The Engineering Design Discipline:
Is its Confounding Lexicon Hindering its Evolution?

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Abstract

In this paper, we invite the engineering design research community to examine the current state of the *engineering design lexicon*. We expose the nature and the persuasiveness of practices that may hinder intelligible discourse within the engineering design literature. In particular, we show how such commonly used terms as *criterion* and *metric* are used sometimes as synonyms and sometimes not, often leading to material miscommunications. In our view, the engineering design discipline has reached a point in its evolution where *clarity and conciseness of its lexicon* should be a priority. Today's design activity takes place in a truly multidisciplinary environment, which often involves engineers of divers backgrounds. Written and oral design discourse among design researchers does not rely on a generally accepted and documented lexicon. These situations are symptomatic of a communication infrastructure that is not effectively facilitating the vigorous evolution of the engineering design discipline of recent years. In addition to detailing the outlines of the design lexicon deficiency, we also propose some avenues to a constructive and productive community-wide discussion on this subject, including conducting open discussions at the web site: http://www.eng.buffalo.edu/Research/DBD. We hope that this effort will be a catalyst for the development of an engineering design dictionary that will enjoy broad acceptance within the design community. A developed design lexicon will form a critical foundational component of Decision-Based-Design, the central topic of this special issue.

1. Introduction

In recent years, the field of engineering design has experienced significant advances. The increased international economic competitiveness has caused government, industry, and academe to reassess their most traveled roads. Government agencies have increased research funding in design; most industries have at least begun reforming their approaches to engineering design and manufacturing; and educational institutions have, or are in the process of reforming their design curriculum – partly due to new ABET requirements and focus on synthesis-based design education. In tandem with these important new developments, long-time and recent design researchers are pushing the frontiers of engineering design, bringing rigor and scholarship to *a discipline* that had historically been perceived to be *more an art than a science*. Some will argue that it is a science, others will argue that it is both a science and an art, but few – if any – will argue that it is purely an art form.

References [1, 2] provide a comprehensive review of different research topics in engineering design, and of the significant progress made toward a better understanding of design and design tools. We believe that these recent activities and developments point to the importance of scientific research in engineering design, which is actually a new notion in need of careful analysis. In the pursuit of these goals, we aim to contribute to an aspect of engineering design, the engineering design lexicon, that we believe is of foundational importance. (We use the dictionary definition of the word *lexicon:* a special vocabulary of a science, discipline, etc.). The vigorous evolution of the field of engineering design of recent years has not proceeded in tandem with that of an equally maturing lexicon. In fact, the engineering design lexicon can be characterized as generally being in a state of unstructured evolution. Motivated by these observations, we present a critical analytical perspective of the state of the engineering design lexicon, and of its effect on the evolution of the engineering design discipline.

In this paper, we expose common confounding situations that routinely occur in our everyday use of the engineering design lexicon. The unfortunate reality is that we employ implicit or explicit definitions that may vary from author to author, in a given context; from paper to paper, for a given author; or even from paragraph to paragraph, in a given paper. For example, the state of the engineering design lexicon does not make a clear distinction between a *design metric* and an *objective function*. We pose the following questions: Does this alleged confounding state of the engineering design lexicon matter? And if it does, what is its effect, and how should the design community address it? We propose the notion that it does matter, and that it constitutes a hindrance to the continued scholarly development of the engineering design discipline.

As this less-than-mature discipline experiences the re-invigorated evolution that began in the recent past from both academic and industry perspectives, a more rigorous approach to the teaching and the practice of engineering design will play a constructive role. We note that the existence of a broadly accepted engineering design lexicon will not only benefit the engineering design discipline in general, but will also facilitate other specific activities, such as the development of engineering design taxonomies [3, 4]. We also note that the motivation for a mature design lexicon is rooted on practical considerations. Today's design activity takes place in a truly multidisciplinary environment, which often involves engineers of divers backgrounds.

As we consider the consequences of the present state of the engineering design lexicon, it is helpful to briefly examine the evolution of the English and French languages, and uncover some possible lessons. In the seventeenth century, the french king Louis XIV founded the French Academy, with the mandate of preserving, promoting and managing the evolution of the French language. The officials of the French Academy alone would make official decisions regarding the French language (*e.g.*, create and accept new words and new definitions). To this day, the evolution of the French language attempts to follow a relatively controlled path, often guided by governmental forces. In contrast, the evolution of the English language followed a more liberal path. Some might argue that these differences in evolutionary paths partially resulted in the larger vocabulary and in the more dynamic evolution of the English language, particularly in the technological area. Others, on the other hand, might argue that the technological richness of the English language is purely due to the world economic order of the post World War II era. Regardless of the degree of correctness of each of these views, most might agree that a healthy degree of *dynamism* and *freedom* will generally benefit the evolution of a language, or of a parochial technical lexicon as well. Although, we note that there are fundamental differences between the development of a language and that of a lexicon. In light of these comments, we explicitly discourage adopting the French Academy model.

While the above discussion argues for dynamism and freedom in the development of a lexicon, we note that for almost every mature technological area, there exists in tandem an equally mature lexicon – one that allows for and promotes concise and intelligible discourse. The field of engineering design is unfortunately not so blessed, as yet. In view of this possibly conflicting need for both *flexibility* and *conciseness*, we feel it appropriate that a design lexicon development effort be undertaken in a way that is not restrictive, but that nevertheless does promote and facilitate conciseness of discourse. Too restrictive a set of boundaries would be counterproductive by hindering the very evolution of the design discipline, while the absence of discernible delineations in word-definitions results in the inadequate design lexicon that exists today. We make the important note that such fields as economics and accountancy have recognized the need to develop their own lexicons, and have done so deliberately. Several dictionaries of economics and accounting terms exist; some resulting from ambitious efforts of significant scope intended to accomplish this end [5]. Interestingly, some of these dictionaries go beyond the typical dictionary format. The definitions of the terms are presented in an expansive fashion that elaborates on the contexts of the terms' use.

