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A Simulation-Based Vehicle Design Strategy for Acquisition and Requirements Validation

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ABSTRACT

To acquire a new fleet of vehicles, Army decision-makers must consider many conflicting requirements including the needs of users, the vehicle's life cycle implications in terms of reliability, maintainability, and survivability, and the design and production capabilities of the contractor. Army decision-makers choose appropriate vehicle characteristic targets to maximize military objectives within an acquisition budget. This budgetary constraint is especially important when costly new technology is considered. Once product characteristic targets are decided, contractors bid for the design and production contract. This approach is limited if the military does not directly account for the contractors' design capabilities when targeting specific vehicle characteristics. This limitation can result in the inability of the winning contractor to meet some or all of the product targets, leading to costly delays in product delivery and potentially sub-optimal performance.

An analytical tool that captures the tradeoffs among military objectives and models the design capabilities of suppliers can aid decision-makers during the acquisition process. This article builds on the Analytical Target Cascading methodology by developing extensions of Analytical Target Setting to facilitate requirements validation, developing acquisition decision models, and examining a case study for dual-use technology. These methods use comprehensive vehicle simulation models, which represent the contractor's design capabilities, to drive vehicle target setting decisions. Conclusions will be drawn from previous research applied in the commercial sector to show how the military can take advantage of formalizing the links between engineering design decisions and non-technical decisions to reduce risk and improve quality of the final product.

INTRODUCTION

The Army's acquisition process for a new vehicle considers the needs of the soldier, vehicle performance, life cycle and cost management, and potential contractor capabilities. Generally, tradeoffs exist among soldier needs, life cycle implications, and the actual technical capabilities of the contractor. A program manager, referred to here as the "Army decision-maker", must balance these tradeoffs to set targets for vehicles that best meet military needs. Typically, the decision-maker addresses information sequentially. For example, first s/he may receive a description of soldier needs in the form of an operations requirement document (ORD), then s/he may work with Army divisions focusing on the life cycle and cost implications of the vehicle, and finally, s/he may set design targets and a budget for the contractor bidding process. However, these often conflicting considerations are interdependent, and treating each concern in isolation can lead to sub-optimal decision-making.

This article provides an overview of methods to model the Army's acquisition process using a decision model that incorporates soldier needs, life cycle and cost considerations, and competitive bidding. The acquisition decision model makes use of comprehensive vehicle simulations, which represent the contractor's technical capabilities, and battlefield simulations to reveal the impact of vehicle design targets on both the contractor and the military.

The acquisition decision models serve as tools that help decision-makers formally organize the major elements of the acquisition process to evaluate vehicle decisions and set vehicle targets systematically. This article proceeds by providing background on the Analytical Target Cascading methodology for complex system design and showing how it can be extended for requirements validation using Analytical Target Setting. Army and supplier decision models are then developed for the acquisition process, and finally, a case study is examined for dual-use technology valuation.

BACKGROUND: ANALYTICAL TARGET CASCADING

Analytical target cascading is an optimization methodology for systems design that works by decomposing a complex system into a hierarchy of interrelated subsystems (Kim 2001). ATC requires a mathematical model for each subsystem that computes the subsystem response characteristics as a function of the decisions at that subsystem. The subsystem models are organized into elements of a hierarchy, as in the example shown in Figure 1, where the top level represents the overall system and each lower level represents a subsystem of its parent element. Papalambros (2001) provides an overview of the ATC literature, and Michalek and Papalambros (2004) provide details of the generalized ATC formulation.

