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CONCEPTUAL STRESS AND CONCEPTUAL STRENGTH FOR FUNCTIONAL DESIGN-FOR-RELIABILITY

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ABSTRACT

Stress and Strength Interference Theory (SSIT) is a fundamental theory for reliability assessment. It has been widely used as a foundation for design-for-reliability (DFR). However, SSIT and associated methodology and tools, that require detailed definitions of constructional and form structure, are only applicable to an embodiment design. As many researchers have attempted to push DFR upfront to a conceptual and functional design stage, SSIT loses its usefulness, while other equivalent theory and tools for conceptual and functional design-for-reliability do not exist. Therefore, DFR for conceptual and function design becomes ad-hoc that lacks a systematic approach and parametric reliability quantification. In this paper, we first review the literature on stress and strength interference, and then extend the concepts of stress and strength to *conceptual stress and conceptual strength* that are relevant to conceptual and functional designs. Based on the conceptual stress and conceptual strength, we introduce a Conceptual Stress and Conceptual Strength Interference Theory (CSCSIT) and discuss how it can be applied to support conceptual and function design-for-reliability. We illustrate our theoretical work with a conceptual and function design example. We conclude the paper with a discussion of the future research to further define and substantiate the CSCSIT work.

Keywords: Reliability, Design-for-reliability (DFR), Conceptual design, Embodiment design, Functional design, Stress and Strength Interference Theory (SSIT).

1 INTRODUCTION

Reliability engineering was formally established after World War II in the United States to primarily address effectiveness of war airplanes, weapon systems and rockets. Many reliability engineering related military standards were generated since then under Department of Defense to guide the reliability engineering implementation [1, 2, 3]. It might not have been an original intention but to large extent reliability engineering in the industry practice has been primarily a *post-design* assessment and quality assurance discipline not so much a *design-in* reliability activity. It was not until 1980's design engineering was significantly involved to address design-in reliability. The early effort of the involvement of design engineering was to introduce probabilistic design methodology. It quantifies randomness of engineering parameters in factor of safety calculation of stress analysis then calculates the probability of failures [4, 5, 6]. The theoretical foundation of this approach is the Stress and Strength Interference Theory (SSIT) [7, 8, 9]. However, such an approach can only be implemented during an embodiment design stage with explicitly defined constructional structures for the reason that a probabilistic design calculation has to take detailed form design information, such as part geometries, material properties, and operating loads, as inputs [6, 10]. It has been recognized that design-for-reliability considerations during a conceptual design stage is very challenging. This is because a conceptual design primarily deals with concept formulations and function structures that respond to product top-level functional

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requirements, which usually do not address formation of physical components.

Reliability is defined as the probability that a system or component performs the intended functions under a set of specified operation conditions for a specified period of time [3, 11, 12, 13]. Early stage of the reliability activities focused on program control, program surveillance and quality assurance, and emphasized product reliability evaluation to ensure a good product after the design was completed. As such, lots of reliability efforts were on reliability demonstration and qualification test set up and analysis. It was very loosely connected with the engineering design. During the last 20 to 30 years, both reliability engineering and engineering design have evolved significantly. Many tools and methods from each discipline have been developed and implemented. But in many instances, tools and methods from reliability engineering and engineering design didn't integrate together well to support design improvement. Many traditional reliability analysis methods are probability and statistical based, which are drastically different from engineering design that is primarily physics based. Typical probability and statistics based reliability approaches are given by Nelson [14], Lawless [15] and Bain and Engelehardt [16]. The detailed statistical analysis from traditional reliability engineering mainly focuses on local failure analysis and probability and statistical treatment of the data. Probability Risk Analysis and some system reliability modeling efforts have attempted to address system reliability modeling [17, 18, 19, 20]. But the results of these efforts are generally viewed as not fruitful by design community. Two United States Space Shuttle failures (Space Shuttle Challenge explosion during its ascent on 1986, and Space Shuttle Columbia explosion during re-entry on 2003) brought an eye-opening warning that reliability engineering has a long way to go to be effective and to work with engineering design for product improvement. Nowadays, many NASA and Department of Defense programs consider reliability as one of the most important requirements (MIRs) in their Request-For-Proposal (RFP) solicitations. NASA is developing a new Ares launch vehicle that will return astronautics to Moon, is aggressively chasing design for reliability and safety, and is adapting a risk based design approach. This brings a significant challenge to NASA and contractors' reliability engineering and engineering design communities to develop and implement an effective design for reliability approach to accomplish the NASA's mission.

Various approaches have been taken toward providing better understanding as well as effective support for engineering design. The systematic design framework proposed by Pahl and Beitz is a practice driven methodology that closely reflects reality and industry design practice from a design process flow perspective [11]. The systematic treatment of the design process makes it possible for designers to manage their design activities and information more effectively. Suh's Axiomatic Design process [21] provides a prescriptive way to address design detail progressions from customer needs (CNs) to function requirement (FR) design, to design parameter (DP) set up, and to process variable (PV) implementation. The key ingredients of Axiomatic Design are the zigzag design process and the two axioms (Independence Axiom and Information Axiom). The axiomatic design process provides a systematic way for designers to generate design solutions and make design decisions that lead to simple, rather than complex, designs. Altshuller's TRIZ approach provides a roadmap to obtain innovative design solutions through a set of pre-established inventive principles and abstracted design solutions [22]. The aim of the approach is to overcome technical and physical contradictions with near-ideal solutions, defined by maximizing the ratio of useful functions over undesired functions, and minimizing required resources. While the extant design methods include those mentioned above do not explicitly consider the issues of reliability, they provide a foundation for us to address reliability at the early stage of engineering design.

There has been much research on design-for-reliability in the literature [4, 6, 9, 11, 13]. However, little has been done that systematically addresses design-for-reliability (DFR) by truly integrating engineering design closely with reliability assessment into an interdisciplinary process. This is especially true for conceptual and function designs. There is no formal definition of DFR that can guide DFR research and implementation at the early stage of design. In our research, we define Design-For-Reliability as *a structured design methodology that guides design decision-making with parametric reliability models to meet quantitative reliability requirements or goals during all design phases*. We emphasize several key points in this definition. First, we emphasize the *pro-active* nature of the DFR. We want a design decision to be made based on reliability as one of the selection criteria. Secondly, we emphasize the use of a *parametric reliability model* tied with synthesizing, analyzing and selecting a design solution, whether at a conceptual design phase or at an embodiment design phase, to meet system reliability goal. Thirdly, we emphasize a *structured* approach. That means we want to elevate the mostly descriptive and ad-hoc DFR methods that many researchers have to a prescriptive design methodology.

