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# War Gaming Applications For Achieving Optimum Acquisition Of Future Space

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# War Gaming Applications for Achieving Optimum Acquisition of Future Space Systems


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Abstract

In 2014, the federal government spent nearly half a trillion dollars on contractor projects. The Department of Defense wants to develop an algorithm to optimize the acquisition of new technologies. This project makes use of game theory, probability and statistics, non-linear programming and mathematical models to model negotiations between governmental agencies and private contractors. It focuses on generating the optimum solution and its corresponding acquisition strategy for different contract types. This project culminates in a collection of MATLAB (MathWorks) programs and the newly developed strategy shows strong convergence to Nash equilibrium values and successful selection of optimum solutions.

## 1. Introduction

In 2013, the Air Force instituted the Space Modernization Initiative (SMI) as a way to tackle the issue of introducing modernized versions of existing technologies into the Space Based Infrared System while simultaneously lowering the risk level for the next wave of infrared satellites [2][7]. Under this initiative, the Air Force hopes to explore ventures that will allow them to try new affordable alternatives. Similarly, in late 2014, the Department of Defense (DoD) released the Defense Innovation Initiative (DII) and the Modular Open Systems Architecture (MOSA) Initiative. The DII aims to "pursue innovative ways to sustain and advance our military superiority for the 21st Century" while the department faces budget cuts [3] and the MOSA aims to have a cohesive system structure [8].

For the past decade, the federal government has spent nearly half a trillion dollars a year on private contracts alone [1]. This caused the DoD to want advanced mathematical algorithms to optimize the acquisition of government contracts. The Aerospace Corporation, a federal research and development center and Air Force partner, developed a mathematical framework [6] to improve how the government acquires new technologies by reinventing the acquisition process.

This paper focuses on the War-Gaming Engine (WGE) that Heather Barcomb (SUNY Geneseo), William Avery Black (Lehigh University), Paul Vienhage (Emory University), and I developed in response to the SMI and the DII. This Bayesian [4] game based MATLAB program resulted from a collaboration between Aerospace and the North Carolina State

University's Modeling and Industrial Applied Mathematics Research Experience for Undergraduates. The WGE takes the government's needs, generates the optimum Program and Technical Baseline (PTB) [5] combination of technologies, and demonstrates the corresponding bidding and acquisition strategy.

### Key Terms:

**Warfighter needs** are abstract operational needs that the military has.

A **capability** is an ability a system has. A number of capabilities fulfill a warfighter need.

Different **technology enablers (TEs)** are concrete technologies. Groupings of technology enablers meet a capability.

An **Architectural Solution Set (ARCS)** is a set of capabilities and technology enablers. Although each ARCS has a different composition, they still meet the same warfighter need.

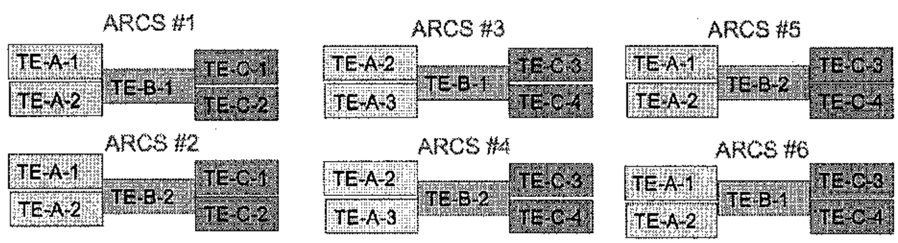


**Figure 1.** Notional ARCS and their composition

## 2. Methods

### 2.a. Stage 1: Program and Technical Baseline War Gaming Engine (PTB-WGE)

Once the DoD declares a warfighter need, various entities compile a list of all the available technologies that could do the job and investigate various contractors to see who can supply the DoD with the technologies. The entities then send the list of technologies to each contractor and ask them to rank how risky they think each technology would be. The government also submits information about the contractors' previous performance. The PTB-WGE takes in Excel files containing this information, picks the best set of technologies, calculates the risk level, and outputs the winning set of technologies and its corresponding PTB Solution Type.