In the ATC process, top-level system design targets are propagated down to subsystems, which are then optimized to match the targets as closely as possible. The resulting responses are then rebalanced at higher levels by iteratively adjusting targets and designs throughout the hierarchy to achieve consistency. Michelena *et al.* (2003) and Michalek and Papalambros (2004) proved that by using certain classes of coordination strategies to coordinate elements in the ATC hierarchy, the ATC formulation will converge, within a user-specified tolerance, to the same solution as if all variables in the entire system were optimized simultaneously (or, "all-at-once"). Using ATC can be advantageous because it organizes and separates models and information by focus or discipline, providing communication only where necessary. Problems that are computationally difficult or impossible to solve all-at-once can be solved using ATC, and in some cases ATC can result in improved computational efficiency because the formulation of each individual element typically has fewer degrees of freedom and fewer constraints than the all-at-once formulation.

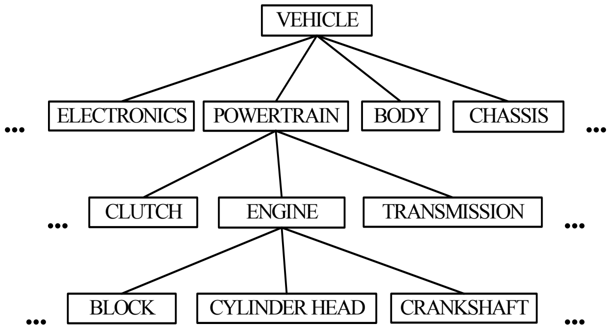

Figure 1. Hypothetical product decomposition for Analytical Target Cascading

The ATC process formally addresses technical tradeoffs in the design of a complex system by coordinating subsystem models in order to produce a consistent, feasible design.

REQUIREMENTS VALIDATION USING ANALYTICAL TARGET SETTING

Modeling a process for setting top level ATC targets in the design of a new vehicle allows decision-makers to capture not only technical tradeoffs, such as the tradeoff between production cost and fuel economy improvement, but also the impact of the design on the organization's operations. For a commercial manufacturer, this includes the enterprise's production capabilities and market presence, which helps define profitability.

In Cooper *et al.* (2003), the decision-making process of setting targets in an enterprise context is explored for commercial hybrid truck design and production. This process, termed Analytical Target Setting (ATS), can be used to determine the value of a new technology using profit as the objective and considering both technical and non-technical decisions. In the ATS process, profit is driven by tradeoff decisions that are represented using low fidelity engineering information rather than expensive, comprehensive vehicle simulations. The low fidelity tradeoff models may be derived from comprehensive engineering models or from past data. In Cooper *et al.* (2003), a design of experiments was conducted using a high fidelity vehicle simulation to develop a simplified model of technical tradeoffs for use in the ATS process. The design tradeoff is used in conjunction with production cost and pricing models to show the impact of the product on profit for the enterprise. The Analytical Target Setting problem is formulated as follows:

$$\begin{array}{rl} \text{maximize} & \text{profit} \\ \text{with respect to} & \text{hybrid cost, price premium,} \\ & \text{production volume} \\ \text{subject to} & \text{price premium} \geq \text{consumer threshold,} \\ & \text{production volume} \leq \text{capacity,} \\ & \text{fuel economy} = f(\text{hybrid cost}) \end{array} \tag{1}$$

where profit is modeled as price minus cost multiplied by production volume. In this formulation, hybrid cost is treated as a decision that corresponds to a particular fuel economy target level such that increasing the fuel economy of the hybrid system is achieved at a higher cost. This tradeoff is captured in the low fidelity model. Clearly defining the organization's objective using models that incorporate design information and enterprise capabilities is a way for decision-makers to estimate the value of new technology decisions and reduce the risk of costly re-designs or delays in production. Similarly, the Army can use such a target setting model to estimate the value of a new vehicle technology.

