Requirements Risk Assessment - Integrating QFD and Risk Assessment

C. Robert Kenley
Kenley Consulting, LLC
165 S 20TH ST
RICHMOND, IN USA 47374-5723

Fourteenth Annual International Symposium of the
International Council On Systems Engineering (INCOSE)
21 June – 24 June 2004

Abstract. A modified Quality Function Deployment (QFD) analysis [Hauser and Clausing, 1988] was applied to evaluate development risk for user requirements across multiple system architectures. Applying QFD to the risk assessments required tailoring the approach to capture and quantify subjective risk judgments and to reconcile them with raw risk assessment data from specific designs. Initial evaluation of development risk from each architecture showed that overall risk reduction activities were acceptable as planned. Risk assessments were also conducted on updated designs using the QFD assessment to confirm validity of the final risk reduction plans.

This method extends previous work by Clausing and Cohen [1999], which described the use of QFD to capture requirements relationships, and U.S. Air Force guidance [AFMC, 1977], which describes methods for risk evaluation. It allows capture of the strength of relationship between user requirements and development risk early in a program by use of conceptual system architectures. This permits early evaluation of the trade offs between user requirements and risk mitigation efforts prior to committing a program to a functional baseline is established for user requirements and the design solution.

Requirements Risk Assessment Methodology

Introduction. U.S. Air Force guidance on risk assessment describes methods to evaluate programmatic risk for developmental items that are key to achieving system performance, cost, and schedule objectives [AFMC, 1977]. Major system development under the U.S. Air Force are now governed by the principle of Reduced Total Ownership Cost (R-TOC) using cost as an independent variable [CAIV] to define systems that are balanced across multiple dimensions including risk as shown in Figure 1 taken from Kaye, et al [2000]. They state:

> Cost as an independent variable is a key tool in the thrust to reduce total ownership cost for defense systems. While the need for CAIV is driven by cost constraints, success relies upon identification and use of viable performance, cost, schedule, and risk “trade space.”

If one is to ask the question, “What are the tradeoffs between performance and risk?”, it is necessary to develop a methodology to relate system-level performance requirements to the development items and their programmatic risks. During the early stages of a program, the detailed requirements analysis may not be complete, but it is possible to capture the strength of requirements relationships using QFD methods [Clausing, 1994; Clausing and Cohen, 1999].

This article presents a case study to provide an understanding of how one can analyze the trade offs between performance requirements and risk. The method uses the pillar of risk-based management to provide better support for integrating risk into the trade space capstone shown in Figure 1. More research and experimentation is needed to further integrate cost and schedule tradeoffs using the QFD approach.

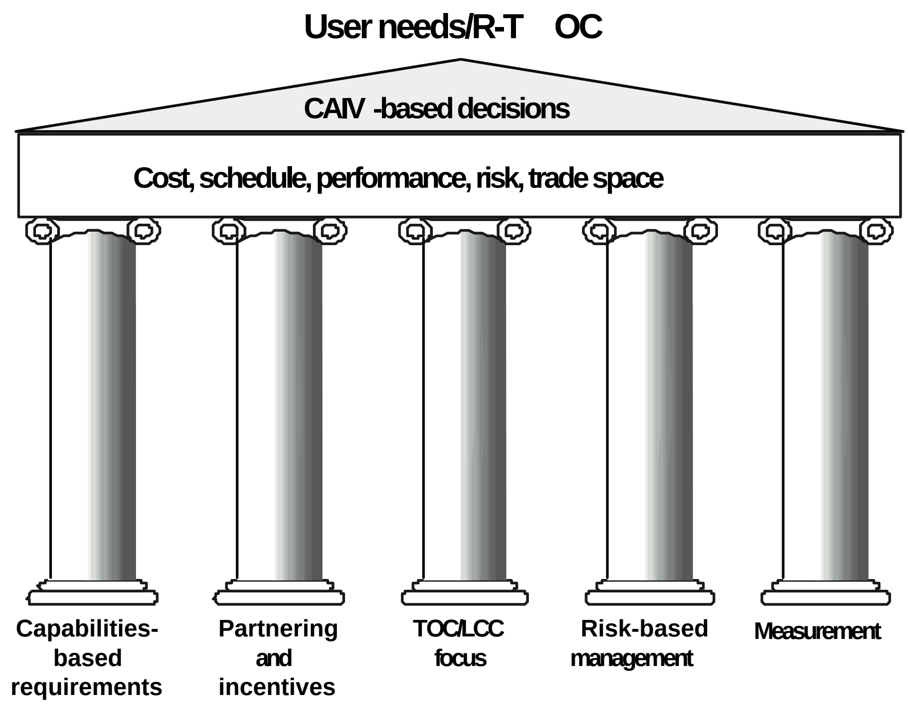

Figure 1. The Five Pillars of Reduced Total Ownership Cost (R-TOC)

