Bounding the Value of Collaboration in Federated Systems

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Presentation Outline

• Valuing federated systems as a Stag Hunt
• Multi-actor system value models and SE/SoSE
• Example: *Orbital Federates* Simulation
  • Bounding the value of collaboration
  • Assessing the risk of collaboration
• Conclusions and future work
Valuing Federated Systems

- Why join a federated system?
  - Technical risk of distributed systems
  - Non-technical risk of collaboration
- Example: DARPA System F6 Program
  - Value-centric design methodology (VCDM) to quantify system value
  - Program cancelled citing:
    - “lack of an overall mission integrator”
    - “lack of a clear ‘business case’ for heterogeneous, fractionated space missions”

Federated systems demand multi-actor valuation methods
Historical Analog: The Stag Hunt

• Simultaneous, symmetric coordination game with perfect information

• Moving from risk-dominant to payoff-dominant equilibrium requires social contracts to govern players’ behaviors

<table>
<thead>
<tr>
<th></th>
<th>Stag</th>
<th>Hare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stag</td>
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<td>0, 6</td>
</tr>
<tr>
<td>Hare</td>
<td>6, 0</td>
<td>4, 4</td>
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</table>


Federated Systems as a Stag Hunt

- Existing VCDM considers single-actor value $V_{II}$
- How can VCDM consider multi-actor value?

<table>
<thead>
<tr>
<th>Federated</th>
<th>Independent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{FF}, V_{FF}$</td>
<td>$V_{FI}, V_{IF}$</td>
</tr>
<tr>
<td>$V_{IF}, V_{FI}$</td>
<td>$V_{IF}, V_{II}$</td>
</tr>
</tbody>
</table>

$V_{FF} > V_{IF} \geq V_{II} > V_{FI}$
Cooperative Multi-actor SVM

\[ V_i = V_i(d_i, d_j, c_i, c_j), \quad V_{ij} = f(V_i, V_j) \]

• SE design with a cooperative multi-actor SVM:
  • \( d_i^*, c_i^* = \arg \max_{d_i, c_i} E[V_i(d_i, d_j, c_i, c_j)] \)

• SoSE design (ideal) with a cooperative multi-actor SVM:
  • \( d_i', d_j', c' = \arg \max_{d_i, d_j, c} E[V_{ij}(d_i, d_j, c, c)] \)

• SoSE design (realistic) with a cooperative multi-actor SVM:
  • \( c^* = \arg \max_{c} E[V_{ij}(d_i, d_j, c, c)] \)
Payoff Matrix for Collaborative Design

\[ c^* = \arg \max_c E[V_{ij}(d_i, d_j, c, c)] \]

| \( C = c' \) | \( \ldots \) | \( F \) | \( \ldots \) | \( I \) |
|-------------|-------------|-------------|-------------|
| \( C = c' \) | \( V_{i}^{CC}, V_{j}^{CC} \) | \( \ldots, \ldots \) | \( V_{i}^{CF}, V_{j}^{FC} \) | \( \ldots, \ldots \) |
| \( F \) | \( V_{i}^{FF}, V_{j}^{CF} \) | \( \ldots, \ldots \) | \( V_{i}^{FI}, V_{j}^{IF} \) | \( \ldots, \ldots \) |
| \( I \) | \( V_{i}^{IC}, V_{j}^{CI} \) | \( \ldots, \ldots \) | \( V_{i}^{IF}, V_{j}^{FI} \) | \( \ldots, \ldots \) |

\[ V_{i}^{CC} = E[V_{i}(d_i^c, d_j^c, C, C)] \]
\[ V_{i}^{FF} = E[V_{i}(d_i^F, d_j^F, F, F)] \]
\[ V_{i}^{II} = E[V_{i}(d_i^I, d_j^I, I, I)] \]

\[ d_i', d_j', c' = \arg \max_{d_i, d_j, c} E[V_{ij}(d_i, d_j, c, c)] \]

\[ V_{i}^{CC} \geq V_{i}^{FF} > V_{i}^{II} \]
Orbital Federates Simulation (OFS)

Design and strategy decisions, RNG seed

Initial cost and final value outcomes
2-player symmetric designs
1-3 satellites and 1 station ea.
530 total design alternatives
Independent Strategy

- Independent strategy: local/local optimization

- Solves MILPs to choose actions each turn:
  - Accept contracts
  - Sense, transport, and store data
  - Resolve contracts

Time (Turn)
Tradespace of 530 design alternatives under independent strategy I

Error bars show 95% confidence interval on expected value over 50 seeded executions.
• Centralized strategy: global optimization

• Solves MILP to choose actions each turn:
  • Accept contracts
  • Sense, transport, and store data
  • Resolve contracts

Centralized Strategy
Tradespace of 530 design alternatives under centralized strategy $C$

Error bars show 95% confidence interval on expected value over 50 seeded executions.
Example: §2000 Initial Cost Limit

<table>
<thead>
<tr>
<th>Pareto-optimal Design ($d_i^C$)</th>
<th>Cost ($)</th>
<th>$C = c'$</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C = c'$</td>
<td>53</td>
<td>1900</td>
<td>3978, 3978, 1132, 1846</td>
</tr>
<tr>
<td>$I$</td>
<td>63</td>
<td>1950</td>
<td>1846, 1132, 1846</td>
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</table>
Risk-reward tradespace bounding the value of collaboration

