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(R) Use of Model Verification and Validation in Product Reliability and Confidence Assessments

RATIONALE

Document is being reviewed for Five-Year Review and corrections throughout.

FOREWORD

Model-based product reliability assessments are usually made with limited component or system test data, and are heavily reliant on results of the model. As such, the value of the model's assessment of product reliability is always in question. The purpose of model V&V is to add confidence, both qualitative and quantitative, to these assessments. At this point, we note the following:

1. It is not rigorous to have qualitative confidence in a model-based product reliability assessment, unless the same model can produce a quantitative assessment of confidence C; i.e., a number such that $0 \leq C \leq 1$.
2. The most modern standards for model V&V⁶ stress the need to quantify confidence C, $0 \leq C \leq 1$, during the V&V process.
3. All that is therefore lacking is a standard describing accepted practice and methods to link confidence C, from model V&V, with quantified model assessed product reliability R, where $0 \leq R \leq 1$ is obtained from a combination of product requirements, relevant experimental testing, and use of the Model that has undergone V&V for quantitative confidence C.
4. This standard (SAE J2940) prescribes that a when quantitative assessment of reliability R, $0 \leq R \leq 1$, is based on a model claimed to be validated^{1,5,6,39,50,58}, the assessment of reliability R should be accompanied by a quantitative assessment of confidence C, such that $0 \leq C \leq 1$.

The message and requirement of this standard is simple: to assert compliance with this SAE J2940 standard, the model-based reliability assessment must:

1. Undergo quantitative model V&V per procedures consistent with those listed in the 4.1 of this standard.
2. Contain statements as the output of the V&V process that quantify confidence, such as⁴⁹ "I am 90% confident that if I build and test the product, the results will be on the model's predicted (point or line or region) $\pm 12\%$," etc.
3. During subsequent assessments of product reliability with the model, each reliability R, $0 \leq R \leq 1$, at the component or system level, shall be paired with a quantitative confidence C, $0 \leq C \leq 1$.

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The following outlines methods that can be used to meet this standard. The referenced methods are all peer reviewed and published in the literature or as standards. They provide a graded implementation from very simple to very complex, depending on the organization's assessment of the risk associated with a given reliability assessment. The list is not all inclusive and may be expanded in the future. The list intentionally covers a wide range of possible methods and implementations so as to remain flexible enough to accommodate various risk levels and organizational cultures.

1. SCOPE

This SAE standard outlines the steps and known accepted methodologies and standards for linking Model V&V with model-based product reliability assessments. The standard's main emphasis is that quantified values for model-based product reliability must be accompanied by a quantified confidence value if the users of the model wish to claim use of a "Verified and Validated" model, and if they wish to further link into business and investment decisions that are informed by quantitative second-order risk and benefit cost considerations.

1.1 Purpose

The purpose of this standard is to provide a process for linking demonstrated and accepted standards for model V&V with peer reviewed and published methods and standards for model-based assessments of product reliability. The result will be a standard that enables a design process providing validated model-based assessments of product reliability at a quantified confidence level. This will justify and enhance the success of investments and business decisions that are based on model assessments of product reliability.

1.2 Applicability and Intended Use

The intended use of this standard is in design and assessment situations where the reliability of a physical product is being assessed using a combination of a numerical model and relevant physical test data. This is not the same as either (a) reliability assessment of a product via "go versus no-go" testing, or (b) reliability assessment of software through algorithmic computer simulation. In the situation for which this standard was written, there is usually limited test data; therefore, it is a fair consensus that, under such constraints, a numerical value for assessed reliability has little credibility without an accompanying numerical value for assessed confidence. It is the goal of this standard to provide the basic essential steps toward such an assessment: use of verified and validated models to quantitatively assess reliability at a specified quantitative confidence. To enable implementation, the standard references numerous published and peer-reviewed procedures that can meet the specifications of this standard.

1.3 Tailoring

This standard does not specify or mandate a particular numerical procedure to meet its requirements. Instead, this document provides a list (which may evolve in the future) of methods for both Model V&V and Product Reliability (at confidence) assessment that can be tailored to the risk and business considerations of a particular design or product.

A complete, but simple, procedure is given in Appendices A and B. Expanded procedures are discussed in 5.1.

2. REFERENCES

There are two procedural components needed to satisfy this standard (V&V and R at C). The following references contain procedures that vary in complexity, enabling implementation of each component on a graded scale.

