ACHIEVING BALANCED SYSTEMS THROUGH STRUCTURED DECISIONS

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ABSTRACT

To support customers during product development, General Dynamics Land Systems (GDLS) utilizes a set of Operations Research/Decision Support processes and tools to facilitate all levels of decision-making aimed at achieving a balanced system design. GDLS employs a rigorous Structured Decision (SD) process that allows for large, highly complex or strategic decisions to be made at the system-of-systems, system, and/or subsystem level. Powerful, robust tools - the Advanced Collaborative System Optimization Modeler (ACSOM) and Logical Decisions for Windows (LDW) - are used to make relatively quick assessments and provide recommendations. The latest ACSOM algorithms have increased the response time for trade study analysis by over 2,000 times and future versions will incorporate logistics analysis helping to reduce vehicle Life Cycle Cost.

INTRODUCTION

General Dynamics Land Systems (GDLS) designs, builds, and supports a full spectrum of land and amphibious combat systems, subsystems, and components worldwide. To support customers during product development, GDLS utilizes a set of Operations Research/Decision Support processes and tools to facilitate all levels of decision-making aimed at achieving a balanced system design. Structured Decision (SD) analysis is facilitated by the Decision and Risk Analysis (DRA) Team, an element of the GDLS Systems Engineering (SE) Directorate. The DRA Team's primary mission is to manage and support the transformation of operational needs and requirements into a defined system configuration. To accomplish this mission, the Team applies an integrated set of tools and methods selected from Decision Analysis, Structured Decision Making (Trade Study or Analysis of Alternatives), Risk Management, and Operations Research Modeling and Simulation (M&S). Furthermore, GDLS maintains active participation in key industry conferences, professional societies, and joint R&D projects with local universities and suppliers to advance the DRA Team's mission. Finally, DRA Team members are cleared to support U.S. Government classified projects using classified computing equipment.

STRUCTURED DECISION PROCESS OVERVIEW

GDLS employs a rigorous SD process that allows for complex or strategic decisions to be made at the system and/or subsystem level, by utilizing a cross-functional team facilitated by a DRA Team member. Although this process description is keyed to military vehicle and system-of-systems applications, it is flexible enough to be applied to most any system or system-of-systems category. System-level decisions can include a communications network, fleet of vehicles or watercraft, and port (air, land, sea) security concepts. Decisions at the subsystem-level can include selection of software packages, weapons, equipment, and resources. The SD process can also be applied to decisions that are less complex or of less strategic importance. Generally, these decisions do not require formal facilitation and can be conducted wholly by the Decision Maker (DM). For these informal decisions, the DRA Team offers an in-house developed Desktop Decision Tool that guides the DM through identifying (1) the purpose of the decision, (2) needs or requirements that must be met, (3) evaluation criteria, and (4) solution alternatives/options. For formal decisions, the same process is facilitated by experienced and trained DRA Team members who employ more robust tools, the Advanced Collaborative System Optimization Modeler (ACSOM) and Logical Decisions for Windows (LDW), to document and provide assessment results.

Appropriate Subject Matter Experts (SMEs) and stakeholders participate in the entire process. Typically, key customer representatives are identified as stakeholders and may also be the DM. Once requirements are verified and understood, appropriate evaluation criteria based on those requirements are defined. Technology parameters and subsystems are then described and options for each subsystem identified. SMEs score the subsystem options with respect to each evaluation criterion and, based on that data as input, ACSOM produces a Pareto set of feasible and non-dominated system alternatives. From that Pareto set, stakeholders select a manageable number of candidate system alternatives (typically 3-5) based on key requirements, such as performance, cost, and physical weight. The candidate system alternatives are assessed for operational effectiveness by the GDLS Battle Lab via M&S, resulting in Measures of Effectiveness that are approved by stakeholders and used to measure performance of the system alternatives. For each system evaluation criterion, a Relative Importance Weight (RIW) and Single Utility Function (SUF) are assessed by the stakeholders. Based on the evaluation criteria data, RIWs, and SUFs, LDW delivers a ranking of the system alternatives, and facilitates sensitivity analysis with respect to the RIWs, enabling the stakeholders to decide on a preferred system solution.