- Independent Pareto Frontier $V_H$
- Centralized Pareto Frontier, Successful $V_{CC}$
- Centralized Pareto Frontier, Failed $V_{CI}$

Upside Potential of Centralized Strategy

Upside Potential of any Federated Strategy

Downside Risk of Centralized Strategy

24-turn Expected Net Value ($) vs. Initial Cost ($\dollar$)
Opportunistic Fixed-Cost Service Strategy

- Federation only uses excess capacity
  - $100 to receive SGL
  - $50 to receive ISL

- Federated strategy: local/local, local+/local+ optimization
Tradespace of 530 design alternatives under federated strategy $F_{OFC}$

Error bars show 95% confidence interval on expected value over 50 seeded executions.
Example: §2000 Initial Cost Limit

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</table>
Risk-reward tradespace assessing the value of collaboration

- Independent Pareto Frontier $V_I$
- Centralized Pareto Frontier, Successful $V_C$
- Centralized Pareto Frontier, Failed $V_{CI}$
- Federated Pareto Frontier, Successful $V_{FF}$
- Federated Pareto Frontier, Failed $V_{FI}$
Assumptions and Limitations

• Simultaneous, symmetric decisions for 2 players
  • No first-actor effect
  • No flexible/responsive designs
  • No asymmetric design decisions
  • No market saturation (no competition)

• OFC is a simple federated strategy
  • No mechanisms to ensure cooperation
  • No simple way to enumerate and assess alternative strategies

• OFS is a stylized FSS model for demonstration
  • Unrealistic cost and revenue models
  • Simplified technical system models
Conclusions and Future Work

• Multi-actor SVM and SoSE/SE activities:
  • SoSE finds strategies to meet global objectives (adds rows/columns in payoff matrix)
  • SE finds designs to meet local objectives under each strategy (fills entries in payoff matrix)

• Risk-reward tradespaces bound value of federated strategies:
  • Independent strategy is lower bound
  • Centralized strategy is upper bound
  • No comparable bounds on downside risk

• Future work to address OFS and study limitations
  • Design asymmetry, market saturation, dynamic decisions, auction pricing mechanisms, player coalitions, bargaining
  • Manage computational complexity of combinatorial tradespaces
Thank you!

Please contact the authors for access to:

• OFS source code (Python 2.7, cross-platform)
• Full working paper (~23 pages)

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Research Objectives

• Formally define a multi-actor system value model
  • How does it relate to SE and SoSE design activities?
  • How to apply game theory to tradespace exploration?
• Demonstrate an example application for FSS
  • Bound the value of collaboration
    • Lower bound: value of independent operations
    • Upper bound: value of centralized operations
  • Assess the risk of collaboration
VCDM System Value Model (SVM)

• SE design with a single-actor SVM
  • \( d_i^* = \arg \max_{d_i} E[V_i(d_i)] \)

• SE design with a non-cooperative multi-actor SVM
  • \( d_i^* = \arg \max_{d_i} E[V_i(d_i, d_j)] \)
    \[ = \arg \max_{d_i} \sum_{d \in D_j} \left( E[V_i(d_i, d)] \cdot P(d_j = d) \right) \]
Cooperative Multi-actor SVM

• SE design with a collaborative multi-actor SVM:

\[ d_i^*, c_i^* = \arg\max_{d_i, c_i} E[V_i(d_i, d_j, c_i, c_j)] \]
\[ = \arg\max_{d_i, c_i} \sum_c \sum_{d \in D_j} (E[V_i(d_i, d, c_i, c)] \cdot P(d_j = d|c_j = c) \cdot P(c_j = c)) \]

• SoSE design (ideal) with a collaborative multi-actor SVM:

\[ d_i', d_j', c' = \arg\max_{d_i, d_j, c} E[V_{ij}(d_i, d_j, c, c)] \]

• SoSE design (realistic) with a collaborative multi-actor SVM:

\[ c^* = \arg\max_c E[V_{ij}(d_i, d_j, c, c)] \]
\[ = \arg\max_c \sum_{d \in D_i} \sum_{d' \in D_j} ((E[V_{ij}(d, d', c, c)]) \cdot P(d_i = d|c_i = c) \cdot P(c_i = c) \cdot P(d_j = d'|c_j = c) \cdot P(c_j = c)) \]
SoSE vs. SE Design Activities

SoSE Design Activities
• Find cooperative strategy to maximize global value
• Adds rows/columns to the payoff matrix

SE Design Activities
• Find design alternatives to maximize local value within each strategy
• Fills entries in the payoff matrix
Discussion

• Centralized and independent strategies bound value of any federated strategy: $V_{i}^{CC} \geq V_{i}^{FF} > V_{i}^{II}$
  • Easy to compute due to complete control over decisions
  • Preliminary test for federation viability

• OFC strategy yields significant value in this case
  • Benefits from structural design space constraints
  • No guaranteed bound on associated risk

• Ideal federated strategy also reduces downside risk
  • Similar to robust design or robust optimization