2.1 Procedures and Issues for Quantitative Model V&V

(See procedure in Appendices A and B, and Appendix C references, especially those noted below and in 5.1.)

The most recent consensus documents on Model V&V include the following guides and standards:

¹ AIAA, 1998): AIAA, "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations," AIAA-G-077-1998, Reston, VA, 1998.

⁵ ASME, 2006): ASME, "Guide for Verification and Validation in Computational Structural Mechanics," ANSI Standard, ASME V&V-10, Dec 2006.

- ⁶ ASME, 2009): ASME, “Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer,” ANSI Standard, ASME V&V-20, Dec 2009.
- ⁵⁰ (DoD, 2009): DoD, “DoD Modeling & Simulation (M&S) Verification, Validation, and Accreditation (VV&A),” DoD Instruction 5000.61, Dec 2009. <http://www.dtic.mil/whs/directives/corres/pdf/500061p.pdf>
- ⁵⁸ (NASA, 2008): NASA, “Standard for Modeling & Simulation,” NASA-STD-7009, Jul 2008. <http://standards.nasa.gov/documents/detail/3315599>

As a specific first-level implementation example, Appendix A contains a copy of the major sections of SAE 2009-01-0569^{56,57} and provides a step-by-step example of an extension of the procedure in ASME V&V-20⁶, compatible with the principles of the other recent V&V guides and standards. This is done such that interpolation or extrapolation (with appropriate caveats) can be done to the real-world application domain and then linked to model assessments of product reliability at confidence. Appendix B contains additional comments and clarification regarding model form uncertainty.

2.2 Procedures and Issues for Model-Based Assessment of Product Reliability at Confidence

(See procedure in Appendices A and B, and Appendix C references, especially those noted in 5.2.)

There is no standard implementation of a linkage between model V&V and assessment of reliability at confidence.

The first level procedure in Appendix A is offered as the simplest of peer reviewed and published starting points. This implementation and example may be coupled in series or parallel using methods such as discussed by (Epstein and Liao, 2005)⁵¹ or (SAE, 2010c)⁷³ for a complete hierarchical system level procedure. A simple procedure such as Appendix A is recommended as a first, but not necessarily sufficient, step. Its greatest value in a high-risk scenario is to provide a timely roadmap so the simplifications, assumptions, and need for more elaborate methods are visible and compelling.

At that point, a shift to the procedures in the remaining references (see 5.2) may (or may not) be necessary, depending on the balance of risk, benefit, cost, and schedule. Some of these references offer partial and complete procedures and examples for model assessed reliability at confidence. In some cases (some Bayesian formulations), the term “Credibility” is used instead of “confidence,” but still on a scale such that credibility $b = C$, $0 \leq C \leq 1$, and the values of credibility C trade off directly with values of reliability R .

2.3 General References

The general references appear in Appendix C, and provide a supplemental list of relevant references on the topics of Model V&V and model-based assessment of reliability (with confidence specified or unspecified).

3. DEFINITIONS

- 3.1 This standard is consistent with the definitions given in SAE JA1000⁶¹, and the V&V standards from AIAA¹, ASME^{5,6}, DoD⁵⁰, and NASA⁵⁸, with clarifications and additions per below:

Confidence: A number C , $0 \leq C \leq 1$ or $0\% \leq C \leq 100\%$, expressing the credibility of the model to make assessments and predictions of product reliability. A model can be used with high confidence (e.g., $C = 95\%$ or $C = 99\%$) or point estimate confidence (i.e., low confidence or $C = 50\%$ one-tail, or $C = 0\%$ two-tail) depending on the risks in the subsequent business and safety decisions. However, it must always be possible to assess and report a value of $0 \leq C \leq 1$ from the Model V&V process. This value of C is paired with the model assessed value of product reliability R .

Reliability: A number R , $0 \leq R \leq 1$ or $0\% \leq R \leq 100\%$, expressing (refer to SAE JA1000⁶¹), “The ability of a product to perform a required function, under stated conditions, for a stated period of time.” Also, the “period of time” may involve a one-time, one-shot use of the product that may occur during any point in a given time interval (e.g., airbag deployment) or it may involve periodic or continual usage (e.g., gun barrel life or valve spring life). Reliability as discussed in this standard is assessed using numerical or computer models of the product that have undergone the model V&V process so that reliability can always be reported with an accompanying level of confidence.

