JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 41, No. 1, January–February 2004

Method for Determining Margins in Conceptual Design

Daniel P. Thunnissen*
California Institute of Technology, Pasadena, California 91125-4500

A method for propagating and mitigating the effect of uncertainty in conceptual level design via probabilistic methods is described. This method provides a rigorous foundation for determining design margins in complex multidisciplinary engineering systems. As an example application, the investigated method is applied to the conceptual design and development of a composite overwrapped pressure vessel. The method begins with identifying a set of tradable system-level parameters. The variables of the design are then classified and assigned appropriate probability density functions. To characterize the resulting system, a Monte Carlo simulation is used. Last, results of this simulation are combined with the risk tolerance of the decision maker(s) to guide in the determination of margin levels. The method is repeated until the decision maker is satisfied with the balance of system-level parameter values. For the pressure vessel example, margins for mass, schedule, cost, and risk form a set of tradable system-level parameters. Use of this approach for the example presented yielded important differences between the calculated design margins and the values typically assumed in conceptual design.

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

Nomenclature

C = total cost, fiscal year 2002 dollars in thousands (K) (FY2002$K)
f = composite overwrap factor for fiber strength
g_0 = Earth's gravitational acceleration, 9.80665 m/s^2
hh = tank head height, m
l = tank length, m
m = mass, kg
P = pressure, Pa
P_x = xth percentile value
$R_{\mathrm{ax-hoop}}$ = axial-to-hoop stress ratio
R_{det} = deterministic result value
$R_{\mathrm{hh-r}}$ = ratio of the head height to radius of the tank
r = tank radius, m
S = stress, Pa
s = worforce salary, FY2002$K
t = thickness, m
V = volume, m^3
α = composite overwrap angle, rad
β = ballistic coefficient, kg/m^2
γ = expense rate
ζ = composite overwrap fiber strength, Pa
η = composite overwrap volume fraction
κ = burden factor
μ = mean of a normal probability distribution
ρ = density, kg/m^3
σ = standard deviation of a normal probability distribution
τ = total workforce time, workdays
ϕ = diameter, m
ω = workdays per month

Subscripts

adh = adhesive
b = burdened
i = inner tank
j = individual task
k = individual workforce member
LAH = low-angle helical
lin = liner
long = longitudinal
MEOP = maximum expected operating pressure
o = outer tank
total = total tank
ub = unburdened
ui = uninflated
wrap = composite overwrap

Introduction

SPACE systems range widely from Earth-orbiting satellites to interplanetary spacecraft. Space systems are built by one or more organizations that must have a significant knowledge base in a multitude of disciplines such as structures, thermal control, and propulsion. One or more designers/decision makers represent each of these spacecraft disciplines (subsystems). Such multidisciplinary designs often have hundreds of independent variables that uniquely define the design. When multiple organizations are involved, the complexity often increases further because interaction among specialists is more difficult. Although some space systems such as NASA's QuickSCAT have been built in 12 months, most take on the order of years, and some, such as NASA's Chandra, have taken as long as a decade.[1,2] Although the typical unit cost for a spacecraft is on the order of U.S. $100 million, some spacecraft have cost in the hundreds of millions of dollars (NASA's Cassini, U.S. Air Force's Milstar 2, ESA's Envisat).[2,3] Moreover, space systems are often unique and high unit costs are not amortized in building subsequent models of that design. Upgrading and extending the capability of space systems in orbit is prohibitively expensive and difficult.[4] Software upgrades take time on the ground in testing and delay possible revenue-generating operations in space. These ongoing issues provide opportunities and impetus for research in improving how these systems are designed and built.

The design and development of a spacecraft generally involves three major stages: conceptual (preliminary) design; detailed design and fabrication; and assembly, test, and launch operations. The transition from conceptual to detailed design occurs at different times for different disciplines. Conceptual design is typically unstructured, with engineers and designers pursuing a single concept or modifying an existing design.[5] Conceptual design is generally done deterministically, operating as though all quantities of the design are known with complete certainty. A design factor or margin is applied ex post facto to account for the uncertainties in the design because rigorous techniques for uncertainty mitigation and propagation are not available. In one extreme, uncertainty leads to systems that are over

---

Received 16 January 2003; revision received 10 June 2003; accepted for publication 12 June 2003. Copyright © 2003 by Daniel P. Thunnissen. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0022-4650/04 $10.00 in correspondence with the CCC.

*Ph.D. Student, Division of Engineering and Applied Science, M/C 205-45, 1200 East California Boulevard. Member AIAA.

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

budget, delivered late, descoped, or canceled. In the other extreme, uncertainty leads to uncompetitive, overdesigned systems that are not optimized for the requirements they are designed to satisfy.

A spacecraft is one example of a complex multidisciplinary system. Missiles, automobiles, aircraft, power plants, and submarines are all complex multidisciplinary systems that require developers to deal with issues of design uncertainty. Multidisciplinary systems are intrinsically difficult to model and understand because no single person has the detailed knowledge in all discipline areas that is required.[6] Designers often make systems complex to reduce uncertainty and allow for reliable predictability. For example, spacecraft constellations are designed to counter uncertainties in the location where a signal, such as a phone call or missile launch, may be generated. Likewise, missiles have added sensors, actuators, and computers to counter uncertainties in atmospheric conditions, release conditions, and target movement. The increased complexity of such systems shifts uncertainty in the environment to uncertainty in components and in the system as a whole. This is a significant system benefit if the critical components are sufficiently reliable. However, to realize this benefit, it is critical to have explicit models of component uncertainties and to propagate these uncertainties through the system.

The remainder of this paper documents how to reduce the effort to design and build space systems by addressing this issue of uncertainty. First, the current method of margin management is introduced. Next, the investigated method is summarized. An application of the method to a composite overwrapped pressure vessel follows. The paper ends with concluding remarks.