STRUCTURED DECISION PROCESS IN DETAIL

The following steps outline the GDLS SD process and will serve as the basis for the rest of this paper. The numbered steps correspond to the numbers in Figure 1 and subsequent paragraphs. This process describes how GDLS approaches the problem of achieving balanced design in a system. The process can be generalized for use on any system or system-of-systems involving hardware and/or software. Note: the term "subsystem" includes components, installation items, and other items below the system level.

1. Identify driving requirements and gain Voice of the Customer.
2. Identify performance and burden evaluation criteria.
3. Identify subsystems to be traded and options for each.
4. Characterize subsystem options (generate/consolidate data).
5. Identify candidate system alternatives.
6. Conduct operational effectiveness analysis on candidate system alternatives.
7. Select preferred system alternative.
    a. Finalize evaluation criteria and conduct additional system-level analysis to finalize data.
    b. Elicit RIW/SUF from stakeholders for each evaluation criteria.

8. Conduct final SE review to verify subsystem-to-system integration and requirements compliance; generate report and brief customer.

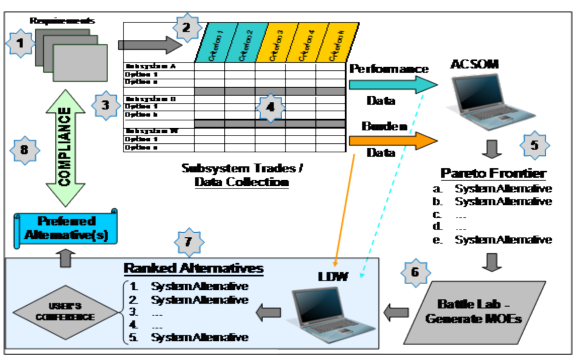

Figure 1: The GDLS Whole System Structured Decision Process Drives a Balanced System Design.

1. Voice of the Customer

The initial step in any analysis is to gain a thorough understanding of the problem and the needs of the customer. Throughout the entire span of a project, the GDLS requirements organization conducts its process to understand, document, derive necessary additional requirements, and allocate those requirements. Following an initial review of the preliminary requirements, GDLS meets with the customer to clarify any requirements that are unclear and to resolve any identified conflicts between requirements. Furthermore, GDLS elicits from the customer all preferences with respect to their requirements, giving special attention to identifying which ones drive the solution and which ones are not tradable. This establishes the trade space parameters and allows the customer to focus limited resources on the factors that most impact the system design.

2. Identify Evaluation Criteria

Beginning with customer-identified driving requirements, evaluation criteria that will measure both performance and burdens of the subsystems are identified and defined. Burden criteria include, but are not limited to: size (internal and external volumes), weight, power required, coolant required, costs (developmental, production, and life-cycle), risk (cost, schedule, and performance), and RAM (reliability, availability, and maintainability). Specific units-of-measure can be modified to meet the needs and focus of the SD, such as pounds or kilograms for weight, cubic inches or meters for volume, etc. In most analyses, data collection requires a significant portion of the SD schedule; therefore, time constraint and data availability must be seriously considered when evaluation criteria are identified. For all evaluation criteria, natural data is preferred (e.g. miles per gallon, rounds per minute, pounds, dollars). However, when natural data is not readily available, constructed criteria can be used (e.g., Preferred/Acceptable/Unacceptable; Excellent/Above Average/Average/Below Average/Poor; Pass/Fail), but must be defined in sufficient detail to minimize imprecision and subjectivity. Furthermore, although it's recognized that there are exceptions to most rules, research supports the constructed criteria parameter of an odd number of scoring levels with a maximum of seven.

3. Identify Subsystems & Respective Options to be Traded

Starting with requirements and the product work breakdown structure, a decision tree is developed to identify and document the subsystems that require some level of analysis before a selection is approved. Sometimes analysis is sufficient to identify that only one subsystem option exists, since constraining requirements may lead to a single solution or technology may not be mature enough to provide multiple solutions. For subsystems that have multiple potential options, those options need to be identified and characterized.