The engine starts by asking the user to pick a player—either the DoD Acquisition Authority (DAA) or an individual contractor. If one chooses to play as the DAA, he or she then enters a market survey file that contains information for all the contractors. If one chooses to play as a contractor, then he or she enters a market survey file that contains only that contractor's information. The market survey file contains the risk level the contactors assigned to the various technologies. Low risk corresponds from 0 percent to 30 percent risk, medium risk from 30 percent to 65 percent risk, and high risk from 65 percent to 100 percent risk.

| Desired Capabilities to Meet Warfighter Needs | Technology Enabler (TE) | | Notional Data Obtained From Market Survey: Complete and Imperfect Information – Mixed Game Template | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Technology Assessment | | | | Market Assessment | | | |
| | TE No. | Weight | Supplier #1 | Supplier #2 | Supplier #3 | Supplier #4 | Supplier #1 | Supplier #2 | Supplier #3 | Supplier #4 |
| Capability #A | TE-A-1 | $W_1$ | Low Risk | High Risk | Low Risk | Low Risk | Low Risk | High Risk | Low Risk | Low Risk |
| | TE-A-2 | $W_2$ | Low Risk | Low Risk | High Risk | Medium Risk | Low Risk | Low Risk | High Risk | Low Risk |
| | TE-A-3 | $W_3$ | Medium Risk | Low Risk | Low Risk | High Risk | Medium Risk | Low Risk | Low Risk | High Risk |
| Capability #B | TE-B-1 | $W_4$ | Low Risk | Low Risk | Medium Risk | Medium Risk | Low Risk | Low Risk | Medium Risk | Medium Risk |
| | TE-B-2 | $W_5$ | High Risk | Medium Risk | Low Risk | Medium Risk | High Risk | Medium Risk | Low Risk | Medium Risk |
| Capability #C | TE-C-1 | $W_6$ | High Risk | High Risk | Medium Risk | Medium Risk | High Risk | High Risk | Medium Risk | Medium Risk |
| | TE-C-2 | $W_7$ | Medium Risk | Medium Risk | High Risk | Low Risk | Medium Risk | Medium Risk | High Risk | Low Risk |
| | TE-C-3 | $W_8$ | Low Risk | High Risk | High Risk | High Risk | Low Risk | High Risk | High Risk | High Risk |
| | TE-C-4 | $W_9$ | Low Risk | Low Risk | Medium Risk | Medium Risk | Low Risk | Low Risk | Medium Risk | Medium Risk |

**Table 1.** Market Survey Compiled for the DAA

| Desired Capabilities to Meet Warfighter Needs | Technology Enabler (TE) | | Proposed Template for Market Survey | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Technology Assessment | | | | Market Assessment | | | |
| | TE No. | Weight | KTR #1 | KTR #2 | KTR #3 | KTR #4 | KTR #1 | KTR #2 | KTR #3 | KTR #4 |
| Capability #A | TE-A-1 | $W_1$ | Low Risk | | | | Low Risk | | | |
| | TE-A-2 | $W_2$ | Low Risk | | | | Low Risk | | | |
| | TE-A-3 | $W_3$ | Medium Risk | | | | Medium Risk | | | |
| Capability #B | TE-B-1 | $W_4$ | Low Risk | | | | Low Risk | | | |
| | TE-B-2 | $W_5$ | High Risk | | | | High Risk | | | |
| Capability #C | TE-C-1 | $W_6$ | High Risk | | | | High Risk | | | |
| | TE-C-2 | $W_7$ | Medium Risk | | | | Medium Risk | | | |
| | TE-C-3 | $W_8$ | Low Risk | | | | Low Risk | | | |
| | TE-C-4 | $W_9$ | Low Risk | | | | Low Risk | | | |

**Table 2.** Market Survey Compiled for an individual contractor

The program then asks for the file with the set of ARCS. After the different sets of technologies are defined, we create a matrix from the table below. This table defines the configuration of each set of technology enablers. A TE gets a 1 when in the set and a 0 when not.

| | ARCS 1 | ARCS 2 | ARCS 3 | ARCS 4 | ARCS 5 | ARCS 6 |
|---|---|---|---|---|---|---|
| TE-A-1 | 1 | 1 | 0 | 0 | 1 | 1 |
| TE-A-2 | 1 | 1 | 1 | 1 | 1 | 1 |
| TE-A-3 | 0 | 0 | 1 | 1 | 0 | 0 |
| TE-B-1 | 1 | 0 | 1 | 0 | 0 | 1 |
| TE-B-2 | 0 | 1 | 0 | 1 | 1 | 0 |
| TE-C-1 | 1 | 1 | 0 | 0 | 0 | 0 |
| TE-C-2 | 1 | 1 | 0 | 0 | 0 | 0 |
| TE-C-3 | 0 | 0 | 1 | 1 | 1 | 1 |
| TE-C-4 | 0 | 0 | 1 | 1 | 1 | 1 |

