Incorporating Maturity Assessment into Quality Functional Deployment for Improved Decision Support Analysis, Risk Management, and Defense Acquisition

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Abstract— Technology maturity assessment metrics have played a key role in complex system acquisition and technology integration in both the defense and commercial sector. Of these, the U.S. Department of Defense's (DoD's) Technology Readiness Level (TRL) has been the de facto standard since it's inception in the late 1990s. DoD adopted the use of TRLs to provide program managers with critical information on component technology maturity and overall system insertion readiness. However, with the recent increase in system complexity and interface interoperability, TRLs have begun to show limitations in their ability to meet these stated objectives. Furthermore, there is no effective technique, tool, or procedure that incorporates maturity assessment in the design or development phase of a product lifecycle.

To address the above concerns, this paper presents a model that incorporates maturity assessment into an industry standard technique known as the House of Quality (HoQ). HoQ is an established analytical methodology that translates customer requirements to engineering capabilities and ultimately provides a method for requirement tracking and resource allocation. An improved model shall enable the program manager to integrate several inherent systems engineering functions into a standalone-streamlined process.

***Index Terms*—HoQ, maturity, risk, QFD, risk management, acquisition, TRL.**

I. Introduction

"Life was simple before World War II. After that, we had systems."

- Admiral Grace Hooper

Over the last several decades, both the private and public sectors have undergone a transformation in the manner and process in which systems are acquired, sustained, and maintained. Evolving requirements, increased emphasis on systems, globalization, international competition, prolonged life cycles, and an increase in complexities are just a few examples that facilitate this claim (Blachard, 2003).

One of the single most influential factors to modern acquisition is the increase of technology insertion (GAO, 2008). While the general trend is to extend system life cycles, technology life cycles are outpacing the system counterparts, requiring the use of new techniques that facilitate technology advancements (Blachard, 2003). These techniques, such as open-standards and interoperability requirements, have had a significant impact to the manner in which systems are designed, built, and sustained.

In addition to increased technology insertion, a new philosophy known as the Total Package Approach (TPA) has altered the manner in which DoD acquires systems. Rather than focus on pure acquisition, TPA accounts for systemic properties ('abilities') including supportability, manufacturability, maintainability, availability and reliability when designing a system. TPA has removed legacy 'component mentalities' and instilled the *cradle to grave life-cycle* design process (Blachard, 2003). Additionally, life cycle considerations have introduced complexities and dynamics foreign to traditional acquisition; interfaces, environmental impacts, sustainmaint, software compatability and disposal are a few examples of TPA considerations.

To address repeated technology insertion into complex System of Systems (SoS) architectures, the National Aeronautics and Space Administration (NASA) developed a metric called the Technology Readiness Level (TRL) in the late 1990s. Focusing on sub-system maturity, the TRL was designed to provide the program manager with quantifiable "levels" of maturity in assessing specific technology integration. The TRL, a numeric value from 1-9 represents the current state (or maturity) of a given technology and provides a readiness assessment of overall system integration. DoD along with several other organizations later adopted this metric and continue its use in a generally unaltered form.

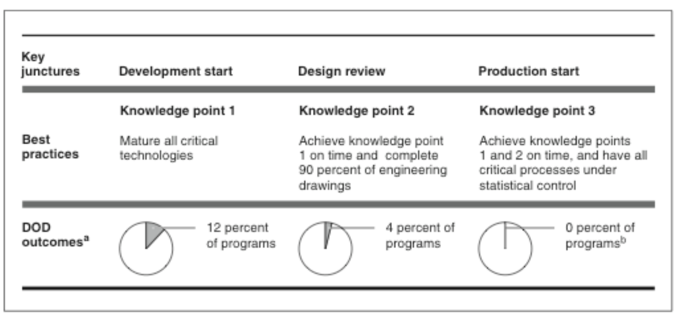
A. Problem Statement

For nearly a decade, TRLs have served as the de-facto standard for technology maturity assessment in both hardware and software intensive systems. TRLs have also played a critical role in DoD's formal Technology Readiness Assessments (TRA) that relate system level capabilities to component maturity (TRA Deskbook, 2005). Although capable of providing a quantitative metric to component maturity, TRLs have significant limitations to overall system acquisition. Currently, TRLs do not account for several TPA considerations including manufacturing, integration, and overall system readiness. This is a significant disadvantage when considering DoD's trends of an overall increase in system complexity, number of interfaces, and interoperability requirements (GAO, 2008).