Margin Management of Complex Multidisciplinary Systems

The current method for mitigating and propagating uncertainties in the design and development of a complex multidisciplinary system is the use of managed system-level margins. Margins are variations in design parameters measured relative to worst-case expected values. Although the definition often differs from resource to resource, many margins are expressed as percentages, using worst-case estimate (WCE) and current best estimate (CBE):

$$\%\,\text{margin}|_{\text{current}} = \frac{\text{WCE} - \text{CBE}}{\text{CBE}} \cdot 100 \tag{1}$$

Margins are implemented to allow the various elements of a design team to work in parallel as much as possible. By providing numbers with margin (holding margin), a team of a given subsystem or discipline is more insulated from changes occurring in other subsystems or disciplines and can proceed with its design and development. As the design progresses, CBEs of resources typically rise using up the margin that was being held. Significant design and management problems can occur when the rise in the CBEs is greater than the margin being held.

For space systems, margins of varying amounts are maintained on mass, power, and telecommunication link for the spacecraft in addition to a margin on the injected capability of the launch vehicle. Some margins pertain to the spacecraft itself and others to the operation of the spacecraft. Margins are also held for cost and schedule. Margins vary throughout the design and development and their allocation is often capricious. For space systems, margins are based on historical data, heuristic, and crudely quantitative, based on such concepts as the current stage of the design and the size of the spacecraft. Furthermore, margins maintained vary not only from organization to organization, but from individual to individual (project manager–chief engineer, chief engineer–flight systems engineer, etc.) within an organization based on the risk tolerance of that organization or individual or both.

A recent space system that illustrates this concept of margin management to mitigate uncertainty is the Jet Propulsion Laboratory (JPL)/NASA Mars Pathfinder mission. Mars Pathfinder was launched on 4 December 1996 and landed on the Martian surface on 4 July 1997. Mars Pathfinder was composed of a cruise stage, lander, and rover. The three elements had a combined mass of 895 kg (fueled) at launch. The Pathfinder mission was successful from a technical, management, and public relations standpoint. This mission exceeded its goals for lifetime and data returned, launched on time and within budget, and created a significant amount of interest in both the United States and abroad.[7] The following flight system margins of Mars Pathfinder are summarized in Table 1[8]: design implementation and cost review (DICR), critical design review (CDR), assembly test and launch operations (ATLO) start, and preship review.

Table 1 illustrates the complicated nature of margin management. Margins were time phased and determined on the basis of organizational (JPL) policy, the experience of the project manager, and experience of the Pathfinder team. The many margins held throughout design and development pertained to the spacecraft itself and to the operation of the spacecraft. Mars Pathfinder also held margins (reserves) on cost and schedule that are not listed in Table 1. In fiscal year (FY) 1992 dollars (FY1992$), Pathfinder originally held a $50 million margin on a $100 million best estimate (50%) (Ref. 9). Pathfinder held a 20-weeks schedule margin on a 38-month development time (13%) (Ref. 10). The mass history of Pathfinder during its design and development is plotted in Fig. 1.[11] Figure 1 shows the WCE, CBE, and CBE plus margin for the entry mass (the mass of the spacecraft excluding the cruise stage). Because the margins for Pathfinder were based primarily on organizational policy and not according to Eq. (1), there is a difference between the WCE and CBE plus margin estimates.

In Fig. 1, the first nine months or so (May 1993–January 1994) were devoted to conceptual/preliminary design. Detailed design and fabrication was carried out from about January 1994 to June 1995. Finally, the period from June 1995 until December 1996 was dedicated to ATLO.[9] Figure 1 shows a typical trend in following a particular flight system parameter and also illustrates the uncertainty in the design and development of a spacecraft. Almost all figures of this kind have a dashed line of a given mass not to exceed that represents the selected launch vehicle capability. Mars Pathfinder was unusual

Table 1 Mars Pathfinder flight system margins

	Time-phased flight system (FS) margins, %			
Commodity	DICR	FS CDR	ATLO start	Preship review
Project manager (% of launch vehicle capability)	10	0	0	0
Launch mass (CBE% of FS allocation)	20	15	5	2
Entry mass (CBE% of entry allocation)	20	15	5	2
Propellant (CBE% of usable tank volume)	20	n/a	n/a	n/a
Power (CBE demand % of available for all phases)	25	15	10	5
Programmable ROM	40	30	20	15
Mass memory	50	40	30	25
Lander CPU processor time	50	40	30	25
Data bus capacity	50	40	20	10

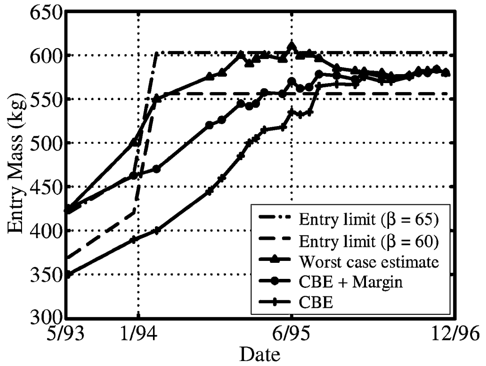


Fig. 1 Mars Pathfinder entry mass history.

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

in that the maximum allowable mass was driven by a constraint that the ballistic coefficient at Mars arrival be less than ~60–65 kg/m^2. Mass growth was a constant problem with Pathfinder, more so than with previous JPL projects. Cost and schedule were used to reduce mass during detailed design and fabrication. For example, the estimate for the maximum allowable entry mass increased three times during design and development as additional trajectory analyses were performed.[10] This updated estimate was critical because the final entry mass of Mars Pathfinder at launch (~580 kg) was considerably greater than the original maximum mass estimates (from ~370 to ~465 kg).

This concept of trading margins from one area to another is typical in the design of space systems, indeed of all complex multidisciplinary systems. The resulting design process is somewhat analogous to determining a Pareto optimal solution in multi-objective optimization.[12] Unfortunately, as the Pathfinder example illustrated, this process of trading parameters in industry is often reactive, not proactive, and unlikely to be optimal. This reactive process is, again, due primarily to uncertainty but is also encouraged by a lack of proper modeling techniques in conceptual design. A repeatable and tenable method for the determination of margins that trades these parameters proactively would be a powerful asset available to the decision maker(s) in the design and development of complex multidisciplinary systems.

