

Composite Design and Manufacturing Critiquing System

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1.0 Introduction

A critiquing system supplies the user with a critique of submitted material. The critique allows that the user submitted material may contain strengths and weaknesses as well as failures to conform to various criteria. The criteria used in the critique may vary in terms of both the aspect being appraised and the importance of the particular appraisal. The Composite Design and Manufacturing Critiquing System (CDMCS) that is currently under development begins with these premises. The system is being built to aid designers in evaluating the incorporation of composite materials into their designs. The current focal point of the system is on process selection, but the system is being designed to incorporate other components of process planning. The system also incorporates the idea that in the design and decision making phase of projects concerning relatively new technology, both the data and the evaluation criteria (metrics) are “spread” or “fuzzy.” The data and criteria are spread or fuzzy in the sense that there are ranges of values that can lead to the satisfaction of a criterion and that those ranges tend to decay away from a clear central point. For example, one might allow that a particular process is acceptable in the range of 100 to 10,000 units, but 5,000 units is a good target number. This might be further qualified by noting that the acceptability of the process falls off quickly as one moves further from the target number. This represents the expert’s knowledge of the system. On the other hand, the end user might know that the expected production range is from 3,000 to 6,000 units. There are, of course, other criteria and data to take into account. Although the system under development aggregates the various degrees of satisfaction of the various criteria, the aggregate value is only taken as a global indicator. The system is designed to provide the user with an account of the strengths and weaknesses of the relation between his or her data and the criteria and make specific suggestions concerning how the aggregate value can be improved by indicating which data items can be changed and how they can be changed to bring them more in line with a target case. In brief, The CDMCS takes a “fuzzy” multi-metric approach to the critique of process plan decisions and provides the user with an explanatory account of the strengths and weaknesses of his or her proposal as well as hints on the data areas that should be examined more closely and the types of changes that would lead the proposal to be more in line with the expert’s knowledge of the target values for the process.

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1.1 Issues

Traditional expert systems efforts within AI have concentrated either on giving advice to an end-user or replacing the end-user. In the former case the knowledge in the system is used to guide the actions of the end-user, while in the latter case the knowledge of the expert, as captured in the system, is deemed of such a high quality that there is no need for the end-user to do any further processing. Another effort within traditional AI has been the construction of intelligent tutoring systems. In this research enterprise, the domain knowledge of the expert, as captured within the system, is used to train the end-user about a particular domain. Typically, the end-user is presented with scenarios on which he or she acts. The actions taken are recorded and compared to what the expert would have done, on the basis of that comparison errors are identified and explained, and the end-user is presented another scenario to improve his or her training level. Each of these AI approaches has value. However, in many situations neither approach is satisfactory. The experts system enterprise often fails to take into account multiple, “fuzzy” criteria for assessing the “goodness” of a solution, and often focuses its explanations on the line of reasoning that the system engaged. The intelligent tutoring enterprise is only concerned with the learning of the end-user and does not readily take into account that the end-user knows some things about the domain. These two weakness can be seen clearly when the task to which the AI system is put is an evaluative task. In such tasks the question is neither “Can a solution to a problem be found?” nor “Can the individual be trained to produce solutions?” Rather in an evaluative task the question is “How can a proposed solution be appraised?” This question calls for a strategy different than that found in the traditional expert systems and intelligent tutoring approaches. Systems that are designed to answer the appraisal question are critiquing systems.

Critiquing systems assume that the end-user knows something, and, perhaps a great deal, about the domain. It also assumes that the end-user has some notion of a solution to his or her problem, and that he or she can provide some data on which a solution is based. From the point of view of the critiquing system, the problem is to use the data to appraise the solution in terms of various appraisal criteria and provide the user with a report on the “goodness” of the proposed solution. This report identifies and explains weaknesses and strengths, and indicates where and how improvements may be made.