**Table 3.** ARCS translated into a table

Lastly, the program asks for the Payoff and Cost Function file. The table in this file allows the contractors to quantitatively rank aspects of each ARCS—effectively explaining how and why they ranked each technology the way they did.

| Notional Payoff-and-Cost Function Template For the Supplier/Contract #1: | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Architecture Assessment for the Architecture Solution #1 and Associated PTB Solution Type 1 | | | | | | | | | | |
| DAA-PWGE Assessment Metric / Yes / No / Plan | Technical Requirements | | | | Affordability Requirements | | | | | |
| | Proposed Tech Reqts and Associated Tech Enablers Incorporated Industry's Input | Align Tech Reqts w/ Warfighter Needs and Tech Enablers | Capability Deliveries Meet the Warfighter Needs | Performance Meet Threshold Reqts | Should Cost Data Available for Each Tech Enabler | Should Cost Data Available for Overall System | Leverage DOD IRAD to Lower Cost | Leverage Contractor's IRAD to Lower Cost | Provide Incentives to Allow Contractor to Make IRAD an Allowable Cost | Leverage MOSA for Architecture Design Solution |
| BBP 3.0 Directive (Weighting factor = 0, 1, 2, 3, and 4) | 4 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | 3 | 4 |
| Yes -> Payoff with Weighting factor 1, 2, 3, 4 | 4 | 1 | 3 | 4 | 1 (Provide Cost Est) | 2 (Provide Cost Est) | 3 (Include in Cost Est) | 0 | 3 (Include in RFP) | 0 |
| No -> Loss/Cost with weighting factor 0, -1, -2, -3 and -4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plan to do it (Potential Payoff) with weighting factor 0.25, 0.5, 0.75, 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Assessment Score | 8 | 1 | 3 | 4 | 2 | 4 | 6 | 4 | 6 | 5 |
| Average Score | 4 | | | | 4.5 | | | | | |
| Total Average Score | 4.25 | | | | | | | | | |

**Table 4.** Notional Payoff and Cost Function Table

The Aerospace Corporation realized that the Air Force would value some technologies over others and created the Belief Function to account for their opinion. The Belief Function, given below, allows the program to assign weighted values in order to assign higher weights to priority TEs.

$$P_{1,j}^{1\_Tech} = \prod_{l=1}^{L} W_l . PrTE_{i,j,l}^{1\_Tech}$$

**Equation 1.**

Once the user puts in all the above information, the PTB-WGE performs the following steps:

- Randomly generates a probability for each TE from the uniform distribution
- Determines the product of the probability of each TE and the adjusted weight
- Normalizes the product across the ARCS
- Constructs an average of each probability over a number of runs
- Compares the average to a set of determined values
- Classifies each ARCS as low, medium, or high risk.

## 2.b. Stage 2: Acquisition/Bidding War Gaming Engine (AB-WGE)

Each risk level has its own PTB Solution Type (column 1), and each Solution Type its own acquisition strategy (column 5).

| Requirements Classifications, Advanced Acquisition Strategy Mapping, PTB Solution Classification and PTB Risk Assessment | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Requirement Type** | **Requirement Type Description** | **Market Uncertainty** | **Technology Uncertainty** | **Advanced Acquisition Strategy Mapping** | **PTB Solution Type Classification** | **PTB Risk Assessment** | |
| | | | | | | **Technical & Performance Risks** | **Cost & Schedule Risks** |
| Type 1 | Firmed and fixed requirements with known Technology Enablers | Low | Low | Enhancement Launch: FFP, FPEPA | PTB Type 1 Solution: Conservative | Low | Low |
| Type 2 | Well-defined requirements with some uncertainties on technology enabler and market | Low | Medium | Platform Launch: FPIF, FPAF | PTB Type 2 Solution: Innovative | Low | Medium |
| | | Medium | Low | | | Medium | Low |
| | | Medium | Medium | | | Medium | Medium |
| Type 3 | Requirements are somewhat known with some market uncertainty but can not identify the exact technology enablers | Medium | High | Positioning Option: CPIF | PTB Type 3 Solution: More Innovative | High | Medium |
| Type 4 | Requirements are somewhat known with some technology uncertainty but can not identify the exact company (or companies) to provide the technology enabler | High | Medium | Scouting Option: CPAF, CPIF | PTB Type 4 Solution: Less Conservative | Medium | High |
| Type 5 | Unknown Requirements with unknown technology enable and market | High | High | Stepping Stone Option: CPAF, CPFF | PTB Type 5 Solution: Most Innovative | High | High |