Summary of Method

The following section describes a method for propagating and mitigating the effect of uncertainty in conceptual level design via probabilistic methods. Application of this method produces a rigorous foundation for determining design margins in complex multidisciplinary systems. The method comprises six distinct steps: identification of tradable parameters, model formulation, classification of variables, probabilistic modeling of variables, Monte Carlo simulation, and analysis. Each step is described in detail.

Identification of Tradable Parameters

The first step is identification of the tradable parameters. The design and development of a complex multidisciplinary system is motivated by requirements. In the case of a spacecraft, the requirement may be high-resolution imaging (reconnaissance), global positioning (navigation), or global mobile telephony (telecommunications). A complex multidisciplinary system may have more than one requirement. In the case of a missile, target accuracy (guidance and navigation), time to target intercept (speed), and low-radar signature (stealth) may all be requirements that must be satisfied to some level. The decision maker must understand the complex multidisciplinary system being analyzed to determine which parameters are truly important in satisfying the requirements placed on the system. Engineering parameters will necessarily result from this analysis. In the case of a reconnaissance spacecraft, image resolution, information relay time, and spacecraft mass may be three engineering parameters critical in meeting the requirements. Parameters such as schedule, cost, and risk, must usually be considered as well. The resulting list of tradable parameters helps guide the design and development of the complex multidisciplinary system.

Generation of Analysis Models

Once a list of tradable parameters has been identified, an analytic model must be generated to calculate each of these parameters. A model that determines engineering parameters often includes dozens or hundreds of equations and relations. A model that calculates the design and development schedule of a complex multidisciplinary system might subdivide the tasks required and estimate workforce requirements for each. A cost model might incorporate the schedule and include additional equations relating procurements, inflation, and burden factors. A risk model might estimate whether the complex multidisciplinary system will fail during development or operation. Ideally a model should be as accurate as possible given the resources available. Some models have good accuracy relative to test data, for example, mechanical structural analysis. Others may have low accuracy for engineering purposes, for example, fatigue modeling.[13] Additionally, highly accurate models may be possible but impractical because of insufficient data available or excessively long computation time. Determining how accurate models need to be, to determine the margin levels effectively in conceptual design, would significantly save time and resources in the design and development of complex multidisciplinary systems but is not addressed in this paper.

Classification of Variables

Once models have been created for all desired tradable parameters, the variables used are classified. A complex multidisciplinary system may have dozens, even hundreds, of these variables. Classifying the variables into three types, constants, design variables, and requirements, is useful in understanding the impact of uncertainty. Constants are variables in nature that the engineer or designer has little control over. Examples include the density of the atmosphere, the strength of a material, and the orbital period of a planet. Design variables are parameters over which the engineer or designer has control. Examples include the operating pressure of a propulsion system, the choice in materials, and the eccentricity of a spacecraft's orbit. Requirements are variables that some organization or individual initially determines independently of the engineer or designer. Examples include the altitude of an orbit, the launch vehicle loads to be experienced, and the latency in data return. Note that this classification is not universal and not always clear. That is, for a given complex multidisciplinary system, a certain variable may be deemed a requirement; for another complex multidisciplinary system, the variable may be deemed a design variable. A spacecraft with a particular subsystem illustrates this concept. A spacecraft may have requirements on the orbit to achieve but leave the orbit insertion design to the mission designer making the change in velocity of the spacecraft a design variable. The change in velocity of the spacecraft, however, would likely place a requirement on the propulsion system.

Probabilistic Modeling and Monte Carlo Simulation

The next step in the investigated method is probabilistic modeling of each variable earlier described. Variables are characterized by a probability density function. Although normal (Gaussian) distributions are by far the most common, other probability distributions are often used. For example, a uniform distribution may be used to model variables whose value is known to be within a range but not about any one particular value. An exponential distribution is often used in lifetime applications. A Weibull distribution is an example of one of the many distributions that can be used in reliability models (see Ref. 14). The probability density distribution applied to each variable may be determined from existing data, expert opinion, or a combination of both.

Once all of the variables involved in the design have been given a probability density function, a Monte Carlo simulation of the complex multidisciplinary system is performed. A Monte Carlo simulation involves hundreds to thousands of simulations, each using different variables generated by their relevant probability distributions. For each simulation, the tradable parameters are recorded. Hence, the Monte Carlo simulation generates probability density distributions of each tradable parameter. The more simulations performed, the smoother are the resulting tradable parameter distributions. Unfortunately, Monte Carlo simulations are often computationally expensive, especially for complex systems analysis.[15] Using parallel high-performance computer systems is one way to alleviate this issue. Otherwise, less computationally intense methods, such as metamodels and fast probability integration, exist, but these methods are not as accurate as a Monte Carlo simulation and were not investigated.[16]

Analysis and Optimization

With distributions of each tradable parameter provided by the Monte Carlo simulation, analysis and optimization of the complex multidisciplinary system is performed. Each tradable parameter distribution yields a mean and three percentiles. A percentile is defined

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

as the value that is greater than a specified percent of all of the values in a set. A percentile of 50 is simply the statistical median of a sample. Percentiles provide a confidence indication in the value of a tradable parameter. The 95, 99, and 99.9 percentiles of a tradable parameter provide a decision maker with a low-, medium-, and high-confidence estimate in the probability that a tradable parameter will not be exceeded. The difference between these 95, 99, and 99.9 percentiles and the deterministic result provide the decision maker with a margin value to be maintained at the current stage of the design. The percent margin is this margin value divided by the deterministic result (and multiplied by 100):

$$\%\,\text{margin}|_{\text{proposed}} = [(P_x - R_{\text{det}})/R_{\text{det}}]\cdot 100 \tag{2}$$

Once the deterministic results, distributions, and percentiles are analyzed, the decision maker may wish to investigate one or more different designs. This process can be accelerated through the use of optimization algorithms. As uncertainty in the values of variables decrease with time, the probability density distributions of each variable can be improved and updated. Repeating the process will yield updated margins as the design progresses. In summary, this method redefines the concept of design margin that was introduced earlier. Here, margins are a function of risk tolerance and are measured relative to mean expected system performance, not variations in design parameters measured relative to WCE values.

