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Whole Systems Trade Analysis

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ABSTRACT

Ground vehicles are complex systems with many interrelated subsystems - finding the sweet-spot among competing objectives such as performance, unit cost, O&S costs, development risk, and growth potential is a non-trivial task. Whole Systems Trade Analysis (WSTA) is a systems analysis and decision support methodology and tool that integrates otherwise separate subsystem models into a holistic system view mapping critical design choices to consequences relevant to stakeholders. As a highly integrated and collaborative effort WSTA generates a holistic systems and Multiple Objective Decision Analysis (MODA) model. The decision support model and tool captures and synthesizes outputs from individual analyses into trade-space visualizations designed to facilitate rapid and complete understanding of the trade-space to stakeholders and provide drill down capability to supporting rationale. The approach has opened up trade space exploration significantly evaluating up to 10^{20+} potential configurations to then return a handful of configurations which meet design and programmatic criteria..

INTRODUCTION

The Product Development and Management Association (PDMA) conducted an international, multi-industry comparative performance assessment study in 2012 and found that approximately 40% of all new product developments fail to achieve market success. The failure rate jumps to about 54% if the new product development includes high levels of innovation. Since the PDMA started conducting this assessment in 1990, the new product development failure rate has consistently been assessed near the 40% mark (1990 - 42%, 1995 - 41%, 2004 - 41%). These data suggest that high failure rates for new product developments are a wide-spread and persistent trend.

Beyond high failure rates, new product development efforts often exhibit other unwanted symptoms of duress such as cost overruns and schedule slips. 56% of new product development projects with a nominal degree of innovation fail to meet development schedule and 51% exceed their allotted development budget. For products with higher levels of innovation, development schedules are missed by 71% of the projects and development budgets are overrun by 68% of the projects.

This record of poor outcomes for development projects around the world and across industries indicates that new product development efforts are tremendously difficult tasks. As such, thousands of documents in the form of journal articles, text books, and conference proceedings have been written by academics and practitioners across the functional areas of marketing, operations research, engineering, and organizational design that are dedicated to at least one aspect of product design and development. To facilitate their review of the literature, Krishnan and Ulrich applied a decision perspective to synthesize findings across the functional areas. Krishnan's and Ulrich's decision perspective sees product development as "a deliberate business process involving hundreds of decisions, many of which can be usefully supported by knowledge and tools." Their extensive literature review concludes with a recommendation for developing tools that facilitate the link between marketing models and engineering models. (Krishnan & K. T. Ulrich 2001)

Several areas for future research seem promising. Research in the marketing community has flourished on methods for modeling consumer preferences and for optimally establishing the values of product attributes. Yet, a weakness identified is that models of the product as a bundle of attributes tend to ignore the constraints of the underlying product and production technologies. Parametric optimization of complex engineering models is a well-developed area within the engineering design community. We see an opportunity for these communities to work together to apply the product-design methods developed in marketing to product domains governed by complex technological constraints.

To confront this challenge and fully comply with the Weapon Systems Acquisition Reform Act (WSARA) of 2009, the Defense acquisition community must develop and demonstrate an in-depth understanding of the complex relationship between requirements, design, and the system level consequences of the sum of design choices across the full set of performance requirements as well as other elements of stakeholder value to include cost and schedule.

This paper outlines a methodology developed within the U.S. Army Program Executive Office Ground Combat Systems (PEO GCS) – an organization which manages some the most complex ground systems in the world. PEO GCS addressed this challenge by commissioning a cross organizational team of analytics professionals from PEO GCS, PM GCV, ARDEC, Sandia National Labs and Booz Allen Hamilton that has successfully developed a systems engineering tradeoff analysis methodology and associated tool referred to as Whole System Trade Analysis (WSTA). WSTA enables the acquisition community to assess a large set of alternatives across competing objectives of performance, acquisition cost, operating and support costs, schedule, and growth potential – see Figure 1.