The U.S. Government Accountability Office (GAO) released a report in 2008 after an assessment of 95 selected DoD weapon systems. The report criticized cost overruns and schedule slips attributing them largely to the following:

"None of the weapon programs we assessed had proceeded through system development meeting the best practices standards for mature technologies, stable design, and mature production processes—all prerequisites for achieving planned cost, schedule, and performance outcomes. In addition, only a small percentage of programs used two key systems engineering tools—preliminary design reviews and prototypes to demonstrate the maturity of the product's design by critical junctures. This lack of disciplined systems engineering, especially prior to starting system development, affects DOD's ability to develop sound business cases for programs and can contribute to contract cost increases and long development cycle times (GAO, 2008)."

The GAO heavily criticized technology maturity (including manufacturing and integration aspects) attributing it, along with a lack of system engineering processes to the general downward shift of DoD program acquisition (GAO, 2008). Figure 1 depicts the GAO's assessment of critical technologies maturity prior to the commencement of key acquisition junctions.



Source: GAO analysis of DOD data.

Figure 1 - Knowledge Achievement for Weapon System Programs (GAO, 2008)

Key issues identified by GAO, a lack of accurate technology maturity and a disregard for systems engineering processes are symptoms of two overarching causes; one, technology metrics that fail to account for system wide considerations, and secondly, the inability to incorporate the said metrics early in the systems engineering process.

Part of the reason for this problem is the lack of clear guidance with respect to component maturity (sub-system solution) early in the design process. TRA and DoD directives emphasize system wide assessment. They do not account for component assessment nor do they provide a clear tool for this process. Furthermore, the preferred metric, the TRL fails to account for several of the system wide considerations as mentioned prior.

B. Expected Benefits

Providing a process for component maturity inclusion early in the acquisition life cycle will surface component design consideration risks and provide valuable information when performing trade off analysis. This paper will demonstrate that the House of Quality (HoQ), an industry standard technique for the said tasks, is capable of accepting numerous maturity metrics and can provide timely component assessments without the need for repeated design iterations.

C. House of Quality (HoQ)

The House of Quality (HoQ) is a tool that falls under the overarching concept of Quality Functional Deployment (QFD) developed in Japan by Yoji Akao in the late 1960s and first published in 1972 (Akao & Mazur, 2003, Han, et al., 2001). Its first major application was executed in 1972 by Mitsubishi Heavy Industries (MHI) to manage military maritime engineering requirements levied by the Japanese government (Kai, 2008, Hauser, 1993). Due to the complex and costly nature of ship construction, MHI required a novel method for managing technical, customer, and government requirements without the luxury of first being able to construct system prototypes. The engineers at MHI developed a quality matrix chart that correlated these three requirement types along with their relative importance to the design process (Akao & Mazur, 2003, Kai, 2008). This allowed them to satisfy the maximum number of customer requirements and identify embedded relationships while minimizing design iterations (Yang, 2007). Although MHI is often credited with developing QFD, recent records show that only the quality matrix chart (albeit a critical component) was developed by MHI, and the concept of QFD, was pioneered prior by Yoji Akao (Akao & Mazur, 2003).