Application: Design of a Composite-Overwrapped Pressure Vessel

The investigated method was applied to a composite-overwrapped pressure vessel. A composite-overwrapped pressure vessel, hereafter referred to as tank, is composed of a liner, an overwrap, and an adhesive that binds the two together. The liner is typically a metal such as aluminum, titanium, or stainless steel. The tank is fabricated by continuously winding a filament over a mandrel of the shape and size of the desired vessel. A matrix (adhesive) material is usually applied simultaneously with the winding operation. The winding of a tank is accomplished by using two independent wrapping systems oriented in the direction of the two principal stresses.[17]

The major design assumptions of this analysis were a titanium-lined, poly (p–phenylene–benzobisoxazole) (PBO) overwrapped tank. The liner material is selected based on the propellant or pressurant. Titanium is often used with many current propellants and pressurants. PBO is a relatively new fiber tested under U.S. Air Force funding. PBO development continues under the name ZYLON® at Toyobo Co., Ltd. (Osaka, Japan).[18] The term composite overwrap will often be abbreviated as overwrap in this paper. A tank was chosen for this analysis because it is a component used in space systems, amenable to deterministic and probabilistic modeling and analysis, and optimizable via traditional gradient methods.

Unfortunately, elements of tank design and processing are proprietary, and assumptions were made in modeling and analysis. Every effort was made to make this analysis as realistic as possible. The method being applied to the tank, however, is the crux of this research, not the actual tank analysis. Typical values for the factor of safety used in tank calculations were removed. Hence, the burst pressure of the tank was set to the maximum expected operating pressure with the understanding that the factor of safety would be a result of this analysis.

Tradable Parameters

The tradable parameters identified for a tank were the mass, schedule, cost, and risk. The tank mass includes the liner, adhesive, and overwrap but does not include the boss or skirt mountings or any expulsion device. The typical mass margin held during conceptual design of such a tank is 30%. The schedule is defined as the time, starting from the authority to proceed by the customer (and allocation of funds), to design, build, test, and deliver the tank. The typical schedule margin held during conceptual design is one week for four weeks of schedule (25%). The cost is defined as the amount in FY2002$ to design, build, test, and deliver the tank. The typical cost margin held during conceptual design is 10%. The risk is defined as the likelihood of irrecoverable technical failure during design, development, testing, or delivery of the tank. The model formulation of each of these tradable parameters follows.

Engineering Pressure Vessel Design Model

Tank properties were determined iteratively using thin-wall and composite material theory.[19] The inner diameter was initially set to the maximum allowable outer diameter of the tank. The low-angle-helical thickness, hoop thickness, overwrap thickness, and overall thickness of the tank were calculated such that the actual inner diameter could be determined. The low-angle-helical thickness is determined from

$$t_{\text{LAH}} = \frac{P_{\text{burst}}(\phi_i/2 + t_{\text{lin}} + t_{\text{adh}})}{2\zeta\ f\ \eta\ R_{\text{ax}-\text{hoop}}\cos^2(\alpha)} \tag{3}$$

The hoop thickness is calculated as

$$t_{\text{hoop}} = \frac{P_{\text{burst}}(\phi_i/2 + t_{\text{lin}} + t_{\text{adh}} + t_{\text{LAH}})}{\zeta f \eta} \tag{4}$$

Equations (3) and (4) are modifications to the familiar $t = Pr/2S_{\text{long}}$ and $t = Pr/S_{\text{hoop}}$ expressions for the thickness of a pressure vessel from thin-wall theory.[20]

The overwrap thickness is the sum of the low-angle-helical and hoop thickness:

$$t_{\text{wrap}} = t_{\text{LAH}} + t_{\text{hoop}} \tag{5}$$

The overall tank thickness is

$$t_{\text{total}} = t_{\text{lin}} + t_{\text{adh}} + t_{\text{wrap}} \tag{6}$$

The inner tank diameter is

$$\phi_i = \phi_o - 2t_{\text{total}} \tag{7}$$

The calculation for the inner tank diameter using this new inner diameter estimate was repeated until the difference between estimates was insignificant, chosen here to be 10^{-9} m.

With the thickness of the various elements of the tank and the inner diameter determined, the inner tank length can be determined from

$$l_i = \frac{4}{\pi\phi_i^2}\left(V_i + \frac{\pi\phi_i^3 R_{\text{hh}-\text{r}}}{12}\right) \tag{8}$$

The tank head height is

$$hh = R_{\text{hh}-\text{r}}\phi_i/2 \tag{9}$$

and the tank outer length is

$$l_o = l_i + 2t_{\text{total}} \tag{10}$$

With the geometry of the tank known, the volume of the liner, the adhesive, and the overwrap can be determined as

$$\begin{aligned}
V_{\text{lin}} &= \pi\left[(\phi_i/2 + t_{\text{lin}})^2 - (\phi_i/2)^2\right](l_i - 2\cdot hh)\\
&\quad + \tfrac{4}{3}\pi\left[(\phi_i/2 + t_{\text{lin}})^2(hh + t_{\text{lin}}) - (\phi_i/2)^2\cdot hh\right]\\
V_{\text{adh}} &= \pi\left[(\phi_i/2 + t_{\text{lin}} + t_{\text{adh}})^2 - (\phi_i/2 + t_{\text{lin}})^2\right](l_i - 2\cdot hh)\\
&\quad + \tfrac{4}{3}\pi\left[(\phi_i/2 + t_{\text{lin}} + t_{\text{adh}})^2(hh + t_{\text{lin}} + t_{\text{adh}})\right.\\
&\quad \left. - (\phi_i/2 + t_{\text{lin}})^2(hh + t_{\text{lin}})\right]\\
V_{\text{wrap}} &= \pi\left[(\phi_i/2 + t_{\text{lin}} + t_{\text{adh}} + t_{\text{wrap}})^2\right.\\
&\quad \left. - (\phi_i/2 + t_{\text{lin}} + t_{\text{adh}})^2\right](l_i - 2\cdot hh)\\
&\quad + \tfrac{4}{3}\pi\left[(\phi_i/2 + t_{\text{lin}} + t_{\text{adh}} + t_{\text{LAH}})^2(hh + t_{\text{lin}} + t_{\text{adh}} + t_{\text{LAH}})\right.\\
&\quad \left. - (\phi_i/2 + t_{\text{lin}} + t_{\text{adh}})^2(hh + t_{\text{lin}} + t_{\text{adh}})\right]
\end{aligned} \tag{11}$$

