

War-Gaming Application for Future Space Systems Acquisition: MATLAB Implementation of War-Gaming Acquisition Models and Simulation Results

Research Experience for Undergraduates (REU) Student Team¹

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Abstract

The paper describes the MATLAB (MathWorks) programs that were developed during the REU workshop¹ to implement The Aerospace Corporation developed Unified Game-based Acquisition Framework and Advanced Game-based Mathematical Framework (UGAF-AGMF) and its associated War-Gaming Engine (WGE) models. Each game can be played from the perspectives of the Department of Defense Acquisition Authority (DAA) or of an individual contractor (KTR). The programs also implement Aerospace's optimum "Program and Technical Baseline (PTB) and associated acquisition" strategy that combines low Total Ownership Cost (TOC) with innovative designs while still meeting warfighter needs. The paper also describes the Bayesian Acquisition War-Gaming approach using Monte Carlo simulations, a numerical analysis technique to account for uncertainty in decision making, which simulate the PTB development and acquisition processes and will detail the procedure of the implementation and the interactions between the games.

Keywords: Unified Game-based Acquisition Framework, Advanced Game-based Mathematical Framework, Bayesian games, Program and Technical Baseline, Warfighter Capability, MATLAB, Nash equilibrium, Monte Carlo simulations, Fixed Price Seal Bid, Firm Fixed Price, Fixed Price Incentive Firm.

1. Introduction

In 2014, the federal government spent nearly half a trillion dollars on private contracts. The Department of Defense (DoD) wants to develop advanced mathematical algorithms and models to optimize the acquisition of government contracts. Recently, The Aerospace Corporation developed a Unified Game-based Acquisition Framework-Advanced Game-based Mathematical Framework (UGAF-AGMF) [1] that makes use of game theory, probability and statistics, non-linear programming and mathematical modeling components to model contract negotiations. Aerospace's proposed advanced mathematical war-gaming models and algorithms to define the PTB [2] and generate its corresponding optimum acquisition strategies will be presented in the upcoming SPIE 2017 conference.

Based on The Aerospace's developed war-gaming models and algorithms [2, 3], this paper describes a collaborative project between The Aerospace Corporation, a REU student team and North Carolina State University (NCSU) through the National Science Foundation (NSF) funded Research Experience for Undergraduates (REU) workshop during summer 2016. The REU project has three goals: (1) Implement the Aerospace's war-gaming models in MATLAB and enhance their computation speed, (2) Generate the optimum Program and Technical Baseline (PTB) solution and its corresponding acquisition strategy, and (3) Provide simulation results for a notional space system acquisition. Similar to the Aerospace's acquisition and bidding war-gaming models [3], the project will focus on

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Fixed Price Seal Bid (FPSB)/Firm Fixed Price (FFP) and Fixed-Price Incentive Firm (FPIF) contract types and games that can be played from the perspectives of the DoD or of a contractor. The simulation results show that the acquisition strategy using the proposed Nash Equilibrium strategy converges to optimum contractor’s bidding values, which simultaneously increases government savings and contractor profit in all bidding games.

The paper is organized as follows: (1) Section 2 describes the simulation approach employed by the REU student team; (2) Section 3 describes an overview of the Program and Technical Baseline (PTB) war-gaming models and the MATLAB implementation of these models; (3) Section 4 presents an overview of the acquisition and bidding war-gaming models and the MATLAB implementation of these models; (4) Section 5 presents the simulation results; and (5) Section 6 provides the conclusion of the paper.

2. Simulation Approach

The team used the following procedure to simulate the acquisition process:

- Step 1: Define a domain for inputs. For our purposes, this translates to the government (or the DoD Acquisition Authority (DAA)) providing a range of possible costs for the proposed project.
- Step 2: Generate inputs—“actual cost” values—randomly based on the uniform or triangle distribution.
- Step 3: Perform a deterministic computation on the inputs. With the actual cost, we use the concept of Nash equilibrium discussed in [1-2] to derive a formula to obtain each contractor’s optimum bid.
- Step 4: Aggregate the results by repeating Steps 2 and 3 for a set number of runs to test the stability of the simulated results. The results are then averaged and evaluated.
- Interactions between Games – Once the PTB game determines the risk of the chosen solution set, this information becomes the contract type that makes up the structure of the Acquisition-Bidding games through the mapping rule shown in Fig 1 below.

