SYSTEMS ENGINEERING RESEARCH CENTER

8TH ANNUAL SERC DOCTORAL STUDENTS FORUM

12TH ANNUAL SERC SPONSOR RESEARCH REVIEW

HOSTED VIRTUALLY ON: NOVEMBER 17-18, 2020

STEVENS INSTITUTE of TECHNOLOGY
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Strategy Dynamics and System-of-Systems Tradespace Exploration

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RESEARCH TASK / OVERVIEW

Existing system-of-system (SoS) design methodologies fail to account for the dynamics resultant from multiple decision makers. Consequently, constituent and SoS level designs may be over-optimized for performance, assuming that mutual benefit alone will sustain collaboration, resulting in fragile designs.

This work applies game-theoretic concepts to study the affects of individual system designs, economic variables, and uncertainty on SoS decision maker strategy dynamics, identifying designs which improve constituent and collective value robustness. The method is applied to a space systems application case.

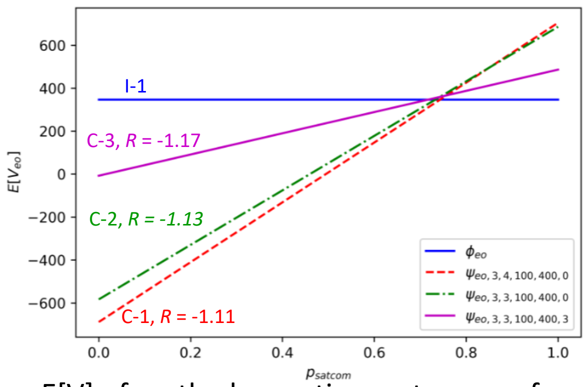
GOALS & OBJECTIVES

Develop a tradespace exploration method to:

1. Improve constituent system utility over stand-alone operations.
2. Minimize down-side risks from SoS dissolution and exogenous uncertainty.
3. Automate the architecting process to find conceptual designs that promote the aforementioned system qualities.
4. Demonstrate the method on a realistic space systems application case.
5. Understand how technical and economic variables interact with one another and uncertainty to shape strategy dynamics.

DATA & ANALYSIS

The method was applied to analysis of commercial earth observation (EO) and communication satellite (SATCOM) systems. SoS formation occurs when both systems implement interoperable links and the EO system pays a fee to use the SATCOM system as a data transport layer. Initial analysis examined technical variables only without uncertainty. SoS architectures are evaluated by three parameters, NPV for each system and *R* (see methodology).



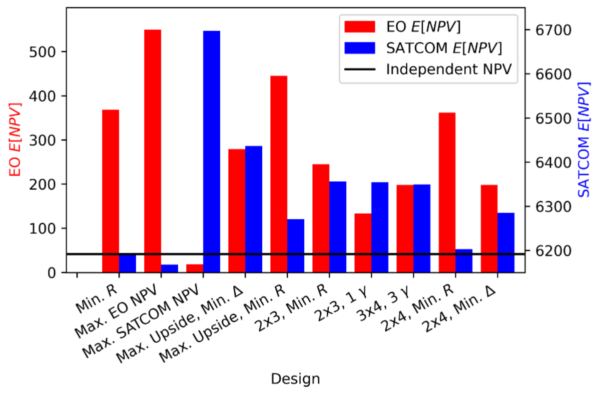
E[V] of earth observation system as a function of design, strategy, and probability of communication system collaboration

Results ID one Pareto efficient SATCOM system design and three EO designs. C-3 minimizes *R* (increasing favorability of SoS participation) with redundant communication functionality; trading upside potential for reduced downside losses.

