA) to develop the maintenance plan while finalizing the design.

Many of the design and maintainability prediction standards developed by the US military have since spread been adapted to other sectors such as telecommunications. These have been developed as Reliability Centered Maintenance (RCM) principles [11] wherein each and every preventative maintenance task, frequency, and time estimates are recorded. From this, a weighted mean of the expected preventative maintenance effort is determined.

1.2 Objectives

The main purpose of this work was to develop an evaluation scheme that can be used at all design stages and focuses on the evaluation of life-cycle performance such as maintainability. The focus of this work would be placed on incorporating these issues into the evaluation scheme. The scheme would allow the designer to use uncertain data in the evaluation process while providing an indication of the risk associated with each solution evaluated. More importantly, it will provide the designer with a measure of the solutions' fulfillment of customer needs including maintainability requirements. It will also provide guidance to the designer by indicating which aspects of a design will have the most influence on customer satisfaction. By following this process, successful products can be developed.

This paper is organized as follows. Section 2 discusses the design evaluation method. Section 3 describes a case study. The discussions and conclusions are given in Section 4.

2. Design Evaluation Method

Designs are evaluated based upon the ability of the product to meet the needs and expectations of the customers. Evaluating designs directly based on customer needs can be very difficult because of the subjective terms in which the needs are often described. In order to maintain their meaning and importance the needs must remain as described by the customer. Customer needs are related to the design objectives through clearly defined specifications that consist of two parts: metrics and values. Designs are thus evaluated directly through these metrics, which in turn related back to an overall product rating by how well they meet the customer needs. Performances of different aspects of each design are evaluated against desired metric values. Weighting factors are applied to each need and metric to reflect their importance and influence in evaluating the design.

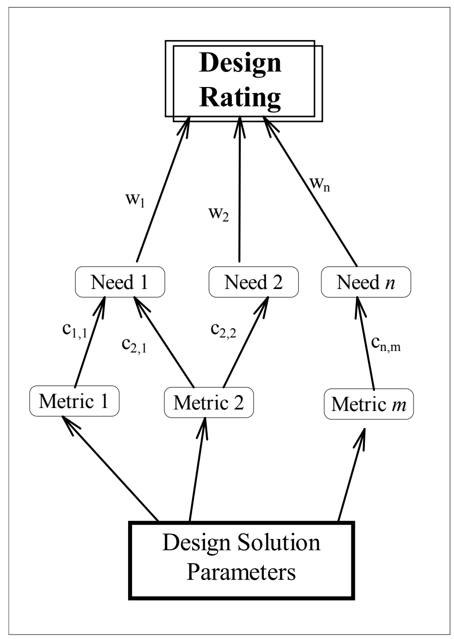


Figure 1 Design Evaluation Structure

2.1 Establishing Customer Needs

Needs can be established from market surveys, research, previous design experience or benchmarking excises. Since it is the customer who is the final judge of product quality, it is their perceived fulfillment and the importance of each need that indicates whether a particular design is good or better than another one. Designs will be evaluated for fulfillment by evaluating individual needs separately. To determine an overall rating of the design, these individual ratings are then combined. Since needs are of varying importance their achievement should influence the quality of the design accordingly. Individual needs are first weighted accordingly and then added together to achieve the overall ranking of the design.

In order to accurately determine the importance that a customer places on a specific need, the rating should come from the customers themselves. This presents a problem, in that a certain degree of expertise is required in order to establish appropriate weights or ranks. Saaty [12] has developed a system called the Analytic Hierarchy Process (AHP) that estimates weights for a set of constraints from pair-wise comparisons of each constraint. By evaluating the relative difference in importance between two individual needs, a comparison of needs is performed. Comparisons, provided by the consumer, are stored in an n by n matrix (**A**), where n is the number of needs. Components of **A** are the individual relative comparisons (a_{ij}). These relative comparisons are approximations of the overall comparison of needs on a wider scaling.

A value ranging from 1 to 9 is used to describe the relative importance of one need over another. The higher the value the more important the need. Since the same need is equally important as itself, $a_{ii}=1$, and values on one half of the diagonal are the inverse of the reverse comparison only $(n^2-n)/2$ comparisons need to be performed. These values can be expressed in the following relationship.

$$AW=\lambda W \quad (1)$$

Non-zero vector W which is a solution to Equation 1 above is an eigenvector for the corresponding eigen value λ. Individual weights, w_i, representing importance of the needs are components of the vector W. The weights (w) calculated are re-scaled (w') so that the sum of the eigen vector components is equal to 1. Each weight is re-scaled by an equal factor so that the resulting distribution represents the weights established using AHP. The largest weight is the most important and therefore takes the maximum value.