In the rest of this paper, we first review the related work in the literature in Section 2. We then introduce the concepts of conceptual stress and conceptual strength, discuss a conceptual failure analysis, and present the Conceptual Stress and Conceptual Strength Interference Theory (CSCSIT) and its working framework in Section 3. In Section 4, we illustrate the application of CSCSIT with a conceptual and function design example. Section 5 summarizes our work and points out the further research direction.

2 RELATED WORK

Disney, Sheth and Lipson [7] and Kapur and Lamberson [8] introduced and discussed a fundamental reliability theory - Stress and Strength Interference Theory. It basically states that a failure occurs, when the stress, in general, exceeds the strength. Mathematically, the theory presents the failure probability (P_f) of the system as the probability that stress is bigger than the strength P(Stress > Strength). Figure 1 illustrates the concept. Equation (1) presents the mathematical formula for the case of single stress and single strength variable situation.

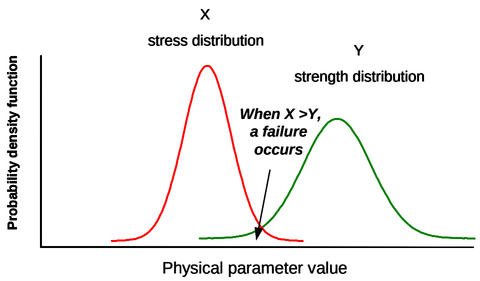


Figure 1: Stress and Strength Interference Diagram

$$P_f = P(X>Y) = \int_{-\infty}^{+\infty} f_y(y)[\int_{y}^{+\infty} f_x(x)dx]dy \qquad (1)$$

Based on this theory, a probabilistic design analysis (PDA) methodology has been developed and advanced significantly during the last 20 to 30 years [4, 5, 6, 10]. The PDA methodology has been evolved as an important design analysis tool, called Reliability Based Design Optimization (RBDO), to support embodiment design optimization and reliability quantification. However, PDA has three limitations. The first limitation is that it only applies to embodiment designs, given a form structure, material selection and defined geometric features. The second limitation is its inapplicability in analyzing a function structure model. The third limitation is its limited capability to analyze a system model. In order to use the PDA type of analysis at a conceptual and functional design stage, the concepts of stress and strength, and stress and strength interference theory need to be extended to include conceptual design concepts such as function structure, function event, functional failure, and energy, material and signal flows, which is the focus of this paper. From the system modeling aspect, many research attempts are under way to address system modeling of a function structure. Wang and Jin proposed to use the Bayesian Net to model function structures for relative reliability comparisons of alternative function structures [23]. Wang and Jin also proposed a graphical model to model and manage general engineering design and functional dependencies [24, 25]. Probabilistic Risk Assessment (PRA) methodology uses fault trees and event trees as system modeling tools [18, 17]. Xu and Dugan introduced a dynamic fault tree analysis technique to supplement event trees for modeling dynamic functional interactions [26]. Kurtoglu and Tumer proposed to analyze function failures with three analysis elements that are function modeling, behavioral simulation and failure reasoning [27]. Stone and Wood proposed a set of functional basis as the first step of functional failure modeling [28]. Krus and Lough attempted to address functional failure propagation by identifying common interfaces and associated faults [29]. Volovoi used Petri Net Aging Token technique to model two shared load failure scenario [30]. Stone, Tumer and Wie correlated function failures to historical failure databases to help achieving a reliable function structure [31]. Some literature work indirectly or ambiguously address design for reliability. Suh presented two axioms (Independence Axiom and Information Axiom) and claimed that following these two axioms will greatly improve a product robustness and quality therefore reliability [21]. Taguchi systematically introduced a robust design concept and developed an experimental based design method [32, 33]. El-Haik in [13] elaborated in details how the Axiomatic Design methodology helps to achieve a robust and six-sigma [34] quality level, and tied matrix mappings from function requirements (FRs) to DPs (design parameters) and PVs (process variables) with reliability quantification. From a design-for-reliability perspective, we observed two typical approaches. One is Pahl and Beitz that discussed a general design methodology and design-for-quality, using ad-hoc ratings to evaluate reliability for conceptual and functional designs [11]. Another is Kececioglu that presented largely mathematical treatments of localized stress and strength interference theory implementation [9]. Literature survey reveals the gaps between local analysis and system analysis, between ad-hoc ratings and physics based approach, and between conceptual design for reliability and embodiment design for reliability. There is a significant need to move design-for-reliability from reactive to proactive that integrates design synthesis with design analysis to support conceptual design for reliability.

3 CONCEPTUAL STRESS AND CONCEPTUAL STRENGTH

Review of related work in Section 3 has revealed that design-for-reliability, in the research literature, at best is ad-hoc and loosely tied with design, especially during a conceptual design stage. Our research attempts to develop a systematic, logical and organized way to analyze reliability simultaneously with the design synthesis for conceptual and functional designs. We observed that the comparable analysis method, similar to the physics based reliability analysis and probabilistic design method, does not exist for conceptual design. We hope to open a door for using well developed embodiment design tools, such as structural probabilistic design method, during a conceptual design stage. Introduction of the conceptual stress and conceptual strength (CSCS) provides this opportunity. We extend the traditional mechanical stress and strength concepts to a general sense, in which the stress represents the energy, material, and signal flows imposed on the function structure, and the strength represents the ability that the function structure can fulfill the function requirements with incoming EMS flows. We anticipate that the successful introduction of CSCS will also open research opportunities for formulating and analyzing unique mathematical relationships between conceptual stress and conceptual strength as well as the relationships between conceptual stress and real stress (or conceptual strength and real strength). There will also be a need for optimizing conceptual stress and conceptual strength for maximizing reliability and minimizing cost. This, in general, will improve engineering design by making design decisions more inline with improved reliability. We are hopeful that it will also greatly promote and enhance design-for-reliability implementation and improve our product quality, reliability and safety in general.