An analytical target setting model of the Army's acquisition process could include life cycle considerations, budgetary considerations, and performance metrics while minimizing life cycle costs. An example ATS model for the acquisition of a military support truck is:

$$\begin{array}{rl} \text{minimize} & \text{life cycle costs} \\ \text{with respect to} & \text{vehicle performance characteristics,} \\ & \text{fleet size} \\ \text{subject to} & \text{price x quantity} \leq \text{acquisition budget} \\ & \text{mobility} \geq \text{mobility threshold} \\ & \text{survivability} \geq \text{survivability threshold} \\ & f_1(\text{performance char.}) \leq 0 \\ & \text{cost} = f_2(\text{performance char.}) \\ & \text{mobility} = f_3(\text{performance char.}) \\ & \text{survivability} = f_4(\text{performance char.}) \\ & \text{price} = f_5(\text{cost}) \end{array} \qquad (2)$$

where vehicle performance characteristics may include fuel economy, gradeability, or acceleration. Performance characteristics are constrained and related to production cost using the low fidelity tradeoff models represented by the functions f_1 and f_2 respectively. Mobility and survivability are determined using battlefield simulations f_3 and f_4 that reveal the truck's performance in battlefield scenarios based on the chosen product performance characteristics. Additionally, price is modeled with f_5 as a negotiated (or assumed) margin over the per-unit cost calculated by f_2. This model offers a way for the military to estimate the value of its decisions from user and life cycle perspectives. The similarity of the two ATS models in Eqs. (1) and (2) is that the objective of each organization is driven by both technical and non-technical decisions, and disjoint decision-making may not properly capture the interactions of these decisions.

Once targets are set, the military can determine if the contractor can feasibly achieve the desired design and fleet targets within the budget during the initial stage of the acquisition process. The ATC process addresses the issue of validating top level targets for a system in a multilevel hierarchically structured product. For this application, ATC represents the design and production capabilities of the contractor. A high fidelity vehicle simulation tool is used to determine feasible truck designs that attempt to match the top level vehicle performance targets set by the ATS decision model in Eq. (2). The vehicle level decisions, such as targets for the battery, motor and engine, are then cascaded down to the sub-system level, which may include detailed engine, transmission, or suspension models. The goal of ATC is to determine a design that is consistent between system and sub-system levels and that matches top level targets as closely as possible.

AQUISITION AND SUPPLIER DECISION MODELS

The Army's acquisition process is a complex system involving the evaluation of new technologies and products to meet the diverse needs of the military. When designing a new vehicle, for example, Army decision-makers must consider the soldier's use of the vehicle, the operating costs during the vehicle's life cycle, and the investment cost to acquire the vehicle fleet.

Much of the current work in acquisition modeling focuses on the tradeoff between a product's performance and cost. For example, Hohn (1999) modeled the tradeoff between the performance of a weapon system and the cost associated with acquiring the system using parametric studies to evaluate battlefield performance gains resulting from increased investment cost. We attempt to extend this line of work by including the product's life cycle considerations in the acquisition decision model in addition to modeling the contractor's ability to achieve desired product performance targets.

Figure 2 illustrates the Army decision model and includes a "supplier model" which is described later. In Figure 2, the Army chooses vehicle performance targets and fleet size, and the Army decides which supplier(s) will be awarded the contract. Suppliers design and build vehicles while attempting to meet the performance targets set by the military as closely as possible, but it is the actual characteristics of the produced vehicle that will determine field performance with respect to the characteristics of enemy army vehicles. The Army's goal is to choose its decisions in such a way that the final product maximizes its objectives.