**Table 5.** PTB Mapping Rules

The AB-WGE uses the winning Solution Type, its corresponding contract type, and the user inputted cost distribution in order to pick the bidding strategy that will either maximize contractor profit or maximize government savings. It outputs the optimal contractor bid and the government's payoff. Each engine has the same basic setup and uses Monte Carlo simulations, or repeated random sampling, to demonstrate the bidding process. The player defines a range of possible inputs and the program generates inputs randomly from the probability distribution of choice, performs a deterministic computation on the inputs using various models, and aggregates the results.

### 2.b.1. Acquisition under PTB Type 1

Solution Type 1—low market risk and low technological risk—corresponds to the Fixed Price Seal Bid/Fixed Firm Price contract type. The government has clear and specific requirements and contracts are non-negotiable. In this case, the lowest bidder wins the contract. For the uniform distribution, the mathematical model used to calculate production costs is

$$c_i = (C_{max} - C_{min}).p_i + C_{min};$$

**Equation 2.**

and the model below represents the Nash equilibrium—the stable state of a system involving the interaction of different participants—optimal bidding function.

$$S_{Non\_Coop\_Opt\_n\_KTR} = b^{opt}(c_j) = \underbrace{C_j}_{\text{Cost}} + \underbrace{\frac{C_{max} - c_j}{n}}_{\text{Profit}}, for\ j = 1,2,..,n$$

**Equation 3.**

### 2.b.2. Acquisition under PTB Types 2 and 5

The existence of moderate risk correlates to Solution Type 2—the Fixed Price Incentive Firm contract type. This strategy allows for some uncertainty in the production cost and profits are adjusted according to the production costs. Contracts are negotiable and the contractor who provides the most cost savings wins the contract.

The Cost Plus Incentive Fee contract type corresponds to Type 5 solutions—ones that have high technological and market risks. The government incurs most of the risk because it must provide cost reimbursements to incentivize contractors to take on the project. The government gives the initial negotiated fee, which it later adjusts. Both contract types use the following models but differ in initial inputs and optimum target cost. Equations 4 and 5 calculate the government and contractors' payoff respectively, Equations 6 and 7 determine the maximum cost, and Equation 8 calculates the target price for acquisition.

$$PCF_{Gov} = (1 - SR_{C_i}(\%)).(T_c - A_{C_i}) - A_{C_i} - PCF_{KTR_i}; i = 1,2, \ldots n$$

Where $PCF_{KTR_i}$ is the i[th] KTR profit given by:

$$PCF_{KTR_i} = (T_{p_i} - T_c) + SR_{C_i}(\%).(T_c - A_{C_i}); i = 1,2, \ldots n$$

**Equations 4 and 5.**

$$\underset{\forall i}{Max}\{F_i: F_i = (PCF_{Gov} - PCF^0_{Gov}).(PCF_{KTR_i} - PCF^0_{KTR_i}); i = 1,2, \ldots n\}$$

Or:

$$\underset{\forall i}{Max}\left\{F_i: F_i = \left((1 - SR_{C_i}(\%)).(T_c - A_{C_i}) - A_{C_i} - PCF_{KTR_i} - PCF^0_{Gov}\right). (PCF_{KTR_i} - PCF^0_{KTR_i}); i = 1,2, \ldots n\right\}$$

**Equations 6 and 7.**

$$T_{p_{1i}} = C_P - 1.5.\,SR_{C_i}(\%).\,(T_c - A_{C_i});\ i = 1,2, \dots n$$

**Equation 8.**

## 3. Results

The PTB-WGE outputs its information in MATLAB's command line interface. Figure 2 displays the final results of a game, using the generic data found in Table 1. The program displays the winning set of technologies and shows how each capability is met by the different technologies. It also shows the risk level for the winning set and its corresponding PTB Solution Type. The results shown below show that the optimal solution is a Type 1 solution, which corresponds to the Fixed Firm Price (FFP) contract type as described in Table 5.

```
Choose Architectural Solution #4 from Supplier 1.

PTB Solution Composition: {TE-2,TE-3,TE-5,TE-8,TE-9}
Capability 1 is met by TE-2,TE-3.
Capability 2 is met by TE-5.
Capability 3 is met by TE-8,TE-9.


Technical risk is: Low Risk.
Market risk is: Low Risk.
So this is a Type 1 solution.
```