In engineering, the need to develop dictionaries for specific fields has been recognized in recent years. An example is the dictionary work being organized by CIRP (International Institution for Production Engineering Research [English translation]) to define terminologies in different fields of manufacturing (e.g., machining, forming, metrology, surface finishing) [6]. Other notable examples are found in Refs. [7-12]. We immediately note that these are generally conventional dictionaries that do not typically address design as a discipline. The English dictionary is inadequate with regard to design lexicon because the definitions are not meant to address engineering design. For example, most do not have an entry for *objective function*; and one that does provides a narrow definition. The definition of the word *objective* will have nothing to do with *objective function*, while the connection between these two terms is strong in the design lexicon.

We invite readers to examine the tenets of this paper, and to contribute to this lexicon development effort in their own distinct ways. To proceed along the path of lexicon development, several avenues can be conceived for broad community participation. The first and most obvious option is for design researchers to publish their own related views and findings in appropriate journals. We hope that active design researchers will form related collaborations that may result in written works that would reflect the broad related thinking in the community – a vital objective of this paper. Further discussion of the subject of proposed related community action is presented in Section 5. While we fully expect various credible views to be expressed in different forums, we hope that this effort will progressively lead to a discernible delineation of some form of community standard or consensus, leading to a set of definitions that will (over time) become more and more mature. In the long term, however, (as discussed in Section 5) a more deliberate, concerted, and intensive effort would be required to credibly address the issues presented in this paper.

We note that the immediate objective of the current paper is not to provide *answers*. Our interest here is to bring the tenet of this paper to the attention of the engineering design community, which is that *the engineering design lexicon is in need of guided scholarly evolution*. Furthermore, it will become evident to the reader that this paper is not meant to be a comprehensive presentation of the issues at hand. We limit the scope of this paper to *presenting* the essence of the problem, and proposing that substantive subsequent work follow. In sum, the primordial intent here is to *engage* the engineering design community, and to bring to light a critical foundational component of Decision-Based Design. To facilitate further dialogues, an open discussion forum has been set at the web site: http://www.eng.buffalo.edu/Research/DBD under "Lexicon".

This paper is organized as follows. Section 2 describes a table example that is used, as a simple artifact, to facilitate subsequent discussions. In Section 3, we provide a discussion of the many pitfalls that one would likely encounter in the common discourse among designers, in the context of designing this table. Section 4 provides a discussion pertaining to a broader set of terms. The outlines of solution approaches are presented in Section 5, and concluding remarks are given in Section 6.

2. Presentation of a Simple Design Example

In this section, we present a table design example (Fig. 1) that we use to facilitate the discussion of some commonly used confounding terms. The table is composed of a flat top and of four nominally identical cylindrically shaped legs. Only those configurations that conform to this geometrical definition are considered. The following information (or, should we say data?) is provided, as a list of <u>statements</u> (issues of interest).

<u>*Statement-i:*</u> (i = 1, ..., 9)

1) The designer has *direct control* over the numerical values of the table width, a, the table length, b, the table height, h, the table top thickness, t, the table leg diameters, d, the table-top extrusion-depth, s, and the table color, c.
2) The leg position, r, is *prescribed* to be equal to 0.1 meter.
3) The mass, m, *should* be *minimized*.
4) The deflection, d, that would result from the application of a force, F, of 100 kg, *should* be *minimized*.
5) The material-used is *prescribed*.
6) The table color, c, *should* be *dark*.
7) The table length, b, *must* be no more than twice its width, a.
8) The table length, b, *should* be as close to 1 meter as possible.
9) Other issues of interest to the designer are:

a) Esthetics (*e.g.*, color, corner radius).

b) Safety (*e.g.*, stability, strength, corner radius, leg buckling load).

c) Manufacturability (*e.g.,* ease of machining).

In the remainder of the paper, we refer to each of these above items as “*statement-i*”.