4. PROGRAM REQUIREMENTS

Regarding compliance, this standard is directly compatible with the procedures in SAE JA1000 (SAE 1998a)⁶¹, and also (AIAA 1998)¹, (ASME 2006)⁵, (ASME 2009)⁶, (DoD 2009)⁵⁰, and (NASA 2008)⁵⁸.

The new requirement of this standard is that assessments conforming to this standard shall:

4.1 Undergo model V&V compatible with peer reviewed and published V&V standards, including at this time:

- a. (AIAA, 1998)¹
- b. (ASME, 2006)⁵
- c. (ASME, 2009)⁶
- d. (DoD, 2009)⁵⁰
- e. (NASA, 2008)⁵⁸
- f. Other V&V standards pending availability and compatibility

4.2 Provide a quantitative confidence $0 \leq C \leq 1$ for model simulations used in the assessment of product reliability.

4.3 Provide quantified model-based assessments of product reliability R , $0 \leq R \leq 1$, where each R is paired with an assessed value of confidence C , $0 \leq C \leq 1$, obtained from model V&V. The method used shall simplify to and form a continuum with a large sample formulation in the presence of sufficient data, even though in most cases this amount of data will never be obtained.

5. PROGRAM ELEMENTS

5.1 Model V&V

Model V&V shall involve the assessment and quantification of four general types of uncertainty terms. In (ASME, 2009)⁶, these can be stated as standard uncertainties without specification of a confidence level $0 \leq C \leq 1$. However, in this standard, it is a requirement to quantify confidence, since this confidence will be linked to assessed product reliability. Therefore, the four types of uncertainty terms must be assessed as a function of confidence C , $0 \leq C \leq 1$. Following is an outline of the four types of terms of uncertainty in the model output quantity of interest to be assessed, along with relevant references to aid with the assessment.

5.1.1 u_D : Data Uncertainty

Obtain and assess relevant experimental data^{4,6,7,11,39,71,72}.

5.1.2 u_N : Numerical Uncertainty

Assess model verification to include software reliability, code verification, and solution verification (grid refinement convergence, etc.)^{6,11,14,27,28,39}.

5.1.3 u_P : Parametric Uncertainty^{5,6,22,24,72}

Assess the degree to which parametric variations in the inputs result in uncertainty u_P in the output quantities of interest.

5.1.4 u_M : Model Form Uncertainty^{26,28,35,70}

Assess the degree to which model physics choices, possible ranges of “tuning knobs” or “fitting parameters,” and choices of distribution forms cause model form uncertainty u_M in the output quantities of interest.

5.2 Model-Based Product Reliability at Confidence Assessment

Model-based product reliability at confidence assessment can take one or more steps as follows:

5.2.1 Component Level

Appendices A and B provide a recommended, but not mandatory, first level procedure. More complex procedures are given in the Appendix C references noted here^{8,10,16,17,18,28,30,33,35,38,41,66,48,72,73}.

5.2.2 System Level

As a first step, the procedure in Appendices A and B may be extended to the system level with methods such as (Epstein and Liao, 2005)⁵¹ or procedures in (SAE 2010c)⁷³. Success will depend on judgment and proper choice of independent inputs and minimization of cross-term interactions. More complex procedures can help mitigate these caveats, but are less transparent and more resource intensive. These begin with methods for reliability^{55,72-73,75-78}, and then expand to include procedures for reliability at confidence. The references provide a range of such procedures^{19,20,55,31,59,66,70-74}.

5.3 Documentation and Reporting

5.3.1 Will document Model V&V per (SAE, 1998a)⁶¹, (AIAA, 1998)¹, (ASME, 2006)⁵, (ASME, 2009)⁶, (DoD, 2009)⁵⁰, or (NASA, 2008)⁵⁸.

5.3.2 Will supply results in a form so that paired values of R and C and the component and system level can be used in subsequent second-order quantitative risk and benefit/cost assessments.

6. NOTES

6.1 Revision Indicator

A change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE GROUND VEHICLE RELIABILITY COMMITTEE

APPENDIX A - A BEGINNING RECIPE LINKING V&V AND RELIABILITY AT CONFIDENCE

Simple, First-Level Procedures for Quantitative Model V&V Coupled with Reliability at Confidence.