**Figure 2.** PTB-WGE Sample Output

Figures 3, 4, 5 and 6 show the AB-WGE results for the FFP contract type. The images show the outcomes for four hypothetical contractors bidding for a Type 1 contract. If all four contractors bid optimally, their bids converge to the same Nash equilibrium value, as seen on the left plot of Figure 3. However, if Contractor 1 is the only one to bid optimally, his bid converges to an equilibrium value significantly lower than the other contractors.

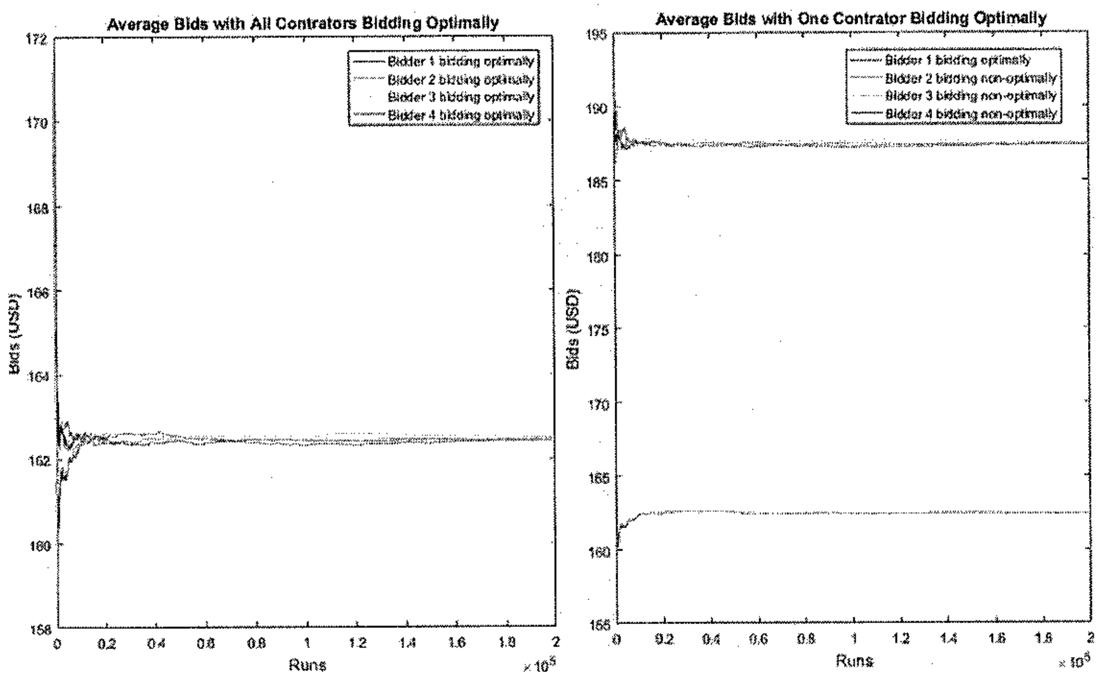


**Figure 3.** Average Bid for Contractors Bidding Optimally vs. Non-optimally

Consequently, if Contractor 1 wins the contract, he makes a lower profit per contract compared to everyone else, as shown by the left plot of Figure 4. A contractor would choose to bid so low because under Type 1, the lowest bidder wins the contract.

