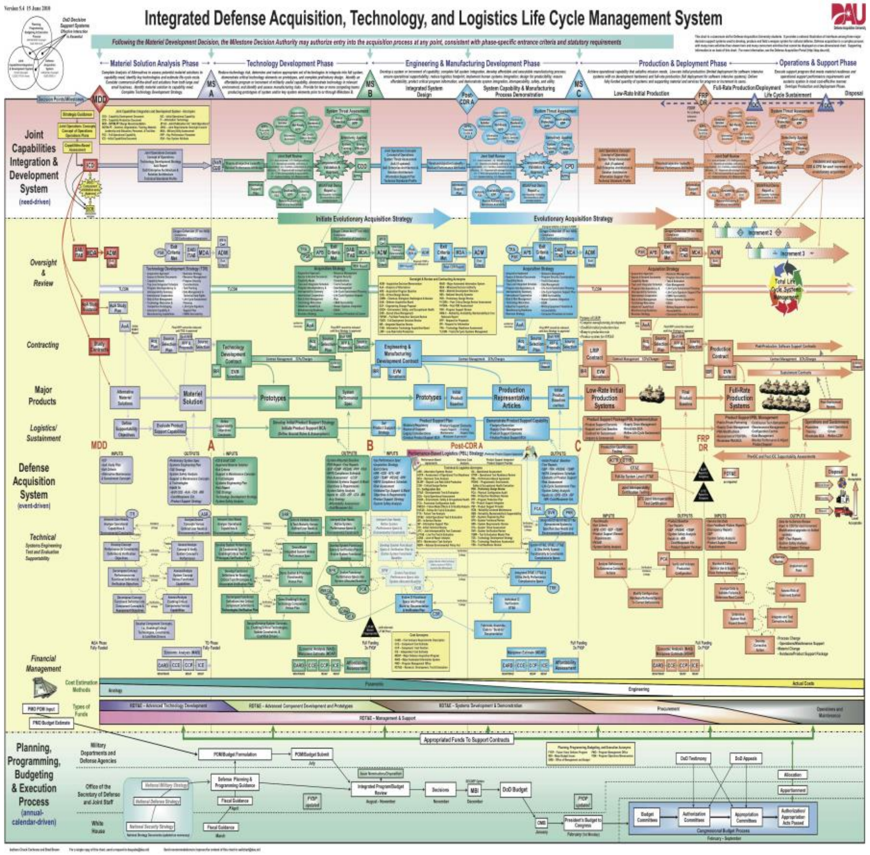
A Game Theory Approach to Negotiations in Defense Acquisitions in the Context of Value-Driven Design: An Aircraft System Case Study

Garima Vinay Bhatia

Iowa State University

Motivation

- Major Defense Acquisition Programs (MDAPs)
  - Acquisition of Large-Scale Complex Engineered Systems
  - Highly complex procedures involving multiple milestones and stages
  - 100s to 1000s of individuals involved right from contracting and design to sustainment and disposal
  - Two prime stakeholders in defense acquisitions:
    i. Government (DoD)
    ii. Commercial Organization (E.g. Boeing)



Butterfield, J., et al., *Digital methods for process development in manufacturing and their relevance to value driven design.* Journal of Aerospace Operations, 2012. **1**(4): p. 387-400.

Motivation

- Challenges in current defense acquisition methods
  - Traditional method of contracting: Based on cost
  - Shift of focus from operations to cost post Cold War
  - Numerous associated cost overruns and schedule delays despite aiming to keep the budget low
  - No commercial market exists for large-scale weapon systems
  - Monopolies (single seller) and even monopsonies (single buyer) do not give DoD the power to dictate prices
  - More than $314 billion at stake annually
  - Current approach based on requirements rather than true preference

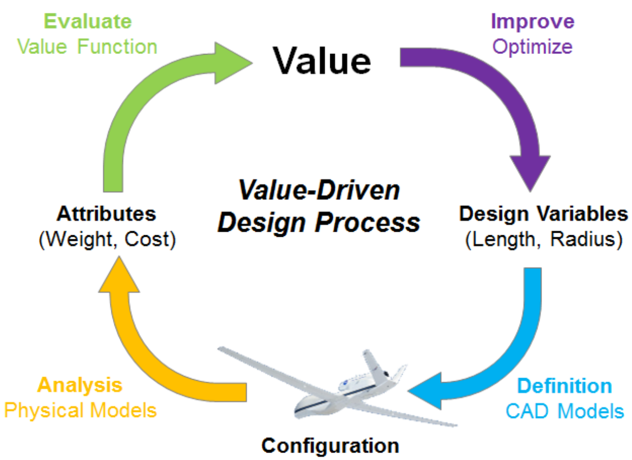
Motivation

- New methods of contracting such as price-based and performance-based proposed
- New methods still based on requirements, which serve as proxies to true preferences
- Value-models help in capturing true preferences of the stakeholders
- Value-based acquisitions proposed in recent times