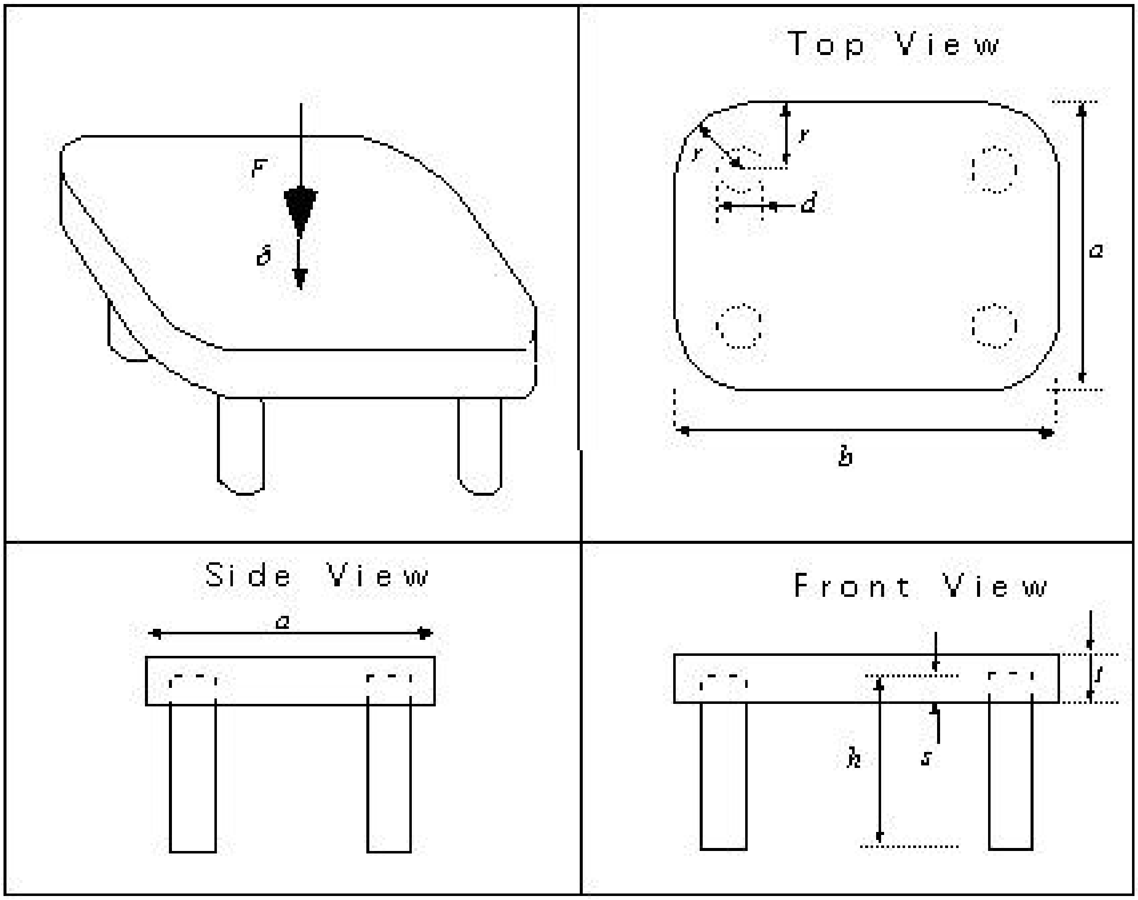

Figure 1. Table Example.

All other characteristics of the table are presumed given by the decision maker. In presenting the table characteristics, we have thus far avoided using such *terms* as *design parameter* or *design variable*. (Throughout the paper, we use the word “term” in both a singular and a collective sense, as allowed by the English language. In other words, we say that “design parameter” is a “term”.) As is observed, the design task above is not stated comprehensively. The table-design presentation only provides sufficient detail to allow for partial discussion of the design lexicon, which is the subject of this paper. Furthermore, some readers might credibly argue that the determination of the above *issues of interest* is itself a part of the design process. However, this potentially interesting discussion is beyond the scope of this paper.

3. Simple Design Example: Confounding Lexicon

In this section, we attempt to describe the design example presented in the previous section through common terms used by the design community. In so doing, we expose some of the difficulties that we typically face in design-related discourse. We find that it is not practical to present the issues in a *linear* fashion, whereby each new item would be analyzed solely in terms of those previously discussed. However, in as much as possible, we generally discuss the design terms in a progressive level of complexity. Sections 3.1 through 3.3 define sub-sections that take on as title a design term that is representative of the issues presented in that sub-section (i.e., Design Parameter, Design Metric, Aggregate vs. Single-Attribute Preference). In Sections 3.4 (Subjective vs. Objective Terms) and 3.5 (Soft vs. Hard Statement), we present helpful views on categorizing various terms.

3.1 Design Parameter

In this section, we discuss the terms that are directly related to what we often call a *design parameter*. We begin by noting that most designers would use statement-1 to designate *design parameters*. The width, a, the length, b, the height, h, the top thickness, t, the leg diameters, d, the table-top extrusion-depth, s, and color might all be called design parameters, with generally clear implied meanings. Some might call these same quantities *design variables*, again with generally clear meanings. Others, on the other hand, might refer to these quantities simply as *parameters*, or *variables* (short for design parameters and design variables, respectively). At this point, we observe that the terms design parameter, design variable, parameter, and variable are used as synonyms in ways that generally raise no questions, but should.

In the above context, a candidate definition for **design parameter** is: *a characteristic or property of an artifact or process, being designed, over which the designer has direct control; this characteristic or property is used by the designer with the expectation that the variation of its value might alter the value of one or more of its characteristics or properties that are used to evaluate this artifact or process; this quantity may be numerically or textually/linguistically valued*. In stating that the constant or quantity may be textually valued, we note that certain quantities used as design parameters might take on values that cannot be placed on the real axis in a self-evident (unique) manner. Color, for example, might be given the value *dark* or *light*, or might be quantified in three dimensions (*e.g.*, its red-blue-green components); and, in *fuzzy* terms, thickness might be given the value *very thin, thin, average, thick*, or *very thick*.

Upon examination of statement-2, many designers might declare the quantity, *r*, to be a *constant* or a *parameter,* or possibly a *constant parameter*. We note that the terms *parameter* and *design parameter* are often treated as being equivalent. If we adopt the above definition for the term design parameter, then we might ask if the quantity, *r*, is a design parameter. If the designer does have *direct control* over the value of *r*, (in order to fix it to the prescribed value) then we may call it a design parameter. If, on the other hand, the quantity, *r,* is regarded as being out of the direct control of the designer and is thought of as being equal to the prescribed value that will not change during the design process, then we might say that it is not a design parameter. According to the candidate definition of design parameter stated above, a quantity is a design parameter if it is varied during the design process in an effort to satisfy designer preference. Similarly, from statement-5, “material-used” is not a design parameter, if it is not actively varied during the design process. Some might call it a parameter that is textually/linguistically valued (the name of the material); but few might call it a constant, which is typically numerically valued (should this always be assumed?). It might also be useful to establish a hierarchy of terms. For example, a set of definitions that the design community produces might state that (i) all design parameters can become constants, but not the reverse; and (ii) all constraints are requirements, but not the reverse (see Sec. 3.2). The message here is that, as a community, we currently do not have definitive answers to the above questions. Furthermore, the previous discussion strongly suggests that creating a coherent set of definitions for the numerous common and less-common terms used in engineering design will likely be an intensive undertaking that will require careful thinking.