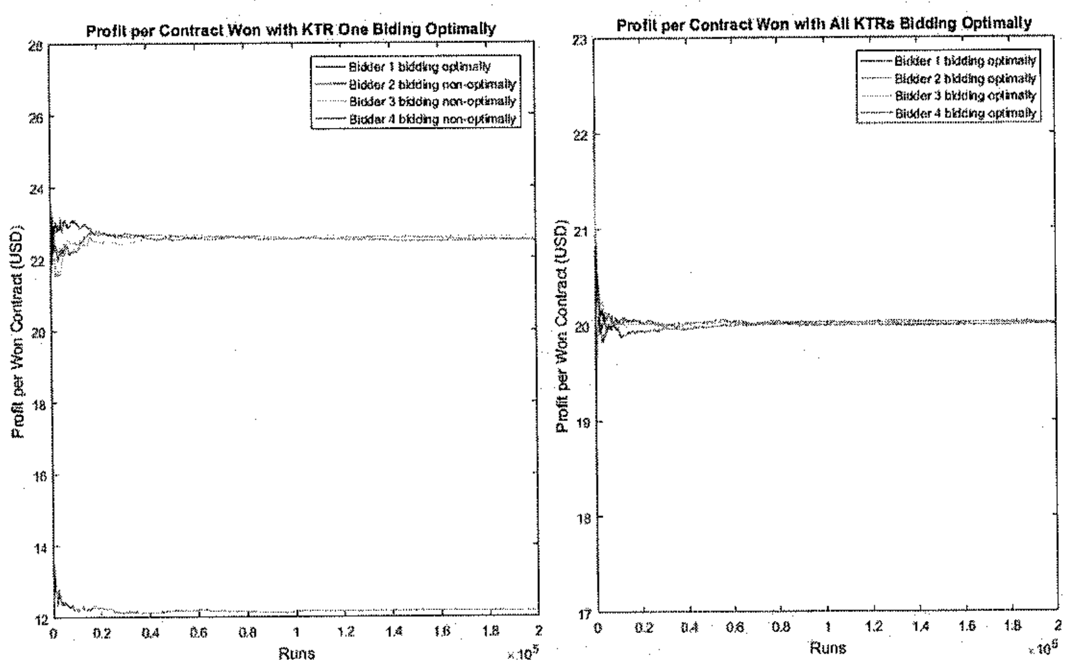


**Figure 4.** Average Profit per Contract with One Contractor Bidding Optimally vs All Contractors Bidding Optimally

Thus, if the contractors keep up this trend, Contractor 1 would win more of the contracts—40 percent, compared to everyone else's 20 percent—bringing his overall profit to a higher value, as shown in the left plot of Figure 6.