System Overview. The system evaluated uses space-based surveillance, detection, and tracking technologies to provide information on missile launches and other infrared events to command authorities and other users. This information is relevant to both global strategic and tactical theater environments, and is used primarily for attack warning, missile defense, and intelligence purposes.

The system consists of three segments: Space, Ground, and Launch. The Space Segment consists of a constellation of space vehicles that have multiple sensors with sophisticated onboard mission planning and target tracking functionality. The Ground Segment provides mission data processing, data distribution, mission planning, constellation management, training/simulation, and interfaces to external entities. The Launch Segment places the initial constellation, the final constellation, and replacement vehicles into orbit.

For Systems Requirements Review (SRR), multiple system architectures were evaluated to provide a range options to meet the user needs. The Cadillac Architecture was the initial reference system design that met all user requirements. The Buick Architecture was developed to lower producibility risk by reducing complexity of the sensor telescopes and focal plane arrays. The Chevrolet Architecture had the same sensor designs as the Buick Architecture, but fewer satellites, which further reduces producibility risks in the sensors and radiation-hardened spacecraft components through reduction in the total quantity of components that are needed to support the system life cycle. Also, the Chevrolet Architecture is designed to less stringent user requirements that were established by reducing the performance expectations for a small number of very stressing user requirements. The other non-stressing user requirements were not changed to accommodate the Chevrolet Architecture. The purpose for developing the Chevrolet Architecture to a reduced set of user requirements was to provide the buyer with an option that significantly reduces the life cycle cost.

Requirements Risk Assessment Process. The process flow for requirements risk assessment is shown in Figure 2.