3.1 Conceptual Stress and Conceptual Strength

Design synthesis and analysis

In order to introduce conceptual stress and conceptual strength, we need to review the general design synthesis and analysis flow from a reliability perspective. During the phase of conceptual design, designers study the customer requirements and then translate the customer requirements into a set of functional requirements. As the design synthesis progresses, top-level functional requirements are decomposed, and energy (E), material (M) and signal (S) flows are identified. As the design further progresses to the stage of formation of working structures and constructional structures, some *stress function*, based on the design configuration and physics laws, is generated. This stress function is then compared with the strength that is the ability that the form structure undertakes the stress to perform the required functions successfully. The strength can be represented by a factor of safety (FS) multiplied by a stress value from the stress function. The system is considered to fail if the strength of the construction form is less than the stress imposed. We summarize the above discussion with the matrix mathematics.

$E = [e_1, e_2, \ldots, e_{ke}]^T$, the energy flow parameter vector

$M = [m_1, m_2, \ldots, m_{km}]^T$, the material flow parameter vector

$S = [s_1, s_2, \ldots, s_{ks}]^T$, the signal flow parameters vector

To simplify the notations, we combine E, M, S vectors together to form an EMS vector V with the elements $v_1, v_2, \ldots v_k$.

$$\begin{aligned} V &= [E^T, M^T, S^T]^T \\ &= [e_1, e_2, \ldots, e_{ke}, m_1, m_2, \ldots, m_{km}, s_1, s_2, \ldots, s_{ks}]^T \\ &\equiv [\, v_1, v_2, \ldots, v_k]^T \end{aligned} \qquad (2)$$

The stress function $F_{ste} = F_{ste}(V)$.

Notice that F_{ste} can be a vector. We then linearize the F_{ste} function, we get

$$F_{ste} = A\,V \qquad (3)$$

Eq (3) is the linear mapping from EMS flow parameters to the stress function. A is the mapping matrix. Its elements are the partial derivatives of F_{ste} over V's elements. For a simple case of one dimensional F_{ste}, we have

$$F_{ste} = A\,V = \sum_{i=1}^{k} \frac{\partial F_{ste}}{\partial V_i} v_i \qquad (4)$$

From the stress function to the strength function F_{stn}, we use the factor of safety to relate each other,

$$F_{stn} = B\,G(F_{ste}) \qquad (5)$$

Here B is the safety of factor matrix, a diagonal matrix with the diagonal elements as the factor of safety for the corresponding stress function. $G(F_{ste})$ is a function of F_{ste} and is usually a percentile of the random variable function F_{ste}. For a simple case of one dimensional stress function, we have

$$F_{stn} = b\,G(F_{ste}) \qquad (6)$$

Here b is a scalar representing the factor of safety for the one-dimensional stress and strength variable situation.

If $G(F_{ste})$ is given as the 95%tile of F_{ste}, $F_{ste,0.95}$, we get

$$F_{stn} = b\,F_{ste,0.95} \qquad (7)$$

The reliability function R, from the stress and strength interference theory, is given by the following

$$\begin{aligned} R &= \text{Probability}(F_{stn} > F_{ste}) \\ &= \text{Probability}(B\,G(F_{ste}) > F_{ste}) \end{aligned} \qquad (8)$$

For the one dimensional case, we have

$$R = \text{Probability}\,(b\,F_{ste,x\%tile} > F_{ste}) \qquad (9)$$

Conceptual Stress and Conceptual Strength

Based on the above discussion and Equations (2) through (9), we introduce the following definitions of conceptual stress and conceptual strength.

Definition 1 (Conceptual Stress - CSte): Given EMS flow vector $V = [\, v_1, v_2, \ldots, v_k]$ of a function structure, the conceptual stress of the function structure CSte is defined as

$$\text{CSte} = \sum_{i=1}^{k} c_i v_i \qquad (10)$$

Here c_i's is a set of constants that will be determined during a conceptual design phase (Later on we will see what c_i's represent and their implication to the design-for-reliability). ■

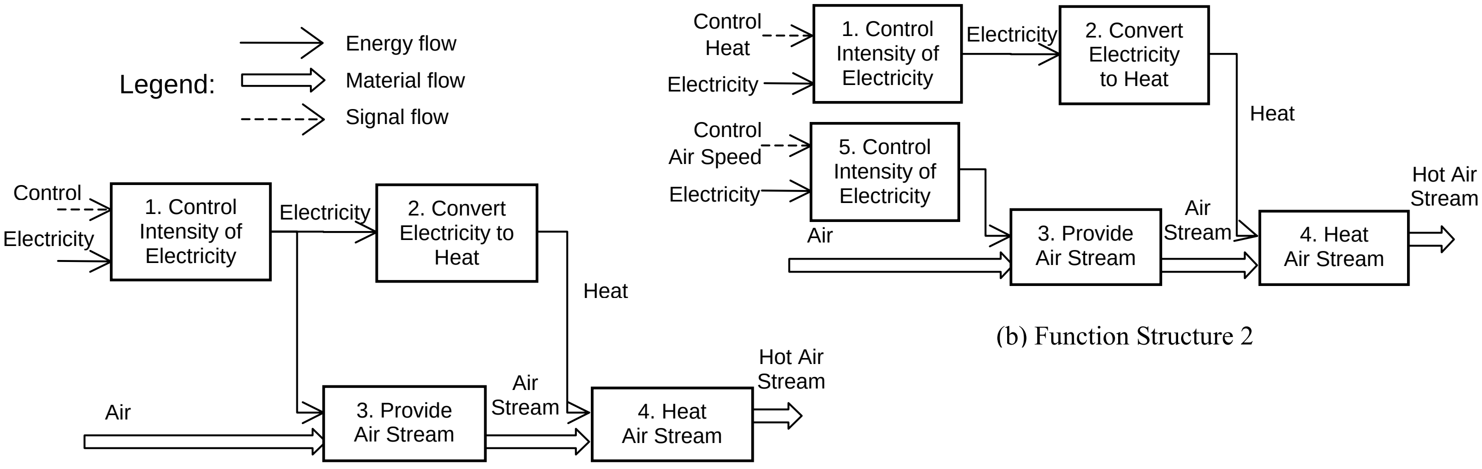
Definition 2 (Conceptual Strength Function - CStn): Given the conceptual stress Cste of a function structure denoted in Equation (10), the conceptual strength of the function structure CStn is defined as

$$\text{CStn} = b\ \text{CSte}_{x\%tile} \qquad (11)$$

Here b is a constant that will also be determined during a conceptual design phase. We call b as a *conceptual factor of safety*. $\text{CSte}_{x\%tile}$ is the x percentile of the random function CSte. X value will also be determined during the conceptual design. (Later we will see the relationship of the conceptual factor of safety with a real factor of safety and its implication to the design-for-reliability.) ■