The mass of the liner, adhesive, and overwrap can then be calculated from the relations

$$m_{\text{lin}} = V_{\text{lin}}\rho_{\text{lin}}, \qquad m_{\text{adh}} = V_{\text{adh}}\rho_{\text{adh}}, \qquad m_{\text{wrap}} = V_{\text{wrap}}\rho_{\text{wrap}} \tag{12}$$

The total tank mass is the sum of these three masses:

$$m_{\text{total}} = m_{\text{lin}} + m_{\text{adh}} + m_{\text{wrap}} \tag{13}$$

The figure of merit for tanks is defined to be PV/W (pressure–volume/weight). This value is, therefore,

$$PV/W = \frac{P_{\text{burst}}V_i}{g_0 m_{\text{total}}} \tag{14}$$

Again note that the boss, skirt, and expulsion device masses were not estimated in this analysis.

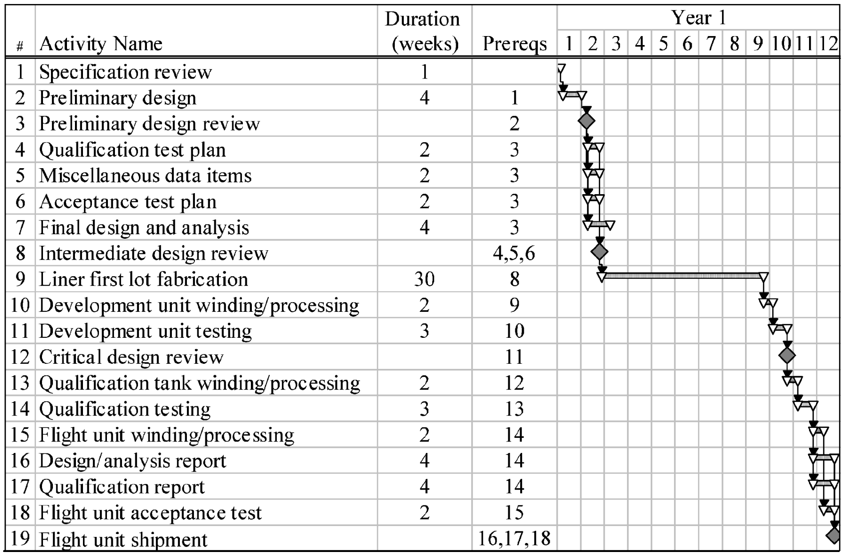
Schedule Model

A schedule model was developed to determine the time in workdays required to design and develop the tank. A nominal, deterministic schedule was created for a typical tank based on industry input. This nominal schedule is shown in Fig. 2. As Fig. 2 illustrates, the design and development of the tank is composed of 19 tasks. The bars represent multiple-day tasks, the diamonds represent single-day tasks, and the arrows indicate prerequisites for that task to proceed. The duration and workforce required is estimated for each task. It is estimated that six individuals were needed for the design and development of the tank: a design engineer, an analysis engineer, a program manager, a process development engineer, a test engineer, and a technician. Table 2 lists this workforce allocation of each individual for each task. For example, the first task, specification review, is estimated to take five workdays (one work week) assuming three individuals are involved: a program manager at two-tenths time, a design engineer at half-time, and an analysis engineer at two-tenths time. Because this is the first task, no prerequisites are required for this task to proceed. The final task, flight unit shipment, is estimated to take one workday assuming three individuals are involved: a program manager at one-tenth time, a test engineer at half-time, and a technician at full time. Three prerequisites are required for this task to proceed: design/analysis report, qualification report, and flight unit acceptance test.

Hence, the schedule model determines the total time to complete the design and development of the tank in addition to the time and workforce required to complete each individual task. Time and

Table 2 Workforce allocation for tank design and development

	% of full-time work allocated					
Task	Program manager	Design engineer	Analysis engineer	Process development engineer	Test engineer	Technician
Specification review	20	50	20	0	0	0
Preliminary design	20	50	20	0	0	0
Preliminary design review	100	100	100	0	0	0
Qualification test plan	20	20	20	0	0	0
Miscellaneous data items	20	40	20	0	0	0
Acceptance test plan	20	20	20	0	0	0
Final design and analysis	20	50	50	0	0	0
Intermediate design review	100	100	100	0	0	0
Liner first lot fabrication	10	0	0	10	0	20
Development unit winding/processing	10	20	20	25	0	0
Development unit testing	10	0	0	25	50	50
CDR	100	100	100	0	0	0
Qualification tank winding/processing	10	20	20	0	0	0
Qualification testing	10	0	0	0	50	50
Flight unit winding/processing	10	20	20	0	0	0
Design/analysis report	20	20	20	0	0	0
Qualification report	20	0	0	0	25	0
Flight unit acceptance test	10	0	0	0	50	25
Flight unit shipment	10	0	0	0	50	100



#	Activity Name	Duration (weeks)	Prereqs
1	Specification review	1	
2	Preliminary design	4	1
3	Preliminary design review		2
4	Qualification test plan	2	3
5	Miscellaneous data items	2	3
6	Acceptance test plan	2	3
7	Final design and analysis	4	3
8	Intermediate design review		4,5,6
9	Liner first lot fabrication	30	8
10	Development unit winding/processing	2	9
11	Development unit testing	3	10
12	Critical design review		11
13	Qualification tank winding/processing	2	12
14	Qualification testing	3	13
15	Flight unit winding/processing	2	14
16	Design/analysis report	4	14
17	Qualification report	4	14
18	Flight unit acceptance test	2	15
19	Flight unit shipment		16,17,18

Fig. 2 Nominal deterministic tank schedule.