1.2 Approach

Appraisals involve the use of criteria by which the “goodness” of an item is determined. We understand the “goodness” of an item to be measured in terms of the degree to which some criterion is satisfied. These criteria are called metrics since they are measures of goodness. In some cases such metrics may be very clear and not admitting of degrees. Such metrics will be called requisite metrics. Requisite metrics correspond to the idea of necessary conditions in more traditional forms of analysis. Thus, if the requisite metrics are not satisfied, then the item is rejected. Additionally there are core metrics. These metrics are essential to the appraisal, but admit of degrees of satisfaction. These degrees of satisfaction are a measure of the “goodness” of an item, given the satisfaction of the requisite metrics. Finally, there are enabling metrics that can alter the basic “goodness” as measured by the core metrics in small ways. Together these three types of metrics are used to appraise an item. It should be clear that these metrics can

be numerous and an aggregate appraisal is required in addition to the appraisal of an individual metric.

The key element for the computation of an appraisal is the idea of satisfaction. Satisfaction is the measure of the degree to which some data item is contained in a metric. In the sense in which we are using the term, satisfaction can be described as follows:

the item I satisfies the metric M to the degree D just in case

- (1) the M applies to I
- (2) there is some function F_I that generates D from I and M

In aggregation the notion of satisfaction is extended to multiple metrics as follows:

a collection of metrics $\{M\}$ relative to a process P has an aggregate value V just in case

- (1) there are a set of metrics $\{M\}$ defined for the process P
- (2) the metric M_i of $\{M\}$ is satisfied to the degree D_i according to the previous definition
- (2) the metrics in $\{M\}$ are categorized as requisite, core, and enabling
- (3) if any requisite or core metric in $\{M\}$ has a value of 0, then the aggregate value is 0; otherwise
- (4) the aggregate value $V = V_{Core} + V_{Enabling}$ where
 V_{Core} is given by a function F_C that sums the values of the core metrics,
and
 $V_{Enabling}$ is given by a function F_E that adds or subtracts
incremental values relative to V_{Core} .

Clearly the key to the critique of a proposal in a multi-metric system is the construction of the functions F_I , F_C , and F_E . It should be noted that the evaluation process continues even in cases where an evaluation has a requisite or core value of 0. This allows for fuller reporting and explanation, and provides the end-user with additional alternatives for action. For example, a requisite metric might be violated which would lead to a 0 value, but the remainder of the evaluation might lead to a high level of "goodness." In this case, the end-user might be able to alter the input so as to satisfy the requisite metric for the proposed process.

1.3 Domain description

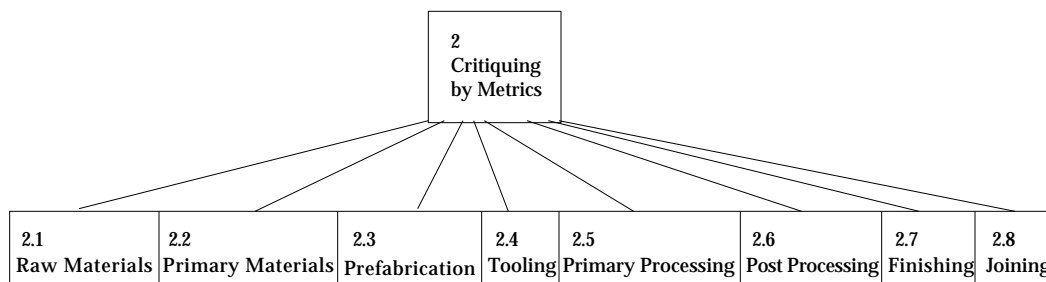
A composite material is a combination of two or more different materials, differing in form or composition on a macro scale; that is, a heterogeneous solid where the components maintain their characteristic structure and properties. Composites are often favored when weight savings are critical (due to their high strength to weight ratio), and when one homogeneous material cannot meet the design requirements.