2.2 Development of Evaluation Metrics

Metrics are used to translate customer needs into measurable entities. Ideally, metrics are developed to rephrase customer requirements into quantifiable terms. They are often an agglomeration of various design parameters, information and constraints. Metrics are developed and selected by the design team to capture the intent of the need in quantifiable terms. This is a difficult task and seldom will a single metric be capable of fulfilling this role. A solution to this problem is to use several metrics to capture the customer's need. This is especially true for complex needs. However, care must be taken to select metrics that measure different characteristics. Selecting multiple metrics, which measure the same behavior, can lead to a false sense of developing an accurate evaluation scheme.

Metrics developed can be used in all stages of the design process and design evaluations. However, at each stage, the method used to calculate the metric may change to reflect the accuracy or amount of information available. Metrics should be dependent parameters rather than independent design variables. They are not required to be objective but they must associate a value with a design attribute.

2.2.1 Correlating Metrics to Needs

Once the metrics are developed, the next step in the design process is to determine how well a metric measures a need and to establish the relative influences of multiple metrics. This is a subjective process that should be performed by the same group that originally established the metrics. Individual weights are assigned for each metric corresponding to a need. A weighting factor, called a correlating factor (c_{ij}), is used to quantify the degree to which metric i is capable of measuring need j between 0 and 1. A high value indicates a metric is more capable of measuring a need. Only objective needs, which have one-to-one relationship with that metric, can have a correlating factor of 1.

After initially assigning correlation factors, their sum for a particular need may be greater than one, appearing that some needs are over-represented. However, this is not an unrealistic occurrence as there may be some overlap in the metrics selected. Correlating factors for that need must be re-scaled such that sum is equal to one.

2.3 Solution Specifications

When it comes to evaluating design concepts, the solutions will be considers as a collection of individual parameters each of which are an indication of the overall performance and quality of the system. Individually, these parameters may impact the behavior of one or more metrics. Equally, one or more of these parameters may influence a metric. Metrics capture the behavior of the entire system as described by the parameters.

2.3.1 Establishing Metric Specifications

Solution parameters, through the metrics, reveal customer expected performance, design requirements and constraints. Traditionally, these criteria are represented by crisp sets and are considered as "go/no-go" values. For example, if a performance criteria states that mass must be $\leq$ 20 kg, a solution is acceptable if its weight is 19.5 kg. This cannot reflect the fact that a solution that weighs 17 kg may be more desirable, since both fully meet the criteria. A second problem is that it suggests there is an exact or clear requirement that this object must meet. It can actually hide the real intent of the requirements. Buried in the requirements might be uncertainty of needs, randomness in interfacing systems and margins of safety, none of which have a clear delineation.

These two problems with traditional specifications can be captured through the use of fuzzy sets. Membership in these fuzzy sets is the degree to which a particular value is known to completely satisfy the customer expectations. The concept of utility shares this main idea that satisfaction of specifications does not result in a fixed payoff regardless of the performance [13]. Unilateral constraints are assumed for this discussion. Bilateral constraints or nominal target values can be handled by applying a second unilateral constraint of the opposite direction. Two values are required to specify these specification fuzzy sets as shown in Figure 2. These are the minimum (or maximum) *acceptable* value and the *ideal* value.

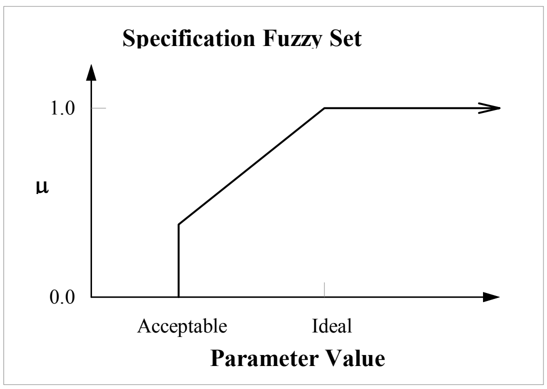


Figure 2 Metric Specification

Acceptable values are determined similar to traditional specifications. They should however, not include any hidden margins for safety or uncertainty. Instead, uncertainty is captured by the extent to which achieving that value will satisfy the design requirements. This is the membership that the target value has in the fuzzy set of meeting the specification. If there is a high degree of potential dissatisfaction with the *acceptable* value then it will have a low membership value or *confidence value*. However, if the requirement is concrete, it will have a high membership value. Any value outside the specification is still assumed to be unacceptable and has a membership of $\mu = 0$.

An *ideal performance* value, on the other hand, is one where any further improvement in the design does not provide increased benefit or more satisfaction to the customer. Increasing the capacity beyond this point does not provide any further benefit. In terms of fuzzy sets, the *ideal* value would have a membership of μ=1 meaning that it completely meets the expectations.