The success of QFD spawned a frenzy of interest, and in 1983, the QFD concept was brought to the U.S. and Europe by Masao Kogure and Yoji Akao in the October issue of Quality Progress (Akao & Mazur, 2003). Today HoQ is used by several Fortune 500 companies including Toyota, General Motors, Ford, Hewlett-Packard, Xerox, Procter & Gamble, and AT&T (Shin, et al., 2002, Clausing & Hauser, 1988). QFD is also one of the three staple components in Total Quality Management (TQM) (Politis, 2005).

D. Methodology

The goal of HoQ is to translate customer requirements into design objectives (Politis, 2005). This is achieved through an iterative process that takes various stages of a design process and correlates them to sections of the HoQ (Politis, 2005). The structure of the HoQ varies depending on the program's goals, acquisition life-cycle phase, and objectives. Although there is no mandated format for the HoQ, it is traditionally accepted to have six (6) sections and follows the format depicted in Figure 2.

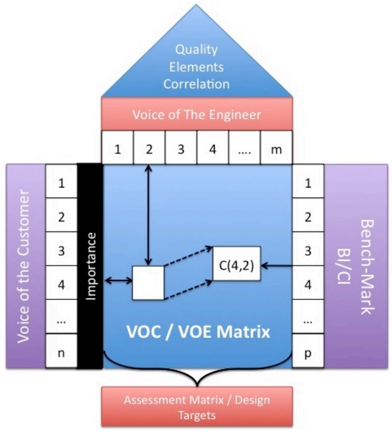


Figure 2 – The House of Quality (HoQ)

E. Sections of the House of Quality (HoQ)

1. Voice of the Customer (VOC)

Translating needs, wants, and objectives into customer requirements is the first step in developing the HoQ. Section one, the leftmost side of the house, stores the prioritized requirements in descending order known as the Voice of the Customer (VOC) (Akao, 1990). To promote simplicity and practicality, if too many requirements are identified, they may be grouped under a taxonomy and only the hierarchical headings listed in the first section (Akao, 1990). The goal of this section is not to identify the maximum number of possible customer requirements, but instead to identify critical elements and the overall "voice of the customer" enabling progressive steps of the HoQ. (Hauser, 1993)

HoQ requirements are categorized by classifications that correlate customer perception to performance (Shiba et al., 1993). These requirements include: one-dimensional, must-be, attractive, and indifferent. Each requirement is typically assessed on a performance versus customer satisfaction level.

Requirement classification is important for several reasons. Not only does it group requirements by category type, but it also discerns imbedded relationships and provides a "normalized" importance to each of the four categories (Han, et al., 2001). For example, enhancing a specific requirement that is already at a satisfactory level may not provide more value, while exceeding expectations in a performance requirement may enhance customer expectations.

2. Business and Competitive Intelligence

Often times referred to as competitive analysis, the second section of the HoQ analyzes the VOC against user perceptions to benchmark the status quo of requirements. These include perceptions of not only ones own firm but also the firm's competitors. (Han, et al., 2001). This is a complicated process that consists of two discrete activities; business and competitive intelligence.

Competitive Intelligence (CI) is a process that gathers competitor information such as public announcements, joint venture statements, and consumer reports to derive a model and rank of competitor perception (Wright and Calof, 2006). With respect to HoQ, CI is used to rank public perception of products and services compared to one's own. This information is vital in that it identifies operational and strategic gaps that not only assist in the design process but also identify areas for self-improvement (Han, et al., 2001).

Business Intelligence (BI) is the converse of CI (Luhn, 1958, Lewis, 2008). Rather than focus on external competition, the intelligence is performed internal to ones firm, providing a "report card" of current perceptions. BI, when combined with CI presents a powerful holistic picture of customer perceptions. This information provides engineers the insight into advantages and disadvantages that they have in relation to their competition. This information is visually depicted in the second section of the HoQ and serves as the current state during the subsequent correlation matrix phase (Han, et al., 2001).