There are many forms of composite materials and several methods of classification. One method of classification divides composites into three categories: laminar (such as plywood), particulate (such as concrete), and fiber-reinforced (such as automobile tires). Fiber-reinforced composites are the most prevalent type of composite material for engineering applications, and are the focus of this research, along with lamination of fiber reinforced sheets. These composites are formed from reinforcing elements, fillers, and a matrix phase. The composite material possesses a unique combination of

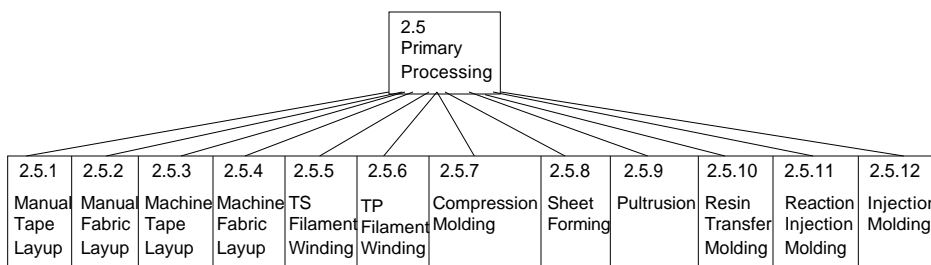
properties, such as stiffness, strength, weight, that depend on the materials used as the binder, the volume fraction of reinforcing elements contained in the matrix, and the orientation of these reinforcing elements.

Matrix phase materials are often some type of polymer, although metal and ceramic matrix composites are emerging as leaders for high operating temperature applications. Only polymer based composites, such as epoxy resins, are being considered in the critiquing system. Common reinforcing materials for these polymer composites include glass, boron, aramid, graphite, and carbon fibers. Innovative uses of polymer based composites can be found in sporting and recreation equipment such as golf clubs and tennis rackets (epoxy matrix/graphite fibers), boats (polyester/glass fibers), fishing rods (epoxy/carbon and glass fibers). Polymer based composites have also found successful application in space and missile systems, and aircraft components as was evidenced in the Voyager aircraft, of which nearly 90% is made from graphite fibers.

The design process for composite parts is different from that used with a homogenous material. If a part is to be manufactured using a metal, the material can be chosen for its properties (i.e., strength, electrical conductivity, corrosion resistance) and then a manufacturing process can be chosen. Composites manufacturing can be viewed as a material transformation process composed of a sequence of stages, as illustrated in the figure below. These decisions are interrelated; decisions made concerning the manufacturing process must take into account matrix material, fiber reinforcement, and fiber volume.



The selection of raw material, the configuration of this raw material, and the choice of a primary processing method are tightly coupled decisions impacting the producibility of the part. The stages are illustrated in the diagram above.

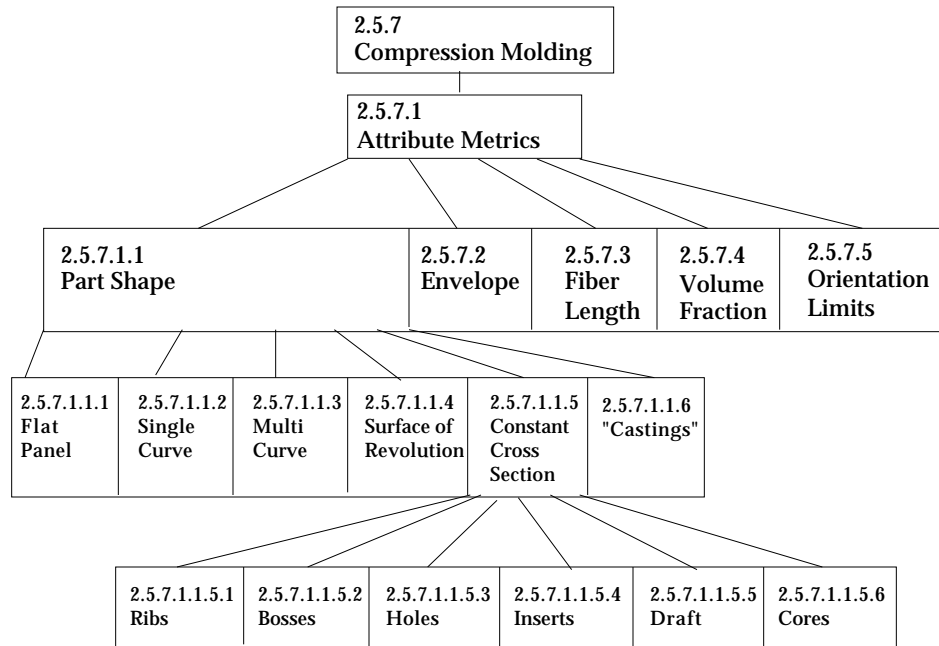


The current focal point of our efforts, illustrated above, is section 2.5, the primary processing.