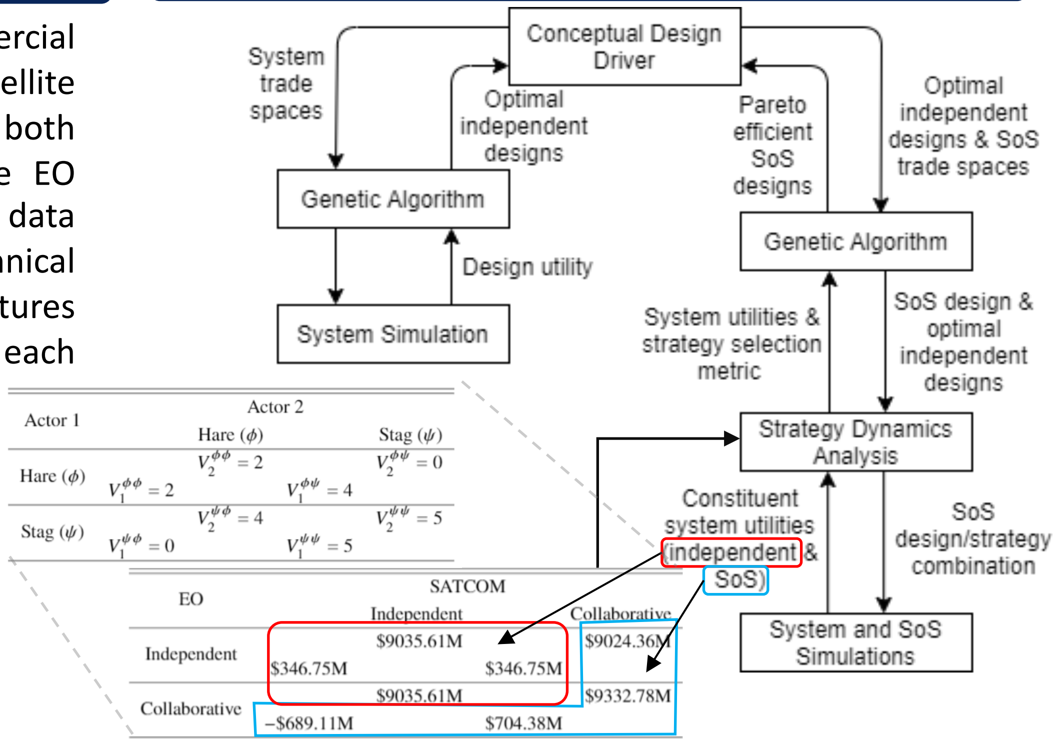
Extended analysis implements cost-share for EO development costs and a service fee as economic design variables. The number of Pareto efficient alternatives is greatly expanded.

A Monte Carlo simulation, with variable schedule delay as a source of operational uncertainty, is applied to a subset of the new Pareto efficient and other promising design combinations.

Results show that designs that over optimize on *R* or maximize upside for one system perform poorly under uncertainty. This highlights a limitation of the method as implemented. Designs which perform consistently well, such as the max. upside, min. Δ design above, have favorable strategy dynamics and sufficient upside for each system to absorb impacts of operational uncertainty.



METHODOLOGY



The stag hunt game is used as an analogy for SoS design. The weighted average log measure of risk dominance, *R,* is used as the strategy selection metric that guides the trade space exploration towards designs that improve the favorability of collaboration.

$$R \equiv \sum_{i=1}^{n} w_i(A) \ln \frac{u_i}{1 - u_i}$$

Where u_i is defined by:

$$u_i(\phi, \psi) = \frac{V_i^{\phi\phi} - V_i^{\psi\phi}}{(V_i^{\phi\phi} - V_i^{\psi\phi}) - (V_i^{\phi\psi} - V_i^{\psi\psi})}$$

And w_i are the influence weights based on the influence matrix A and w_i = 0.5 for two-player games.

System evaluation is performed by simulation and analysis of the space system architectures. Monte Carlo simulation is used to determine the impact of operational uncertainty, such as schedule delay.

FUTURE RESEARCH

Future work will incorporate concepts from Bayesian games and team reasoning to analyze trust and interaction reliability in an SoS context.

CONTACTS / REFERENCES

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Stern, J.L., and Grogan, P. T., "Design of Federated Space Systems for Strategic Stability Under Schedule Uncertainty," *Unpublished manuscript,* Stevens Institute of Technology, 2020.

ACKNOWLEDGEMENTS

The view expressed in this material are those of the authors and do not represent the policy of the U.S. Air Force, the U.S. Department of Defense, or the U.S. Government.