4. Characterize Subsystem Options

As part of the GDLS SE approach, design graphs are developed to identify the physical operating parameters of each subsystem; these graphs assist in identifying the boundaries of the trade space. Within these boundaries, thorough analyses and data collection are conducted to characterize subsystem options with respect to performance and burdens. M&S results, empirical databases, and supplier responses are typical sources for necessary data.

a. To assess the risk associated with each subsystem option, GDLS employs its structured Risk Management (RM) process, which aligns with the Defense Acquisition University and the Project Management Institute guidance. RM is a critical element of GDLS' SE and project management activities. For any SD, potential risks pertaining to respective alternatives are identified and assessed with respect to Likelihood of Occurrence and Consequence. The difficulty of mitigation is roughly assessed with respect to how much additional funding would be necessary to mitigate the risk to an acceptable level. A total risk value is determined for each option for all subsystems and is aggregated to quantify the system risk level. When subsystem options are selected as part of the final concept, the risks for that concept have already been identified and provide a foundation for the project's risk management activities. The integration of SD and RM provides increased customer satisfaction through the streamlined identification, assessment, and mitigation of risks associated with design alternatives.

b. The final data element is subsystem interaction information, describing any constraining relationships between two subsystem options. There are three categories of interaction: (1) co-requisite indicates that if a particular option from subsystem A is selected, it must be paired with a particular option from subsystem B, and only those two can function together (both or none); (2) pre-requisite indicates that if a particular option from subsystem D is selected, it must be paired with a certain option from subsystem C, however, option C can be selected without option D; and (3) non-compatible indicates that two specific subsystem options cannot be paired together.

5. Select Candidate System Alternatives

Once all evaluation criteria have been defined, and all subsystem options have been identified and characterized to the satisfaction of the stakeholders, information and data are entered in ACSOM. ACSOM is a multi-criteria integer linear programming model used to optimize the configuration of a whole system by deciding among multiple subsystem options. In a typical system, there are numerous subsystems and each subsystem generally has multiple options, making the potential configuration trade space significantly large. As an example, a recent Abrams problem included 23 traded subsystems and a total of more than 10 billion possible alternative vehicle configurations. Consequently, complete enumeration is not a viable method for identifying alternative system configurations. ACSOM evaluates configuration alternatives based on a large set of competing criteria: maximizing performance criteria (e.g., speed, fuel efficiency, and survivability) and minimizing burden criteria (e.g., weight, cost, and risk). The output is a Pareto set of feasible and non-dominated system alternatives, typically numbering in the hundreds instead of millions or billions (see Figure 2). In order to reduce the ACSOM output to an even more manageable subset of system alternatives for the stakeholders, the initial output is filtered with threshold burden values set by the stakeholders to eliminate the alternatives deemed too heavy, too expensive, etc. Then the DRA analyst facilitates the stakeholders in identifying alternatives exhibiting high performance, low driving burdens (e.g. cost and weight), and a cross section thereof to capture balanced configurations. One common method is to select the best performing 40-50 alternatives [highest multi-utility function (MUF) values] and then sort that subset by each of the driving burdens (e.g. cost and weight). Another method is to select the lowest 20-30 alternatives for each of the driving burdens and sort each subset by the highest performance (MUF). An additional method is through the comparison of the Utopia Point to those alternatives found by ACSOM. The Utopia Point is a unique point in the criterion trade space which is a point that optimizes all objective functions, and often doesn't exist. The Compromise Solution is that point which is as close as possible to the Utopia Point [1]. The Utopia Point is used in ACSOM to determine the best "balanced" solution (Compromise Solution) using multiple criterion (objective functions: e.g., Performance, Cost, and Weight). This is done by calculating the Euclidean distance between the Utopia Point and the non-dominated system alternatives from ACSOM in three dimensional space using the MATLAB application. The alternative with the smallest Euclidean distance to the Utopia Point would be the best "balanced" solution based on those objective functions.

Through DRA Team facilitation, stakeholders examine and discuss the reduced subset to select a small number of candidate system alternatives, generally 3-5, for further analyses that will feed the final process step of selecting the preferred system configuration.

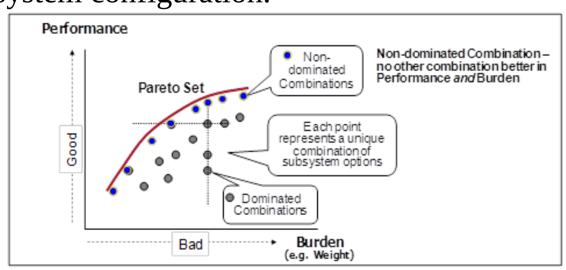

Figure 2. ACSOM Produces a Pareto Set of Non-dominated Alternatives.