We now address the term performance parameter, which is entirely distinct in meaning from the term design parameter. In some writings, the term parameter is used as a synonym of the term performance parameter. As a result, when we read that a quantity is a parameter, we might not be sure if the designer has direct control over its value in the design process (*i.e.*, design parameter); or if the designer has indirect control over its value, and it will be used to evaluate the design (*i.e.*, performance parameter). In a different vein, the term constant can be a source of confusion. We often treat a *constant* as a quantity that does not normally change in the design process. At least, we do not expect a constant to be changed in the same fashion that we expect a design parameter to change. We then ask the question: What is the difference between a *variable*, a *constant*, a *parameter*, or a *constant parameter*? The words constant and variable are often used as antonyms, the words constant and parameter are sometimes used as synonyms, but the words variable and parameter are often used as synonyms, thereby resulting in arbitrariness and confusion. If these three words (*variable*, *constant*, and *parameter*) were defined in a consistent way, one would expect a large degree of *transitivity* in their collective meanings. In addition, we sometimes distinguish between the words variable and constant with regard to time-dependence and time-independence, respectively. However, when time is not involved in the process, this distinction offers no guidance.

In an effort to minimize confusion, we sometimes used the term dependent or independent to precede the words variable and parameter. In particular, we use the term independent parameter (or independent variable) to indicate that the designer has independent control over the value of this *parameter* or *variable*. When used in this way, it is still not clear whether an independent parameter is always used as a design parameter. Actually, we know that the converse is not true. Design parameters are not always independent; very often in optimization, design parameters are not independent from one another (*i.e.*, the presence of constraints). In addition, we know that the mass, *m*, and the deflection, *d*, are dependent parameters (they depend on design parameters, see *statements 3* and *4*). Again, should we assume that dependent parameters are always used to evaluate designs, as are design metrics (discussed later), which might make dependent parameter and design metric synonyms.

The theme of this subsection revolved around the term design parameter, of which we have provided a candidate definition for the mere purpose of facilitating the current discussion. We have also discussed important issues concerning the terms *parameter, variable, constant, constant parameter, design parameter, design variable,* and *independent parameter*. We conclude this sub-section by bringing attention to the following relevant terms*: decision parameter, input parameter, process parameter, tuning parameter, exogenous parameter,* *random parameter, tolerance parameter, noise parameter, fuzzy parameter, uncertainty parameter, state variable.* We note that we may replace in each of the previous terms the word *parameter* by the word *variable*. We finally ask the reader to think of what s/he believes the definition of these terms to be; and as importantly, if s/he feels the design community has adequately defined these terms. The previous discussion leads us to the consideration of a class of terms that are functionally dependent on *design parameters*.

3.2 Design Metric

We now introduce the issues that pertain to the term *design metric*. From the table example defined in Section 2, many designers might declare several characteristics of the table to be **design metrics**, such as the mass, *m*, and the deflection, *d*, (see *statements* 3, and 4). Let's now note three prominent characteristics of these two quantities: (i) they can be functionally expressed in terms of design parameters, (ii) they are used to evaluate the behavior or performance of the design, and (iii) they are measurable.

In light of the above discussion, a candidate definition for **design metric** is: *a characteristic or property of an artifact or process, being designed, that is used to evaluate its performance; such characteristics are measurable, and are dependent on one or more design parameters*. Note that we exclude the possibility that a design metric would not depend on a design parameter. In such a situation, the designer would have no way of controlling the value of the design metric, and the design process would be ill-defined. At a minimum, the design metric should itself be a design parameter to allow for the requisite control of the design metric by the designer.

According to the above definition, mass, *m*, deflection, *d*, and color, *c*, would be design metrics. Note however that color, *c*, could not be uniquely ordered because it is measured as a three-dimensional quantity (*i.e.,* its Red-Blue-Green components) that needs human decision before it can be mapped to a one-dimensional space, which is needed for unique ordering. For all design metrics, we simply require that we be provided a *measure* of their values, *while no human preference is yet expressed*. According to *statements* 2 through 9, leg position, mass, deflection, material used, color, length, width, esthetics, safety, and manufacturability would all be design metrics. Accordingly, a means to *measure* color, esthetics, safety, and manufacturability would have to be provided in order for the designer to have the ability to evaluate their impact on the design.

We now proceed to pose some important questions related to the term design metric. Is it appropriate to use an array of other terms to describe the quantities that we have declared to be design metric in the previous paragraph? In particular, may we also call these quantities *attributes*, *behavior parameters*, *behavior variables*, *costs*, *criteria*, *exogenous parameters, figures-of-merit, goals, merit functions, objectives, objective functions, performance functions, performance metrics, performance parameters, performance variables, specifications, utility functions* (von Neumann [13]), *preference functions, output parameters*, *output variables, target, expectation,* etc.? It is our view that the answer is *no*. To facilitate intelligible discourse, we propose the notion that it is important for the engineering design community to know (or decide what is) the difference between such words as *criterion, goal, target* and *objective*; between *requirement, specification*, and *constraint*; between *preference function* and *utility function*; and between *design metric* and *performance parameter*. In some cases, the difference might be negligible or immaterial, while in others the difference will lead to miscommunications. The important point here is that, as a community, we have no widely accepted and reliable point of reference.

The lexicon we use should make it possible to clearly differentiate between (i) the mass, *m*, and (ii) statement-3 [The mass, *m*, should be minimized]. The former is void of all human preference, and is simply used to evaluate performance (without yet saying how). The latter is not only saying that mass will be used to evaluate performance, but is also saying how (namely that a lower value of mass will be preferred over a higher value thereof.) The lexicon should make an entirely clear distinction between the former and the latter. Our common use of the many terms above (previous paragraph) fails us in that regard. As a possibility, we might call the former a *design metric*, and the latter an *objective*; but not the converse. As the state of the design lexicon stands today, when we read the word *objective*, we cannot be quite sure whether the writer is referring to the former (*mass*, itself) or to the latter (*minimize mass*, as a subjective statement of preference).

Let's now examine the differences between such terms as *constraint, specification, requirement, criterion, goal,* and *objective* by considering the table example *statements*. To begin with, these authors express the view that the above five terms should refer to <u>statements of preference</u> regarding characteristics or properties of the design or process, and not to these characteristics or properties themselves (*e.g.*, to *statement-3*, and rather than to mass, *m*). Many might refer to *statements-2, 5,* and *7* as a *constraints* or *specifications*. The typical understanding is that, if *constraints* or *specifications* are not met, then the design is not acceptable/feasible. On the other hand, *statements-3, 4,* and *6* might be declared to be *objectives*, or *goals*. These statements merely define events that should happen *as much as possible*, with the understanding that these events will in general not be fully satisfied. Partial satisfaction of these events still results in an acceptable/feasible design.