As we have seen in Section 2, a real stress is defined as a physical load that is imposed on a physical part. It is usually represented by engineering parameters such as temperature, pressure, force, flow rate, or a function of them. During a conceptual and a function design phase, constructional structure does not exist. Therefore, we do not know what kind of stress will be applied to a potential constructional form that may accommodate the embodiment design of a particular function event. However, every function event takes some combination of energy, material and signal as the input. The event, based on the energy conservation law, has to output a combination of energy, material and signal. Therefore, it is natural to choose the conceptual stress as a function of energy, material and signal. The simplest choice is a linear function. But we choose the linear function not just for the simplicity. The conceptual stress as chosen, will be naturally transitioned to a real stress as the design evolves from a conceptual design to an embodiment design, as a detailed stress function is established (just take partial derivatives of the stress function over v_i's and substitute the constants c_i with the partial derivatives). For the conceptual strength, we can think of it as the ability that a potential constructional form will undertake the function structure input, which is the conceptual stress, and successfully completes the intended functions. Therefore we measure the conceptual strength as the product of a constant, which we call conceptual factor of safety, and a percentile of the conceptual stress function. The constant, when the design evolves into an embodiment design, becomes the real factor of safety, as in the case of a conventional stress analysis. Choice of the percentile, usually 90%tile or 95%tile, is often governed by design team's analysis policy. By defining the conceptual stress and conceptual strength this way, we provide an analysis framework that is embedded in the synthesis process. The framework is grounded on the reliability concept of the stress and strength interference, therefore many existing reliability tools and methods can be potentially used. It also naturally connects conceptual stress and conceptual strength to real stress and real strength, and provides a possibility of seamless transition from conceptual design-for-reliability to embodiment design-for-reliability.

Throughout this paper, we will use the Hair Dryer Functional Design example from [23] to illustrate the application of the conceptual stress and the conceptual strength. Figure 2a and 2b present two competing function structures of the hair dryer. The objectives are to evaluate and compare two alternative function design candidates, and provide design-for-reliability guidance and actions for a follow-on embodiment design. Here we first apply the conceptual stress and the conceptual strength to it. Table 1 presents the conceptual stress and conceptual strength formulas for all function events. Section 4 will discuss how to establish all to-be-determined parameter values and their implications to design-for-reliability. The details of the function events in Table 1 can be found in [23].



(a) Function Structure 1

(b) Function Structure 2

Figure 2: Function Structures of Hair Dryer Design

Table 1: Conceptual Stress and Conceptual Strength for Hair Dryer Design

Function	Function Structure 1		Function Structure 2	
	Conceptual Stress	**Conceptual Strength**	**Conceptual Stress**	**Conceptual Strength**
1	$\mathrm{CSte}_{1,1} = c_{11,1} s_{1,1} + c_{12,1} e_{1,1}$	$\mathrm{CStn}_{1,1} = b_{1,1} x_{1,1}\%\mathit{tile\ of\ CSte}_{1,1}$	$\mathrm{CSte}_{1,2} = c_{11,2} s_{1,2} + c_{12,1} e_{1,2}$	$\mathrm{CStn}_{1,2} = b_{1,2} x_{1,2}\%\mathit{tile\ of\ CSte}_{1,2}$
2	$\mathrm{CSte}_{2,1} = c_{21,1} e_{2,1}$	$\mathrm{CStn}_{2,1} = b_{2,1} x_{2,1}\%\mathit{tile\ of\ CSt}_{2,1}$	$\mathrm{CSte}_{2,2} = c_{21,2} e_{2,2}$	$\mathrm{CStn}_{2,2} = b_{2,2} x_{2,2}\%\mathit{tile\ of\ CSt}_{2,2}$
3	$\mathrm{CSte}_{3,1} = c_{31,1} m_{1,1} + c_{32,1} e_{3,1}$	$\mathrm{CStn}_{3,1} = b_{3,1} x_{3,1}\%\mathit{tile\ of\ CSte}_{3,1}$	$\mathrm{CSte}_{3,2} = c_{31,2} s_{1,2} + c_{32,2} e_{3,2}$	$\mathrm{CStn}_{3,2} = b_{3,2} x_{3,2}\%\mathit{tile\ of\ CSte}_{3,2}$
4	$\mathrm{CSte}_{4,1} = c_{41,1} m_{2,1} + c_{42,1} e_{4,1}$	$\mathrm{CStn}_{4,1} = b_{4,1} x_{4,1}\%\mathit{tile\ of\ CSte}_{4,1}$	$\mathrm{CSte}_{4,2} = c_{41,2} m_{1,2} + c_{42,2} e_{4,2}$	$\mathrm{CStn}_{4,2} = b_{4,2} x_{4,2}\%\mathit{tile\ of\ CSte}_{4,2}$
5			$\mathrm{CSte}_{5,2} = c_{51,2} m_{2,2} + c_{52,2} e_{5,2}$	$\mathrm{CStn}_{5,2} = b_{5,2} x_{5,2}\%\mathit{tile\ of\ CSte}_{5,2}$

Nomenclature: $s_{i,j}$ – signal flow for the *i*th function block of function structure *j*
$e_{i,j}$ – energy flow for the *i*th function block of function structure *j*
$m_{i,j}$ – material flow for the *i*th function block of function structure *j*