6. Conduct Operational Effectiveness Analysis on Candidate System Alternatives

Although there are multiple methods for assessing system operational effectiveness, the GDLS method-of-choice for combat vehicles is to employ the GDLS Battle Lab. The Battle Lab, an element of the GDLS M&S organization, is comprised of simulations that operate in both stand-alone and federated architecture. It is based on a federation of simulations architecture and is fully interoperable in High Level Architecture and Distributed Interactive Simulation. The Battle Lab was designed to simulate the entire Joint Battle Space for the purpose of replicating a realistic operational environment in which combat platforms are assessed (see Figure 3). The federation allows for flexibility in the size and nature of the analysis. The Battle Lab can simulate and assess systems against any enemy force, anywhere in the world. The Battle Lab's combat analysis data, combined with outputs from the physics-based and dynamics-based simulations, is a critical element in GDLS' system approach to the product development and sustainment decision process. The sheer scalability, supportability, and availability of the Battle Lab and supporting simulations serve as an analysis multiplier. The GDLS M&S organization can rapidly develop simulations of nearly any system or system-of-systems. This capability combined with the ability to have scenarios and related data sets—including terrain, weather, and system performance—immediately available for use is a significant advantage that assists in reducing costs and schedule impacts for the programs. Furthermore, the customer gains additional levels of assurance that design decisions are based on supportive and progressive analyses that provide a very robust response to the proposed solutions. Through the use of the Battle Lab, along with GDLS program and Government teams, assessment of tough questions early in the acquisition process can be achieved and continuously improved throughout the system lifecycle.

Figure 3. The Battle Lab creates simulated operational environments to assess combat platforms.

7. Select Preferred System Alternative

a. LDW Input. The Measures of Effectiveness from the Battle Lab, as well as previous performance and burden evaluation criteria data identified for the system-level analysis, are entered into LDW. For each evaluation criterion, the DRA analyst elicits from the stakeholders an RIW and Single-Utility Function (SUF) curve to reflect the stakeholders' utility preference within the respective data range (see Figure 4). This data is also entered in LDW. The primary purpose of the SUFs, also referred to as Common Units, is to convert all units of measure (i.e., Mission Accomplishment and Unit Price) into one common unit of measure (utility between 0 and 1), so all criteria can be fairly compared against each other.

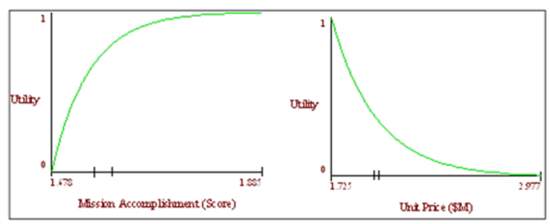

Figure 4. SUF Curves reflect the stakeholders' utility preference.

b. LDW Output. LDW produces a ranked list of the system alternatives (see Figure 5), presented live to the stakeholders to facilitate selection of a preferred system alternative configuration. For each alternative, the multi-colored stacked-bar ranking reflects the level of utility for each evaluation criterion, which is the product of the criterion score for that alternative, multiplied by the RIW of that criterion. The respective RIW is shown in the parentheses following each criterion in the legend.

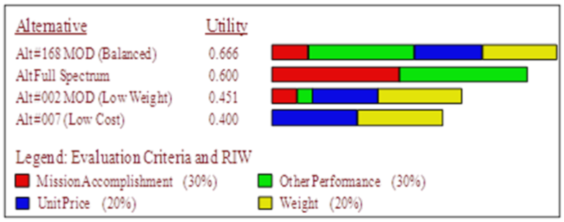

Figure 5. LDW Stacked-Bar Ranking of the Alternatives.

c. LDW also produces a direct comparison of any two alternatives to identify strengths and weaknesses (see Figure 6), and a graph for each criterion that illustrates the sensitivity of that criterion with respect to RIW (see Figure 7). These capabilities provide valuable insight for the stakeholders in selecting their preferred alternative.