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

Figure 1. Mapping Rules for Identifying Acquisition Strategy and Corresponding Risks Associated with Requirement Type and PTB Solution Type

3. Overview of Program and Technical Baseline (PTB) War-Gaming Models and MATLAB Implementation

The following steps outline the MATLAB implementation process for the PTB War-Gaming Engines (PTB-WGEs):

- Inputs: Market Survey results, Architectural Solution (ARCS) sets, Payoff-and-Cost Function evaluation

- What it does: Selects the best ARCS and determines its PTB Solution Type
- Outputs: Optimum PTB solution and associated risks including market uncertainty, technology uncertainty, technical and performance, and cost and schedule risks

The following subsections provide an overview of both the contractor and government (DAA) WGEs, i.e., KTR-PWGE and DAA-PWGE, respectively. Some important terminologies associated with the PTB-WGEs are:

- Capability: also known as a “Warfighter Capability,” is a general need that should be fulfilled by a successful technological solution, e.g. the ability to manage satellite trajectories
- Technology Enabler (TE): a specific technology solution that either meets a capability alone or in combination with other technology enablers, e.g. a telemetry communications system
- Architectural Solution Set (ARCS): the solution set made up of different technology enablers that meets all relevant capabilities

3.a. Contractor PTB WGE (KTR-PWGE)

In this game, the government simulates the games using contractors’ perspective. Market survey data and contractor’s past performance are used to characterize the contractors’ bidding behaviors and the player imports the data for each contractor separately. The evaluated risks are weighted based on the technology enabler priority and the reported technology and market risks using a uniform distribution. Based on a weighting function, each contractor’s optimal PTB solution type is outputted for use in the acquisition game engine (KTR-AWGE) described in [2]. Fig 2 describes a proposed template for the market survey to characterize the contractor’s behavior [2].

Desired Capabilities to Meet Warfighter Needs	Technology Enabler (TE)		Proposed Template for Market Survey							
	TE No.	Weight	Technology Assessment				Market Assessment			
			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			

Figure 2. Proposed Template for Market Survey

The weights shown in Fig. 2 must satisfy the following condition [2]:

$$P_j^k = \sum_{i=1}^L P_{i,j}^k = \sum_{i=1}^L \prod_{l=1}^L W_l \cdot PrTE_{i,j,l}^k = 1$$

Eqn. 1

Here, P_j^k is the “Belief function” assigned for the k^{th} contractor, which is defined as “the probability of selecting a PTB solution type “ j ” given an architecture solution “ i ”, where $i = 1, 2, 3, \dots, L$ [2].

3.b. Government PTB WGE (DAA-PWGE)

In this game, the DoD Acquisition Authority (DAA) simulates the games from the government’s perspective. Similar to the KTR-PWGE, the contractors’ past performance and the player imports the market survey data on each contractor simultaneously. In a Pure Game, the DAA is more certain about their risk assessments on each contractor and no weighting function is needed. Fig. 3 describes notional market survey results for “Pure” games. In a Mixed Game, DAA is more uncertain of their risk assessments on each contractor and a “Belief” function is needed. Note that the Technology Enablers (TEs) can be weighted based on their priority and by using the uniform distribution. Fig. 4 describes notional market survey results for “Mixed” games.

Just like the contractor PTB game, the overall optimal PTB solution with its associated Solution Type, risks and contract type are outputted for use in the acquisition game engine (DAA-AWGE).