2.3.2 Estimating Solution Performance

Evaluation of each metric is performed using uncertain data, which can be portrayed in a variety of probability distributions. Variability in this information results from probabilistic data such as failure rates and uncertainty from future costs or incomplete knowledge. A simple linear distribution is selected to show this evaluation concept. Each parameter is assigned a *lowest*, *highest* and *nominal* expected value, as shown in Figure 3.

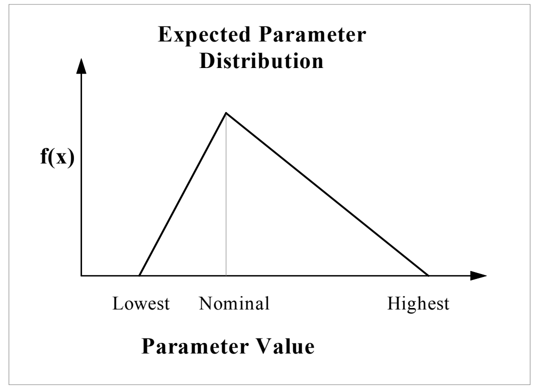


Figure 3 Parameter Probability Distribution

2.3.3 Evaluating Metrics

The product of the parameter value probability distribution and the specification fuzzy set indicates the expectation of the design to meet the metric's expectations. An individual rating is obtained by integrating this new distribution then dividing by the integral of the original parameter distribution. A metric ranking of one indicates complete confidence that expectations will be fully met. If there is any chance the design does not meet the acceptable or ideal values, this ranking will be reduced.

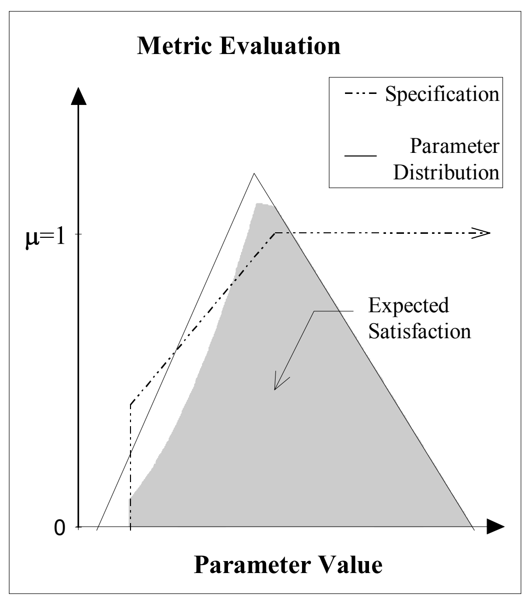


Figure 4 Metric Satisfaction Distribution

The shaded region in Figure 4 shows the distribution representing satisfaction of the metric. This product is evaluated directly for each parameter. The fraction of the distribution remaining is referred to as metric expected satisfaction (E_i).

$$E_i = \frac{\int \mu(x) \cdot f(x)dx}{\int f(x)dx} \tag{2}$$

Where: $u(x)$ is the metric specification.
$f(x)$ is the parameter distribution.

2.3.4 Sensitizing Evaluations

In certain applications it may be desirable to make the evaluation more sensitive to differences in parameter performance. Equipment that is part of a safety system, has a competitive market place or might lead to personal injury or property damage may influence this desire. Taguchi's concept of loss factor [14] is the basis for this adjustment. Under robust design methodologies, a loss factor is calculated which is usually assumed to be proportional to the deviance from the desired performance to the second power. This factor is applied to the calculation of each metric ranking where N is determined by the design team and is dependent on the criticality of the system. Robust rankings (E_i^N) are used in the evaluation scheme in place of the metric ranking (E_i).

2.3.5 Solution Evaluation

After each metric is evaluated, ratings for individual needs are calculated by multiplying the metric ratings against the metric-to-need correlation factors. All ratings for an individual need are then added together. Because a need may not be fully captured by the metrics, the maximum rating of all needs may be less than the number of needs leading to the maximum design rating being less than one. To standardize the results, the accumulative ratings are divided by the maximum attainable rating. A maximum attainable rating is determined in a similar manner by assuming a fully attained metric ranking of one. Following these steps, the overall design ratings are determined. A high rating indicates that a design is expected to perform well.

$$Rating = \frac{\sum_i \left[w'_i \times \sum_j \left(c'_{i,j} \times E_i^N \right) \right]}{\sum_i \left(w'_i \cdot \sum_j c'_{i,j} \right)} \tag{3}$$

Where: $c'_{i,j}$ are the re-scaled correlation factors.
w'_i are the re-scaled weightings of need importance.
E_i is the robust expected metric satisfaction.
N is the loss factor exponent
i is a customer need.
j is an evaluation metric.