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

Table 3 Workforce classifications and salary for tank design and development

Workforce member	Variable	Classification	Salary, FY2002$K/year
Program manager	s_1	Staff	100
Design engineer	s_2	Staff	80
Analysis engineer	s_3	Staff	80
Process development engineer	s_4	Service	150
Test engineer	s_5	Service	150
Technician	s_6	Service	150

workforce allocations are modified slightly for different tank designs. The critical task in the design and development of the tank is the liner first lot fabrication. This task nominally takes between 20 and 40 weeks, depending on the thickness of the liner.

Cost Model

A cost model was developed for the tank that used the time and workforce estimates generated by the schedule model. The workforce is separated into two categories for cost estimation: staff and services. Staff is defined as employees of the organizational division tasked to design and build the tank. Services is defined as either another division of the organization (or an entirely separate organization) tasked to assist in the design and development of the tank. The inclusion of services in the cost model is representative of current industry practice where one organization often does not have the capability or workforce to complete the entire design and development themselves. The workforce types, their classification, and their assumed annual salary in FY2002$ in thousands (K) are provided in Table 3.

The workforce cost is estimated for each staff type, for each task. The total unburdened cost is defined by

$$C_{\text{ub}} = \sum_{j=1}^{19} \sum_{k=1}^{6} \frac{\tau_{j \cdot k} s_k}{12\omega} \tag{15}$$

Note that the total workforce time of each individual for each task is determined by the schedule model and the workdays per month was assumed to be 20.5 for this analysis. The total burdened cost is determined by applying a burden factor to the unburdened costs:

$$C_b = \kappa C_{\text{ub}} \tag{16}$$

The burden factor, assumed to be four in this analysis, accounts for expenses such as the office infrastructure, secretarial salaries, janitorial services, electricity, and so on. The burden factor is generally inversely proportional to the size of the company. An expense rate is applied to the burdened cost to yield the total uninflated cost

$$C_{\text{ui}} = \gamma C_b \tag{17}$$

The expense rate, assumed to be 8%, accounts for computer, network, and telephone support. The workforce cost is also estimated for each services type, for each task. Services cost are unburdened, and no expense rate is applied to the total unburdened cost. The base salary for services, however, is significantly higher than staff, embedding burden and expense costs in the base salary. Based on the schedule model, the uninflated staff and services costs are inflated per a specified inflation rate, assumed to be 3% per year in this analysis, to yield the total inflated cost. The cost model also includes miscellaneous (procurement) and travel expenses.

Procurement and travel expenses are summarized in Table 4. Note that typically only a few tasks in a given project require procurements or travel expenses. For the design and development of the tank discussed, only 5 of the 19 tasks anticipate such expenses. In additional to total costs, the cost model generates cost required per workday for the design and development of the tank.

Table 4 Procurements and travel expenses for tank design and development

Task	Estimated cost, FY2002$K	Expense type
Specification review	3	Travel
Preliminary design	20	Materials
	10	Miscellaneous
Development unit winding/processing	5	Materials
	5	Miscellaneous
Qualification tank winding/processing	5	Materials
	5	Miscellaneous
Flight unit shipment	3	Travel

Table 5 Constant variables for the tank[a]

Variable	Parameter 1	Parameter 2
f	μ: 0.806	σ: 0.00269
ζ	μ: 2.41 GPa	σ: 8.04 MPa
η	μ: 0.65	σ: 0.00217
ρ_{adh}	μ: 1384	σ: 4.61
ρ_{lin}	μ: 4429	σ: 14.76
ρ_{wrap}	μ: 1605	σ: 5.35

[a] Normal distribution.

Table 6 Design variables for the tank[a]

Variable	Parameter 1	Parameter 2
$R_{\text{ax-hoop}}$	μ: 0.75	σ: 0.075
$R_{\text{hh-r}}$	μ: 0.66	σ: 0.066
t_{adh}, mm	μ: 0.127	σ: 0.0762
t_{lin}, mm	μ: 0.508	σ: 0.0762
α	μ: 0.0524	σ: 0.0175

[a] Normal distribution.

Table 7 Requirement variables for the tank[a]

Variable	Parameter 1	Parameter 2
P_{MEOP}, MPa	Minimum: 11.03	Maximum: 16.55
V_i, m^3	Minimum: 0.16	Maximum: 0.24
ϕ_o, m	Minimum: 0.4	Maximum: 0.6

[a] Uniform distribution.

Risk Model

A crude risk model was included. Risk is defined as the likelihood of catastrophic failure during design and development that leads to the tank not being delivered. A catastrophic failure could be fatigue during cycle testing. For this study, a catastrophic failure is modeled as likely to occur when the liner thickness of the tank is less than 0.381 mm (15 mil). For a given analysis, the risk is quantified by a 0 if the tank did not fail and a 1 if the tank did fail. A combination of noncatastrophic events could also lead to the tank not being delivered, but this was not modeled. A more rigorous risk model could be developed to account for other catastrophic and noncatastrophic events.

Classification and Probabilistic Modeling of Variables

The variables discussed in the preceding sections were classified as constants, design variables, or requirements. This classification aids in understanding the impact of uncertainty in the design and development of the tank. Table 5 lists the constants and their assumed probabilistic representation in the analysis. For each variable, the probability distribution assumed and the corresponding parameters that define that probability distribution are provided. Tables 6 and 7 provide the same information for the design variables and requirements in the analysis, respectively. Not listed in Table 6, but nonetheless design variables, are the estimated time to

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

complete each task and the procurement/travel expenses. As was mentioned in the schedule model section, the time to complete each task is estimated along with the workforce required. These estimates are provided in Fig. 2 and Table 2. All tasks except the four one-day tasks are given normal distributions with a mean provided in the third column of Fig. 2 and a standard deviation equal to a 10th of the mean. The four one-day tasks are given normal distributions with a mean of one workday and a standard deviation of zero. The workforce allocations of Table 2 are not varied probabilistically because uncertainty in workforce is assumed in the distributions given to the task times. The procurements and travel expenses are given normal distributions with the mean provided in the second column of Table 4 and a standard deviation equal to a 10th of the mean.