Desired Capabilities to Meet Warfighter Needs	Technology Enabler (TE)		Notional Data Obtained From Market Survey: Complete and Perfect Information – Pure Game Template								
	TE No.	Weight (Optional)	Technology Assessment				Market Assessment				
			Supplier #1	Supplier #2	Supplier #3	Supplier #4	Supplier #1	Supplier #2	Supplier #3	Supplier #4	
Capability #A	TE-A-1	1/9	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk
	TE-A-2	1/9	No Risk	High Risk	No Risk	No Risk	No Risk	High Risk	No Risk	No Risk	
	TE-A-3	1/9	High Risk	No Risk	High Risk	High Risk	High Risk	No Risk	High Risk	High Risk	
Capability #B	TE-B-1	1/9	No Risk	No Risk	High Risk	High Risk	No Risk	No Risk	High Risk	High Risk	
	TE-B-2	1/9	High Risk	High Risk	No Risk	No Risk	High Risk	High Risk	No Risk	No Risk	
Capability #C	TE-C-1	1/9	No Risk	No Risk	No Risk	High Risk	No Risk	No Risk	No Risk	High Risk	
	TE-C-2	1/9	No Risk	High Risk	High Risk	No Risk	No Risk	High Risk	High Risk	No Risk	
	TE-C-3	1/9	High Risk	High Risk	No Risk	No Risk	High Risk	High Risk	No Risk	No Risk	
	TE-C-4	1/9	High Risk	No Risk	High Risk	High Risk	High Risk	No Risk	High Risk	High Risk	

Figure 3. Notional Market Survey Results for Pure Games

Desired Capabilities to Meet Warfighter Needs	Technology Enabler (TE)		Notional Data Obtained From Market Survey: Complete and Imperfect Information – Mixed Game Template							
	TE No.	Weight	Technology Assessment				Market Assessment			
			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

Figure 4. Notional Market Survey Results for Mixed Game

4. Overview of Acquisition and Bidding War-Gaming Models and MATLAB Implementation

The following steps outline the MATLAB implementation process for the Acquisition-Bidding War-Gaming Engines (AB-WGEs):

- Input: Program and Technical Baseline Solution Type, Cost Distribution, Corresponding Contract Type
- What it does:
 - KTR-AWGE selects a bidding strategy to maximize contractor profit.
 - DAA-AWGE selects a target price and related contract parameters that provide the maximum government savings
- Output: Optimal bid, Government Payoff, Contractor Payoff

The following subsections provide an overview of the contractor and government (DAA) Acquisition-Bidding WGEs. Some important terminologies associated with the AB-WGEs are:

- Nash Equilibrium: a stable solution to game theoretic problem involving multiple players in which no individual player can improve their payoff by a unilateral change in behavior
- Non-Cooperative and Incomplete Information Game: each contractor is unaware of the bidding strategy of competitors. Assumed for all contractor games
- Payoff Function: the function used to evaluate the desirable given outcome (bid) for a given player

4.a. Contractor Bidding WGE (KTR-AWGE)

Similar to the KTR-PWGE, the government simulates the bidding games using the contractors' perspective. The following description summarizes the implementation of the KTR-AWGE MATLAB model [3]:

- Input: Contractor PTB solution type and associated contract type, contractor risk assessment results from KTR-PWGE MATLAB model, cost estimates and cost distribution
- Model: Selects a bidding strategy that provides the maximum contractor profit
- Output: Bidding strategy and contractor payoff

4.b. Government Acquisition WGE (DAA-AWGE)

Similar to the DAA-PWGE, the government simulates the games using the DAA's perspective. The following description summarizes the DAA-AWGE MATLAB model [3]:

- Input: Government PTB solution type and associated contract type, government risk assessment results from DAA-PWGE MATLAB model, cost estimates and cost distribution
- Model: Selects a target price that provides the maximum government savings with "increased competition" or "increased number of bidders"

- Output: Government payoff, number of bidders, optimum acquisition strategy including contract type, incentives, target price, sharing ratios, and savings.