2.3.6 Evaluation Risk

After completing the evaluation we do not know the risk of the design not performing as expected. Design evaluation risk is assumed to come from two sources. The first is the inability of the design to meet the performance requirements. If the probability distribution of the metric value shows that the design metric value may be outside the ideal value range, there is a risk that a customer may have some degree of dissatisfaction. The second type of risk is introduced by shortcomings in the evaluation scheme. These shortcomings arise from the difficulty to establish metrics that completely represent customer needs.

Risk that the design will not perform as required is determined by calculating the effect of the design not completely satisfying the customer needs. The process is similar to determination of the overall ranking. The first step is to determine the size of the complement set of the specification fuzzy set and metric probability distribution. The next step is to normalize this subset to the size of the metric value probability distribution. Risks for each need are then calculated using the same correlation factors as used in determining the rankings. Finally, the effect of failing to meet each need is multiplied by the appropriate weighting factor and the values added to determine the overall risk associated with failing to meet the customer needs. This rating is not normalized to the maximum rating as was done to evaluate the design since the incomplete representation of a need is a source of the risk.

$$Risk_{Solution} = \sum_i \left\{ w'_i \times \sum_j \left[c'_{i,j} \times \left(1 - E_i \right) \right] \right\} \tag{4}$$

A measure of the risk from errors in the evaluation scheme is based on information already used in the evaluation. Metric satisfaction is determined in the same manner as was done to obtain the overall rating. However, new correlation error factors are used to determine the risk of misinterpreting the metric values. These correlation error factors ($c''_{i,j}$) are derived from the original correlation factors. To calculate the new value, raise the amount the metric was originally unable to fully capture the intent of the need to the power of the number of metrics influencing the need it correlates.

$$c''_{i,j} = (1 - c_{i,j})^{\mathrm{n}} \tag{5}$$

Where: $c_{i,j}$ are original correlation factors, n is number of metrics correlating need i.

The evaluation scheme risk then becomes:

$$Risk_{Evaluation} = \sum_i \left\{ w_i' \times \sum_j \left[c_{i,j}'' \times \left(1 - E_i\right)\right]\right\} \quad (6)$$

Where: E_i is the expected metric satisfaction.

Finally, the two forms of risk must be combined to provide an estimate of the overall design solution risk. The approach taken here is to combine the risk geometrically. Alternatively, different weighting factors can be applied to each source of risk if one term was found to dominate. Knowing the rating of each design solution and the risk that the design may under-perform, the design team can make informed selection of which solution or solutions they wish to continue to develop.

$$Total\ Risk = Risk_{Solution}^2 + Risk_{Evaluation}^2 \quad (7)$$

2.4 Maintainability Evaluation

Maintainability metrics are generally complex because they utilize multiple design parameters to form the metric. It is desirable that the metrics developed in this section should be used to measure the maintainability of a design at any stage of the design process. Methods used to calculate the value of each metric may change as the available information improves. But the metric will continue to measure the same characteristics of the design and use the same type of information.

2.4.1 Parameter Uncertainty

Solution parameters are used to determine the value of metrics, however, they also have inherent uncertainty. The extent of the uncertainty is partially dependent on the stage of the design. However even for in-service products the parameters affecting maintainability may have some uncertainty. To accurately represent the expected performance of each design, these uncertainties need to be incorporated into the calculation of metrics at every design evaluation stage.

Each parameter used to calculate the metrics developed in this section is represented by a probability distribution. A similar representation, as used for describing expected parameters, has been selected to represent the probability distribution, which is easy for the designer to implement and to understand. For each parameter, a *best estimate* is given along with *high* and *low* bounds to that estimate. It is assumed that the most likely value is the *best estimate*. The *high* and *low* bounds are very unlikely values and the probability that it is somewhere between these values varies linearly between these points and the *best estimate* value. The Monte Carlo simulation is used to calculate each metric using these parameter probability distributions. Using random samples of the parameter values to evaluate the metric a new distribution is determined.

2.4.2 Metrics

Many of the metrics established below are activity based. Activity based valuation techniques gained popularity in recent years through the use of Activity Based Costing (ABC). These approaches are commonly applied today to many types of resources and services. Emblemsvage and Bras [15] present an ABC based approach for design of product retirement.

<u>Cost of Parts</u>

The cost of parts required during the lifetime of the product can have a direct influence on customer satisfaction. Costs of individual parts are determined by multiplying the number of service actions requiring a part replacement, which will be called up during the lifetime of the product by the cost of the parts being replaced. This estimate is repeated for each service action and the costs are totaled. The total cost is then a measure of expected total costs of parts during the product lifetime.

During the conceptual design evaluation, expected service frequencies need to be determined following a failure mode analysis (FMA). Other information necessary to evaluate the metric includes the costs of the parts and expected life of the product. Uncertainty of parameter values used to calculate part costs exists. However, there are always uncertainty associated with the required service frequencies and part costs.