3.2 Conceptual Failure Analysis

To put the concepts of conceptual stress and conceptual strength under the reliability perspective, and to lay down the foundation for the conceptual stress and conceptual strength interference theory, we present our view of conceptual failure analysis. This is the abstraction of general real failure analysis. To help the discussion, we first introduce the definitions of function fault and failure.**Definition 3 (Function Fault):** Given a function f with input flows $\mathrm{Vi} = \{vi_1, \ldots, v_k\}$ and output flows $\mathrm{Vo} = \{vo_1, \ldots, v_{ol}\}$ such that the desired range of $\mathrm{Vo} = f(\mathrm{Vi}) \pm \Delta_f$, there is a functional fault if the function is in its undesired state, i.e., the output flow V falls under the following range: $V < f(\mathrm{Vi}) - \Delta_f$, or $V > f(\mathrm{Vi}) + \Delta_f$. ■

Definition 4 (Function Failure): A function failure of a given function f is defined as the termination of the ability of a function to realize its required function $\mathrm{Vo} = f(\mathrm{Vi}) \pm \Delta_f$.■

From the above definitions, it can be seen that a functional fault is not a functional failure. It may or may not lead to a functional failure. Usually, the analysis of how a functional fault propagates to a function failure can be extremely difficult. A top-level functional failure is the failure of the system.

The first question we ask during a failure analysis is *what can go wrong for a technical system*? Since during the conceptual design phase, we often only have function structure information. The failure analysis at this stage of design must deal with function fault and functional failure as defined above. As the first step toward developing a methodology for conceptual failure analysis, we list the possible failure scenarios as follows.

Scenario 1: *The conceptual stress is bigger than what is assumed such that the corresponding function(s) cannot perform as expected*. In the hair dryer example, if the voltage of the electricity getting into the function "Convert the intensity of the electricity" is twice as assumed, the function "control" probably won't perform adequately. The root cause of such failure can be an uncertainty or wrong assumption in stress, or a more complicate case that is due to dependency of multiple function events that causes the perturbation of the stress, or the most complicate situation that is unknown/unpredictable function fault propagation.

Scenario 2: *The conceptual strength is less than what is designed*. This is the case that the incoming stress is within nominally design range while the potential constructional structure and forms are incapable of deal with the stress. The root causes of this failure scenario can be under design (bad embodiment design), or under build (bad manufacturing). In the air dryer example, if the physical entity that embodies the function event "Convert the intensity of the electricity" is not strong enough, it probably won't be able to take the electric load.

Scenario 3: *A function design has a loophole or a sneak circuit condition* [35] that leads to one of the following situations:

3-1. Sub-functions do not cover the higher-level function.
3-2. Function interactions and/or dependency introduce an unexpected prohibition of execution of a required function.

For Case 3-1, the root cause is a function design failure. The function design either does not decompose a top-level function adequately to sub-functions, or some necessary sub-functions do not exist. For Case 3-2, it is simply an inherent design difficulty for the function design. There are some research attempts to analyze this type of failures [36, 35, 29, 27, 23], but there is lot to do to reach the point that this type of failures can be revealed and analyzed, therefore prevented during a conceptual design phase for a complex technical system.

Scenario 4: A function fault propagates to a function failure. This is also associated with functional interactions, integrations and dependencies. This type of failures is also very difficult to analyze because a functional fault is not easy to define, the boundary of abnormality and normality of the functional performance often cannot be locally and explicitly determined, and the propagation paths and propagation physics can be very dynamic and difficult to simulate and analyze.

For Case 3 or Case 4, the ultimate failure phenomenon still can attribute to over stress or under strength as described in the failure category 1 and 2, or more generally, incompatibility of stress and strength. But the corresponding underlining mathematical models can be difficult to construct and to analyze.

Scenario 5: *A fault of function structure or construction form leads to an unexpected harmful or useless function, regardless whether all required functions perform adequately or not*. The former can be a safety concern, and later is more or less a waste of energy. This can be due to a function design loophole, or complex and unpredictable functional fault propagation, or an embodiment design deficiency, or a manufacturing error, or more generally combination of all. From a physics failure stand, it is the case that energy equilibrium does not obey the desired intention. Energy, material and signal flows go somewhere else not as intended. From the stress and strength interference perspective, there is some fault occurring somewhere in the functional chain of events, either on stress or on strength side or on both, leading to the harmful or useless function but the adverse effect may not be to the extent affecting nominally designed functional performance.

We think the Conceptual Stress and Conceptual Strength Interference approach we present in next section has potential to handle all five failure scenarios discussed above

3.3 Toward a Conceptual Stress and Conceptual Strength Interference Theory

A main goal of our research is to develop a Conceptual Stress and Conceptual Strength Interference Theory (CSCSIT). Following the Stress and Strength Interference Theory (SSIT) [7, 8, 9], CSCSIT is intended to be a reliability theory that evaluates functional failures during a conceptual design stage. In CSCSIT we define that a failure occurs when a conceptual stress exceeds the corresponding conceptual strength. Therefore, the system failure probability (P_f) is given by

$$P_f = \text{Probability (CSte > CStn)} \qquad (12)$$

Here CSte is the conceptual stress and CStn is the conceptual strength, as defined by Equations (10) and (11) respectively.

Our initial CSCSIT is composed of a set of *conceptual parameters* that CSCSIT requires a number of *conceptual design-for-reliability wants*, and the steps through which design-for-reliability is practically implemented. Following are the components of the initial CSCSIT.

CSCSIT Parameter List:

- Function structures that provide EMS (energy, material and signal) flow paths
- EMS parameters flowing in and out of each function
- Probability distributions of EMS parameters
- Coefficients of the conceptual stress (c_i's in Equation (10))
- The X%tile value in the conceptual strength (Equation (11))
- The conceptual factor of safety value in the conceptual strength (Equation (11))

Conceptual Design-for-Reliability Wants:

- Evaluate function structure reliability quantitatively
- Identify function structure weak spots and analyze reliability sensitivity
- Evaluate competing design proposals for reliability deltas
- Identify risky items as actions for embodiment risk-based design

CSCSIT Framework (DFR implementation steps):

1. Define a function structure
2. List EMS parameters for each function from function structure graph
3. Assign the coefficients of the conceptual stress function (c_i's)
4. Estimate or assign probability distributions for EMS parameters
5. Assign X%tile values of the conceptual strength function
6. Assign the conceptual factor of safety of the conceptual strength function (b value)
7. Establish a simulation model to evaluate P_f = Probability (STre>STrn)
8. Run the simulation model, investigate and summarize the simulation results
9. Conduct sensitivity analyses if need to
10. Recommend design-for-reliability and risk based design actions

We briefly describe each of the steps.