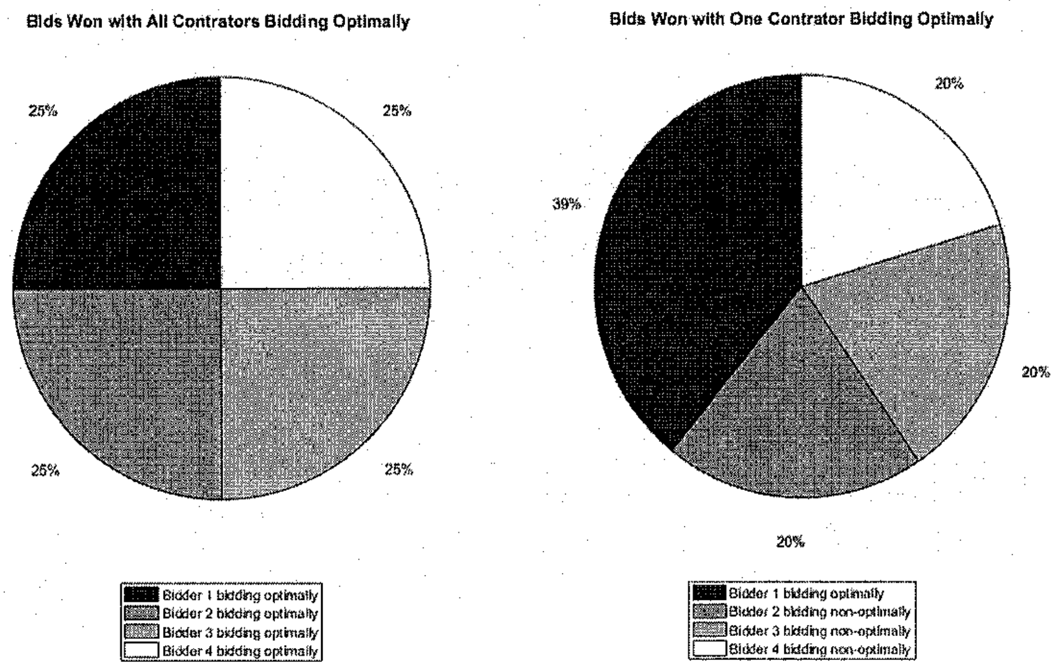


**Figure 5.** Percentage of Contracts Wont for Contractors Bidding Optimally vs. Non-optimally

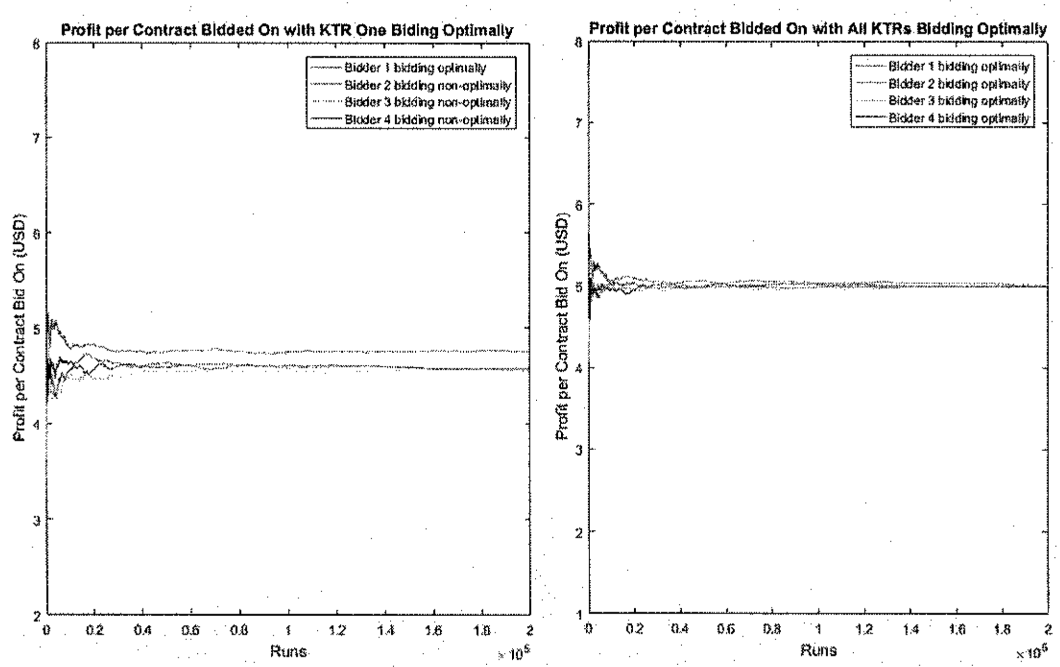


**Figure 6.** Long-term Profit Results for One Contractor Bidding Optimally vs All Contractors Bidding Optimally

## 4. Validation

The process of validation involved testing the models to see if they produced "correct" estimates when given manipulated data, as there will always be a "right" answer. For the Program and Technical Baseline games, I created multiple market surveys and payoff-and-cost function tables and changed the final PCF scores, risk levels and configurations of Architectural Solution Sets to see if the program would accurately pick the right solution each time. We validated the acquisition games by comparing the Nash Equilibrium values to previously won governmental contracts. In all cases, the optimal bidder reduced the government payment while simultaneously increasing contractor profits over time.

## 5. Discussion

In accordance with the DoD's Innovation [3] and MOSA Initiatives [8], The Aerospace Corporation sought to develop a comprehensive war-gaming model [6] to demonstrate optimal bidding strategies for different contract types. My REU team and I implemented the first set of models designed by Aerospace in a set of MATLAB packages, which meet the goals of constructing the optimal PTB solutions and calculating optimal bids. The optimal solutions select the technology architectures that generate the best bids and most competition while achieving warfighter goals. By optimizing all of the game components of the War Gaming Engine, the results have the potential to significantly increase the efficiency of governmental acquisitions.

However, there are seven game selections in total—three "static" games and four "dynamic" games [6]. The static games assume each contractor submits their information once and for all while the dynamic game accounts for real life market changes. At the time of this project, Aerospace had not determined the particulars of the dynamic game and no one had ever attempted to create the static games before. There are also five PTB types and by the end of the REU, my team and I had finished static games for three of the five contract types—PTB Types 1, 2 and 5. Further research and development includes the finishing of the Types 3 and 4 static games and creation of models for the dynamic games plus their MATLAB implementation. Also, the ideas for the WGE are brand new and unique—thus the discovery of alternative contract types, bidding strategies, and new risk level combinations will lead to updates in the mapping rule found in Table 5 and the creation of new and improved models.

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