3. Voice of the Engineer (VOE)

Prior to this section, customer requirements have been gathered, prioritized, and a BI/CI analysis has been performed. Thus far, no "translation" or processing of requirements into design requirements has taken place. The third step in the HoQ development is where this translation takes place and is also where the Voice of Engineer (VOE) is derived (Han, 2001 and Akao, 1990). This translation takes customer requirements and correlates them to measurable design requirements and considerations for the engineer (Han, 2001). The design requirements are listed horizontally in the VOE section and correspond to at least one or more of the customer requirements (Han, 2001). The VOE is a core-derived component that is largely based on customer input and typically does not account for external considerations. The unconstrained derivation helps remove influence and bias from other design factors, and facilitates a new and open look at customer requirement relationships. (Han, 2001).

4. Matrix Analysis

The fourth section of the HoQ assigns weighted values to how each design requirement (VOE) corresponds to the customer requirements (VOC) (Han, *et al.,* 2001). For example, if customer requirement one had a strong positive affect on design consideration one, an appropriate symbol could be used to depict that relationship. If the relationship were strong but negative, the appropriate negative value could be used as well. Traditionally, the correlation matrix legend is broken down into symbols for, strong, medium, weak, negative, and none.

The HoQ matrix is critical to the overarching analysis process in that it will ultimately answer the question of how much each design requirement affects each customer requirement (Han, et al., 2001). This will serve as one of the key pieces of information when ranking design requirements, allocating resources, and setting target goals for design (Han, et al., 2001).

It should be noted that there is a certain amount of subjectivity and limitation when assigning importance weight parameters. First, when performing the analysis, the assumption is made that the designers are able to distinguish the level of relationships in a quantitative fashion (Olewnik and Lewis, 2007). The further assumption that designers can choose the relative weight implies that the relationship is known ahead of time (Olewnik and Lewis, 2007). Although these assumptions provide specific limitations for detailed analysis, they do not affect the high level qualitative correlation that is performed here (Olewnik and Lewis, 2007).

5. Correlation Matrix

This section builds the "roof" of the HoQ and evaluates relationships between each of the design requirements (Han, Chen, Ebrahimpour, & Sodhi, 2001). Normalized from -1 to 1, each design requirement is compared against the others and a +, -, or 0 is assigned. If improving one requirement has a positive affect on the other, a + is used. If the relationship is negative, a – is used. In the context here, a positive relationship refers to the ability to meet a design requirement by satisfying another. In essence, the correlation matrix answers, Are these enabling or destructive relationships?

6. Design Targets

Once the matrix analysis and correlation matrix are complete, the engineering team can begin setting design targets and target values to the design requirements. Design targets are calculated from the VOC and VOE and drive the subsequent design process (Han, Chen, Ebrahimpour, & Sodhi, 2001). These targets serve as a reflection of customer requirement importance as seen by the engineers and are one of the major outcomes of successful QFD implementation (Han, Chen, Ebrahimpour, & Sodhi, 2001).

F. HoQ Limitations

Although the HoQ serves as a tool that provides a unique and novel approach to traditional engineering design and quality, there are several factors, outside the inherent process that can inhibit the full potential of the tool.

First and foremost, HoQ is a iterative process that requires significant resources of both time and human capital. The organization must support a creative and innovative environment that allows the resources necessary to implement QFD and HoQ or risk process failure (Politis, 2005) . Secondly, the HoQ requires strict adherence to detail and correctness, for any inaccuracies, assumptions, and/or inconsistency in correlating the relationship matrix to the roof matrix can have negative trickle down effects to the remaining process (Shin, Kim, & Chandra, 2002). The third limitation deals with the subjectiveness of the designer to distinguish qualitative levels of relationships between the VOC and the VOE in the design process (Olewnik & Lewis, 2008). Lastly, as it stands now, there is no approved methodology or process for incorporating component maturity into the design process, designers are oftentimes forced to overlook capabilities assigned to particular design aspects and fail to include any degree of dificulty or critical path components to the process. This creates a significant flaw that forces program managers to assign subjective and potentially biased decisions on trade-offs without a complete and accurate depiction of the facts.