In the literature, the words *objective*, *criteria*, and *goal* are typically used as synonyms. English dictionary definitions, however, would suggest that these words are not always synonymous. The words *constraint* and *criterion* are also sometimes used as synonyms. (In the hierarchy of these words, we might say that a constraint is always a criterion, but that the converse is not necessarily true (?) [Please note the question mark!]) The important point here is that there is no referential authoritative source on which we can rely, noting that the English dictionary is glaringly inadequate with regard to the design lexicon, and that <u>general design dictionaries have yet to be developed by the community</u>. In the same vein, regarding the word criterion, the plural form, *criteria*, is often used when the singular form, *criterion*, should be used. The American Heritage Dictionary [8] tells us under the definition of *criterion* – usage – "*Criteria* is a plural form only. It should not be substituted for the singular *criterion*." Some dictionaries focus more on the engineering terms [7-12]. One might assume that they might form a good source for design term definitions. While they do offer adequate definitions for such terms as *shaft*, some do not define, or incomprehensively, define, other important terms (e.g., *objective function*). For example, Ref. [7] defines objective function in terms of the limited scope of structural optimization.

In a similar vein, the word **attribute** has not quite found its appropriate place in the engineering design lexicon. From its English dictionary meaning, it seems that every *characteristic* or *property* of an artifact or process is one of its *attributes*. As such, we could call every design parameter and every design metric an *attribute* of the artifact or process. Furthermore, it seems self-evident that every design must be *multi-attribute*. Often, the term multi-attribute is used where other designers use the terms multi-objective and multi-criteria. While every design parameter and design metric is an attribute of the design, not every attribute must be a design parameter or a design metric. For example, the smoothness of the table surface (Fig. 1) is an attribute of the design, but is not a design parameter (by choice), nor is it a design metric (again by choice).

We also point to the fact that the term multi-attribute refers to the attributes of the design (*e.g.*, mass, color), while the terms multi-objective points to the objectives that are associated with these attributes. While (as stated above) every practical design is multi-attribute, not every design need be multi-objective. One could design a product that would have the sole objective of *making money for the designer legally*. The same product design might also become multi-objective by proposing that as many employees be hired as possible (possibly for altruistic reasons). In light of the above discussion, it does not seem appropriate to use the terms multi-attribute, multi-objective, and multi-criteria interchangeably. Use of the term *multi-attribute utility function*, on the other hand, seems to entail no ambiguity [15]. This term refers to the fact that several attributes (not objectives) of the design are used to create a utility function (which expresses the designer's objectives).

3.3 Aggregate vs. Single-Attribute Preference

This sub-section presents a discussion that leads to some questions regarding the use of the term *aggregate objective function*. Let's begin by considering the meaning of certain common terms in the context of optimization and utility function development [13, 16]. The application of utility to engineering design is presented in [16], where the role of decision-making in engineering design (**Decision-Based Design**) is addressed. If we form functions that will be minimized using an optimization model to account for statements 3, 4, and 8, such functions might take the form:

For statement-3 $$f_m = \alpha_m m^2 \tag{1}$$

For statement-4 $$f_\delta = \alpha_\delta \delta^2 \tag{2}$$

For statement-8 $$f_b = \alpha_b \left(b - 1\right)^2 \tag{3}$$

where α_m, α_δ, and α_b are weighting factors.

The actual function to be minimized might take the form

$$\begin{aligned} J &= f_m + f_\delta + f_b \\ &= \alpha_m m^2 + \alpha_\delta \delta^2 + \alpha_b \left(b - 1\right)^2 \end{aligned} \tag{4}$$

We now pose related questions. Should the functions f_m, f_δ, and f_b be *called objectives, objective functions, costs, goals, cost functions, criteria, design metrics, behavior parameters, performance parameters, performance functions, performance metrics, figures-of-merit, merit functions, preference functions, value, value functions, utilities,* or *utility functions*? One could say that some of these terms are more appropriate, in the subject context. However, if one accepts the definition of the term design metric, previously provided, then using the term design metric to describe the subject functions would be inappropriate. Furthermore, the unfortunate reality is that most of the above terms are often used interchangeably, in ways that are not particularly clear to most (including these authors). The rationale for differentiating between these terms is generally unclear, if at all existent. And as the state of the engineering design lexicon stands today, no definitive clarifying reference exists.

Similarly, regarding the function J above, the following question can be posed. Should we refer to J as *an objective, an objective function, an aggregate objective function, a preference* *function, an aggregate preference function, a utility function, a multi-attribute utility function, a design metric (!), a merit function, a cost, a cost function, a value, a value function, a measure,* or *a metric*? We feel that it should be possible to succinctly distinguish between the function that pertains to one attribute (*e.g.*, f_{m}, for mass, m) and the function that expresses the multi-objective (aggregate) preference, J. Unfortunately, interchangeable use of the above terms does not allow for this desirable distinction. For example, when we simply say objective function, it is not clear which applies (does it apply to a single objective, or to several?) Similarly, when we read the word *objective,* it might refer to mass, m, to f_{m}, or to J. In many cases this lack of linguistic clarity might be immaterial, but in other important cases it might.

We conclude this subsection with some comments regarding the terms *multi-objective, multi-criteria,* and *multi-attribute*. It seems that, since we say multi-objective (singular form of objective), we should also say multi-criterion (singular form of criterion). Multi, when used as a prefix, does not render the original word plural. This is why we say multi-objective, and not multi-objectives. Furthermore, if the words *multi-objective, multi-criteria,* and *multi-attribute* are declared synonyms, then by implication, the words *objective, criterion,* and *attribute* would also be synonyms. However, as discussed above, the implied equivalence of these terms should be regarded with dubiosity.