A Broad Overview of the Traditional Acquisitions Process

Background

- Value-Driven Design
  - A value function is created that captures the true preferences of the stake-holder and is flowed down to guide the subsystem designers instead of requirements
  - Enables direct comparison of alternatives through value
  - Reduces requirements – removes restrictions on design space
  - Value, V = f(System attributes)
  - Can be used as an objective function in MDO



Background

- Theory of Bargaining
  - Used for cooperative decision making
  - In sequential bargaining, players take turn at making offers for dividing a resource
  - If an offer is rejected by a player, he gets to make a counter offer in the next round
  - Process continues till an offer is accepted
  - Value of the resource decreases by a factor δ after each round
  - δ represents a discount factor or patience level of players
  - δ: Number between 0 & 1

Background

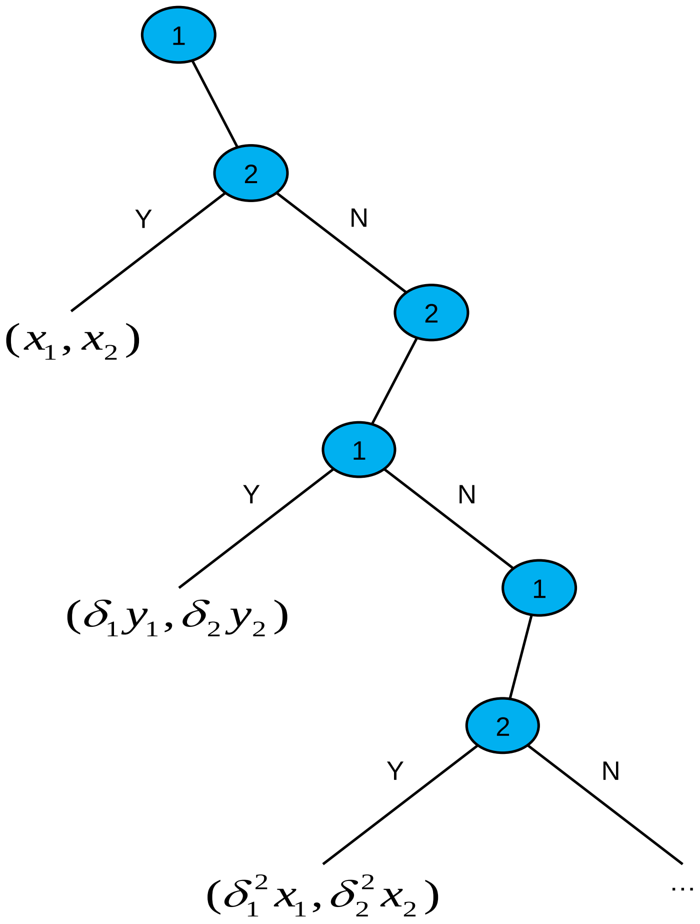
- Theory of Bargaining (Contd.)
  - Proposals by players:

$$Player\ 1 = x^* = (x_1^*, x_2^*)$$
$$Player\ 2 = y^* = (y_1^*, y_2^*)$$

  - Equilibria conditions for players:

$$x_2^* \geq \delta_2 y_2^*$$
$$y_1^* \geq \delta_1 x_1^*$$

  - A player accepts an offer only if he believes that he can't receive a better payoff by waiting for the next round and making an offer