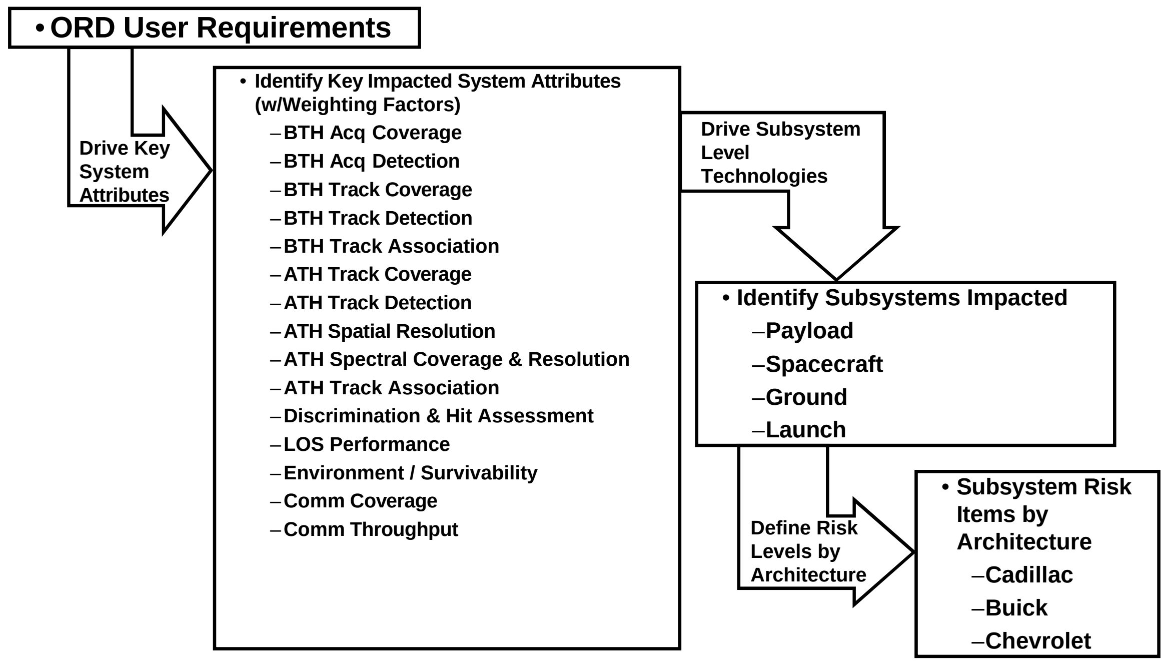

Figure 2. Requirements Risk Assessment Process Flow

All operational user requirements were contained in the Operational Requirements Document (ORD). For each user requirement, the strength of its driving relationship to key system attributes is assessed using QFD weighting factors. The strength of the relationship between a requirement and a system attribute varies according to architecture. Key system attributes drive key subsystem technologies. In turn, these technologies were assessed for programmatic risk. The risk level for each risk item is derived from the designers' assessment of future Preliminary Design Review (PDR) implementation risk based on anticipated technology maturity at PDR. The risk level of a risk item does vary with architecture, because the risk of implementing an individual item varies as the subsystem design chosen varies from one architecture to another. Also, the producibility risk varies from one architecture to another, because the risk associated with producing the total number of items varies as the constellation size changes from architecture to architecture.

An example of mapping from user requirements to system attributes is shown in Table 1. Note the strength of the relationship between the requirement "Global Technical Data Probability of Collection" and the system attribute “Access” is High for the Cadillac and Buick Architectures, but is Medium for the Chevrolet Architecture. For this requirement, it is intended that Technical Data be provided by the satellite constellation anywhere on the surface of the earth for specified data content and quality, and timeliness of delivery. The Cadillac and Buick Architectures were designed to meet the global technical collection requirement, and it was judged that this requirement is a significant driver for the total access to the surface of the earth provided by the combination of the coverage available from data collection sensors that are distributed on the constellation of satellites. The Chevrolet Architecture was designed to meet the requirement only in northern latitudes and not at the equator, and it was judged that it is only partially driven by the reduced requirement that applied to the Chevrolet Architecture. The "Detection" system attribute measures the strength of signal that the data collection sensors must detect. The system is required to detect very dim objects for Global Technical Data Collection, which stresses the state of the art of sensor design. The lower cost Chevrolet Architecture is expected to only detect these targets in northern latitudes, whereas the Cadillac and Buick Architectures detect these targets globally. Regardless of the location of these dim objects, they are difficult to detect; therefore, the relationship between "Global Technical Data Probability of Collection" and "Detection" is High for all architectures. The system attribute "Typing Algs" in Table 1 is the performance of algorithms that distinguish the type or class of object using raw detection data. The use of raw detection data from satellites to detect object types is described in Kenley and Coffman [1999]. The Technical Data Collection requirement does not specify a typing performance capability; therefore, Table l one shows "NA" as the relationship between the requirement and the system attribute.

	Impacted Key System Attributes								
ORD Requirement Title	Access (Cadillac)	Access (Buick)	Access (Chevrolet)	Detection (Cadillac)	Detection (Buick)	Detection (Chevrolet)	Typing Algs (Cadillac)	Typing Algs (Buick)	Typing Algs (Chevrolet)
Global Technical Data Probability of Collection	H	H	M	H	H	H	NA	NA	NA
Missile Typing	M	M	L	L	L	L	H	H	H

Table 1: Example Mapping of User Requirements to System Attributes

The second row of Table 1 shows the relationship between the user requirement "Missile Typing" and the same three system attributes. This is a requirement to identify classes of missiles using raw detection data. Although it is necessary to provide sensor coverage of missiles to collect raw detection data for use in missile typing, the system access needed is not as stressing as the access needed to meet the "Global Technical Data Probability of Collection" requirement. Thus, the relationship is shown a Medium for the Cadillac and Buick Architectures. The Chevrolet Architecture is not required to provide this missile typing for missiles launched near the equator. Thus, the relationship is Low between "Missile Typing" and "Access" for the Chevrolet Architecture. Missiles are very large objects and are easily detected by currently available sensing technology; therefore, the relationship between "Missile Typing" and "Detection" is Low. The Missile Typing requirement requires developing typing algorithms that currently are not available. The features that stress the system capability are part of the Missile Typing requirement for all three architectures; therefore, the relationship between "Missile Typing" and "Typing Algs" is High for all three architectures.