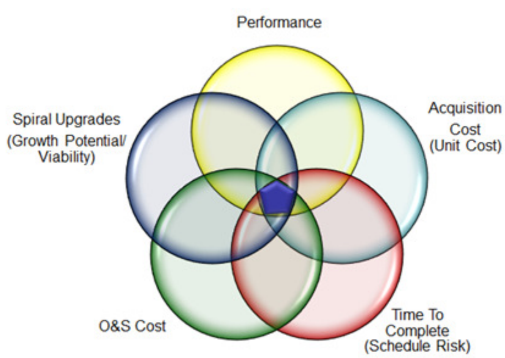

Figure 1: Challenge to balance competing objectives

APPROACH

Overview

As a systems analysis methodology and decision support tool WSTA integrates otherwise separate subsystem models into a holistic system view mapping critical design choices to consequences relevant to stakeholders. Each WSTA engagement is a highly integrated and collaborative effort which leverages Subject Matter Expertise to develop the necessary inputs for the modeling effort. The WSTA team integrates these inputs to generate a holistic systems model which involves a thorough examination of the requirements, the creation of a value model that uses requirements based functional objectives (FO) to capture the measures relevant to the analysis. The effort assigns utility functions to the FOs and gathers and assigns priority weightings for the FOs from the user community. Inputs are, in the case for a vehicle platform, technology options such as engines, armor packages or cannons that can be combined to form vehicle configurations. With system performance models, technology options and design rules in place a genetic algorithm returns a non-dominated Pareto Frontier of configurations along a five dimensional value space. A decision support model and tool captures and synthesizes outputs from individual analyses into trade-space visualizations designed to facilitate rapid and complete understanding of the trade-space to stakeholders and provide drill down capability to supporting rationale. The approach has opened up trade space exploration significantly evaluating up to 10^{20+} potential configurations to then return a handful of configurations which meet design and programmatic criteria.

Methodology

It is a methodology that allows full exploration of trade space especially as requirements and system design approaches are being refined early in the acquisition process, but certainly applicable across all of the acquisition phases. This transformative methodology was first applied on the Ground Combat Vehicle (GCV) program as part of the GCV Technology Development phase, PM GCV used WSTA with Army and OSD senior leadership to explore the GCV systems engineering trade space. For the first time in acquisition history, senior level stakeholders could view on a single page the relative attractiveness of competing alternatives across all five dimensions of defense acquisition decision-making - unit cost, sustainment costs, development risk, growth potential, and performance. Prior to WSTA, senior leadership was presented with an array of separate analyses with minimal synthesis. WSTA was used successfully on the GCV program and is currently being used and developed for multiple programs within PEO GCS, its application is robust and transferable. At the completion of the on-going Validation and Verification process, PEO