4.c. Acquisition under Fixed Price Seal Bid/Firm Fixed Price (FPSB/FFP)

These contract types are used when the government's requirements are specific and well defined with low risks (PTB Solution Type 1) and provide contractors a single, non-negotiable price. All of the risk becomes the responsibility of the contractor which provides the maximum incentive for the contractors to control costs. The lowest bidder wins the contract. For optimum bidders, the optimum bid using the Nash equilibrium strategy has been derived in [3] and given below:

$$b^{opt}(c_j) = \underbrace{C_j}_{\text{Cost}} + \underbrace{\frac{C_{max} - c_j}{n}}_{\text{Profit}}, \text{ for } j = 1, 2, \dots, n \quad \text{Eqn. 2}$$

Under this contract type, the non-optimal bidders select their bids based on an assigned percentage of cost. The simulation selects this percentage randomly within the range of expected profit indicated by industry.

4.d. Acquisition under Fixed Price Incentive Firm (FPIF)

The FPIF contract provides the government more flexibility to adjust the contractor's profits based on where the actual cost of project falls with respect to the government's target cost. A contractor can get more profit when the actual cost falls below the target cost and vice versa. The DAA chooses this contract type when the government's requirements have moderate technology and market uncertainty [2-3]. The games minimize the government payoff and maximize the contractor profit based on an objective function, giving it the name the "Min-Max" game [3]. The Pay-Off Functions (PCF) are defined as [3]:

Government Pay-off/Cost Function (PCF_{Gov}) or Government's Cost Saving (affordability) is defined as:

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

Where PCF_{KTR_i} is the i^{th} KTR profit given by:

$$PCF_{KTR_i} = (T_{p_i} - T_c) + SR_{C_i}(\%).(T_c - A_{C_i}); i = 1, 2, \dots, n \quad \text{Eqn. 3}$$

Equation 4, given below, defines the objective function for the FPIF contract [3]:

$$\begin{aligned} & \underset{\forall i}{\text{Max}} \{F_i: F_i = (PCF_{Gov} - PCF_{Gov}^0). (PCF_{KTR_i} - PCF_{KTR_i}^0); i = 1, 2, \dots, n\} \\ & \text{Or:} \\ & \underset{\forall i}{\text{Max}} \left\{ F_i: F_i = \left((1 - SR_{C_i}(\%)).(T_c - A_{C_i}) - A_{C_i} - PCF_{KTR_i} - PCF_{Gov}^0 \right) \cdot \right. \\ & \quad \left. (PCF_{KTR_i} - PCF_{KTR_i}^0); i = 1, 2, \dots, n \right\} \quad \text{Eqn. 4} \end{aligned}$$

5. Simulation Results

Fig 5 shows the PTB simulation results taking the form of a command line interface in MATLAB. Fig. 5 displays the final results of this interface using generic data to propagate the inputs of the PTB game. The PTB MATLAB program determines the required technology enablers, what requirements they satisfy, the risk profile and the solution type. The PTB solution shown in Fig. 5 assumed the market survey template results shown in Fig. 3. The PTB results for this example show that the optimal PTB solution is a Type 1 Solution, which corresponds to the Firm Fixed Price (FFP) contract type as described in Fig. 1.

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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 5. Simulation Results for PTB Pure Game:
Output of a MATLAB Interface Displaying PTB Solution with Selected TEs, Risk Profile and Calculated Solution Type

Figs. 6, 7 and 8 show the simulation results for the AB-WGE model for the FFP contract type. The left plot of Fig. 6 describes the average bids for all contractors bidding optimally. The right plot of Fig. 6 shows the average bids for one contractor bidding optimally and three contractors bidding non-optimally. The average bid for a contractor bidding optimally converges to a lower price than for those contractors bidding non-optimally.