<u>Maintenance Effort</u>

Maintenance actions may require that a number of maintenance tasks be performed to complete the action. Accumulation of maintenance task times describes the amount of effort required to complete a maintenance action.

Measures of expected maintenance effort can be described in terms of cost or person-time units (i.e. maintainer hours). Estimates for times required by different work forces and their rates to perform each task are the basis for the effort. These parameters are then applied at the frequencies called for by each maintenance action to calculate the net maintenance effort. Because multiple maintenance actions may be required for a component, they are the basis for the evaluation and their contribution depends on the expected frequency of occurrence.

Service actions were identified and frequencies of each estimated by performing an FMA. Each service action was then subdivided into tasks that require different resources to complete. The maintenance effort is then the accumulation of individual action efforts during the specified period of time. Effort can be calculated for any period of interest by determining the number of expected occurrences of each service during that period. Using this approach an average cost of maintenance can be reported for each period.

Planned Service Effort

Some designs may require that specific service actions be performed on a routine basis because of uncontrollable external influences. These high demands on specific service actions can have a large influence on the maintainability of the product and the customer's perception of quality. Designs that minimize this service effort required will be of better quality to the customer.

Generally, service costs are calculated by first determining which components may require servicing during the lifetime of the product. However, in this instance, the service action frequency is dictated. Because of the importance of this action, extra effort should be placed into accurately determining estimates for each task comprising the service action.

Again, the number of person-hours should first be calculated, then by applying the rates for the appropriate maintainer, an estimate of the costs are calculated. When calculating service costs, it is possible to include costs of any materials or parts needed to perform the maintenance action.

Maintenance Overhead Costs

Tools and other support equipment will likely be needed to perform most maintenance actions. Additionally, training may be required before maintainers are able to perform the necessary service actions. To estimate the new overhead costs, one should begin by comparing which tools and training *may* be needed to those that are available. Those items or skills that may be required but are not available to the customer are identified and recorded. Then, by applying the probability that an item will be required and its probable cost, an expected cost for new tools, equipment and training can be established. This value will become the design evaluation's expected parameter value.

3. Case Study

This case study example evaluates the ability of three alternative conceptual designs to satisfying the maintainability and performance needs of the customer. Such a design task would be initiated following the identification of a void in the market place or a customer request. In this case study, a hypothetical design team was assigned the task of designing a hand operated pressurized bottle filling system identified during a market study. As this paper focuses on the design evaluation, the design concept generation is not discussed. However, the three design solutions show in Figures 5-7 were generated and are evaluated in the following sections.