Currently there are 12 primary processes under consideration. The end-user selects one of these as his or her first candidate for a process to manufacture the part. The system is intended to be of use during both design and manufacture. To accommodate this, the basic ideas of the critiquing systems are extended to include multiple levels of default information. This

default information is noted by the system and is specially noted in the explanation of the aggregate value.

The diagram to the right illustrates a lower level breakout of the metrics for one of the primary processes. It is at this level that the metrics are classified as requisite, core, and enabling. It should also be noted that some of the metrics have a more Boolean character (ribs or holes) while others may be “fuzzy” (envelope or volume fraction). Individual determinations of satisfaction are performed at the lowest metric level and aggregation proceeds from the bottom to the top for the relevant metrics. The critique that is produced identifies the strengths and weaknesses of the proposed plan, indicates areas of special attention, and calls attention to assumption made through default values.



2.0 Overall design strategy: Data, information, knowledge

The data components of the system include the following:

- definitions of terms
- specifications of particular metrics
- specification of the metrics relevant to the process including their classification as requisite, core, and enhancing
- user supplied parameter data for the metrics

There are four general data components: definitions, metrics, process classifications, and parameter data.

2.1 Definitions

The definitions of terms are the data items that contain the information relating to the terms that are used in the system. The definitions include text descriptions of the meanings of the terms, references, associated pictures, and associated terms. The information in the definition and optional picture are provided by the expert, and additional text may be added by the end-user. The reference indicates the source for the definition. These are separate files that are associated with the definition of the particular term. Associated terms, supplied by the expert, are also provided with the definition. These associated terms are “hot links” that allow the end user to jump to the definition of other terms.

2.2 Parameters

Parameters are supplied by the user. The parameter data include a central value, a range, and a decay. The central value represents the user's best belief about the value of the parameter. The range represents the bound of the user's belief. The decay represents how rapidly the user's confidence diminishes as the bound is approached. Parameters have associated default values that are presented to the user in a spreadsheet-like template which the end-user may then alter to reflect his or her particular case. Term definitions are directly accessed through this interface and some data entry validation is performed.

2.3 Metrics

Metric data describes a particular metric. A particular metric may be used in the evaluation of more than one process. The metrics are the smallest units of the evaluation and critiquing process. The metric has a name and family name; the name is the name of the metric itself while the family name indicates the general family to which this particular metric is attached. Additionally the metric specifies the parameters that it uses and the frontier of acceptability (which may be numerical or Boolean). The satisfaction of a metric is determined by the metric data, the parameter data, and the computations to be described below. The satisfaction is stored with the metric definition. This ensures that any functions that need access to the satisfaction value of the metric will always receive the same value.

2.4 Processes

Process data describes the particular processes that the systems knows. These process descriptions indicate the relevant metrics and their status as requisite, core, or enabling. Process specific default values can be specified for the parameters in cases where these should override the general parameter defaults. Additional information about the process may also be included in the description. This additional information may concern certain key elements about the process that should be examined more closely, and other information not directly contained in the metrics that may make a process undesirable. These latter elements may be related to particular industries, types of contracts, or other circumstances that are relevant but external to the appraisal of the process selection. They are stored as text information and are for user information purposes only. Process evaluation is not effected by these elements.

2.5 Classification and description

The process classification is associated with a particular process. The classification groups the metrics that are relevant to the particular process, and these are designated as requisite, core, or enabling for that process. The requisite metrics express Boolean characteristics. The failure to meet the requisite metrics is enough to demonstrate that the process ought not to be used; however, processing of the complete metric set is carried-out to provide a complete appraisal of the selected process. Once the requisite metrics are evaluated, the core and enabling metrics are evaluated. Core and enabling metrics have continuous numeric values or qualitative values that can be translated into numeric ranges. Due to this numeric quality, partial metric satisfaction is possible. The core metrics are those metrics that are essential for the process assuming that requisite metrics are satisfied. The calculation of the aggregate value for these metrics is described below. The aggregate value of the core metrics is modified by the values of the enabling metrics. The classification of the metrics is given by the expert.