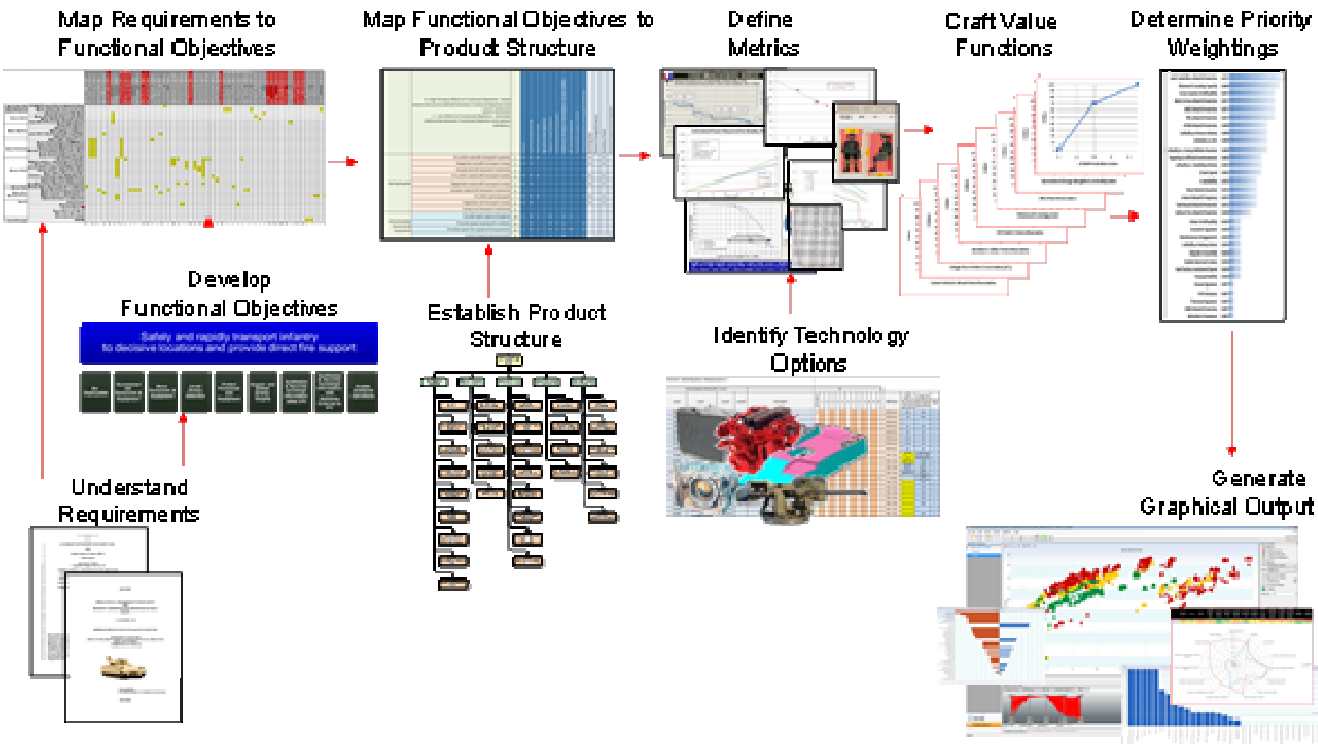

Figure 2: WSTA Key Products

GCS intends to utilize the WSTA tool in future source selection initiatives, per the request of OSD (ATL) and other senior leaders in HQDA.

Program managers face the perpetual trade space management challenge to develop and demonstrate an in-depth understanding of the complex relationship between requirements, design, and the system level consequences of the sum of design choices across the full set of performance requirements as well as other elements of stakeholder value.

To fully characterize this dynamic and evolving trade space the WSTA effort requires the collaboration of diverse set of stakeholders to express system level performance. The necessary collaboration across organizations, domains and functional disciplines is a significant and critical undertaking. To express key aspects of system level performance the Whole Systems Trades Analysis effort is underpinned by a rigorous data collection effort spanning several months of in-depth discussions with subject matter experts (SMEs) across the Army.

Through these discussions on the GCV program the WSTA team identified 43 product structure elements and 207 distinct physical design choices within that product structure. The core of the SME discussions were focused on developing relationships between the 207 distinct physical design choices available to the GCV weapon system design team and the 38 fundamental objectives used to assess stakeholder value - fundamental objectives constructed by a thorough, three-level functional decomposition of the GCV system. The WSTA team cross-walked these objectives against the draft CDD and PSpec as a check to ensure the decomposition completely addressed the elements of stakeholder value voiced in available documents. A priority weighting for each objective was first established through a MCoE User Panel facilitated by the WSTA team to capture beliefs regarding the importance of each GCV function (defining function, critical function, enabling function) and the difference between incumbent performance and ideal performance for each objective. Importance and differentiation levels for each objective were then used to establish priority weightings for each objective. The WSTA team meticulously captured supporting rationale voiced throughout the user panel event ensuring the priority weightings and value functions for each objective were well reasoned and documented from an end-user point of view. The WSTA team collected and documented additional priority weighting sets from stakeholders that held different views regarding the nature of future conflicts and used this data to conduct sensitivity analyses.

The resulting WSTA tool outputs a set of possible system configurations tied to the product structure and the component-level choices – in doing so significant numbers