In order to satisfy SAE J2940, any model claiming V&V shall report its V&V as discussed in the text of SAE J2940, and shall also assess reliability and confidence as paired quantities in any subsequent reliability analysis using that validated model. The example procedure in Appendices A and B is a recommended, but not mandatory, first-level assessment process to meet SAE J2940. See also more complex procedures referenced in 5.2, and see Appendix C. These more complex procedures may be used in lieu of, or together with, the example procedures of Appendices A and B.

The text of Appendix A is taken verbatim from portions of SAE 2009-01-0569 (later in SAE International Journal of Materials and Manufacturing)⁵⁶, so as to preserve its peer-reviewed and published content without changes. It is a discussion of topics presented at the panel session “Evaluation of Studies on Non-Deterministic Approaches (NDA) for Complex Systems” at the 2007 SAE World Congress, and is presented as a first level example of the entire process from model V&V through assessment of reliability at confidence. The caveats are discussed during the example along with suggestions to consider more complex procedures such as those referenced in 5.2 for the reliability at confidence assessment.

A.1 SUMMARY OF MAJOR POINTS

- Credible integration of models and design requires quantitative model V&V.
- Quantitative model V&V must quantify terms of four types as discussed below.
- Quantitative model V&V couples to the design to give bounds on reliability, i.e., the model assessed reliability as a function of confidence.
- The process described next is compatible with the newest V&V standards, and couples readily into reliability-based design.

A.2 SIMPLE BUT ILLUSTRATIVE PROCEDURE TO LINK MODEL V&V TO PRODUCT RELIABILITY ASSESSMENT

Following is a simplified step-by-step methodology for a quantified linkage between models, V&V, and reliability in design. Detail, depth, and alternatives are provided by reference to existing standards, guides, and reviewed, published literature in this area. The example is relatively easy to follow, and is compatible with SAE^{42-44,66}, AIAA¹, and ASME^{4,5,6} guides and standards in this area. However, the quantitative path it illustrates from model V&V to reliability assessment has been greatly simplified for illustrative purposes.

Our goal will be to assess reliability, using a combination of models (sometimes, but not always, finite element models) and data, with the data typically sparse and sometimes not of the pedigree we might desire. The challenge of cost is always present, so that while higher fidelity simulations and higher quality, more abundant validation-specific test data are always desirable, we must have a methodology that lets us say what we can say with limitations on our computational and test resources, and then make that methodology compatible with the case where we have all the computational and test resources we want.

The discussion that follows is simplified, but can be linked to more elaborate treatments of each topic already in existence. In other words, it is a procedure to go from a “potpourri of models and test data,” to quantitative V&V, then on to a quantitative assessment of reliability at a specific confidence level.

A.2.1 Simple Formula for Reliability Assuming A Normal PDF

Consider (Figure A1) a bolt with fixed load L and random variable strength S , with mean μ_S .

Then the *central* margin:

$$M = \mu_S - L \quad (\text{Eq. 1})$$

And, the *central* factor of safety:

$$FOS = \mu_S / L \quad (\text{Eq. 2})$$

Assume that L is known and fixed, and that the *mean* μ_S of strength S is also known with 100% confidence, and fixed, and that the random variable S has a known standard deviation σ_S .

If the distribution of S is normal, we assess the reliability index RI , or β , as:

$$\beta = (M / \sigma_S) \quad (\text{Eq. 3})$$

And we have reliability R such that:

$$R = \Phi(\beta) \quad (\text{Eq. 4})$$

Table 1 shows the resulting one-tail reliability R versus reliability index β :