	Impacted Key System Attributes											
	Access				**Detection**				**Typing Algorithms**			
Subsystem Impacted	Risk Items Related to System Attribute	Cadillac Risk	Buick Risk	Chevrolet Risk	Risk Items Related to System Attribute	Cadillac Risk	Buick Risk	Chevrolet Risk	Risk Items Related to System Attribute	Cadillac Risk	Buick Risk	Chevrolet Risk
Payload	Item 69	H	M	M	Item 56	M	M	M	NONE	-	-	-
	Item 26	L	L	L	Item 59	M	M	M				
					Item 58	M	M	M				
					Item 26	L	L	L				
					Item 22	H	H	H				
Spacecraft	Item 27	M	M	M	NONE	-	-	-	NONE	-	-	-
	Item 28	M	M	M								
Ground	NONE	-	-	-	NONE	-	-	-	Item 11	M	M	M
	NONE	-	-	-	NONE	-	-	-	Item 02	H	H	H
	NONE	-	-	-	NONE	-	-	-	Item 09	M	M	M
Launch	NONE	-	-	-	NONE	-	-	-	NONE	-	-	-
Risk Area	Producibility				Performance				Performance			
Weighted Sums	H	9	0	0	H	9	9	9	H	9	9	9
	M	6	9	9	M	9	9	9	M	6	6	6
	L	1	1	1	L	1	1	1	L	0	0	0
Weighted Totals		16	10	10		19	19	19		15	15	15

Table 2: Example Mapping of System Attributes to Subsystem Risk Items

The mapping between requirements and system attribute was completed for 112 user requirements against 18 system attributes for each of the three architectures. A total of 6,048 assessments were needed to complete the mapping of ORD requirements to key system attributes. The next step is to map the system attributes to subsystems and risk items. Table 2 provides a direct mapping of system attributes for each architecture to risk items, which are categorized according to the subsystems in the first column of Table 2.

If there is a relationship between a system attribute and a risk item it is shown by entering the risk level of the risk item in the intersection in the table. The risk levels shown are the assessed risk mitigation plan effectiveness at PDR for the given risk item. The assessment was performed based on risk mitigation plans in place at SRR, which occurred several years prior to PDR for this program. As an example, the risk for item 69 (short wave infrared detector producibility) is reduced from High to Medium as the architecture changes from Cadillac to Buick. This is because the ability to produce the total quantity of detectors is less of a risk as the total number of satellites is reduced when the architecture is changed from Cadillac to Buick. Risk item 27 (the cycle time for production of space vehicles) has the same risk level for all architectures, because the reduction in numbers of spacecraft produced as the architecture is varied is not significant enough to reduce the risk.

The mapping between system attributes and subsystem risk items was completed for 18 system attributes against 44 risk items for each of the three architectures, requiring a total of 2,376 assessments. As design engineers develop risk mitigation plans, the risk levels of the various risk items will change. For example, alternate sources of production for short wave infrared detector can be funded to reduce the assessment of High for the risk of production for short wave infrared detectors using the Cadillac Architecture to Medium. If it is decided to make this investment the entry in Table 2, which captures the relationship between subsystem risk item 69 and the system attribute "Access", is updated to "M".

For each architecture and each risk item, in Table 2 high risks are given a weight of 9, medium risks a weight of 3, and low risks a weight of 1. This weighting is the standard weighting for QFD analysis, from which weighted totals are calculated. For example, the system attribute "Access" for the Cadillac Architecture in Table 1 has one High risk item for a weight sum of 9; two medium items for a weighted sum of 6; and one low item for a weighted sum of 1. The three weighted sums are totaled to yield a value of 16. The overall risk score for each requirement calculated using the entries in Table 1 to roll up the weighted totals in Table 2. Each mapping in Table 1 with a High value has a weight of 9, each Medium has a weight of 3, each Low has a weight of 1, and each NA has a weight of 0. For example, the requirement "Global Technical Data Probability of Collection" for the Cadillac Architecture would have a risk score of 9 x 16 + 9 x 19 + 0 x 15 = 315. This abbreviated example is the sum of three terms that relate the system attributes "Access", "Detection", and "Typing Algs". For the full data set, there are 18 terms for this sum, as there are 18 system attributes in the mapping from requirements to systems attributes.