Monte Carlo Simulation and Analysis of Results

A deterministic analysis was performed with the schedule, workforce, constants, design variables, and requirements discussed. This analysis will be referred to as design A. The tradable parameters mass, schedule, cost, and risk of design A were determined to be 15.8 kg, 259 workdays, FY2002$274K, and 0, respectively. A second analysis followed in which the constants, design variables, and requirements were randomly generated 10,000 times based on their probability distributions. The results of this 10,000-sample analysis are summarized in Figs. 3 and 4. Figure 3 shows the probability density functions (PDFs) of the mass, schedule, and cost. Comparing the 95, 99, and 99.9 percentile values of mass, schedule, and cost listed in the cumulative distribution functions (CDFs) of Fig. 4 with the corresponding deterministic values establishes a low-, medium-, and high-confidence estimate of the margin to hold at the current stage of the design. In the case of mass, the low-, medium-, and high-confidence estimates of margin (percent margin) are 4.5 (28.5), 6.1 (38.6), and 7.8 kg (49.4%), respectively. The low-, medium-, and high-confidence estimates of schedule margin are 28 workdays (10.8), 38 workdays (14.7), and 49 workdays (18.9%), respectively. Finally, the low-, medium-, and high-confidence estimates of cost margin are FY2002$14K (5.1), FY2002$19K (6.9), and FY2002$25K (9.1%), respectively. The risk was determined to be 4.87%, the percentage of tanks that failed testing.

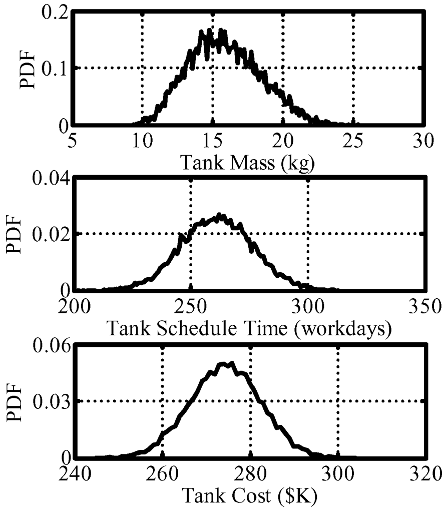


Fig. 3 PDFs of mass, schedule, and cost for design A.

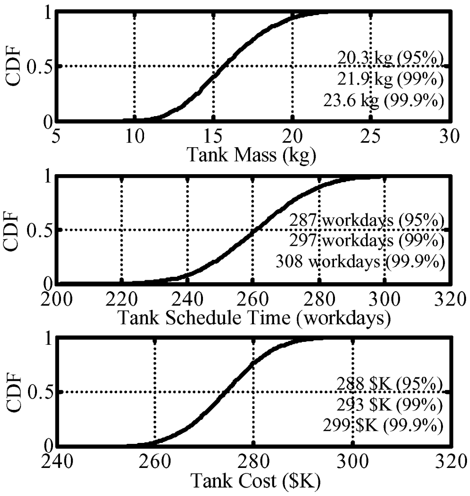


Fig. 4 CDFs of mass, schedule, and cost for design A.

A different design, design B, was investigated to see whether it was possible to trade margin among the four parameters. A deterministic analysis was performed with the schedule, workforce, constants, design variables, and requirements of design A with two changes: The mean liner was assumed to be 0.635 mm, and the liner first lot fabrication was assumed to be 100 days. These two changes represent the decision maker's desire to investigate how a mass increase (slightly thicker liner) will impact the other three tradable parameters of schedule, cost, and risk. The tradable parameters mass, schedule, cost, and risk of design B were determined to be 16.8 kg, 209 workdays, FY2002$256K, and 0, respectively. A second analysis followed in which the constants, design variables, and requirements were randomly generated 10,000 times based on their probability distributions. The results of this 10,000-sample analysis are summarized in Figs. 5 and 6. Figure 5 shows the PDFs of the mass, schedule, and cost. Comparing the 95, 99, and 99.9 percentile values of mass, schedule, and cost listed in Fig. 6 with the corresponding

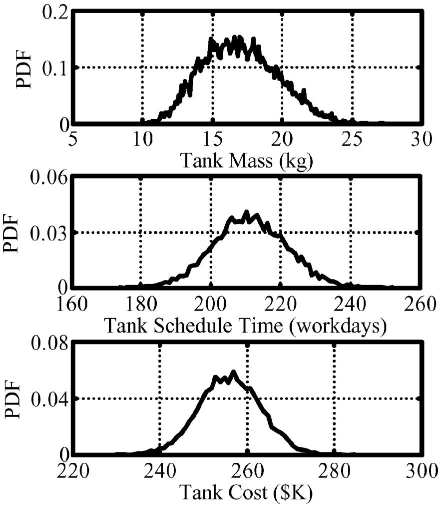


Fig. 5 PDFs of mass, schedule, and cost for design B.

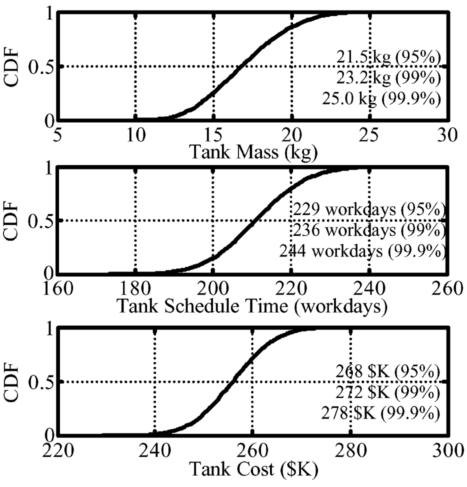


Fig. 6 CDFs of mass, schedule, and cost for design B.

Downloaded by LOCKHEED MARTIN MS2 on January 2, 2014 | http://arc.aiaa.org | DOI: 10.2514/1.9211

deterministic values updates the low-, medium-, and high-confidence estimates of the margin to hold at this stage of the design. In the case of mass, the low-, medium-, and high-confidence estimates of margin are now 4.7 (28.0), 6.4 (38.1), and 8.2 kg (48.8%), respectively. The low-, medium-, and high-confidence estimates of schedule margin are 20 workdays (9.6), 27 workdays (12.9), and 35 workdays (16.7%), respectively. Finally, the low-, medium-, and high-confidence estimates of cost margin are FY2002$12K (4.7), FY2002$16K (6.3), and FY2002$22K (8.6%), respectively. The risk was determined to be 0.03%, the percentage of tanks that failed testing. Hence, the deterministic and probabilistic analyses indicate that design B yields a more robust and less expensive tank that can be designed and delivered sooner than design A. Design B, however, has a slightly greater mass whose increase would be critical in a mass-constrained design. Arguably the most important conclusion with respect to this research is that the established and updated margins determined by this method are not the values typically assumed during the conceptual design stage (30% for mass, 25% for schedule, and 10% for cost). Based on the analysis, holding 30% mass margin is risky; holding 25% schedule margin is conservative.