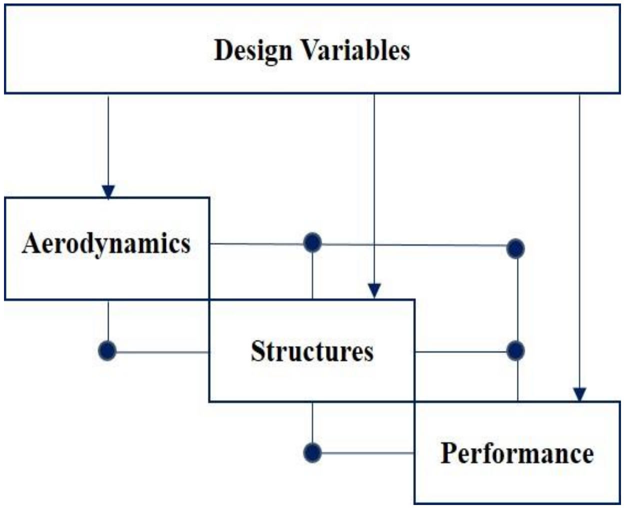


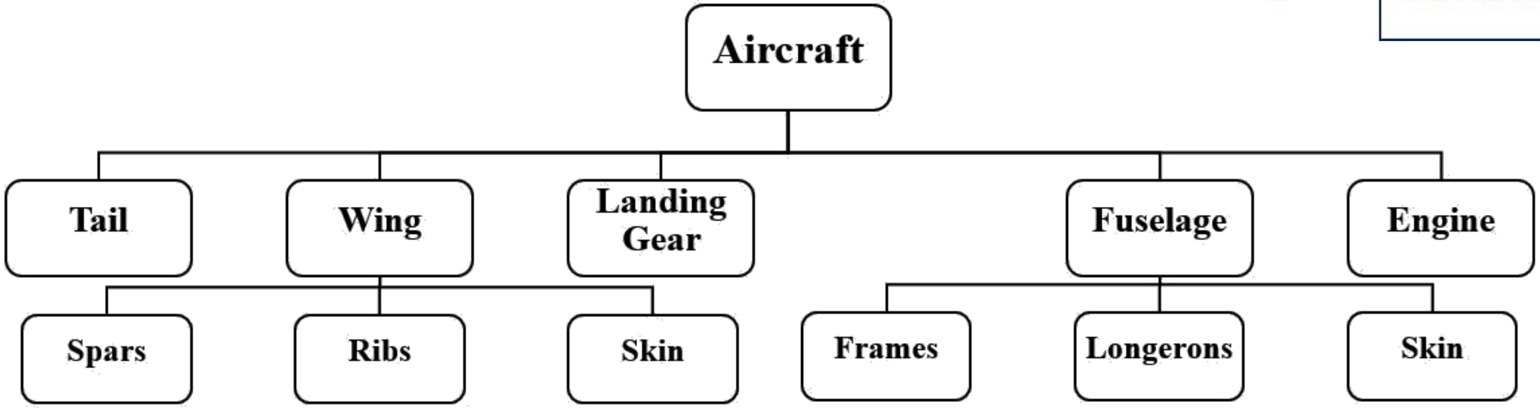
Research Question 1 – Combined Contracting

- "Can a game theory enhanced value approach to negotiations in a combined priced and performance-based contracting scenario lead to a better system design as compared to that obtained by using the traditional requirements-driven method?"

Aircraft System Example

- Mission objective: Transport personnel and ammunition to war site and back
- Teams designed as per aircraft components





Hierarchical Decomposition of Organization

Value Functions

- Government
  - True preference of government: Operational Success
  - Depends on survivability $(p(S))$ and effectiveness $(p(E/S))$
  - Value function: Probability of Operational Success $\left(p(OS_i)\right)$

$$\boldsymbol{p(OS_i) = p(S \cap E) = p(S).p(E/S)}$$

  - p(S) = f(Velocity,Stealth)
  - p(E/S) = f(Range,$M_{payload}$)

Value Functions

- Contractor
  - True preference of contractor: Profit
  - Function of price and cost

$$\boldsymbol{Profit = Total\ price - Total\ cost}$$

  - Total price = No. of aircraft sold * Price per aircraft
  - Total Cost = No. of aircraft sold * Cost per aircraft
  - Cost per aircraft = Sum of costs of all subsystems

Combined Contracting

- Performance factor
  - Government lays operational requirement, in this case taken to be the probability of operational success
  - Assumed value: Atleast 72% successful

$$p(OS_i) \geq 0.72$$

- Price Factor
  - Contractor uses this requirement to come up with an optimal price for system based on total cost and return rate (*r*) on investment
  - Generally, 15% return offered by government
  - In this case, price evaluated for return rates from 10% to 20%

Contractor

Combined Contracting

- Value Factor
  - Profit (value) evaluated as a function of price
- Formal Optimization Statement

$$find\ X = [X_{discrete}, X_{integer}, L_{wing}, L_{chord}, L_{fuselage}, Mass_{payload}]$$

$$Min\ f(X) = -Profit\ per\ aircraft = -(r * Cost\ per\ aircraft)$$

$$s.t\ g_1: 0.72 - p(OS_i) \leq 0$$

Contractor

  - Obtained values of operational attributes and price

Attribute	Value
Range (in km)	17,800
Mass of payload (in kg)	80,000
Cruise velocity (in m/s)	510
Stealth	0.9
$p(OS_i)$	0.72

r	Price per aircraft ($M)	Profit per aircraft ($M)	Total Profit ($B)
10%	590	53.67	5.36
15%	616	80.4	8.04
20%	644	107	10.7