ORD User Requirement Title	Total Risk (Cadillac)	Total Risk (Buick)	Associated High and Medium Performance Risks (Cadillac)	Associated High and Medium Producibility Risks (Buick)
Global Technical Data Probability of Collection	1074	984	Band Selection, Global Clutter Algorithm Database, Background Database, Clutter Suppression Algorithms, Mission Management, Cryogenic Cooler, Contamination, Calibration, Long Wavelength Infrared Sensor	Large Area Short Wavelength Focal Plane Array, Space Vehicle Assembly Integration & Test Cycle Time, Space Vehicle Producibility, Cryogenic Cooler, Contamination, Calibration, Long Wavelength Infrared Sensor, Track Optical Telescope Assembly
Probability of Post-Boost / Midcourse Track	798	768	Band Selection, Global Clutter Database, Calibration, Clutter Suppression Algorithms, Mission Mgmt, Ground Testing, Star Trackers, GPS Receiver	Space Vehicle Assembly Integration & Test Cycle Time, Space Vehicle Producibility
Missile Typing	632	632	Band Selection, Global Clutter Database, Calibration, Clutter Suppression Algorithms, Upgrade Software Integration, Missile Typing Algorithms, Ground Software Schedule	None
Raid Count	632	632	Band Selection, Global Clutter Database, Calibration, Clutter Suppression Algorithms, Upgrade Software Integration, Missile Typing Algorithms, Ground Software Schedule	None

Table 3: Initial Top Four Requirements Risks

Table 3 shows the four requirements that have the highest total risk scores after rolling up the weighted risk scores for the 18 systems attributes and 44 risk items for each architecture. A requirement in Table 3 is categorized a High risk requirements if the total score is greater than or equal to 600, a Medium risk if the score is greater than or equal to 400 and less than 600, and Low if otherwise. The associated performance and producibility risks shown in Table 3 are the Risk Items from Table 2 that have a high or medium risk at PDR under a given system attribute and for which system attribute relationship to the requirement is High in Table 1. These associated risks provide an indication of the implementation risk areas that were most affected by a user requirement.

One of the most important findings was that Global Technical Data Probability of Collection requirements was rated as the highest risk user requirement. This requirement was originally inserted as a "bonus" requirement that was assumed to be readily achievable for any concept that meets the other user requirements. The analysis showed that requirement causes much more implementation risk than was anticipated.

According to Kaye, et al [2000]:

> CAIV relies on acceptance of higher risk to aggressively pursue a "best value" system for the user. Contractors and IPTs should be given incentives to conduct effective and meaningful cost performance tradeoffs.

This result of the requirements risk assessment summarized in Table 3 was used to identify risk tradeoffs – particularly, the acceptance the higher risk Cadillac Architecture and expenditure additional risk mitigation funds to reduce risk prior to PDR. Initially, eleven requirements were evaluated as high risk, and fifteen were evaluated as medium risk for the Cadillac Architecture, as shown in Figure 3. In response to this evaluation, system developers defined more aggressive risk mitigation plans that were well within the program budget and eliminated all of the high risk user requirements and reduced the number of medium risk user requirements to two.