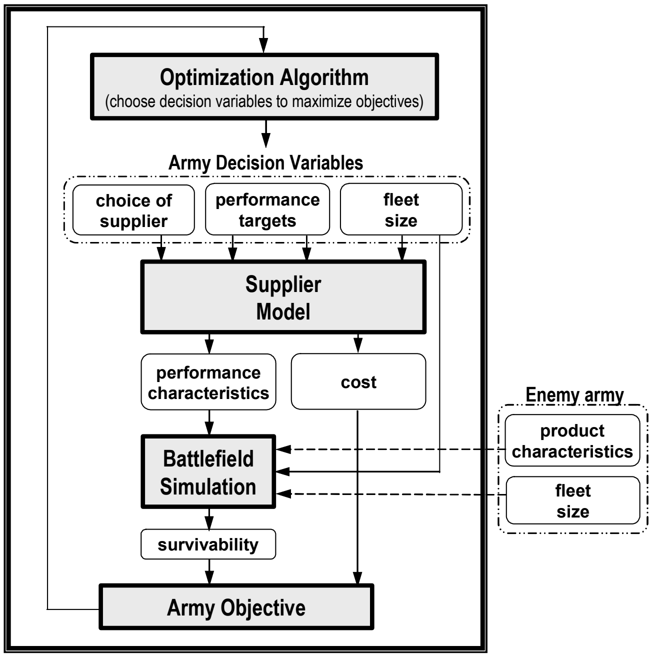

Figure 2. Army decision framework for military implementation

By linking the military and supplier models, Army decision-makers can fully understand the implications of their decisions and realize during the early stages of the acquisition whether the decision will result in optimal vehicles. The decision-maker can then re-analyze the initial targets set by Eq. (2) based on the validated targets from target cascading.

Validating the acquisition target setting process with competitive bidding models and comprehensive engineering simulations reduces decision-maker risk of setting design and fleet targets that are not realizable and therefore result in sub-optimal cost or performance.

If the bidding process is explicitly considered when Army decision-makers set vehicle targets, then improved decisions can be made. Often the winning contractor is unable to produce a vehicle that meets all of the targets set by the Army, resulting in delays and potentially sub-optimal designs that may not meet Army needs. Alternatively, if the winning contractor is able to produce a vehicle that meets all targets with ease, then the targets may have not been set aggressively enough. Thus, including the competitive bidding process into acquisition modeling can reduce the risk of sub-optimal product target setting.

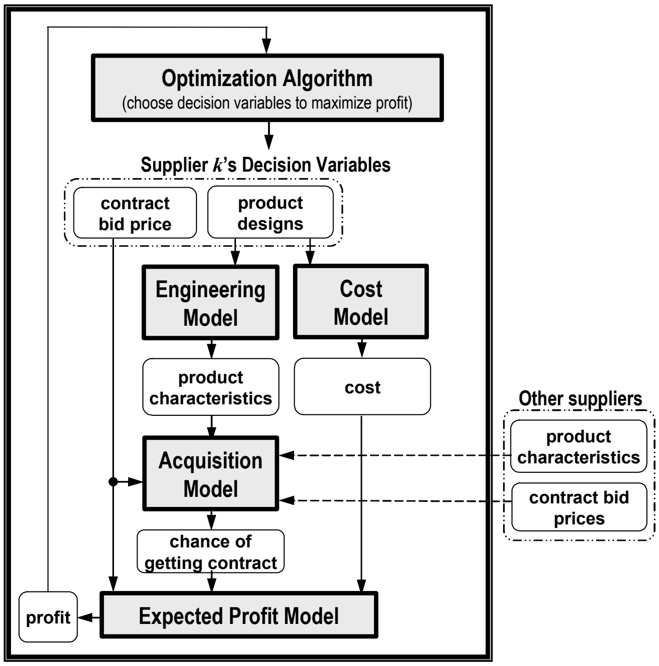

Figure 3. Supplier model of competitive bidding for a military contract

An example from a commercial application is adapted here to provide a roadmap of how competitive bidding can be modeled in the acquisition process. Michalek *et al.* (2003) studied the effect of vehicle emission regulation policy on the design decisions of commercial vehicle manufacturers using game theory to model competition. In the study, each manufacturer is modeled as a profit maximizing decision-maker. Combining engineering, demand, cost, and profit models, game-theoretic oligopoly analysis is used to find the Nash equilibrium for vehicle design and pricing decisions in the market. This framework can be adapted to model decision-making of competing contractors, where the contractors compete for an Army contract rather than for market share, as shown in Figure 3. Suppliers make decisions about product design and the bid price. A cost model predicts production cost, and an engineering model predicts product characteristics as a function of the design decisions. The supplier's acquisition model predicts the chances of winning the Army contract depending on the supplier product's characteristics and bid price compared to those of other suppliers. Each supplier chooses the decision variables in order to maximize expected profit. The Army can potentially make vehicle decisions more effectively by using such a model to account for supplier objectives and supplier competition during the target setting process.