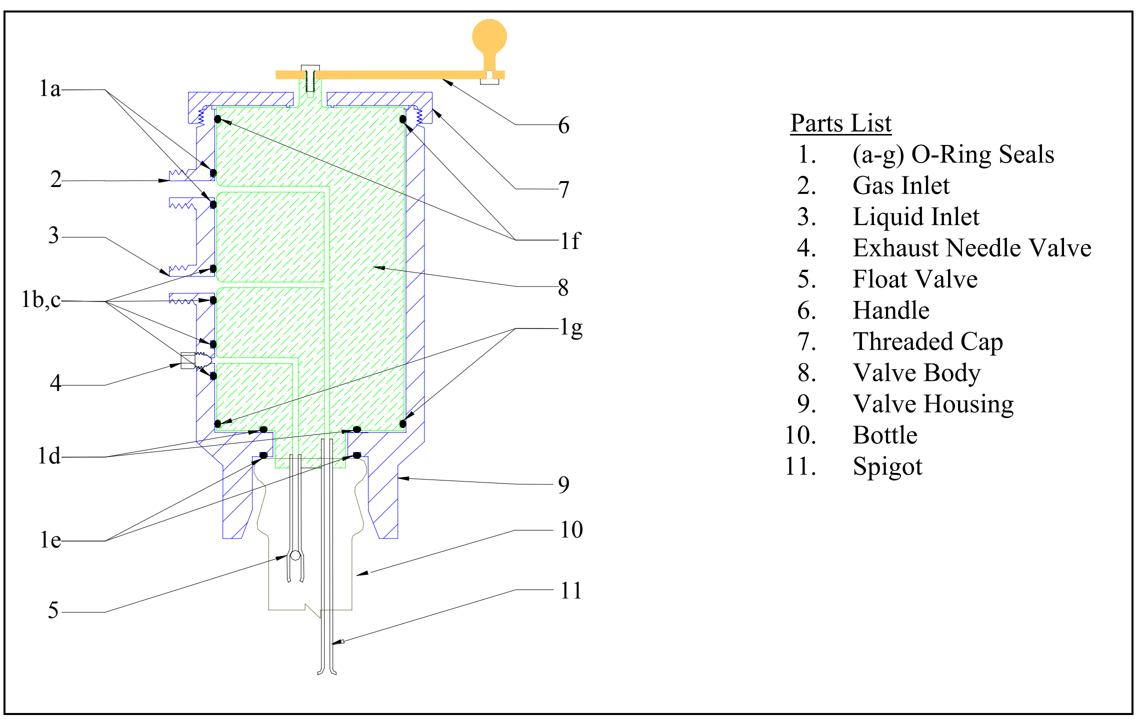
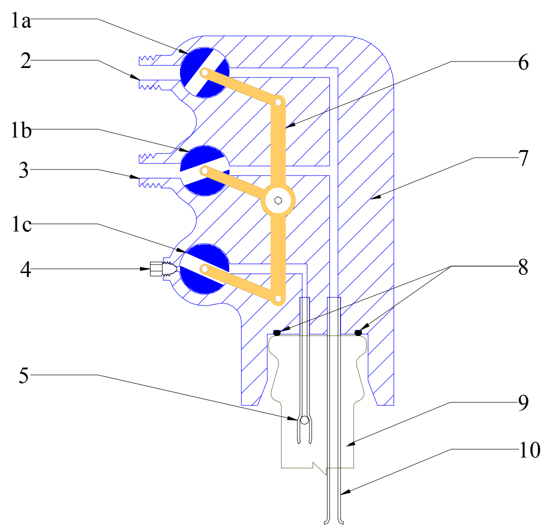
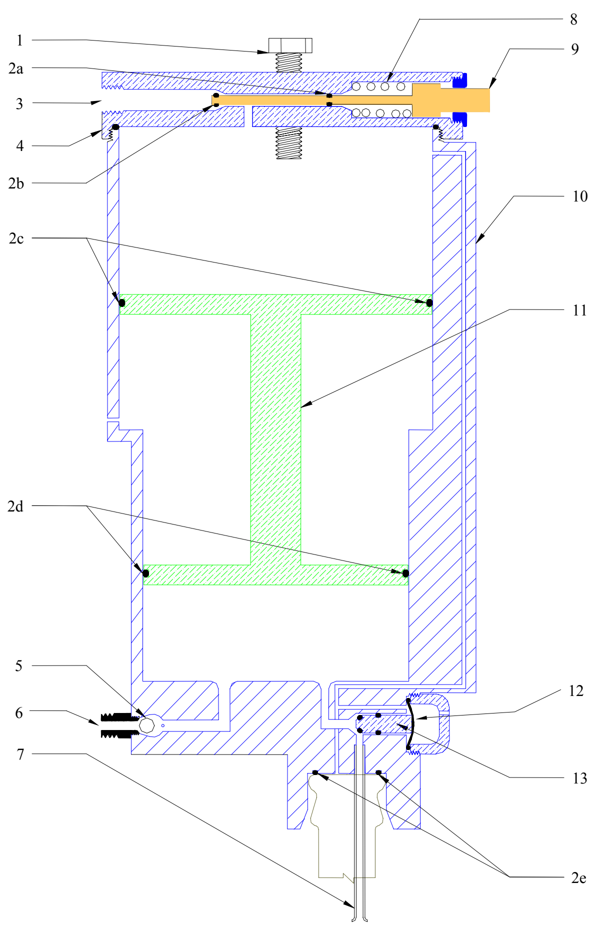


Figure 5 Case Study Design Concept 1



Parts List
1. (a,b,c) Valves
2. Gas Inlet
3. Liquid Inlet
4. Exhaust Needle Valve
5. Float Valve
6. Crank
7. Valve Body
8. O-Ring Seal
9. Bottle
10. Spigot

Figure 6 Case Study Design Concept 2



Parts List
1. Limiting Screw
2. (a-d) O-Ring Seals
3. Gas Inlet
4. Valve Cap
5. Check Valve
6. Liquid Inlet
7. Spigot
8. Actuator Spring
9. Actuator Valve
10. Valve Chamber
11. Displacement Piston
12. Diaphragm
13. Regulator Valve

Figure 7 Case Study Design Concept 3

3.1 Design Candidates

Concept 1 is a cylindrical multi-port valve. A full operation cycle is achieved by rotating the valve 360°. Gas and liquid lines feed into the outer valve housing. The central spool aligns with these intakes as the operator turns the valve into the appropriate stage. A seal is created between the container and valve. Both a liquid in-line and gas line, which allows flow in both directions, extend into the container. A buoyant ball seal on the gas line in the container prevents liquid from overfilling the bottle and entering the valve.

In the second concept, three valves control the flow of materials. Each valve is connected to maintain the same relative orientation to the others by turning one valve. Sequencing of the opening and closing of valves is accomplished by correct phasing of the difference in valve orientation.