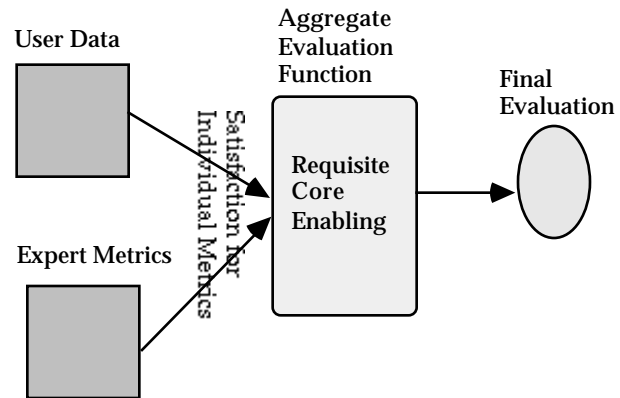
3.0 Computations: Satisfaction and aggregation

The core computational components include the following;

- computational mechanisms for the determination of the degree of satisfaction of a particular metric
- computational mechanisms for aggregating the values of the particular metrics relevant to their classification as requisite, core, and enhancing.

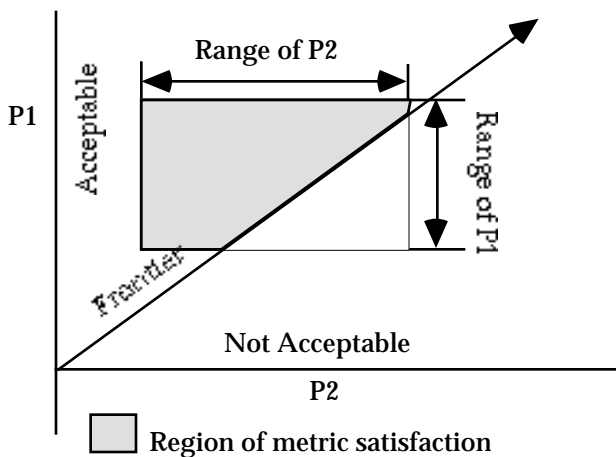
3.1 Guiding principles

The degree of satisfaction and the aggregation of individual metric satisfactions will be computed for each relevant metric based on the expert's definition of the metric and end-user supplied data. The determination of the aggregate value is a function of both the user input data and the expert's understanding of the metrics. The end-user will not alter the metrics. The diagram to the right is a graphical presentation of this. The degree of satisfaction will be in the range of 0-1.



This is trivially satisfied in the case of the requisite metrics. The evaluation of the individual metrics, whether core or enabling, preserve this range. The metrics relevant to the process will be evaluated in terms of the rules relevant to their classification as requisite, core, and enhancing. This allows for the possibility that other types of metrics consistent with the general system could be added at a later date.

3.2 Satisfaction



The satisfaction of a particular metric is a function of the frontier boundary defined by the expert and the "fuzzy" data supplied by the user. The determination of the degree of satisfaction is a probabilistic calculation of the degree to which the user defined data would not exceed the frontier. (See diagram at left) The region of metric satisfaction provides the range of the calculation process. The satisfaction calculation is a numerical integration over the intersection surface (shown as region of metric satisfaction in the diagram) of the parameter definition(s) and the

metric feasibility range. This is required because the parameters decay over the area. The metric satisfaction integral has the form for the two-dimensional case

$$\int_{Surface} W(x, y) P_x(x) P_y(y) M(x, y) dx dy$$

and for the one-dimensional case

$$W(x) P(x) M(x) dx$$

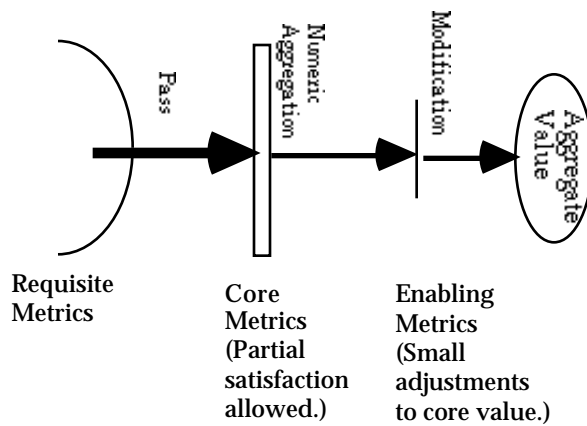
where

W is a unitizing weighting function
 P is the corresponding decay function for each parameter
 and M is the Metric Satisfaction Decline function.