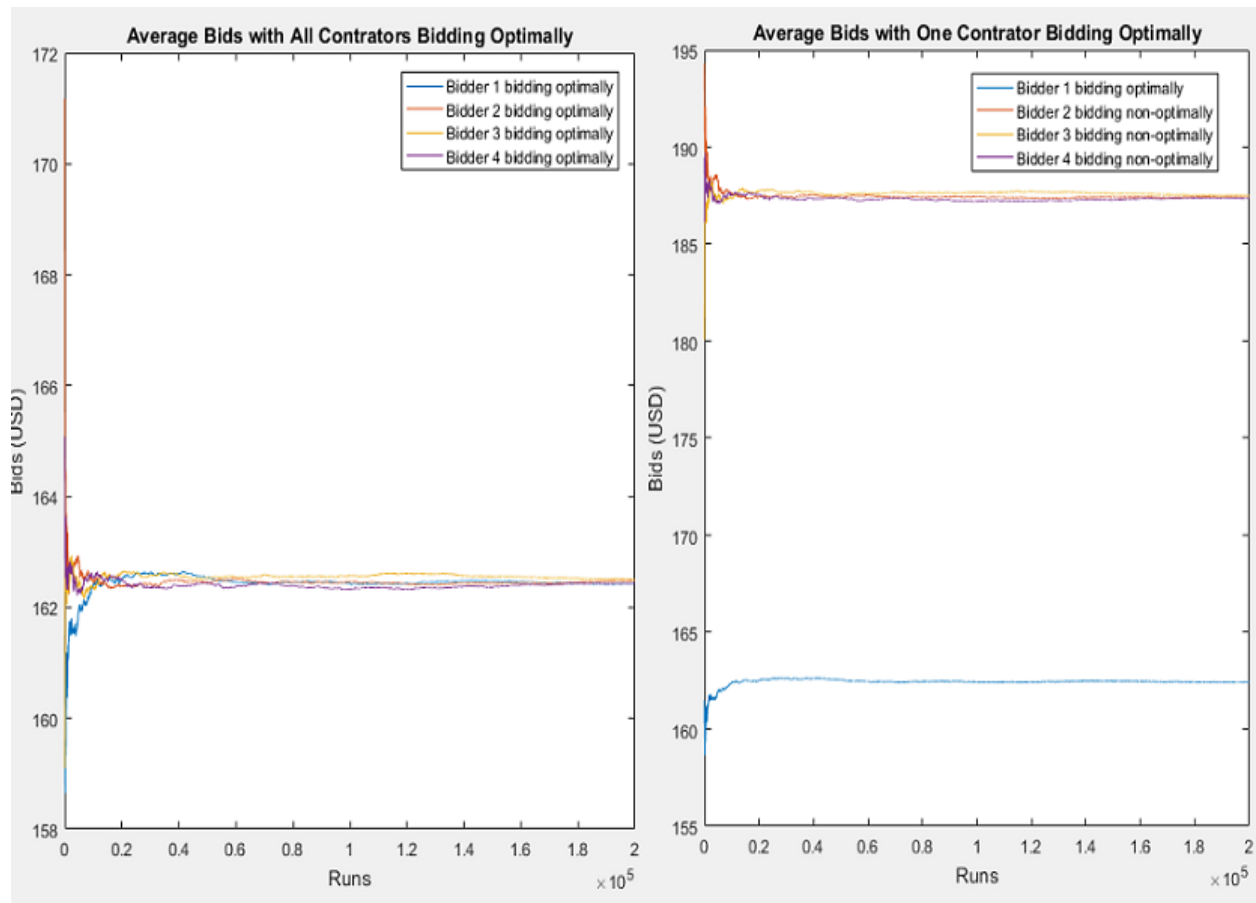


Figure 6. Simulation Results for FFP Contract Type:
Average Bid for Contractor Bidding Optimally vs. Contractor Bidding Non-Optimally

Fig. 7 shows the simulation results for the contractor profit per contract bid. The results show that the profit is higher for optimal bidder as they win more contracts than the non-optimal bidders. The left plot of Fig. 7 describes the

average profits for all contractors bidding optimally. The right plot of Fig. 7 shows the average profits for one contractor bidding optimally and three contractors bidding non-optimally.