Combined Contracting

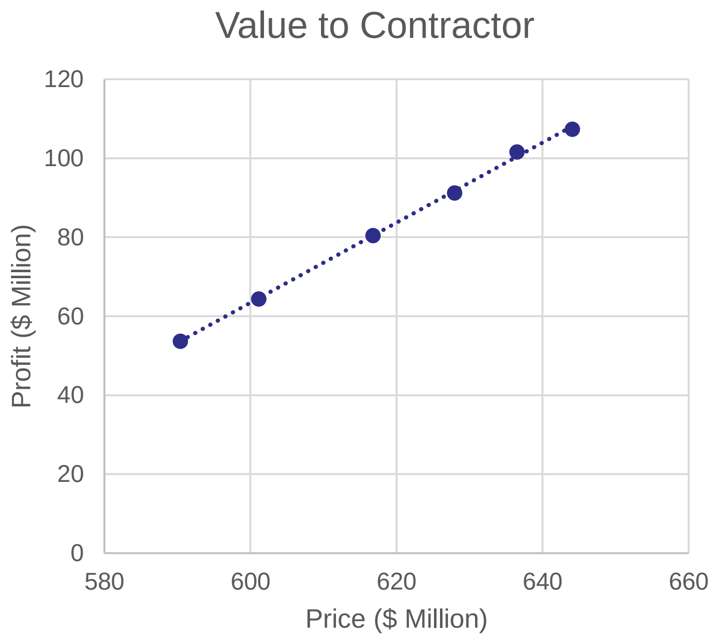
- Value function

$$V_c = Profit\ per\ aircraft$$
$$= 1.0142 * Price\ per\ aircraft - 536.709 * 10^6$$

  - Assumed: No. of aircraft sold = 100
  - Thus, Total profit = Profit per aircraft*100

- Government
- Performs a market research to determine price of system
- Value to government: Arbitrary measure of benefit depending on price
- Value decreases with increase in price

$$V_g = Value\ per\ aircraft$$
$$= -0.0205 * Price\ per\ aircraft + 13.3225 * 10^6$$



Combined Contracting

- Threshold values
- Negotiation
  - Government starts with lowest price
  - Contractor starts with highest price
  - Government increases price with every rejected offer
  - Contractor reduces price with every rejected offer
  - Offer accepted if equilibrium condition met

$$Vc \geq \delta_g * Vg$$
$$V_g \geq \delta_c * V_c$$

  - Results evaluated for different values of δ

	Threshold price ($M)	Starting offer ($M)
Government	645	601
Contractor	590	644

Combined Contracting

- Offer accepted immediately when patience level is very low
- Lower patience yields lower value
- Sensitivity of value function important
- When both players are highly patient, offer accepted by government

Patience factors (δ)		Rounds	Offer accepted		Final price per aircraft ($M)	V_g $(*\,10^3)$	V_c ($B) (Profit from 100 aircraft)
δ_g	δ_c		Govt	Comp			
0.1	0.95	2	✓	×	644.05	119	11.06
0.2	0.9	4	✓	×	637.61	251	8.84
0.9	0.1	1	×	✓	601.11	999	7.29
0.3	0.8	3	×	✓	607.12	262	7.90
0.5	0.5	1	×	✓	601.11	999	7.29
0.6	0.7	3	×	✓	607.12	525	7.90
0.98	0.98	8	✓	×	624.92	511	9.31

Cost-Based Contracting

- Comparison of proposed method made with traditional method
- Requirement: Minimize cost
- Secondary requirements:
  - Total weight ≤ 150000 kg
  - Total range ≥ 9000 km
- Requirements passed down hierarchy of company
  - Additional requirements formed

$$find\ X = [X_{discrete}, X_{integers}, X_{cont}]$$
$$Min\ f(X) = Cost\ per\ aircraft$$
$$= \sum_{i=1}^{m} Cost_i$$
$$s.t\ g_1: Mass_{total} - 150000\ kg \leq 0$$
$$g_2: 9000\ km - Range \leq 0$$
$$g_3: 165\ m/s - V_{crusie} \leq 0$$
$$8\ m \leq L_{wing} \leq 12\ m$$
$$2m \leq L_{chord} \leq 4m$$
$$12\ m \leq L_{fuselage} \leq 20\ m$$
$$15000\ kg \leq Mass_{payload} \leq 50000kg$$