Along the same line of thought, several researchers have decided to use exclusively the term multi-attribute. We note, however, that it is the number of design metrics (more than one) that one generally wishes to bring attention to, since every design is multi-attribute. This observation would lead to the term *multi-design-metric,* or *multi-metric*. However, since most practical designs are performed using more than one design metric, in general there seems to be little reason to be reminded of it. Also, the term *multi-objective* implies that the word *objective* (when invoked alone) is used in the context of *one* design metric, creating the need of say *multi* (in the case of more than one objective). Yet, we routinely use the term *objective function* to mean multi-metric (aggregate) preference function. This is an inconsistent use of the term *objective*. This is one of many reasons why it would promote good communication to use the term *aggregate* as a prefix to *objective function* or *preference function* [17, 18] when we invoke the *multi-metric* sense.

3.4 Subjective vs. Objective Terms

(Terms Related to Human Preference vs. Terms Objectively Measurable)

In an attempt to define more clearly the many terms that describe the objective state of the design and the related subjective preference of the designer [15], we might find it helpful to classify some design terms with regards to this objectivism and subjectivism. In particular, we all agree that the mass, *m*, of the table is an *objective* measure of the amount of mass comprised in the table, and that the length, *b*, of the table – too – is an *objective* measure of one of the table's characteristics. The numerical values associated with the table's mass and length do not reflect the designer's subjective preference. These quantities might be referred to as *features*, *characteristics*, or *attributes* of the table. And if we accept previously provided definitions, the mass could also be referred to as a design metric (since it is used to evaluate the table's performance), and the length could be referred to as a design parameter (since the designer has direct control of its value). Since these quantities provide no information regarding the designer's preference, we could regard these as *objective* terms. However, examining statements 3 and 8, in conjunction with Eq. (1) and (3), respectively, we might find it appropriate to refer to these statements as *objectives* or *goals*, and to Eqs. (1) and (3) as the associated *objective functions*.

These terms (objectives and goals) could be referred to as subjective terms, as they do make a statement regarding the designer's (subjective) preference. The quantities functions f_m, and f_b could be called the objective functions (and not simply the *objectives*), as they are the mathematical representations of the objectives.

According to the above classification, under the objective terms category we would find such terms as *design metric*, *design parameter,* and *attribute* (if we exclude preference information from their definitions). Similarly, under the subjective terms category, we would find such terms as *preference function, utility function, goal, specification, constraint, cost function, criterion, figure-of-merit, merit function, objective function, performance function,* and *requirement*. We note that the morphology of the latter class of terms incorporates at least some degree of the designer's preference. In addition, if clear definitions exist for a sufficient number of terms in each category, these authors find no need for such a long list of terms, whose mutual differences in meanings would become dubious at best.

3.5 Soft vs. Hard Statements

Another means to categorize these many terms is with respect to the *hardness* and *softness* of their implications. In particular, such terms as *constraint*, and *subject to* are entirely clear/sharp in their implications. That is, unless the statement of the word *constraint* or the statement following *subject to* is fully met, then the design is not acceptable/feasible. At the other end of the spectrum, such terms as *wish, preference* and *goal* are less categorical (soft) in their implications. These terms merely express statements that the designer would like to see satisfied to the maximum extent possible, while no extent of satisfaction of these statements is a prerequisite to the acceptability of the design. However, when we employ such terms as *hard* *goal,* we essentially destroy the meaning of the word goal. It seems to these authors that a *hard goal* is nothing but a *constraint*, but one that is dubiously stated. The users of the term *hard goal* then find the need to inject another term, *soft goal*, when simply *goal* might have sufficed.

Many terms, however, do not naturally lend themselves to this classification. For example, the English dictionary does not provide a succinct definition of the term *requirement,* in the context of engineering design. Can a requirement be a constraint? We might say yes. Can a requirement be a goal? We might again say yes. That is, we might *require* that mass be *minimized* (a *soft* term). The same line of questioning might apply to the term specification. It seems to these authors that this abundance of terms, which promotes the likelihood of diverging interpretation, significantly contributes to muddying the waters. We might ask the following questions. Is a requirement a preference? Is a preference a requirement? What is the difference between a specification and a requirement, if any? The questions are plentiful, while authoritative clarifying sources are glaringly lacking. The next section discusses the design lexicon deficiencies from a broader (higher-level) perspective, leading credence to the notion that the inadequate state of the design lexicon is both broad and deep in scope.

4. Discussion of a Broader Class of Terms

In Section 3, we presented a critical perspective of the engineering design lexicon using a class of terms that were discussed with the aid of a simple table design example. This Section is intended to show that the deficiency of the current design lexicon is significantly broader in scope than the limited class of terms of the previous section would suggest. At a different level of discourse that does not involve the table example, this section goes somewhat beyond the most commonly used terms, as were those discussed earlier. We discuss the use of several terms that are often employed with dubious implications. As is often the case in engineering design discourse, use of the English dictionary here again offers little assistance in uncovering appropriate definitions for this broader class of terms. In particular, we discuss such terms as data, information, knowledge, risk, uncertainty, probability, imprecision, fuzzy, and robustness. Importantly, we also note that a comprehensive analysis of the state of the design lexicon would devote significantly more attention to non-mechanical design than does this publication. The focus, herein, on mechanical design is not intended to suggest that the lexicon problem is more significant in the mechanical design arena. We made this choice merely for the sake of practical (scope) considerations.

We begin by considering the terms *data, information, knowledge,* and *design*. In the development of taxonomies for design, or in the activity of general research in engineering design, it might become necessary to clarify what the above terms really mean. Faced with this need, the researcher would, *currently*, have to either define his/her own definitions, or possibly adopt one of several existing definitions. Again, we note that no authoritative clarifying source exists. Adopting definitions from such fields as artificial intelligence, mathematics, operations research, computer science, or economics may not always be wise. We also note that, again in this instance, the English dictionary is unfortunately not helpful, as it defines information in terms of knowledge, and knowledge in terms of information [14].