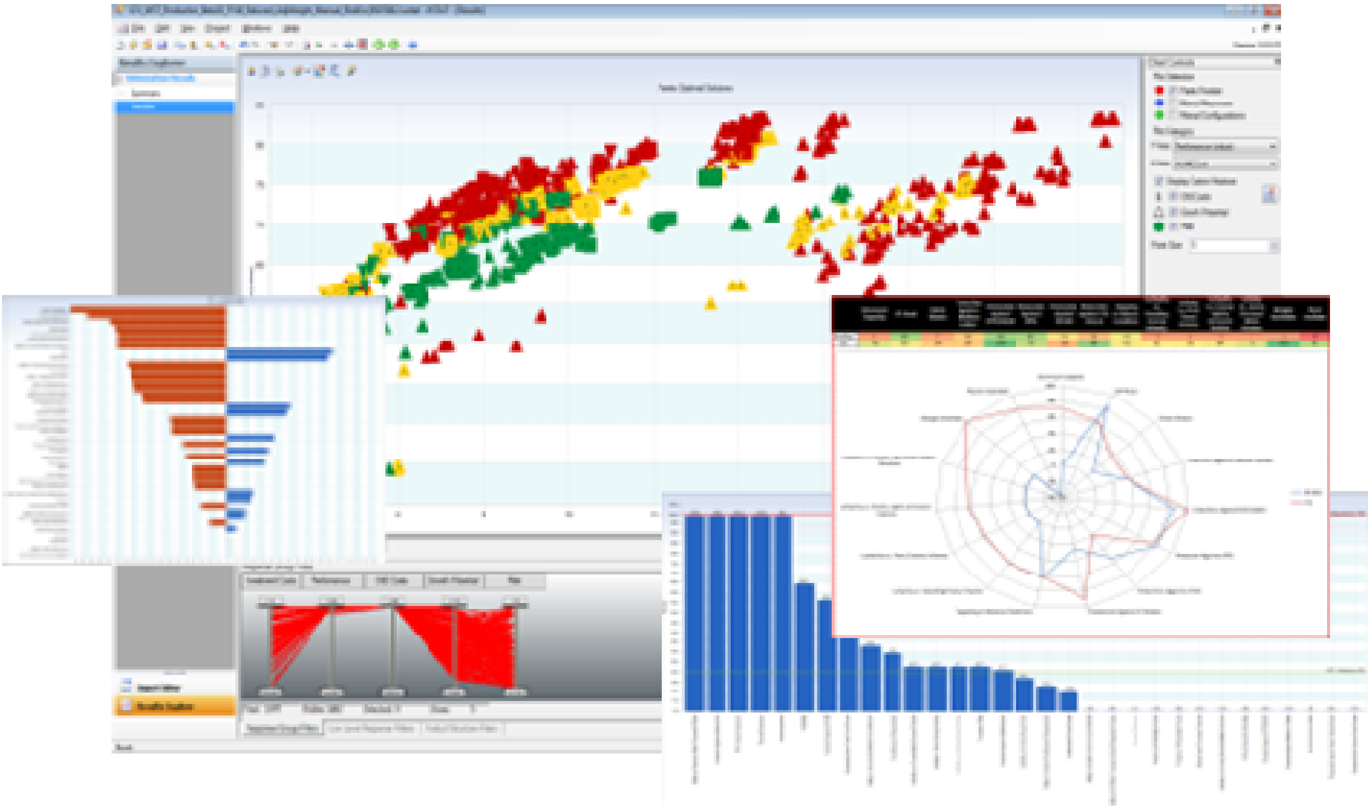

Figure 3: WSTA Tool Output

of possible system configurations can be generated growing to thousands or even millions of plausible combinations. To cope with this extremely large set of options, WSTA uses a genetic algorithm to systematically explore several thousand alternatives to identify several hundred alternatives on the Pareto Frontier - representing the set of non-dominated configurations across the five dimensions of stakeholder value. Figure 3 below show some the WSTA Tool outputs which give the decision maker the ability to explore the trade space.

For context, the WSTA team then adds aggregated assessments of non-developmental-vehicle alternatives and assessments of Government in-house conceptual designs to the trade space visualizations of the WSTA tool. From here, stakeholders can engage in an informed debate regarding cost, performance, risk trades to include trades of commonly competing requirements such as of mobility vs. protection.

VV&A status:

As an on-going process improvement program, WSTA is currently going through the Validation and Verification process with AMSAA. The current timeline projects that the tool will be V&V by July 2014. Upon completion of the V&V, PEO GCS intends to include WSTA in all future program source selection assessments; this will provide significant insights into the trades done by the OEMs as well as holistic evaluations of the systems against the requirements and specs.

WSTA creates demand across the Army's acquisition community:

Following socialization across the acquisition community, multiple PEO's and RDEC's have requested access to the tool. PEO GCS has implemented the WSTA methodology to the Bradley Engineering Change Proposal (ECP) 2, Armored Multi-Purposed Vehicle (AMPV) new start program, Paladin Integrated Management Program, and the Robotic Systems suite of platforms. PEO CS&CSS has implemented the WSTA methodology in their new Contingency Basing Infrastructure and their Operational

Energy programs. This common analytical approach signifies the tremendous change that has occurred because of WSTA as decision makers will now accept the results and recommendations from WSTA as an authoritative source for systems engineering analysis. Additionally, the Whole Systems Trades Analysis method provides a conduit of information flow from RDECOM to the PMs. WSTA's technical SMEs are able to provide technical solutions to the optimization tool and based on the results can identify candidate systems for future technology insertion projects.