Cost-Based Contracting

- Obtained values of operational attributes and price

Attribute	Value
Range (in km)	9000
Mass of payload (in kg)	50,000
Cruise velocity (in m/s)	257
Stealth	0.5
$p(OS_i)$	0.40

r	Price per aircraft ($M)	Profit per aircraft ($M)	Total Profit ($M)
10%	29	2.64	264
15%	30	3.96	396
20%	31	5.28	528

- Low values of operational attributes
- Remarkably low profit and probability of operational success
- Requirements act as proxies

- Threshold values

	Threshold price ($M)	Starting offer ($M)
Government	32.00	29.50
Contractor	29.05	31.69

Cost-Based Contracting

- Offer accepted immediately when patience level is very low
- Lower patience yields lower value
- Sensitivity of value function important
- When both players are highly patient, offer accepted by contractor

Patience factors (δ)		Rounds	Offer accepted		Final price per aircraft ($M)	P_g $(*\,10^3)$	P_c ($M) (Profit from 100 aircraft)
δ_g	δ_c		Govt	Comp			
0.1	0.95	2	✓	×	31.690	100	528.70
0.2	0.9	4	✓	×	31.380	208	447.30
0.9	0.1	1	×	✓	29.500	848	309.00
0.3	0.8	3	×	✓	29.790	224	338.50
0.5	0.5	1	×	✓	29.500	848	309.00
0.6	0.7	3	×	✓	29.795	448	399.72
0.98	0.98	9	×	✓	30.697	421	428.78

Comparison of Results

	Cost-based acquisitions	Combined acquisitions
Range (in km)	9000	17,800
Mass of payload (in kg)	50,000	80,000
Cruise velocity (in m/s)	257	510
Stealth	0.5	0.9
$\boldsymbol{p(OS_i)}$	0.40	0.72
Total profit for lowest contractor patience ($)	309.00 million	7.29 billion

- Significantly higher operational success and profit, i.e. higher payoffs to both players
- Much better operational attributes using combined contracting
- Reduced requirements and value approach yielded better results than traditional requirements-driven cost-based approach
- Player order affects payoff of player whose offer is accepted
- Making the first offer yields better results if offer is accepted

Negotiating over Attributes

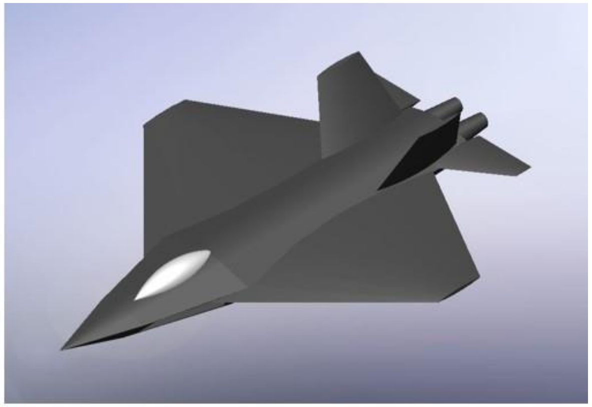
- Purely value-based approach
- Assumption: Government not concerned with cost
- Each player aims at maximizing his value
- Attributes: Reflect value
- Each player has own optimal attribute set that maximizes his value
- Player wishes for system to be designed using his attribute set
- Negotiation directly over attributes

Common attributes

I. Range
II. Mass of payload
III. Velocity at cruise
IV. Stealth

Negotiation over Attributes

Company's Preferred Design



Government's Preferred Design

Negotiated Final Design

Conclusion

- The research showed that a value-based approach to defense contracting can help in capturing true preferences of both the government and the contractor and help achieve a better system design as compared to the traditional requirements-driven approaches

Contact

- Dr. Christina Bloebaum

  Iowa State University

  Email: bloebaum@iastate.edu

- Garima V. Bhatia

  UAH

  Email: gb0027@uah.edu

Present

- Graduate student in Industrial and Systems Engineering, UAH (PhD)
- Advisor: Dr. Bryan Mesmer

Present work

- Journal article on previous work
- Analysis of the trends in Systems Engineering through the years (Journal article)
  - MBSE
  - Lean
  - Scrum
  - Value

Thank you!
Questions?