Step1: Define a function structure. The candidate function structures are generated based on customer requirements, design team's experience, physical principles and limits, and engineering common senses. Many textbooks and literature papers discussed how to creatively generate function structures. In this research, we assume function structures are given.

Step 2: List EMS parameters for each function. These parameters are listed in the function structure diagram or can be derived from the function event description. This approach is not just a coincident but a carefully planned activity. It requires function structure development identifies all possible and independent EMS parameters explicitly.

Step 3: Assign the coefficients of the conceptual stress function (c_i's). As we mentioned early, c_i's will be evolved to partial derivatives of the real stress function over the EMS parameters. But during the conceptual design stage, we don't know the stress function. We use the survey method, i.e., to survey the design team experts to obtain the relative importance ratings of all EMS parameters then convert them to c_i's. The

CSCSIT methodology has been devised such that only relative ratings matter (both conceptual stress and conceptual strength functions contain the same c_i constants). The set of importance measures, c_i's, represent the design team's knowledge on the EMS parameters. It also represents the team's desire to design the system with pre-designated c_i's for DFR. This also naturally closes the gap between synthesis and analysis. As the design progresses to a working structure and form structure formulation, c_i's will be updated accordingly and eventually will converge to the partial derivatives of the real stress function. It is recognized that during the conceptual design stage, the knowledge on c_i's is very limited. The assignment of c_i's is subjective. But in our view, this subjectivity is a necessity to evolve the design and to drive design-for-reliability. One can not wait for all data available for design to proceed. It is natural that a subjective desire and objective data/evidence will converge during a progressive design cycle toward a final design and a final product.

Step 4: Estimate or assign probability distributions for EMS parameters. Either physics boundary of the system, or some constraints, or system specification, or energy and mass conservation laws will tell you or allow you to derive what the limits of EMS parameters are. For the parameter probability distribution, we assign a normal distribution for symmetric bell shape distribution, and log-normal or Gamma or Weibull or Beta distribution for a skewed distribution. The distribution parameters, such as mean, standard deviation, and location, can be anchored to the parameter limits. The distribution choice usually is not sensitive to the analysis results and the difference is often within the noise level, or otherwise, a sensitivity analysis can be conducted to investigate the sensitivity of the distribution selection. If EMS parameters are not physically or statistically independent, dependency relationships need to be defined using physics models or experimental or historical data.

Step 5: Assign x%tile values of the conceptual strength function. For the real stress and strength interference analysis, the X values are usually defined in a design team's analysis policy book. X values are usually a tail end point of the distribution that is 90% or 95%.

Step 6: Assign the conceptual factor of safety of the conceptual strength function (b value). Again, similar to the X%tile values, a starting value of b is also defined in a design team's analysis policy book as a minimum factor of safety.

Step 7: Establish a simulation model to evaluate P_f = Probability(STre>STrn). For this paper, we use Crystal Ball simulation tool to build the model and estimate P_f.

For Step 8, 9, and 10, we will illustrate them with the example in the following Section.

4 A CASE EXAMPLE

We use the hair dryer example. Figure 2(a) and 2(b) present two competing function structures. Table 2 lists all EMS parameters for each of the function structures. The way of determining EMS parameters are straightforward that is to read from the Function Structure graphs of Figure 2. This approach is not just a coincident but a carefully planned activity. It requires function structure development lists all possible EMS parameters explicitly.

Table 2: EMS Parameters for the Hair Dryer Function Design

F#	Function Structure 1		Function Structure 2	
	Inlet	**Outlet**	**Inlet**	**Outlet**
F1	Control signal - signal type - magnitude Electricity - voltage - current	Electricity - voltage - current	Control signal - signal type - magnitude Electricity - voltage - current	Electricity - voltage - current
F2	Electricity - voltage - current	Heat - enthalpy	Electricity - voltage - current	Heat - enthalpy
F3	Electricity - voltage - current Air - temperature - flow rate	Air - temperature - flow rate	Control signal - signal type - magnitude Electricity - voltage - current	Electricity - voltage - current
F4	Heat - enthalpy Air - temperature - flow rate	Air - temperature - flow rate	Air - temperature - flow rate Electricity - voltage - current	Air -temperature - flow rate
F5			Heat - enthalpy Air - temperature - flow rate	Air - temperature - flow rate

As we mentioned early, the design team should decide what the c_i's should be (coefficients of the conceptual stress function). For the illustrative purpose, we chose to ignore the c_i's for signal and air (c_i's=0). So we only have one constant left for each function event for both inlet and outlet EMS flows. So all remaining c_i's = 1 (Remember c_i's are about relative importance. Since only one c_i is left, any non-zero value can be assigned which will not affect CSCSIT analysis results). Table 1 provides all conceptual stress and conceptual strength functions. For probability distributions, we assign normal distributions to all EMS parameters with means and standard deviations following energy and mass conservation laws. For Function structure 1, function 1 has a sub function "split", we assign a uniform distribution for the electricity flow distribution to the downstream function 2 and 3. For the X%tile of the conceptual strength random function, we chose X% as 95%. For the conceptual factor of safety values, we use b=1.1 as a starting value. As we mentioned early, all these values are determined either based on experience, history data, or design team's policy. All are the inputs to the simulation model and all can be changed easily as sensitivity analysis parameters. We establish a computer simulation model using the Crystal Ball simulation tool [37]. Before we show the simulation results, we list all the assumptions for this analysis.

- Strength variable is treated as deterministic and its variability is not counted (this means this simulation does not count variability in design parameters and process variables)
- All EMS parameters are statistically independent
- Failure is defined as a failure to perform any desired function, measured by P(STre>STrn). So for Function Structure 1, failure of any one or more of the 4 functional events leads to a system failure. For Function Structure 2, failure of any one or more of the 5 functional events leads to a system failure.