II. The Technology Readiness Assessment Process

Before we can enable HoQ maturity based assessment, it is imperative to understand the present de-facto standard for technology maturity assessment. Unfortunately, there is little literature in this field for either commercial or defense applications and most of the guidance comes from the DoD's latest version of the Technology Readiness Deskbook, TRA 2005.

A. The Technology Readiness Assessment

For major Department of Defense (DoD) Acquisition programs (knows as MDAPs), the System Program Office (SPO) is required by Congress to conduct a Technology Readiness Assessment (TRA), typically during the Technology Development phase of the DoD Acquisition Lifecycle as shown in Figure 4. The purpose of the TRA, as cited in the TRA 2005 deskbook is to "surface data and assess information relevant to the maturity of the Critical Technology Elements (CTEs) in acquisition programs." The TRA is used to support risk assessment, technology integration, and trace critical capabilities to specific elements.

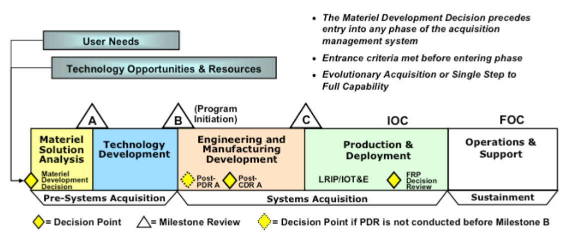


Figure 4 - DoD Acquisition Lifecycle

The TRA process consists of two discrete events; first, CTE identification and second, CTE readiness assessment (DoD TRA Deskbook, 2005). CTE identification does not solely focus on performance or capability elements but instead encompasses the entire gamut of cradle to grave management. This includes but is not limited to performance, manufacturing, integration, tooling, and even infrastructure perspective elements that can operate in the physical, logical, data, security, and user environment. This process is typically held to a rigorous schedule given time constraints associated with data collection, analysis, and reporting.

The second phase, referred to as the CTE readiness assessment, assigns TRLs to each specific CTE and reports the findings to the PM in-charge of the TRA that then reports to the respective oversight of the DoD MDAP.

TRA Deskbook (2005) does not mention any other technology metrics or tools aside from the TRL. It also offers no recommendation nor does it require any subsequent assessments that tie requirements to functional components and maturity readiness. This leaves the decision makers inept of making critical path assessments or performing capability risks during system design.

III. Integration

As explained in Section II, the majority of analysis performed in the HoQ is fed into the assessment matrix. It is here where critical decisions are made that determine the direction and overall path of the program. To date, engineers have incorporated various assessment parameters, but no analysis or incorporation has been performed with respect to component maturity.

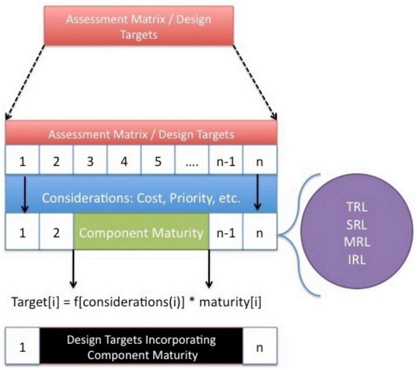


Figure 5 - Improved Risk Assessment Breakout

Figure 5 proposes an improved process for assessment matrix analysis and setting design targets. Olewnik and Lewis (2008) identified a critical flaw in the HoQ, in which the designer engineers introduced bias and subjectivity when setting design targets against the correlation matrix. This resulted in the incomplete and inaccurate depiction of engineering considerations and in some cases, inhibited optimal product quality design. One option for removing this subjectivity is via the introduction of Component Importance Measures (CIM). CIMs not only assign an importance value to each design consideration but can also be compounded with maturity assessment for each component. This advanced metric provides a dynamic evaluation of each design consideration and outputs a weighted and accurate component index for the decision matrix.