It is interesting to note that the definitions of the words data, information, and knowledge that exist in the literature do not clearly (mutually consistently) establish their hierarchy. Which of these three words is at a higher level. We present in the sequel a sample of definitions used in the literature, which suggests material difference of views among design researchers. **Knowledge**: An agreed upon set of facts. Knowledge can be defined as an understanding of the laws of nature and the ability to apply those laws to predict the behavior of physical systems [16]. **Knowledge**:

The sum and range of what has been perceived, discovered and learned about a product [21]. **Information**: The degree of freedom that exists in a given situation to choose among signal symbols, messages, or patterns to be transmitted" [19]. (This definition is a formalism of the notion that more information leads to a reduction in uncertainty). **Information**: Information relates to a specific decision. Quantitatively, it can be measured as the probability that the preferred choice in a decision will lead to the most desired outcome [16]. **Information**: Information is the measure of knowledge required to satisfy a given FR (Functional Requirement) at a given level of the FR hierarchy. The notion of information is very closely related to the probability of achieving the FR [20]. **Data, Information, and Knowledge**: Based on dictionary definitions, the perception of knowledge and information can be stated as follows. Knowledge is the most complex form (among data, information, and knowledge). Knowledge is derived by human beings from information. Information is required before we obtain knowledge. Data is the simplest form and is characterized by a sense of hardness. Data and facts are often considered synonyms. Data is information, but not all information is data. Based on the above perception, designing is stated as "a process of converting information that characterizes the need and requirements for a project into knowledge about a product." [21]. The important message from the above quotations is that the above definitions are not in mutual agreement.

In terms of the relationships between knowledge, information, and design, Hazelrigg's [16] definitions indicate that knowledge is associated with the inputs of a design process, while information is related to the design outcome (design decision). On the other hand, Ref. [21] defines a design equation that takes the information (that characterizes the need) as inputs and generate the knowledge (about a product) as outputs. Suh [20] simply considers information as the measure of knowledge, while his design equation is associated with FRs and Design parameters. Suh defines **design** as: The creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the FRs and the DPs (Design Parameters) of the physical domain. Further, in terms of the human involvement in the design activity, we may also ask: since *designers* make decisions, is the *designer* always (or, sometimes) understood to be the *decision maker*. Additional work *by the community* (not by individual researchers in isolation) in the definitions of these words is needed.

Robust Design is another term that is used with diverse interpretations. The English dictionary defines *robust* as strongly formed or constructed. *Design for Robustness* in engineering practice often refers to the adoption of Taguchi's [22] philosophy of quality, which involves minimizing variability in performance due to environmental and manufacturing conditions. In light of the previous comments, how do we differentiate between the terms *robust design, quality-based design, design for tolerance,* and *design for variation,* etc.? In a similar vein, in control design, high robustness and high performance are typically understood as opposite objectives. One is considered obtainable only at the expense of the other. That is, a high performing design is not robust, and a very robust design is not high performing. In other words, control engineers do not generally accept the notion that *a robust design may be of high performance, even though the robust design might be performing very well according to our wishes*. This difference in meaning across disciplines can become a serious source of miscommunication. Again, the existence of a design dictionary would, in this case, assist the control engineer who intends to interact with design engineers or researchers.

We now turn our attention to such terms as *uncertainty, risk, imprecision,* and *fuzzy*. For the table example defined in Section 2, a precise (crisp) number (0.1 meter) is used to describe the leg position, *r*, in statement-2. If we change the statement to "the leg position, *r*, is *about* 0.1

meter", we now introduce some vagueness into our problem description. Another example of vague description is associated with statement-6. When we say the table color, *c*, should be *dark*, one may inquire about the meaning and implication of the word *dark*. No one would argue that black is a dark color; however, would we consider green or blue (or some version thereof) as dark? In terms of the lexicon used for these vague quantities, some might call both parameters (*r* and *c*) *uncertainty parameters*, while others might refer to the leg position *r* as *imprecise parameter* and name the desired color of the table, *c*, a *fuzzy numbers*. It has been recognized that there are different classes of uncertainties in a design process, delineated along the amount of available information and along some special characteristics of the uncertainties. However, a universally accepted terminology does not exist. We hereby examine the terms uncertainty, risk, imprecision and fuzzy , which are often used for uncertainty analysis in engineering design, and we expose pertaining confounding situations regarding the use of these terms in the current design literature.

We begin with the dictionary definitions of these terms [14].

Uncertainty - the quality or state of being uncertain.

Risk - possibility of loss or injury.

Imprecision - state of being vague, inexact, not precise.

Fuzzy - of the nature of or resembling fuzz; indistinct; blurred.

We note from the above definitions that, *uncertainty*, *imprecision* and *fuzzy* are all associated with the states of being uncertain while *risk* is more or less related to the outcome of an action. However, these dictionary definitions do not delineate a clear distinction between these terms, with regards to classes of uncertainties. We further examine definitions of these terms provided by researchers in different fields. We observe that it seems to be a common practice to relate the terms uncertainty and risk to *probability analysis*, though the views are quite different as to which term is associated with probability analysis and which is not. For example, in the economics dictionary mentioned earlier [5], risk and uncertainty is defined as follows:

Risk: A context in which an event occurs with some PROBABILITY or where the size of the event has a PROBABILITY DISTRIBUTION. Thus, the return on an investment may be *risky* in that it has a 1 in 10 (0.1 probability) chance of being a loss , a 5 in 10 chance of being a particular size, and a 4 in 10 chance of being larger still.

Uncertainty: A situation in which the likelihood of an event occurring is not known at all. That is, no PROBABILITY DISTRIBUTION can be attached to the outcomes. If the event in question is an investment in a project, uncertain returns would mean that the conceivable returns will be known but their probability of occurrence will not be known.