We should point out, these assumptions are listed for us to correctly understand and interpret the result of this specific analysis. None of these assumptions impair the CSCSIT methodology. Conversely, assumption variations will help CSCSIT to refine detailed modeling treatment techniques. For example, for the case that not all EMS parameters are statistically independent, a computer simulation can assign statistical correlations among correlated parameters, based on some historical data or engineering knowledge.

Figure 3 presents the result showing failure probability comparison between Function Structure 1 and Structure 2. It shows Function Structure 2 is much more reliable than Function Structure 1 (about 20 times more). *Why?* We can look into the individual failure probabilities of Function Structure 1, which is shown in Figure 4.

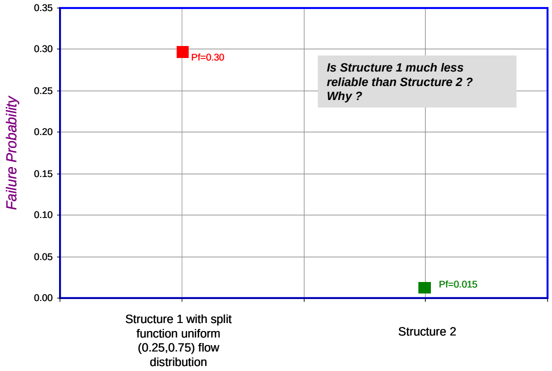


Figure 3: Hair Dryer Failure Probability

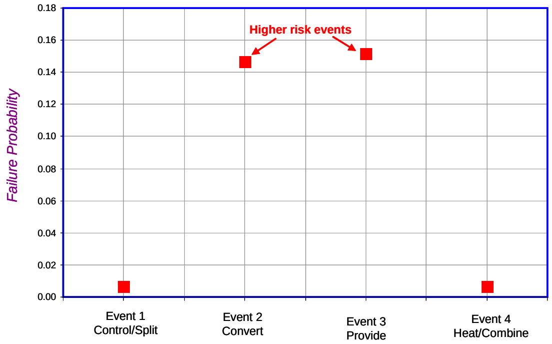


Figure 4: Individual Event Failure Probability (Function Structure 1)

Figure 4 points out Function 2 and 3 are higher risk items. This is due to electricity flow disturbance and variability from upstream Function 1 split function. Figure 5 shows the sensitivity of flow split stability on the system failure probability. It indicates, the more the electricity flow splits accurately and steadily, more reliable the system. When the flow splits 50%/50% exactly as intended, Function Structure 1 is actually more reliable than Function Structure 2. The cause of unreliability of Function Structure 1 is the split function's uncertainty and variability. How do we fix the problem to prevent failures? There are two ways. One way is to carefully design the split function and tightly control the split uncertainty and variability as Figure 5 suggests. Another way is to enhance the strengths of the downstream functions 2 and 3 such that they can tolerate more electricity variation. Figure 6 shows the sensitivity how failure probability changes when we enhance the strengths of the functions 2 and 3 with increased factor of safety from 1.1 to 1.5. When the factor of safety is increased to 1.5 for these two events, the failure probability of Function Structure 1 is reduced to about the same level as Function Structure 2's.

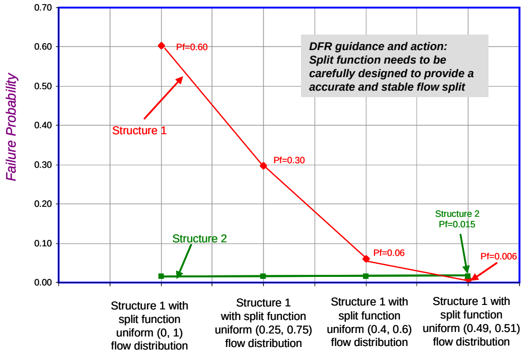


Figure 5: Failure Probability of Function Structure 1 As function of split function variability

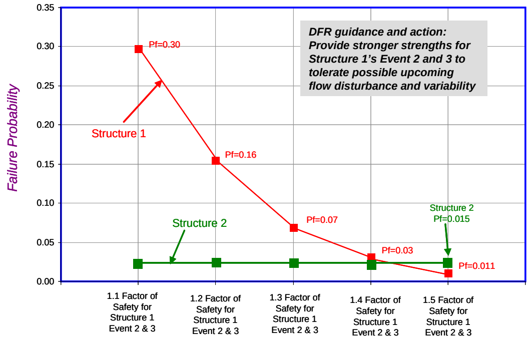


Figure 6: Failure Probability of Function Structure 1 As function of increased factor of safety for functions 2 and 3

To summarize, Function Structure 2 is more reliable than Function Structure 1 unless we pay a greater attention to Structure 1's split function design and embodiment implementation, or alternatively pay extra cost to address "higher risk items" that is to enhance the down stream functions' strengths. The result provides a clear roadmap for design for reliability and pinpoints specific design actions to address high-risk items for reliability improvement. It quantifies reliability deltas for alternative design improvement options, which is very useful information for a design team to make benefit-cost trades decision. This example shows the CSCSIT methodology enables us to satisfy all DFR wants outlined in Section 3.3 with only conceptual design data available.

5 SUMMARY AND FUTURE WORK

We introduced the concepts of *conceptual stress and conceptual strength*. We extended the traditional reliability stress and strength interference theory to a Conceptual Stress and Conceptual Strength Interference Theory (CSCSIT). We defined the implementation details for CSCSIT applications to support conceptual Design for Reliability. The CSCSIT methodology simplifies functional modeling, behavior modeling and failure modeling by just focusing on EMS (energy, material and signal) flow paths, flow anomalies and acceptable anomaly thresholds. It enables us to close or reduce the gap between design synthesis and design analysis. It also naturally and seamlessly bridges conceptual design-for-reliability to embodiment design-for-reliability. The computer simulation model allows us to model functional dependency through simulating EMS flow characteristics, and to model statistical dependency by assigning correlation variables among random EMS flows. The illustrative example demonstrates the powerfulness, effectiveness, and easiness of the CSCSIT methodology and its implementation.

The introduction of CSCSIT brings many research opportunities to further substantiate, enhance and refine the methodology. Our future research direction is to further define CSCSIT details such as conceptual stress and conceptual strength relevant to various conceptual and functional design entities, how available physics equations for a conceptual design can be used to model conceptual stress and conceptual strength. Other potential research areas are to devise conceptual design-for-reliability optimization methods and algorithms based on the CSCSIT framework, to develop CSCSIT methodology details to address function interactions, function fault/failure propagation and dynamic function effect, to develop system modeling tools to model complex function structure flow paths, to develop computer tools for general CSCSIT implementation, and to further enhance the link between CSCSIT and embodiment design-for-reliability.