Table A1 - Reliability index β and assessed reliability R , normal distribution

β	R
0.0	0.5000
1.0	0.8413
2.0	0.9772
3.0	0.9986

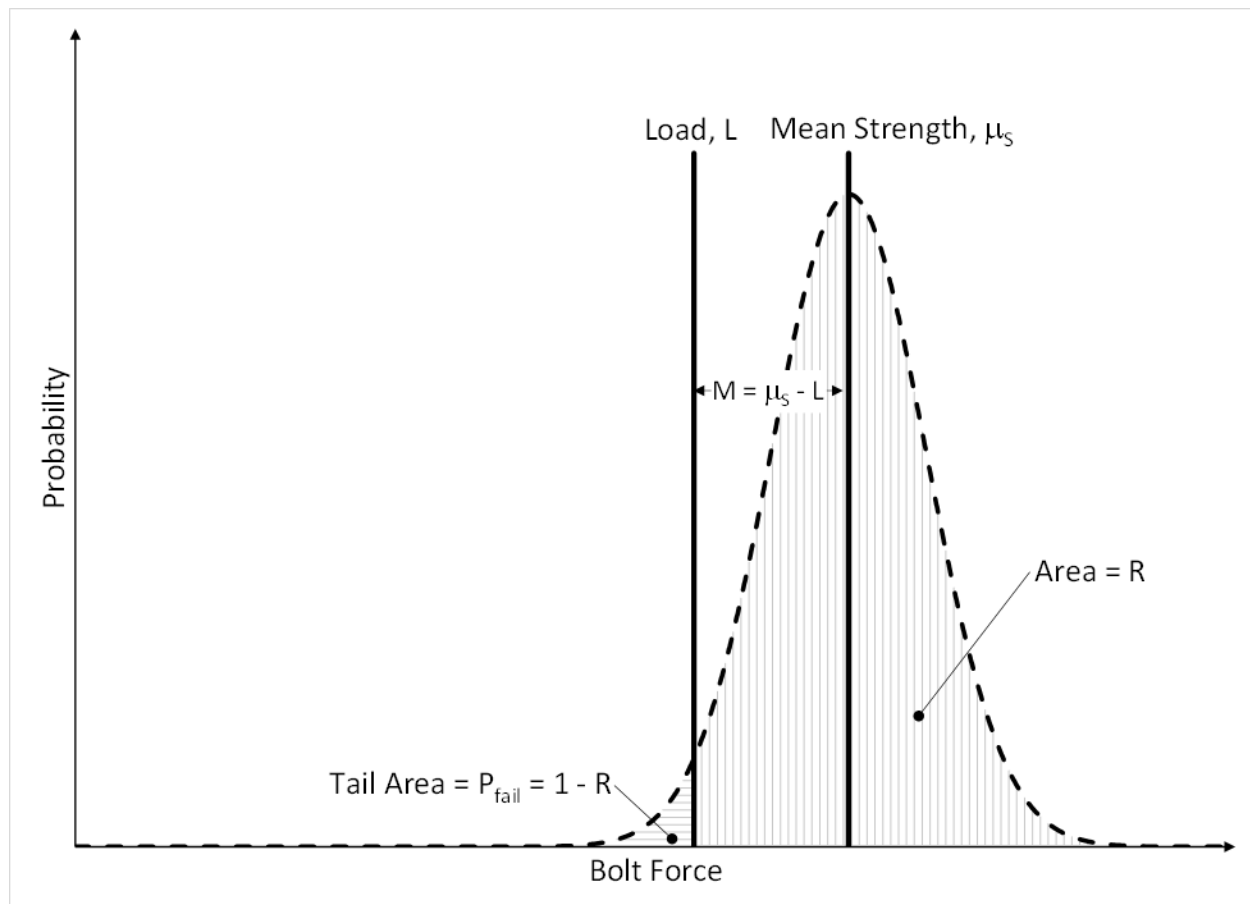


Figure A1 - Quantities for simple reliability assessment, normal distribution

A.2.2 Simple Formula for Reliability Assuming a Uniform PDF

Assume again that μ_S , the mean of S , is known at 100% confidence and fixed, and that S has a standard deviation σ_S but with a uniform PDF (Figure A2). Let the uniform PDF vary from a to b , where a is the lower limit and b is the upper limit.

Given this, the mean μ_S is equal to $(a+b)/2$, and the standard deviation σ_S is equal to $(b-a)/(2\sqrt{3})$.

Now, the distribution of strength S varies uniformly from $\mu_S - \sigma_S\sqrt{3}$ to $\mu_S + \sigma_S\sqrt{3}$.

Let:

$$U = \sigma_S\sqrt{3} = (b-a)/2 \quad (\text{Eq. 5})$$

Then, if we construct the uniform reliability index, B_u , as the ratio of margin M (mean strength - mean load) normalized by half the range of the strength:

$$B_u = (M/U) \quad (\text{Eq. 6})$$

Note carefully that $B_u \neq \beta$. We now have one-tailed reliability R_u such that:

$$R = R_u = 0.5 + 0.5 * B_u \quad (\text{Eq. 7})$$

$$(0 \leq R \leq 1)$$

Table A2 shows the resulting one-tail reliability R_u versus (uniform) reliability index B_u :

Table A2 - Reliability index B_u and assessed reliability R , normal distribution

B_u	R_u
0.00	0.5000
0.25	0.6250
0.50	0.7500
1.00	1.0000

The above is an oversimplified depiction of reliability assessment; however, it will suffice in order to make our points in linking V&V with reliability.