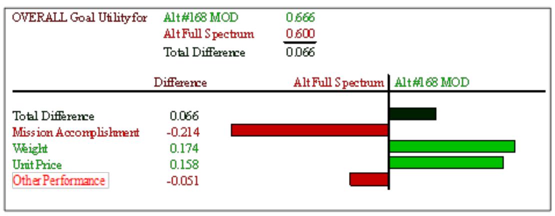

Figure 6. The top-ranked #168 MOD Alternative is superior to the second-ranked Full Spectrum Alternative in Weight and Unit Price criteria, but inferior in Mission Accomplishment and Other Performance criteria

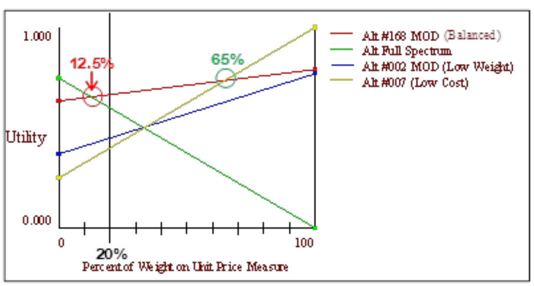

Figure 7. With respect to the Unit Price Measure (or evaluation criterion), decreasing the RIW from 20% to 12.5% would result in a rank reversal between the top two alternatives, indicating a moderate degree of sensitivity. However, it would require an increase in RIW to 65% to cause a rank reversal between the top and bottom ranked alternatives, indicating very low sensitivity.

8. Final SE Review and Report

All incorporated subsystems of the preferred solution are subjected to a follow-on SE evaluation to confirm requirements' compliance and resolution of any subsystem-to-system interoperability issues. Necessary updates and modifications are made, with the final trade results being incorporated into the final optimized design concept. Lastly, a comprehensive report is delivered to the customer, along with an out-brief, if the customer desires.

ACSOM BACKGROUND

ACSOM was the focus of effort that resulted in its GDLS creator, Mr. David Strimling, receiving the 2006 National Defense Industrial Association (NDIA) Lt Gen Thomas R. Ferguson, Jr. Systems Engineering Excellence Award (see Figure 8). Mr. Steve Rapp (GDLS) contributed to the foundation of ACSOM through knowledge created in his master's thesis at the U.S. Naval Postgraduate School, which earned him the 1987 Military Operations Research Society (MORS) award for the "Thesis Most Likely to Improve National Defense" and the 1989 ORSA/TIMS (Operations Research Society of America/The Institute for Management Science) Military Application Society (MAS) Koopman prize. Improvements to ACSOM continue to be implemented.

GDLS also has an SD process for Capital Acquisition and Internal Research and Development projects. This process is similar to the process described above, but uses Logical Decisions for Windows Portfolio (LDWP) as the tool of choice. This tool has the capability to evaluate combinations of projects (portfolios) at distinct budget levels with several methods to be chosen by the stakeholders. The methods include Benefit Only, Cost-to-Benefit, and Linear Integer Optimization Rankings of Portfolios. Constraints can be applied to projects such as co-requisite where two or more projects must be worked together and mutually exclusive where two or more projects cannot be worked together; Sequential project constraints may also be applied. Also, budget levels may be allocated to organizations and finally, projects may be stipulated to be chosen regardless of their value. This tool and respective methodology make the selection of large numbers of projects a very rigorous endeavor.

Figure 8. NDIA Award for SE Excellence.

CONCLUSION

GDLS employs a rigorous Structured Decision process that has been used effectively in major defense acquisition programs including Abrams, Stryker, Expeditionary Fighting Vehicle (EFV), Future Combat System (FCS), and Ground Combat Vehicle (GCV). The process was formally recognized by the Chief of Systems Engineering and Program Manager, Heavy Brigade Combat Team (PM-HBCT) for contributions to the Abrams Evolutionary Design project (see Figure 9). Furthermore, when used to establish the Stryker Modernization configuration for the U.S. Army, the process was recognized by the Department of Defense (DoD) Executive for Systems Engineering as an innovative process. This recognition formed the basis for the NDIA's selection of the Stryker Modernization program as a 2008 Top-5 DoD Program. More importantly, this process is available for most any customer to facilitate achieving balanced system design for their own applications.

Figure 9. Certificate from PM-HBCT.

REFERENCES

[1] R.T. Marler and J.S. Arora, "Structural and Multidisciplinary Optimization", Volume 26, Number 6, pp. 369-395, Springer, 2004.