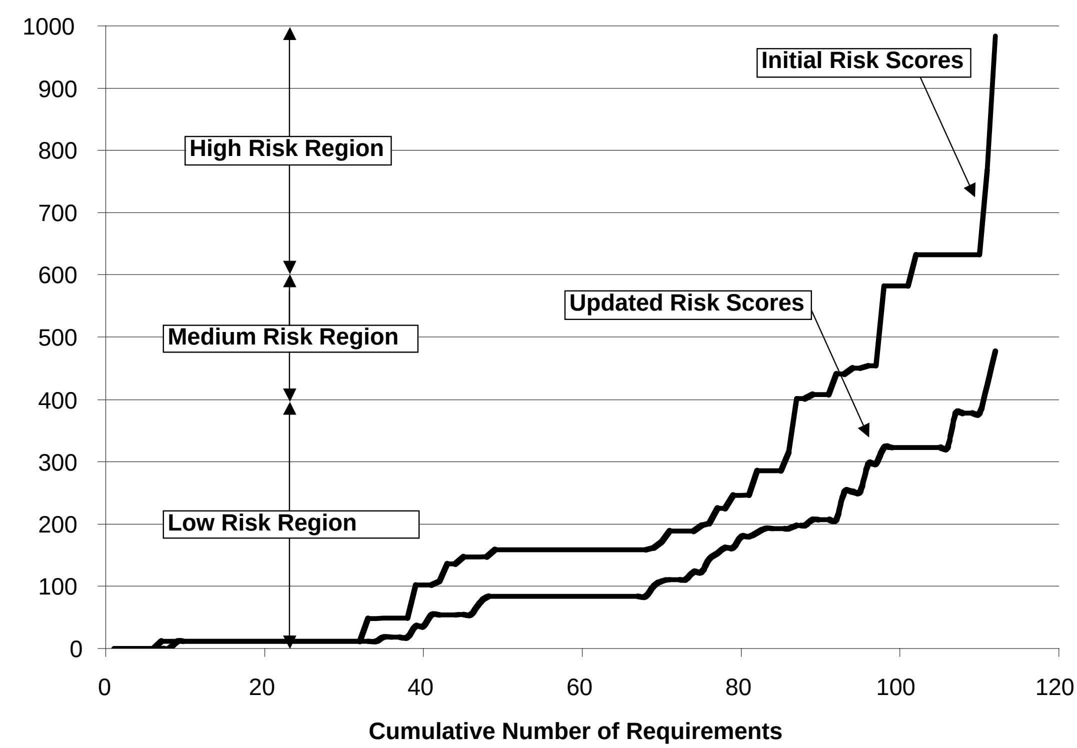

Figure 3. Updated Risk Mitigation Plans Reduced User Requirements Risk

Summary

A methodology was developed for requirements risk assessment that characterizes the degree to which a design architecture for a particular requirement invokes specific system attributes, the degree to which those system attributes invoke specific implementation risks that have been identified and evaluated to date, and the degree to which those system risks are likely to be mitigated based on current risk mitigation plans. The insight into the driving risk factors enabled system developers to focus risk mitigation resources and provide significant risk reduction early in the program while maintaining a high level of user requirements satisfaction.

The application of QFD methodology for relating requirements to risk is one approach to relating the Customer Preference Surface to the Design Reference System, as was first conceptualized by Paul and Kenley [1999]. In this paper, the customer preferences are the user requirements and the key design attribute is risk. The method presented here uses key system attributes as intermediaries to bring the Customer Preference Surface (user requirements) into contact with the Design Reference System (the risk level for a architecture) to assess whether the design community is providing a concept that meets customer needs with respect to risk. Expansion of QFD-based requirements flow down and sensitivity analysis to the other key design attributes of cost and schedule should provide additional insight into the relationship between customer preferences and design approaches during early phases of system development when programmatic decisions have the largest impact on total ownership cost.

References

AFMC Pamphlet 63-101, "Acquisition: Risk Management", Air Force Materiel Command, Wright Patterson Air Force Base, Ohio, July 6, 1997

Clausing, D.P., *Total Quality Development*, ASME Press, New York, 1994.

Clausing, D.P. and Cohen, L., "System Flowdown Using Enhanced QFD", *Proceedings of the Ninth Annual Symposium of INCOSE*, Brighton, England, June 6-11, 1999, pp. 867-872.

Hauser, J. and Clausing, D.P., "The House of Quality", *Harvard Business Review*, Harvard Press, Boston, May - June 1988.

Kaye, M. A., Sobota, M. S., Graham, D. R. and Gotwald, A. L., "Cost As An Independent Variable: Principles And Implementation", *Defense Acquisition Quarterly*, Defense Acquisition University, Fort Belvoir, Virginia, Fall 2000, pp. 353-372.

Kenley, C. R. and Robert B. Coffman, R.B., "The Error Budget Process: An Example from Environmental Remote Sensing", *Systems Engineering*, January 1999, pp. 275-282.

Paul, D. J. and Kenley, C. R., "System Engineering and Marketing", *Proceedings of the Ninth Annual Symposium of INCOSE*, Brighton, England, June 6-11, 1999, pp. 849-854.

Biography

C. Robert Kenley holds a Ph.D. and M.S. in Engineering-Economic Systems from Stanford, a M.S. in Statistics from Purdue, and a S.B. in Management from MIT. He has over 20 years experience in aerospace and nuclear systems engineering. He currently provides clients with insight and understanding of systems problems as an independent consultant, and is the chair of the INCOSE Ways and Means Committee. He is a published author of several papers and journal articles in the fields of systems engineering, decision analysis, Bayesian probability networks, and applied meteorology.