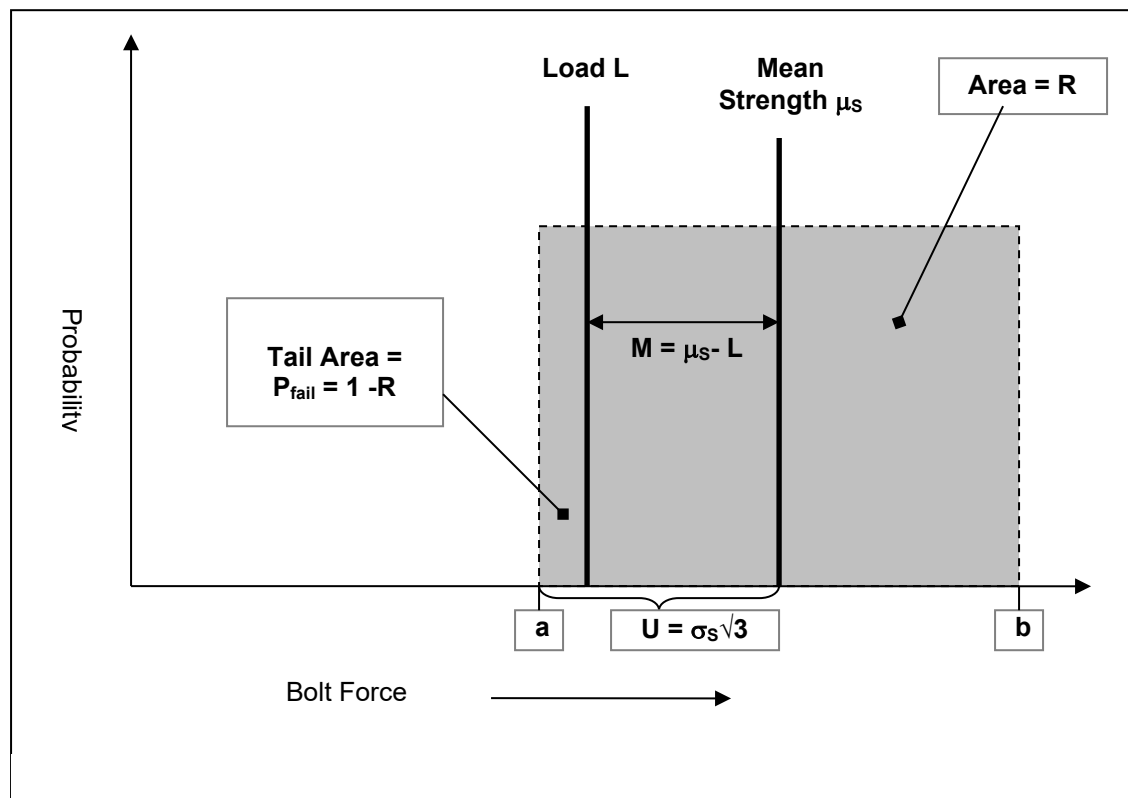


Figure A2 - Quantities for simple reliability assessment, uniform distribution

A.2.3 Details of the Model V&V to Reliability at Confidence Process

Consider the case above for the normal distribution:

$$\beta = (M/\sigma_s) \quad (\text{Eq. 3})$$

$$R = \Phi(\beta) \quad (\text{Eq. 4})$$

This looks simple enough, but we still must describe a procedure to obtain “M” and “ σ_s .”

First, we will change notation from σ_s to σ_T , and denote this as the standard (T = total, from all contributors) uncertainty of the quantity of interest (QOI). The QOI is the focus of the model V&V, and also the focus of our reliability assessment equations above. We must now link our computer model results to these terms in reliability, and we will do so using the products of model V&V. This discussion borrows heavily from the language in the AIAA Guide for V&V¹, the ASME V&V-10 Guide for V&V in Computational Structural Mechanics⁵, and the ASME V&V-20 Standard for V&V in Computational Fluid Dynamics and Computational Heat Transfer⁶.