In addition to creating dynamic weighted targets, this improved process enables parallel systems engineering functions that up until this point have been at a disconnect. One of these processes is risk analysis.

A. *Risk Management*

Traditional risk analysis (not to be confused with issue management) is composed of five steps: identification, analysis, mitigation planning, mitigation implementation, and tracking (DoD Risk Management Guide, 2006). But even with this process, identification is still a time critical activity with no real process or methodology. This lack of formal process improvement presents a gap for the engineering manager and prolongs the rate at which risks are identified. This reduces the time available for risk mitigation, contingency planning, tracking, and ultimately to ineffective risk management.

The enhanced HoQ model, with weighted designed targets and assessments provides a first contact approach for mitigating these deficiencies. As shown in Figures 6 & 7, the assessment matrix provides a foundation for risk identification. One of the outcomes of the enhanced HoQ process is a functional design target that includes present component maturity assessment and also the relative importance to the VOC. By taking these factors and extrapolating them, a fundamental risk assessment platform begins to emerge.

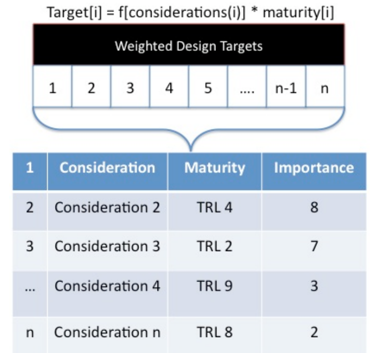


Figure 6 - Assessment Matrix Translation

This process can be taken a step further with a simple transformation to a more standard five by five risk analysis matrix plot. As shown in Figure 7, maturity and importance requirements serve as factors of the overall impact and probability of the risk assessment.

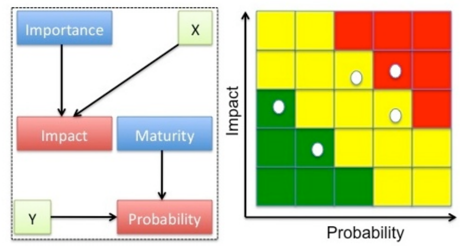


Figure 7 - Assessment Matrix Incorporation into Risk Analysis

By performing a pre-design analysis on importance (capabilities) versus maturity (probability), one can gain an early perspective on the potential risks associated with maturing technologies and concurrently, the impact of failure.

IV. Academic Example

In the following example, we introduce a simplified version of the HoQ that incorporates maturity assessment as a low-density function. For simplistic purposes, the correlation matrix (roof) and BI/CI analysis has been omitted.

In this example, we are correlating customer requirements to specific technical design considerations in an upcoming automotive release. The VOC has been captured in Figure 8, along with the relative importance of each requirement. Using a normalizing function from zero to one, each requirement has been weighed such that the sum of the requirements equals one.

Voice of the Customer (VOC)	Importance	Normalized
Efficiency (Gas Mileage)	7	0.10
Interior (Size, Comfort, Durability)	9	0.13
Exterior (Performance over Time / Appeal)	5	0.07
Performance (Power Ratio, Stability, Balance)	7	0.10
Safety Features (Airbags, ABS, Traction Control)	8	0.11
Status Perception (Image / Appeal)	4	0.06
Environmental Responsibility	7	0.10
Customization (Individualism)	8	0.11
Cutting Edge Features	7	0.10
Costs (Initial and Sustainment)	8	0.11

Figure 8 - VOC Requirements

After the VOC has been quantified, engineers are able to provide feedback to each VOE responsible for addressing the said requirements. The inputs are gathered, a cross matrix has

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been performed, and numeric values are assigned (from 1-9) correlating each VOC to VOE. For this example, the correlation has been simulated. Figure 9 displays these values.

Once the correlation matrix is complete, a similar procedure to normalize the VOE is performed. In this example, we are solely interested in knowing how each engineering consideration will map to the customer requirements. Therefore, the normalized values produce a percentage requirements mapping to each of the VOCs. A higher percentage is more significant, and vice-versa.