The integration process produces the satisfaction value in the range of 0-1

3.3 Aggregation

Aggregating the values of the particular metrics relevant to their classification as requisite, core, and enhancing.



Aggregating the value of the metrics is a multi-step process. (Illustrated to the left) In the first step the requisite conditions are treated similar to a logical conjunction of Boolean arguments. Requisite conditions are those conditions that must be satisfied crisply, if the process is acceptable. The calculation in this case is straight forward. Next, two things are considered. Some metrics are core metrics and others are enabling metrics. Core metrics, like the requisite metrics, must also be satisfied

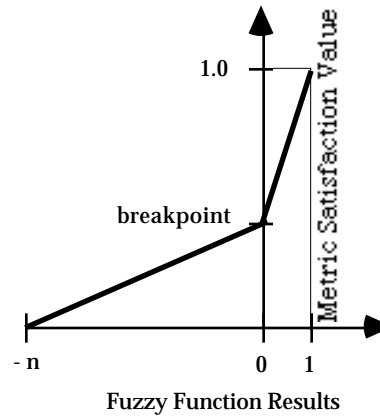
but partial satisfaction is allowed. The distinction between the core and enabling metrics is fairly clear. The core metrics determine a base evaluation and the enabling metrics serve to modify this value slightly. While this might be accomplished by a weighting system, it seems reasonable to add the evaluation of the enabling metrics as a separate step. It is the composite value of the aggregate of the core and enabling metrics when compared to various threshold values that are determined by the expert that determines the acceptability of the process on the user-supplied data.

3.4 Rules of computation

The rule for the collection of requisite metrics is a Boolean conjunction rule. The value of the core and enabling metrics are computed according to a “breakpoint strategy” and the values of the enhancing metrics are used to modify the aggregate core value.

An individual core metric’s satisfaction value is evaluated using a specifically designed aggregate “fuzzy function”. This function is constructed as a two level step polynomial function and is designed to return a value between 1 and -n (where n is the number of metrics evaluated for a specific process). The division between the first level and the second is known as the “breakpoint” of the metric. This break point represents the point at which a metric is assumed to become unlikely to be satisfied. Each metric can have its own unique breakpoint as is determined by how important “absolute satisfaction” of the metric is necessary for overall process satisfaction. The distance of the metric satisfaction from the breakpoint as a percentage of the domain length for the appropriate level of the step function is calculated, and used as input to the fuzzy function.

Graphical Representation of Fuzzy Function



Domain Length Percentage Calculation:

$$\begin{array}{l} \text{Domain} \\ \text{Length} \\ \text{Percentage} \end{array} = \begin{array}{l} \boxed{\text{(Metric Satisfaction - Breakpoint) / (1 - Breakpoint)}} \\ \text{OR} \\ \boxed{\text{(Breakpoint - Metric Satisfaction) / Breakpoint}} \end{array}$$

Like core metrics, individual enabling metric satisfaction values are calculated by a polynomial fuzzy function utilizing a break-point strategy. However, the range for these metrics is not -n to 1, but rather a much more confined region such as -0.2 to 0.2. The purpose of these metrics is to only slightly modify the over-all aggregate score of the process evaluation, not to allow or disallow a process from consideration.

The overall aggregated results are found by simply averaging the individual metric fuzzy function evaluations. This value is then used to directly map to a qualified result such as “good”, “fair”, etc. It is assumed that every core metric must be satisfied (at least to some degree); therefore any metric that is not satisfied to at least some minimum degree should strongly adverse the overall aggregate value. This explains the necessity of the two level function. The first function as a promoter of satisfaction among the aggregate, and the second as a promoter of dissatisfaction. The difference in the functional range for each of the levels can be explained by noting that if a single core metric fails (or nearly fails), then the entire aggregate score should be reduced to failure. The multiplier of n provides this effect.