6 REFERENCES

[1] Department of Defense (1980), "MIL-STD-785 Reliability Program for System and Equipment Development and Production," Washington D.C.

[2] Department of Defense (1980), "MIL-STD-1629A Procedures For Performing A Failure Mode, Effects and Criticality Analysis," Washington D.C.

[3] Ireson, G.W, C.F. Commbs, and R. Moss (1995),"Handbook of Reliability Engineering and Management," John Wiley & Sons, Inc., New York

[4] Haugen, E.B. (1980),"Probabilistic Mechanical Design," John Wiley & Sons

[5] Augusti, G., A. Baratta and F. Casciati (1984), "Probabilistic Methods in Structural Engineering," Chapman and Hall, London

[6] Nikolaidis, E., D.M. Ghiocel and S. Singhal (2005), "Engineering Design Reliability Handbook," CPC Press, London

[7] Disney, R.L., N.J. Sheth and C. Lipson (1968), "The Determination of the Probability of Failure by Stress/Strength Interference Theory, "Proceedings of Annual Symposium on Reliability, 1968, pp. 417-422

[8] Kapur, C.K. and L.R. Lamberson (1983), "Reliability in Engineering Design," Marcel Dekker, New York

[9] Kececioglu, D. (2003), "Robust Engineering Design-By-Reliability," DEStech Publications, Lancaster, PA

[10] Chiralaksanakul, A. and S. Mahadevan (2005), "First-Order Approximation Methods in Reliability-based Design Optimization," Journal of Mechanical Design, September 2005, Volume 127, No. 5, pp. 851-857

[11] Pahl, G. and W. Beitz (1996), "Engineering Design – A Systematic Approach," Springer, New York

[12] Lloyd, K.D. and M. Lipow (1984), "Reliability Management, Methods, and Mathematics," ASQ, Milwaukee

[13] El-Haik, B.S. (2005), 'Axiomatic Quality – Integrating Axiomatic Design with Six-Sigma, Reliability and Quality Engineering," John Wiley & Sons

[14] Nelson, W. (2004), "Applied Life Data Analysis," John Wiley & Sons

[15] Lawless, J.F. (2003, "Statistical Models and Methods for Lifetime data," John Wiley & Sons, New York

[16] Bain, L.J. and M. Englehardt (1991), "Statistical Analysis of Reliability and Life-Testing Models," Marcel Dekker, Inc.

[17] Kumamoto, H., E.J., Henley (1996), "Probabilistic Risk Assessment and Management for Engineers and Scientists", IEEE, New York

[18] Bedford, T. and R. Cooke (2001), "Probabilistic Risk Analysis – Foundation and Methods," Cambridge University Press, Cambridge, UK

[19] Frankel, E.G. (1984), "Systems reliability and Risk Analysis," Martinius Nijhoft, The Hague

[20] Kuo, W., V.R. Prasad, F.A. Tillman and C.L. Hwang (2001), "Optimal Reliability Design," Cambridge University Press

[21] Suh, N.P. (2001), "Axiomatic Design – Advances and Applications," Oxford University Press, Oxford

[22] Altshuller, G., H. Altov and L. Shulyak (1994), "And Suddenly the Inventor Appeared, TRIZ, Theory of Inventive Problem Solving," Technial Innovation Center, Inc., Worcester, MA

[23] Wang, K.L. and Y. Jin (2002), "An Analytical Approach to Functional Design," ASME DETC 2002-34084, Montreal, Canada

[24] Wang, K.L. and Y. Jin (1999), "Modeling dependencies in Engineering Design," DETC99/DTM-8778, Proceedings, 1999 ASME Design Theory and Methodology Conference, Las Vegas, Nevada

[25] Wang, K.L. and Y. Jin (2000), "Managing Dependencies For Collaborative Design," DETC 2000/DTM-14552, Proceedings, 2000 ASME Design Theory and Methodology Conference, Baltimore, Maryland

[26] Xu., H and J.B. Dukan (2004), "Combining Dynamic Fault Trees and Event Trees for probabilistic Risk Assessment," Proceedings, Annual Reliability and Maintainability Symposium, 2004, pp. 214-219

[27] Kurtoglu, T. and I.Y. Tumer (2007), "A Graph-Based Framework for Early Assessment of Functional Failures in Complex Systems," ASME DETC2007-35421

[28] Stone, R. and K. Wood (2002), "Development of a Functional Basis for Design," Journal of Mechanical Design, Vol. 122, No. 4, pp. 359-370

[29] Krus, D. and K.G. Lough (2007), "Applying Function-Based Failure Propagation In Conceptual Design," ASME DET C2007-35475, Las Vegas, Nevada

[30] Volovoi, V. (2006), "Stochastic Petri Net Modeling Using Aging SPN@," Proceedings, Annual Reliability and Maintainability Symposium, 2006, Newport Beach, CA, pp. 75-81

[31] Stone, R., I.Y. Tumer and M.V. Wie (2005), "The Function-Failure Design Method," Journal of Mechanical Design, Vol., 127, No. 2, pp. 397-407

[32] Taguchi, g.(1986),"Introduction to Quality Engineering," American Supplier Institute, Dearborn, MI.

[33] Taguchi, g. (1993), "Taguchi on Robust Technology Development: Bring Quality Engineering Upstream," ASME, New York

[34] Harry, M.J., (1994), "The Vision of Six-Sigma: A Roadmap for Breakthrough," Sigma Publishing Company, Phoenix, AZ

[35] American National Standard Institute (2005), "Performance Based Sneak Circuit Analysis Requirements," AIAA, Reston, VA

[36] Huncheson, R.S., D.A. McAdams, R.B. Stone, and I. Y. Tumer (2006), "A Function-Based Methodology for Analyzing Critical Events," Proceedings, DETC 2006-99535, Philadelphia, PA

[37] Decisioneering (2000), "Crystal Ball User Manual," Denver, Colorado