Voice of the Engineer (VoE)									
Engine	Single Speed Transmission	Supension	Production Facilities	Component Redundancy	Advanced Safety Features	Interior Microfabrics	LightWeight Body Materials	Modern Materiel Selection (Composties,	
9	7	3	1	6	2	1	9	6	
1	1	5	1	6	3	9	6	6	
3	1	1	1	6	3	1	6	6	
6	6	3	1	6	3	1	6	3	
2	3	1	1	6	9	1	3	4	
6	3	3	1	1	2	3	6	4	
6	6	1	9	6	4	6	6	5	
1	2	1	6	3	1	3	1	3	
3	6	2	1	3	9	6	1	4	
6	5	3	6	6	6	4	6	5	
4.1	4.0	2.4	2.9	5.1	4.3	3.7	4.9	4.6	VOE (Unscaled)
11.4%	11.1%	6.5%	8.2%	14.1%	12.0%	10.3%	13.6%	12.8%	VOE (Normalized)
									Manufacturing Readiness
Removed For Simplicity									Integration Readiness
									System Readiness
9	6	3	4	7	6	5	2	2	Maturity Assessment (via TRL)
37.0	24.1	7.1	11.8	35.5	26.1	18.6	9.8	9.2	Weighed Maturity
20.7%	13.5%	3.9%	6.6%	19.8%	14.6%	10.4%	5.5%	5.1%	**VOE (Normalized with Maturity)**
9.3%	2.3%	-2.6%	-1.6%	5.8%	2.5%	0.1%	-8.1%	-7.6%	Impact

Figure 9 - VOE Correlation Matrix

Traditional HoQ users would typically stop at this point to review the results. No additional analysis is usually performed post the VOE mapping. In this example we've taken it a step further and added simulated maturity assessments (TRLs) to each VOE. This value was factored into each design consideration and normalized. Please note that no other maturity assessment has been added at this time. The two results were compared and depicted in the figure below.

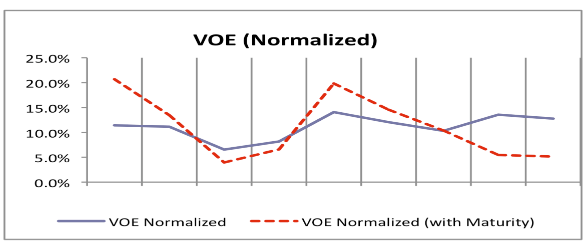

Figure 10 - Normalized VOE

The percentages on the left represent tracing of each VOE back to the VOC. They are presented in the same order as Figure 8 from efficiency to costs. While the solid line represents VOE mapping, the dashed line present a more accurate picture with the relative maturity of each component. In this particular example, engine size and component redundancy pose less risk and add more customer value given their relative maturity. Conversely, lightweight and nanotechnology materials add risk and have the potential of reducing percentage mapping due to their low readiness level.

V. Conclusion

As presently designed, the HoQ facilitates the analysis of engineering considerations and customer requirements that improve both product design and quality. At the same time, the HoQ has limitations when respect to engineer subjectivity, capability to component mapping, and the lack of CIM inclusion. These limitations prevent the tool from presenting an accurate depiction of design difficulty and offer no capability to component mapping.

To address these issues, an improved HoQ model has been introduced that incorporates component maturity and presents a natural flow for risk management. The inclusions of these components removes subjectivity inherent to design targets and provides the decision maker with an objective look at the manner in which design considerations are correlated.

In addition to the benefits listed above, the improved model provides a logical step with respect to risk analysis and CTE mapping. The inclusion of maturity and importance metrics provides probability and importance metrics that serve as input criteria into risk management. This process enhances and enables the overall systems engineering discipline and better conditions areas that have until now been treated discretely; system design, CTE maturity, and risk management.

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