Fig. 8 shows the number of times in terms of percentage that each contractor won. This shows that the optimally bidding contractor will win much more over non-optimal bidders. The left plot of Fig. 8 describes the percentage of bids won for all contractors bidding optimally. The right plot of Fig. 8 shows the percentage of bids won for one contractor bidding optimally and three contractors bidding non-optimally.

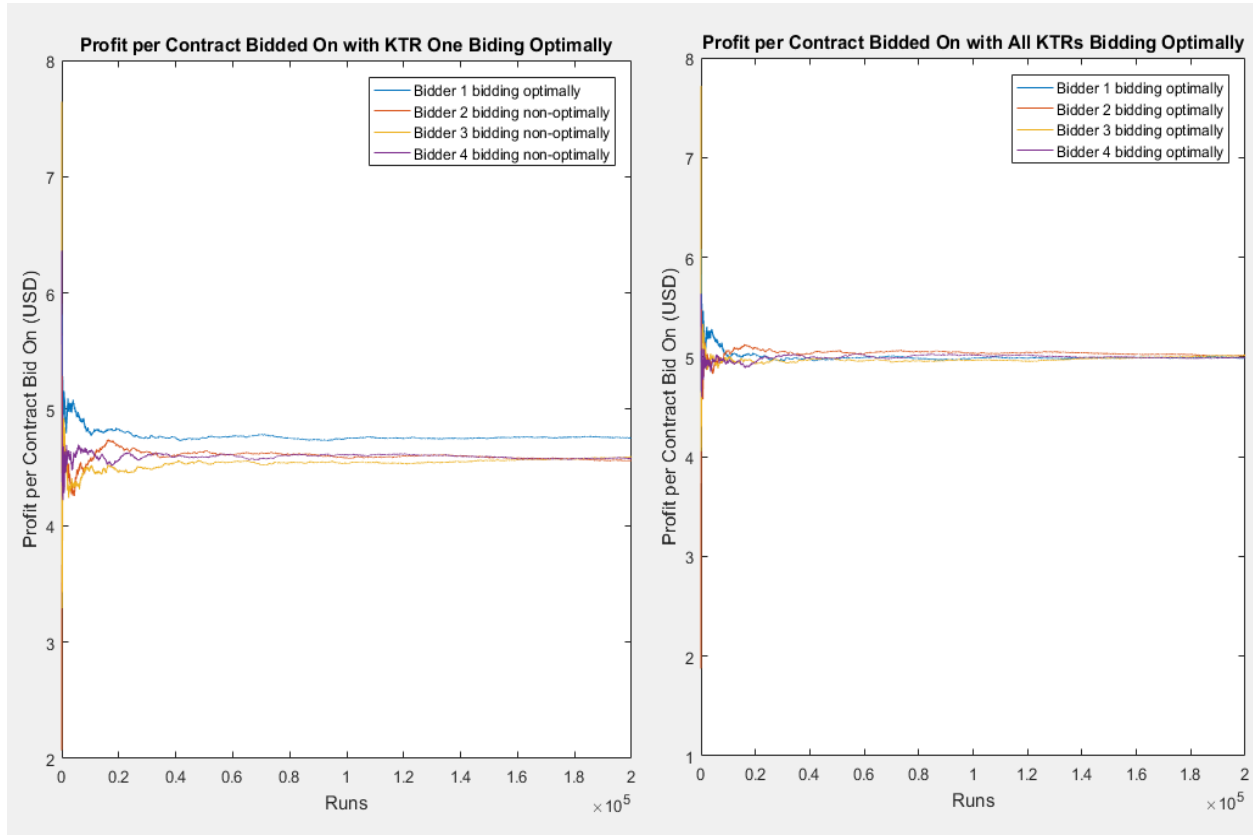


Figure 7. Simulation Results for FFP Contract Type:
Average Profit for Contractor Bidding Optimally vs. Contractor Bidding Non-Optimally