Conclusions

A method for propagating and mitigating the effect of uncertainty in conceptual level design via probabilistic methods has been presented. The goal of this research is to develop a rigorous foundation for determining design margins in complex multidisciplinary systems. A result of this work is a redefinition of the concept of design margin. Here, margins are a function of risk tolerance and are measured relative to mean expected system performance, not variations in design parameters measured relative to worst-case expected values. The investigated method was applied to the conceptual design and development of a composite overwrapped pressure vessel (COPV). For the COPV example presented, margins for mass, schedule, cost, and risk formed a set of tradable system-level parameters. Assuming a conservative, high-confidence approach to design and development, the first point design established that margins of 49.4, 18.9, and 9.1% should be maintained for mass, cost, and schedule, respectively. The second design, which traded two design variables, updated these margins to 48.8, 16.7, and 8.6%. Both cases indicate an important difference from the margins of 30, 25, and 10%, that are typically assumed at the conceptual design stage. This difference would have a significant impact on the design and development of a complex multidisciplinary system under tight mass, cost, schedule, and risk constraints.

Acknowledgments

This research is funded by the Space Systems, Policy, and Architecture Research Consortium. The author thanks F. Culick and J. Sercel, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California; J. Lewis, L. Grimes-Ledesma, and R. Baker, Propulsion Flight Systems Group, Jet Propulsion Laboratory (JPL), Pasadena, California; J. Harris and M. Higgins, Pressure Technology Division, Carleton Technologies, Glen Burnie, Maryland; B. Muirhead, Deep Impact Project, JPL, Pasadena, California; and S. Chung, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

References

[1] Scott, W., "QuickSCAT Validates New NASA Strategy," *Aviation Week and Space Technology*, Vol. 150, No. 20, 17 May 1999, pp. 68–69.

[2] Baker, D., *Jane's Space Directory*, 18th ed., Jane's Information Group, Ltd., Coulsdon, England, U.K., 2002, pp. 452, 462, 555.

[3] Taverna, M., "Europe Prepares to Orbit Its Largest Satellite Ever," *Aviation Week and Space Technology*, Vol. 156, No. 3, 21 Jan. 2002, p. 49.

[4] Griffin, J., "Background and Programmatic Approach for the Development of Orbital Fluid Resupply Tankers," AIAA Paper 86-1601, June 1986.

[5] Mosher, T., "Conceptual Spacecraft Design Using a Genetic Algorithm Trade Selection Process," *Journal of Aircraft*, Vol. 36, No. 1, 1999, p. 200.

[6] Griffin, M., and French, J., "The Team," *Space Vehicle Design*, AIAA, Washington, DC, 1991, p. 4.

[7] Golombek, M., "The Mars Pathfinder Mission," *Scientific American*, Vol. 279, July 1998, pp. 44, 45.

[8] Muirhead, B., "MESUR Pathfinder Project Flight System Implementation Plan," Jet Propulsion Lab., Rept. JPL D-10897, PF-100-1.4.A, California Inst. of Technology, Pasadena, CA, Feb. 1994, p. 21.

[9] Spear, A., "Mars Pathfinder Project Progress Report," *Acta Astronautica*, Vol. 39, No. 1–4, 1996, pp. 94–98.

[10] Muirhead, B., "Mars Pathfinder Flight System Design and Implementation," *Proceedings of the 17th IEEE Aerospace Applications Conference*, IEEE Publications, Piscataway, NJ, 1996, pp. 170–171.

[11] Muirhead, B., and Cook, R., "Mars Pathfinder Flight System Lessons Learned," Jet Propulsion Lab., Rept. JPL D-14531, PF-100-97-LL1, California Inst. of Technology, Pasadena, CA, April, 1997, p. 25.

[12] Keeney, R., and Raiffa, H., "The Efficient Frontier," *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*, Wiley, New York, 1976, pp. 70–72.

[13] Du, X., and Chen, W., "Methodology for Managing the Effect of Uncertainty in Simulation-Based Design," *AIAA Journal*, Vol. 38, No. 8, 2000, p. 1471.

[14] Evans, M., Hastings, N., and Peacock, B., "Weibull Distribution," *Statistical Distributions*, 3rd ed., Wiley, New York, 2000, p. 192.

[15] DeLaurentis, D., and Mavris, D., "Uncertainty Modeling and Management in Multidisciplinary Analysis and Synthesis," AIAA Paper 2000-0422, Jan. 2000.

[16] Fox, E., "The Pratt and Whitney Probabilistic Design System," AIAA Paper 94-1442, April 1994.

[17] Harvey, J., "Filament-Wound Pressure Vessels," *Theory and Design of Modern Pressure Vessels*, 2nd ed., Van Nostrand Reinhold, New York, 1974, p. 413.

[18] Peters, S., Humphrey, W., and Foral, R., "New Fiber Developments," *Filament Winding Composite Structure Fabrication*, 2nd ed., Society for Advancement of Material and Process Engineering, Covina, CA, 1999, pp. 2–9.

[19] Peters, S., Humphrey, W., and Foral, R., "Rocket Motor and Pressure Vessels," *Filament Winding Composite Structure Fabrication*, 2nd ed., Society for Advancement of Material and Process Engineering, Covina, CA, 1999, Chap. 6.

[20] Beer, F., Johnston, E., and DeWolf, J., "Stresses in Thin-Walled Pressure Vessels," *Mechanics of Materials*, 3rd ed., McGraw–Hill, Boston, 2002, pp. 462–465.

J. Korte
Guest Editor