4.0 Interface issues

The computer interface for the critiquing system is divided into two components. One component is the domain expert's interface, the other is the end user's interface. The former is essentially an editing and import facility that allows the expert to enter the definitional material and the parameter, metric, and process information. The expert user's interface is designed to allow the expert to present to the end-user what he or she wants represented. Hence, the expert establishes the structure for the parameters and their default values, and establishes the metrics and the status of the metrics relative to a given process. Assuming that the domain expert has provided the necessary materials for the critiquing system, the end user interface should be able to apply this knowledge to the information provided by the end-user. Thus, the end-user interface should as far as possible allow the end user to freely enter his or her information and provide the end-user relevant information and examples of terms with which he or she would be unfamiliar.

4.1 Interface components

The components of the interface are designed to facilitate end-user interactions. For example, the main user interface for inserting parameter information is a spreadsheet-like interface. The spreadsheet presents the user with the default values for the relevant parameter. The user may obtain more information about these or alter any of the values. The output components of the interface use both graphics and textural descriptions to present the user with the systems critique. Graphical display are used to indicate metric satisfaction for individual metrics. Text is constructed for explanations of aggregate satisfaction, satisfaction of the individual metrics, specification of metrics that could be improved, and indications of special factors connected to the desired process. Additional text is constructed to provide hints on how an individual metric could be better satisfied.

4.2 Explanations and hints

PROCESS RATING: <Rating>
<Metric Family> Types of Discrepancies

Metric: <Metric-Name>
A value of <Required-Value> is required for the
<Parameter-Name> parameter. The specified value was
<Parameter-Value>. The process FAILED!"

Metric: <Parameter #1> Vs <Parameter #2>
The analysis of the metric proved that
the current parameter values satisfied
the metric by <Satisfaction>%. See detailed
information for further explanation.

The basic frame for explanation is illustrated to the left. The explanation is an account of why a particular evaluation has the result that it has. The explanation indicates the aggregate value for the proposed process, and the particular evaluations for the various metrics for that process grouped by metric type (geometric, economic, strength, etc.). The first metric frame indicates the type of construction that is used for a requisite

metric. The second frame indicates the construction for a 2-parameter core metric.

The basic frame for hints is illustrated to the right. The hint presents the current degree of satisfaction, and indicates whether an increase or decrease in the parameter's value would increase satisfaction. Additionally, the system indicates the range of the increase or decrease as a percentage of the current value that would have a positive effect on the metric's satisfaction.

Analysis of <Parameter #1> Vs <Parameter #2>:

The parameters currently have a probability of <satisfaction>% of satisfying the constraints of the Metric. Analysis indicates that if the parameters could be modified by <Increasing or decreasing> the value of <Parameter #1> by 0% to <limit #1>% and/or <Increasing or decreasing> the value of <Parameter #2> by 0% to <limit #2>%, the Metric satisfaction can be improved.

5.0 Conclusion and further research directions

Problems in which one can expect the end-user to be knowledgeable in a field and have proposals at hand are ideal candidates for critiquing systems. The user needs to have his or her proposal evaluated in a specific and informative manner. In cases where there are multiple "fuzzy" criteria, critiques are essential. This approach is ideally suited to the current domain. The end-users of CDMCS will be engineers that can be reasonably expected to be knowledgeable and have specific proposals that will need to be critiqued. The explanations and hints that are produced by the system allow the end-user to refine his or her proposal to more clearly satisfy the current metrics for the system. Additionally, the domain of composite materials is marked by many rules-of-thumb that allow for a great deal of variation. Typically there are values for certain parameters that the composite domain expert can identify as good values, but also acknowledges that some deviation from these values can still produce good values.

The system is being implemented in Macintosh™ Common LISP. This paper has described the features of the system that are currently implemented. The system is currently being extended to cover more than the primary process component of the domain. Additional work is under way. We plan to add hypertext links to the explanations and hints that will provide expanding levels of detail and related information. We also plan to provide an option to iterate across processes and explain why some other primary process may be more well-suited to his or her data.

The approach we have taken is a general one. It is not specifically about composite materials. In the future we intend to extend the system to provide a tool that will be of general use for any multi-metric critiquing problem.

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