The third concept works on a much different concept from the other two. In this concept, the pressurized gas is used to create a positive displacement pneumatic pump to fill the bottles. In this concept, one valve is manipulated by the operator to displace the liquid in the chamber. It acts as a relay for a gas-operated valve that controls liquid leaving the pump and entering the container. A third valve is a one-way valve that allows liquid to enter the pump chamber but prevents it from returning to the supply. By pushing the valve the operator would actuate the piston pushing the liquid into the bottle. Releasing the valve de-pressurizes the container.

3.2 Customer Needs

Customer needs were collected. Listed in random order these are:

a) Hand-Held Operation.
b) Liquid is not wasted.
c) Simple to clean.
d) Can fill a variety of container sizes.
e) Easy to maintain.
f) Always fill containers to the right amount.
g) Quick and simple to use.
h) Doesn't change the quality of the product.

A pair-wise comparison of the each need, rating the relative importance of two needs, was performed for the needs established in the previous section. The relative importance (a_{ij}) of each need was recorded in the table below representing the comparison matrix (**A**). Twenty-eight comparisons were required to complete the table shown below.

Table 1 Needs Pair-wise Comparison

	a	b	c	d	e	f	g	h
a	1	3	2	7	5	3	5	2
b	1/3	1	1/5	3	1/3	2	3	1/5
c	1/2	5	1	7	4	6	5	2
d	1/7	1/3	1/7	1	1/3	3	1/4	1/6
e	1/5	3	1/4	3	1	3	3	1/3
f	1/3	1/2	1/6	1/3	1/3	1	1/3	1/5
g	1/5	1/3	1/5	4	1/3	3	1	1/4
h	1/2	5	1/2	6	3	5	4	1

After completing the pair-wise comparison, the eigenvector and eigenvalue of the relationship were calculated and re-scaled to obtain the following weights and importance ranking.

Table 2 Ranking of Needs

	Need	W'
a	Hand-Held Operation	0.275
c	Simple to clean	0.248
h	Doesn't change the quality of the product	0.118
e	Easy to maintain	0.096
b	Liquid is not wasted	0.069
g	Quick and simple to use	0.056
d	Can fill a variety of container sizes	0.035
f	Always fill containers to the right amount	0.034

3.3 Selection of Metrics and Correlations to Needs

Thirteen metrics were selected to measure the customer's needs. The first four address the customer's maintainability requirements. The thirteen metrics are:

- Time required to clean
- Annual Labour effort required to maintain
- Annual expected parts cost
- Overhead costs (training & equipment)
- Weight of device in service
- Number of hands required to operate
- Amount of liquid spilled in 100 fills
- Amount of liquid lost in the system
- Volume of foam released in 100 fills
- Maximum Volume container
- Minimum Volume container
- Repeatability of filling
- Time to complete one cycle

3.4 Correlating Metrics to Needs

In Table 3, the metrics are correlated to the needs.

Table 3 Correlation of Metrics to Needs

Need	metric	Weight of device in service	Number of hand positions to hold &/or operate	Amount of liquid spilled in 100 fills	Amount of liquid lost in the system	Volume of foam released in 100 fills	Time required to clean	Maximum Volume container	Minimum Volume container	Annual Labour effort required to maintain	Annual expected parts cost	Overhead costs (training&equipment)	Repeatability of filling	Time to complete one cycle	sum
		1	2	3	4	5	6	7	8	9	10	11	12	13	
Hand-Held Operation	a	0.6	0.4												1
Liquid is not wasted	b			0.5	0.3	0.2									1
Simple to clean.	c						0.8								0.8
Can fill a variety of container sizes.	d							0.5	0.5						1
Easy to maintain	e									0.5	0.3	0.3			1
Always fill containers to the right amount	f												0.8		0.8
Quick and simple to use	g		0.3				0.4							0.4	1
Doesn't change the quality of the product.	h					0.8									0.8
sum		0.6	0.7	0.5	0.3	1	1.2	0.5	0.5	0.5	0.3	0.3	0.8	0.4	7.4

After initially assigning correlation factors, their sum for a particular need may be greater than one, appearing that some needs are over-represented. However, this is not an unrealistic occurrence as there may be some overlap in the metrics selected. Correlating factors for that need must be re-scaled such that sum is equal to one. Sometimes, because of the challenge in developing metrics, the sum of correlating factors may be less than one, indicating that the need is not completely represented by the selected metrics. If this under-representation is significant (<0.6), a new metric should be developed. In this case study, the lowest numbers are 0.8 (the last column of Table 3).

3.5 Metric Specifications

Performance expectations for designs are listed below. They describe the contribution to design rating for different values of a metric using the fuzzy set concepts.