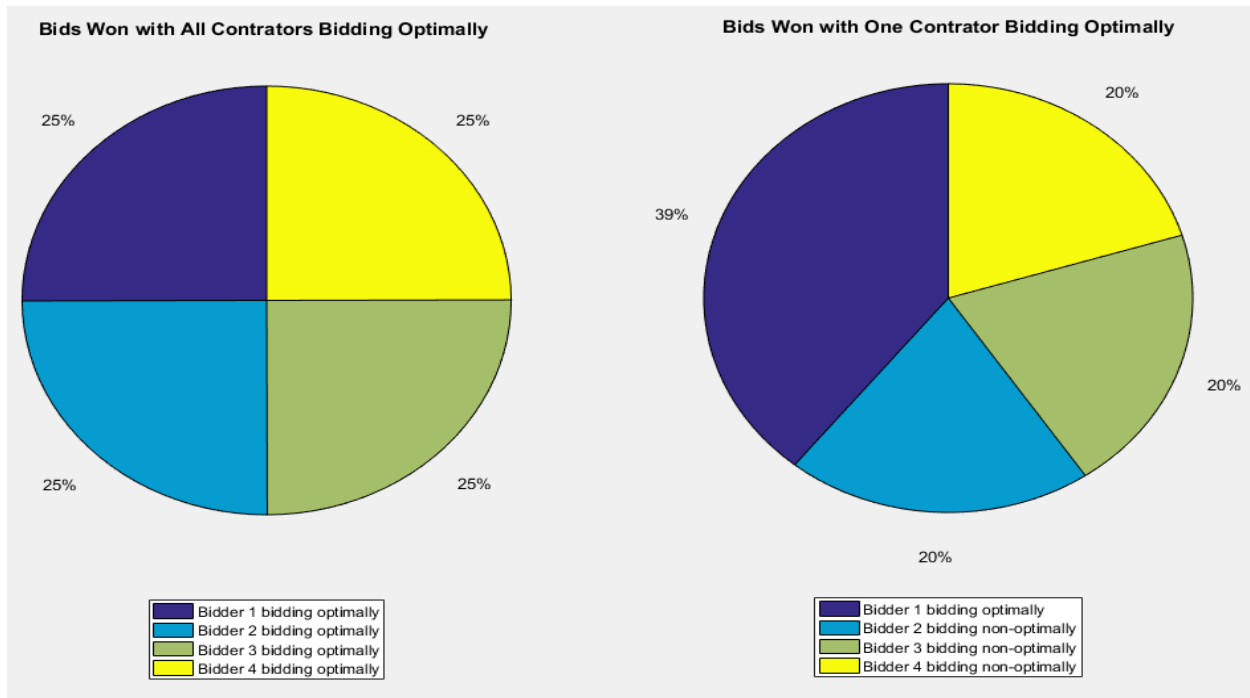


Figure 8. Simulation Results for FFP Contract Type:
Percentage of Bids Won for Contractor Bidding Optimally vs. Contractor Bidding Non-Optimally

6. Conclusion

In accordance with the DoD's Modernization and MOSA² Initiatives, the Aerospace Corporation sought to develop a comprehensive war-gaming model to show optimal bidding and contract types. The REU Student Team and NCSU Team have implemented the models designed by the Aerospace Corporation Team in a set of MATLAB packages, which meet the goals of constructing the optimal PTB solutions and bidding optimally. The optimal PTB solutions select the technology architectures which will generate the best bids and most competition while achieving warfighter goals. The REU Student Team has verified these results by comparing the optimally bidding contractor with non-optimal bidders and in all cases the Nash equilibrium bidder reduced the government payment while simultaneously increasing contractor profits over time. By optimizing all of the game components of the Advanced War Gaming Engine, the results have the potential to significantly increase the efficiency of governmental acquisitions.

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² MOSA = Modular Open Architecture Approach

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