IMPACT

WSTA Made Significant Impact:

As part of the GCV Technology Development phase, PM GCV used WSTA with Army and OSD senior leadership to explore the GCV systems engineering trade space. For the first time in acquisition history, senior level stakeholders could view on a single page the relative attractiveness of competing alternatives across all five dimensions of defense acquisition decision-making: unit cost, operation and support costs, development risk, growth potential, and performance. Prior to WSTA, senior leadership was presented with an array of separate analyses with minimal synthesis. Furthermore, because of WSTA's rich data base of subsystem choices and associated attributes, senior level stakeholders could ask "what if" questions of the systems engineering trade space and expect answers within hours and days rather than weeks and months. With its powerful trade space visualizations and responsive drill down capability into a deep database and assessment rationale library, one of the senior TRADOC stakeholders participating in GCV's Knowledge Point 2 meeting was heard saying that they finally had access to sufficient data to make an informed decision. No longer constrained to the assessment of just three or four alternatives across a handful of criteria, PM GCV can now clearly demonstrate a strong understanding of the full systems engineering trade space and perform an "…aggressive exploration of the capabilities trade space and the full range of alternatives prior to finalizing requirements" as required by the AUG 2011 GCV IFV MSA Acquisition Decision Memorandum (ADM). As a multiple objective value model, WSTA is well suited for efficient exploration of GCV's large trade space and as such is used to complement computerized force-on-force combat simulations. This dual model approach to the GCV systems engineering trade analysis provides a clearer, more complete view of the trade space than either model could in isolation.

Military Relevance: The GCV WSTAT process allowed PM GCV to identify technologies that will likely yield low returns on investment and technologies that have a good chance to provide high returns on investment thus improving the expected rate of technology transition to product development and in turn increasing the pace at which superior capabilities will be delivered to the warfighter.

Decision Enabling: The GCV WSTAT process enabled PM GCV to develop an in-depth understanding of the complex relationship between requirements, the design choices made to address each requirement, and the system level consequences of the sum of design choices across the full set of performance requirements as well as other elements of stakeholder value to include cost and schedule. Through data visualization techniques, decision makers can quickly understand and crisply communicate a complex trade-space and converge on recommendations that are robust in the presence of uncertainty. Specifically, WSTA was used to discover GCV design trends by weight class, identify requirements driving cost, uncover requirements ripe for refinement, conduct a non-developmental-vehicle (NDV) assessment, search for optimal primary armament design, find preferred targeting sensor subsystem, investigate armor and active protection system alternatives, conduct dismount carrying capacity trades, and understand impacts of anti-armor missile options.

CONCLUSIONS

Review of the operations research / management science literature reveals that Multiple Objective Decision Analysis (MODA) techniques can be been applied in a way that effectively provides this conceptual link between engineering models and stakeholder value. MODA techniques allow decision makers to synthesize subsystem level performance data at the system level for all alternatives across all dimensions of stakeholder value. Major system projects often generate large amounts of data from many separate analyses performed at the system, subsystem, component, or technology level by different organizations. Each analysis, however, only delivers one dimension of the decision at hand, one piece of the puzzle that the decision makers are trying to assemble. These analyses may have varying assumptions, and may be reported as standalone documents, from which decision makers must somehow aggregate system level data for all alternatives across all dimensions of the trade space in his or her head. This would prove to be an ill-fated task as all decision makers and stakeholders have cognitive limits that preclude them from successfully processing this amount of information in their short term memory (Miller 1956). When faced with a deluge of information that exceeds human cognitive limits, decision makers may be tempted to oversimplify the trade space by drastically truncating objectives and/or reducing the set of alternatives under consideration but such oversimplification runs a high risk of generating decisions that lead to poor outcomes. By providing techniques to decompose a trade decision into logical segments and then synthesize the parts into a coherent whole, a formal decision management process offers an approach that allows the decision makers to work within human cognitive limits without oversimplifying the problem. In addition, by decomposing the overall decision problem into smaller elements, experts can provide assessments of alternatives as they perform within the objective associated with their area of expertise.

A wide variety of MODA based models have been created and applied to product design problems over the past decade with varying degrees of success. Variations of MODA model design include the methods used to generate creative alternatives, the approach taken to determine decision objectives, the degree to which information is aggregated, the variety and quality of visualization techniques used to display the aggregated data, the extent to which uncertainty is captured and the way in which the impact of uncertainty to the overall decision is visualized. As demonstrated by the extensive use by PEO GCS - WSTAT has struck an uncommonly useful blend of features and state of the art techniques.

The Whole Systems Trade Analysis (WSTA) methodology developed within PEO GCS has been applied successfully across several programs to include X, Y and Z. The methodology directly addresses the Department of Defense's (DoD) request to pursue methods for greater efficiency and productivity in Defense spending (Better Buying Power 2.0 Memorandum - "do more without more.") as well as its Engineered Resilient Systems (ERS) emphasis area directing the use of systems analysis methods, advanced architecture and design analysis techniques and the use of advanced algorithms.

REFERENCES

[1]Forthcoming…