Table 4 Metric Specifications

#	Acceptable Value	Confidence Level	Ideal Value	Units
1	3	0.6	0.8	kg
2	4	0.5	1	#
3	250	0.6	50	ml
4	100	0.7	10	ml
5	1200	0.6	200	ml
6	75	0.8	7	hr
7	750	0.6	2000	ml
8	150	0.8	75	ml
9	5	0.5	0.5	hr
10	40	0.3	5	$
11	100	0.4	25	$
12	15	0.5	5	±%
13	20	0.8	5	s

3.6 Solution Parameters

Maintainability metrics 6, 9, 10 and 11 use a number of different parameters to determine the maintainability metric's resulting distribution. Parameters for these metrics are represented by the simplified probability distributions. For each failure mode, the action and its tasks and costs are were collected. Task times and costs are the parameters used in the evaluation.

Table 5 Concept 1 Solution Parameters

Metric	Low Estimate	Best Estimate	High Estimate	Units
1	0.8	1.7	2.5	kg
2	2	2	3	#
3	25	75	400	ml
4	10	25	75	ml
5	300	800	1500	ml
7	2000	2500	3000	ml
8	25	50	100	ml
12	5	15	20	±%
13	10	18	30	s

Table 6 Concept 2 Solution Parameters

Metric	Low Estimate	Best Estimate	High Estimate	Units
1	0.7	1.5	2	kg
2	2	3	4	#
3	75	125	150	ml
4	25	50	100	ml
5	300	800	1500	ml
7	2000	2500	3000	ml
8	25	50	100	ml
12	5	15	20	±%
13	10	18	30	s

Table 7 Concept 3 Solution Parameters

Metric	Low Estimate	Best Estimate	High Estimate	Units
1	1.5	2.2	4	kg
2	1	2	2	#
3	75	150	300	ml
4	25	60	120	ml
5	250	350	700	ml
7	600	1000	1200	ml
8	25	50	75	ml
12	4	7	10	±%
13	6	12	18	s

3.7 Evaluation Results

The expected satisfaction of metrics of each concept was calculated using the methods described in Sections 2.3.3 and 2.3.4. Metrics 6, 9, 10 and 11 were determined using a stochastic simulation with a sample size of 1000 for each metric using the approach of Section 2.4.1. The calculated robust metric satisfaction is provided in **Table 9**.

Expected satisfaction of each metric was used to determine fulfillment of the concepts' needs using the correlating factors. Finally, the weights representing the relative importance of needs were applied to determine the ranking for the three concepts. The risk associated with the uncertainty in each design concept and potential errors in the evaluation scheme was also calculated. Concept 3 was selected for further development.

Table 8 Concept Ratings

	Solution Rating	Risk Rating
Concept 1	0.67	0.18
Concept 2	0.57	0.10
Concept 3	0.71	0.08

4. Discussions and Conclusions

This paper reported a method for evaluation of conceptual designs and maintainability incorporating uncertainties. The fuzzy logic was employed to handle the uncertainty and the evaluation risk was also determined for the designers to select design solution. A set of maintainability metrics was used in design evaluation. Predictions of product maintainability were incorporated into the evaluation scheme through the development of several specialized metrics. These metrics combined multiple maintenance and product parameters generally including failure rates to estimate a maintainability characteristic. A simple distribution was used to describe each uncertain parameter.

The case study also showed how uncertain information could be used to evaluate alternative design solutions for fulfillment of customer expectations and maintainability related issues. Parameter probability distributions were compared against fuzzy sets, which represent acceptable metric values, to determine the expected metric satisfaction rating. Each metric rating was then used to calculate satisfaction of various customers' needs so that an overall rating of the design could be determined. Risk from two separate sources was determined in a similar manner.

The evaluation resulted in the identification of one concept for further development based on its superior rating and lower risk. Aspects requiring the most attention can be identified based on their relative influence on the product rating. The influential parameters can be reviewed on a metric or needs basis. This information could then be used by the designer to identify the most promising design solutions for further development based on the overall rating and risk calculated for each solution.

Table 9 Robust Metric Satisfaction Evaluations

Metric	1	2	3	4	5	6	7	8	9	10	11	12	13
Concept 1	0.79	0.72	0.63	0.89	0.62	0.81	1.00	1.00	0.79	0.79	0.72	0.38	0.41
Concept 2	0.87	0.61	0.84	0.81	0.62	0.33	1.00	0.99	0.82	0.82	0.88	0.38	0.42
Concept 3	0.50	0.89	0.67	0.73	0.90	0.81	0.55	1.00	0.75	0.75	0.97	0.88	0.89

Acknowledgement

This research was supported by the National Science and Engineering Research Council of Canada (NSERC) and the Atomic Energy Canada Ltd. through the Industrial Research Chair grants.

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