TECHNOLOGY VALUATION FOR DUAL USE

Product characteristics and technologies used for military applications are often different than those used for commercial user needs. However, if similar technology needs exist in both the commercial and military markets the two parties can take advantage of "dual-use" synergies.

Dual-use is defined here as technology and design that is shared between military and commercial vehicles. This notion relates to the 21st Century Truck Initiative, which is the transformation of the U.S. Army to a lighter, more mobile force while helping commercial manufacturers develop and reduce the cost of new technologies (Skalny *et al.*, 2001). The basic premise is that developing the new technology for military vehicles, such as support trucks, will reduce the development and production cost of incorporating the new technology in commercial trucks. In return, the military receives lower prices because of the shared technology development cost.

A study for developing hybrid technology in the medium truck market, detailed in Cooper *et al.* (2003), revealed that dual-use decision-making can add value for both parties. In this study, military product attribute and fleet size targets are set to fixed values, and the Army operates under a pre-determined acquisition budget. Additionally, a single commercial producer is assumed to have won the bid for the design and production of the military hybrid trucks. The producer's design decisions are modeled using high-fidelity vehicle simulations which describe the producer's actual design capabilities compared with design targets set by the military.

This study compared design and production decisions made in a dual-use scenario (i.e. simultaneous military and commercial decisions) with design and production decisions made in a disjoint scenario (i.e. independent military and commercial decisions). Figure 4 illustrates the two scenarios.

The results of this study show that in the dual-use scenario, the producer can afford to use a larger, more expensive hybrid system in the military truck, allowing the producer to more closely meet the military's fuel economy target than in the disjoint scenario. This is because economies of scale in simultaneous production of the commercial and Army fleets reduces production cost compared to the disjoint case. From the commercial market perspective, the decrease in hybrid truck production cost allows the manufacturer to capture more market demand by increasing production capacity for commercial hybrid trucks.

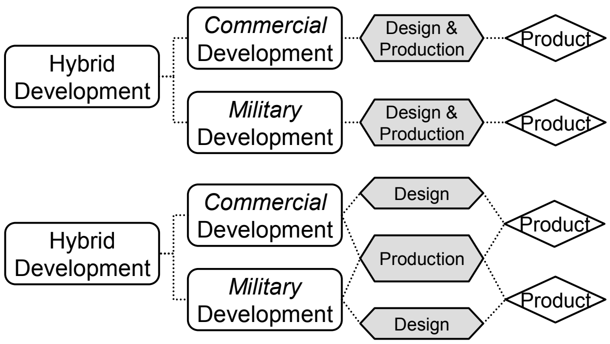

Figure 4. Disjoint (top) and dual-use (bottom) design and production organizational structure for hybrid product development

CONCLUSION

The Army acquisition process is a complex process involving consideration of and tradeoffs among many conflicting requirements. This article has introduced several decision-making models related to the acquisition process which address a range of conflicting concerns, such as soldier needs, life cycle costs, new technology and design, budget allocation, competitive bidding, and the ability of contractors to meet military targets. Dual-use technology was shown to add value for both the military and the commercial supplier, and models of suppler decision-making and competitive contract bidding are shown to be of value to the military in setting realistic vehicle targets to avoid sub-optimal performance. These models are intended to aid the decision-maker in making systematic tradeoff decisions among these concerns in order to reduce the risk of costly delays and redesign. The models have been applied to commercial applications, and future work includes the application of these models to hybrid technology for future tactical support vehicles and other military vehicles.

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