We note similar definitions provided by Siddall [23], who defines **risk** as “each action has several possible outcomes for which the probabilities are known”, and **uncertainty** as “each action has several possible outcomes for which the probabilities are unknown”. While the above two quotes relate uncertainty to the situation in which the probabilities are unknown, we also find other definitions that instead relate uncertainty to probability analysis. For example in Hazelrigg [16], uncertainty is defined as

Uncertainty. Any time we conduct an experiment for which we cannot predict the outcome, that is, when the sample space contains more than one element with nonzero probability, we say that there is uncertainty.

We note that the above definition is consistent with that used in conventional decision analysis [24]. This leads to the following questions. Which is associated with probability? Is it risk, or is it uncertainty?

While *uncertainty* or *risk* is generally associated with *probability* in the classical normative decision theory, recent years have seen the applications of descriptive decision theory [25] that introduces the concept of *imprecision* and *fuzzy number* [26-28] into *uncertainty analysis*. As pointed out by Zimmermann, in descriptive decision theory, the precision of the problem description is no longer assumed; but ambiguity and vagueness are very often modeled only verbally (linguistically). The early publications in fuzzy set theory [29] generalize the classical notion of a set, and propose to accommodate this type of uncertainty to the non-stochastic regime. Under Zadeh's theory, *imprecision* is used in the sense of vagueness rather than lack of knowledge about the value of a parameter, as is done in *tolerance analysis*. We find a review of the literature of imprecision in engineering design [26] where several definitions are provided, including:

Uncertainty, which usually represents uncontrolled stochastic variations with the mathematics of probability, is distinct from imprecision.

Imprecision. In the context of engineering design, the term imprecision is used to mean uncertainty in choosing among alternatives. An imprecise variable in preliminary design is a variable that may potentially assume any value within a possible range (a concept related to interval analysis) because the designer does not know, a priori, the final value that will emerge from the design process.

Wood and Antonsson, 1989 [28] relate *imprecision* to *fuzzy numbers* by defining **imprecision** as: the range (support) or spread of values about the peak [preference of one (1)] of a parameter's fuzzy set.

A comparison between *fuzzy sets* and *probability methods* is made in [30]. This publication discusses different types of uncertainties and suggest the terms *stochastic uncertainty* and *possibilistic uncertainty* to differentiate those uncertainties that could be modeled using stochastic representations from those that could be modeled by imprecision. Though the use of these terms is still worthy of debate, the important point here is that these authors recognized the need to clarify their specific use of terms. While we may keep the word *uncertainty* as a general term for any vague or unclear representation, it is necessary to reach an agreement on the terms we use for *uncertainties* with different characteristics, including those that could be modeled neither stochastically nor using fuzzy numbers.

The conclusion of this section leads us to the important issue of identifying viable solution approaches.

5. Possible Solution Approaches

In this section we briefly address the issue of determining pragmatic solution approaches to the design lexicon problem exposed by this paper. We begin by expressing our strong view that the task of charting a solution path should itself be a community endeavor. Throughout this paper we have never ceased to refer to this omnipresent *design community*, which is in a sense both the object and the subject of the problem.

We now attempt to define the morphology of the segment of the community, which should play an active part in this prospective activity. We shall refer to this segment as the *lexicon* *community*. We believe this lexicon community should be composed of a diverse, manageably small group of design researchers and practitioners, in consultation with a significantly broader group of individuals directly and indirectly connected to the activity of engineering design. The lexicon community should comprise researchers (1) from different schools of *design thinking*, (2) from a generationally mixed make-up, (3) from disparate levels of design research experience, and (4) from diverse disciplinary backgrounds (*e.g.*, civil, mechanical, electrical, and environmental engineering). Most importantly, the members of this lexicon community should come to the table with an open mind, ready to advance the overriding objective of near-consensus. We believe that this last point in critical. In the case of dictionary development efforts in such fields as accounting and economics, the opportunity for controversial roadblocks can be readily managed because of these disciplines relatively mature development stage. The field of engineering design in unfortunately not so blessed. The opportunities for credible disagreements abound, making it critical that participants understand the paramount necessity for building consensus.

To the extent that the experiences are transferable, the lexicon community should learn from other recent successful efforts (*e.g.*, the Economics dictionary development effort [5]). Several specific activities could pave the way to a strong developmental activity. (1) The first involves active participation of the community in carefully designed and well-publicized web sites that would solicit community thinking on specific questions. (2) Organization of a well-conceived series of workshops, where participation is limited to those who are will maintain constructive subsequent participation. (3) Develop a program of internationalization of this lexicon development effort. In particular, US researchers could benefit from the areas where Europeans are at a more advanced stage. (4) The publication of articles that explicitly address this problem would serve to both advance our thinking in these regards, and further sharpen the interest of the community. (5) The lexicon community should make the case for support to appropriate government agencies (*e.g.*, NIST, NSF), professional societies (*e.g.*, ASME, ANSI, ISO), and University publishers that are inclined to be part of the solution. These institutions may choose to get involved in various degrees, ranging from mere publication of results, to technical assistance, to financial sponsorship.

6. Concluding Remark

This paper was an invitation, as well as a challenge, to the design community to constructively guide the scholarly evolution of the engineering design lexicon. This lexicon shall support the development of engineering design, and of *Decision-Based-Design* in particular. We exposed numerous routine situations where common practice fails to promote intelligible discourse within the design research community. We posed important rhetorical questions regarding the possible practical detrimental impact of this unclear lexicon; and proposed avenues to broad community involvement in addressing this problem. In this publication, we focused merely on the task of exposing the issues as we (and possibly countless others) see them; we have not provided *answers*. We leave it to subsequent publications, by us and by others, to begin the deliberate and difficult task of developing a comprehensive and concise *design lexicon* that will facilitate the theoretical growth of the science or discipline of engineering design. We do expect that many readers might take exception to specific aspects of (or statements in) the paper. However, if these readers agree with the *general* message of the paper, we will have met our immediate objective. Hoping that we have sharpened the interest of many concerned design researchers, we look forward to the prospect of further work on this subject.

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