Where possible, we follow the ASME V&V-20 nomenclature for standard uncertainty (that is, all types of relevant uncertainty terms “i” expressed as an estimate of the standard uncertainty, u_i) (not corrected for small sample size). Each of these u_i terms is comprised of a bias term b_i and a random uncertainty term s_i (the standard deviation). To obtain the standard uncertainty u_i , the terms b_i and s_i are added in quadrature. In practice, for design, we will later want to do two things:

1. “Dial out” the bias term b_i to calibrate our model to test data. Great caution is required here.
2. Assess our design at a numerical value of confidence, which may be different than the numerical value of confidence inherent in the standard uncertainty u_i (this is a function of the assessed or assumed distribution type).

Both [1] and [2] require special treatment of each u_i . For example, [1] “dialing out” a bias might mean we have added just that: a “dial” or “free parameter,” and we have to count that. On the other hand, if we want to use u_i at say “2 sigma” instead of “1 sigma” coverage (95% versus 68% confidence for the normal distribution) we might want to multiply s_i by two, but leave b_i unaltered. So we have to separate these terms back out b_i , multiply s_i by two, and then recombine. But then, it is subsequently still a good idea to multiply this new U_i by a small-sample correction factor as we will see in Section A.3.

In its simplest form, we must quantify the following four types of uncertainty terms during the model V&V process:

- u_D : The uncertainty in the experimental data and measurement of the output QOI^{4,6,7}.
- u_N : The numerical uncertainty in the spatial, temporal, and iterative solution domains, obtained from solution verification^{12,27,28,39}.
- u_P : The parametric uncertainty in the model solution output, due to known or estimated uncertainties in the input parameters (geometry, material properties, boundary and loading conditions, etc.). This is usually obtained via sensitivity coefficient analysis or Monte Carlo-style sampling methods to get *model* sensitivity to each input and their combinations, multiplied by input distributions to get u_P . In the process of obtaining, u_P we also get importance factors^{5,6,22,26,56,67}.
- u_M : The model form uncertainty. This elusive⁶ term contains all the remaining uncertainty not accounted for or underestimated in the above terms. Model form uncertainty may be due to missing physics, simplistic approximations, underestimating the width of the distribution of one of the other uncertainty terms, etc. It may be possible to assess u_M by integral^{26,59} or top down validation³⁶, or by cross-validation⁵³ or assessment of predictive capability^{28,37}.

It seems legitimate by definition to view the total standard uncertainty as some combination of these four terms, since the last term, u_M , is a subjective “catch all” term called “model form.” The meaning and quantification of u_M in particular continue to challenge and frustrate the community, but some means of estimating u_M are at least possible, if not universally accepted. A generalized combination of these four terms into a total standard uncertainty is given by:

$$\sigma_T = \sigma_T (\sigma_D, \sigma_N, \sigma_P, \sigma_M) \quad (\text{Eq. 8a})$$

In the ideal case where these four terms are separable and independent, we can express the total standard uncertainty in our model's characterization of the reality of interest (e.g., the product performing its job) as σ_T , where:

$$\sigma_T^2 \approx \sigma_D^2 + \sigma_N^2 + \sigma_P^2 + \sigma_M^2 \quad (\text{Eq. 8b})$$

Or, as used without correcting for small sample size, in the ASME V&V-20 nomenclature:

$$u_T = u_T (u_D, u_N, u_P, u_M) \quad (\text{Eq. 8c})$$

And again, *in the ideal case* where these four terms are separable and independent,

$$u_T^2 \approx u_D^2 + u_N^2 + u_P^2 + u_M^2 \quad (\text{Eq. 8d})$$

In reality, the situation is rarely this simplistic, and even when it is this simple and independent, the model validation procedure to assess values for the terms in Equation 8 is complex. However, the forthcoming ASME V&V-20 document provides methods and relationships for assessing these terms, whether or not they are independent or separable. These standard uncertainties may be obtained without making assumptions as to the form of their distribution (normal, uniform, etc.). It will be necessary to assess or assume forms for the distributions in order to make numerical assessments of confidence in reliability. For the moment, let us assume the simple case, where the terms in Equation 8 are independent, and furthermore normally distributed, and develop the basic set of equations linking V&V with reliability.

At this point, u_T is the term in the denominator of the reliability index β , so that:

$$\beta = (M/u_T) \quad (\text{Eq. 3})$$

$$R = \Phi(\beta)$$