Game theory applications in systems-of-systems engineering: A literature review and synthesis

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SoSE and game theory – a perfect match?

Systems-of-systems engineering

Maier's characteristics:

- Operational independence
- Managerial independence
- Emergent properties
- Evolutionary development
- Geographical distribution

Independence = each constituent makes their own decisions.

Emergence = the combination of all independent decisions affects everybody.

Game theory

- Mathematical models of distributed, independent decision making.
- Utility of one agent is a function of the decisions of all other agents.
- Widely used in social science, economics, biology, computer science.

Game theory (GT)

Basic structure

- Set of self-interested players trying to maximize their own payoff.
- Set of actions for each player.
- Each player's payoff is a function of all players' actions.

Example: "Prisoner's dilemma"

P1 action	P2 action	P1 payoff	P2 payoff
Collaborate	Collaborate	-1	-1
Collaborate	Defect	-3	0
Defect	Collaborate	0	-3
Defect	Defect	-2	-2

Key concepts and variants

- Nash equilibrium: No player gains from changing their action.
- More advanced types of games:
  - Zero sum: total payoff to all players sums to zero (if one gains, another loses).
  - Sequential: several moves.
  - Repeated: same game played over and over, total payoff is aggregated.
  - Continuous: infinite number of actions.
  - Bayesian: limited information about other players.
  - Collaborative: groups of players compete.
- Mechanism design = reverse game theory

Research questions and method

Research questions

1. What are the characteristics of existing research applying GT to SoSE, including:
   a) application domain;
   b) SoSE problem addressed;
   c) SoS lifecycle phase addressed;
   d) class and type of game used; and
   e) analysis method used?
2. What are the best practices of applying GT to SoSE?

Research method

Systematic literature review

1. Define RQs and review protocol.
2. Conduct search for primary studies.
3. Screen primary studies based on predefined inclusion/exclusion criteria.
4. Extract data using classification scheme and data collection form.
5. Synthesize data and present results.

Results (1): Application areas and SoSE problems

Application areas

- Power and IT infrastructure (5)
- Space and earth observation (4)
- Transportation (4)
- Defense (4)
- Crisis management (2)
- Climate control (1)

SoSE problems addressed

- SoS lifecycle phase in focus:
  - Operations (15)
  - Design (6)
  - Acquisition (3)
- Formation (11) and dissolution (1)
- Security (4)
- Governance and control (4)
- Acquisition (2)
- Architecting (2)
- Policy design (2)

Results (2): Types of games, analysis methods

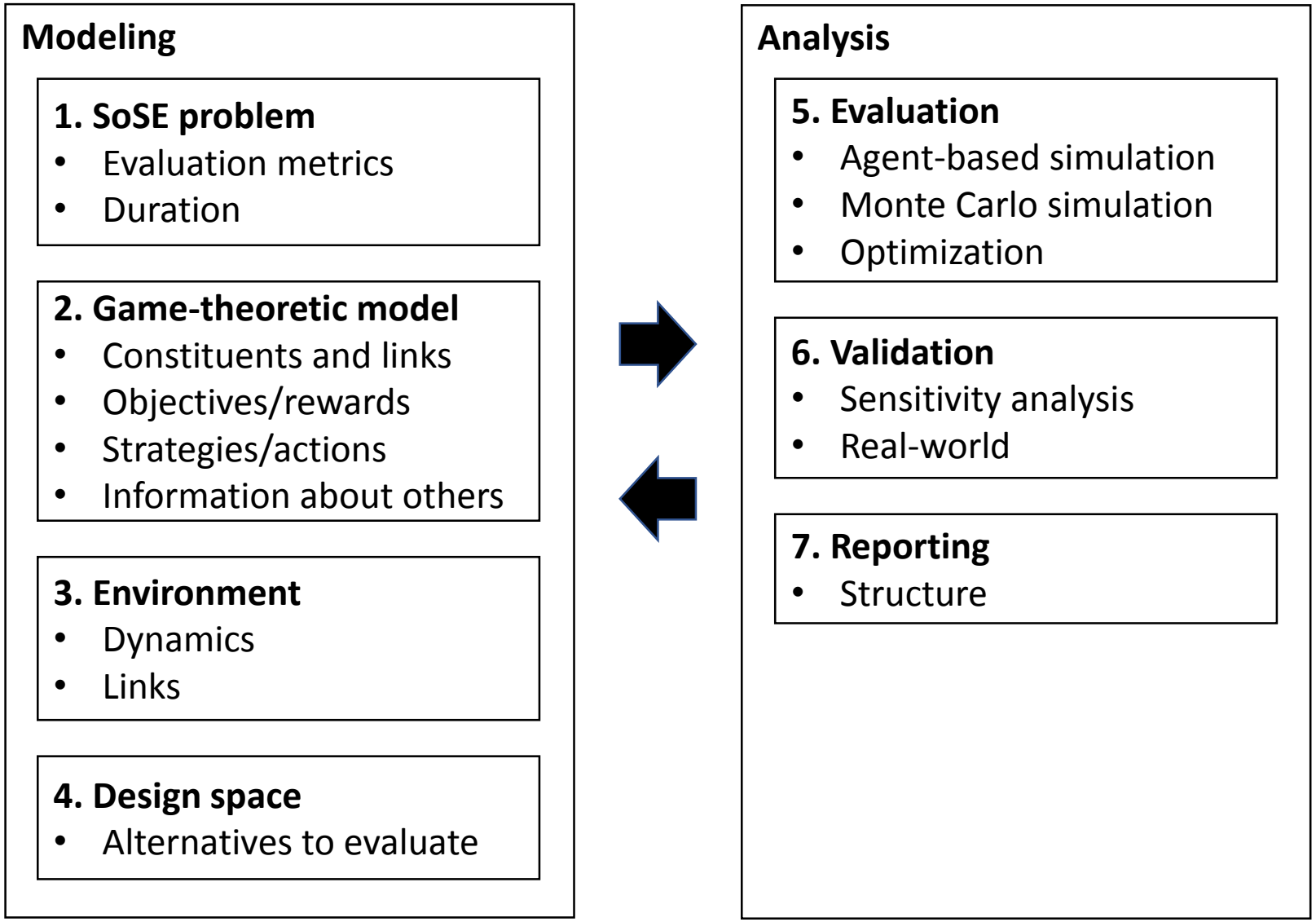
Types of games

- Simple games:
  - Prisoners' dilemma (1)
  - Stag hunt (2)
  - Pursuit-evasion (1)
- Non-zero-sum (4)
- Repeated games (4)
- Continuous or differential (4)
- Bayesian or random (2)

Analysis methods

- Nash equilibrium (9)
- Agent-based simulation (6)
- Monte Carlo (2)
- Agent-based + Monte Carlo (2)
- Optimization (4)

Best practice



Conclusions

- Game theory can be fruitfully applied to SoS in a wide range of application areas and deal with several different SoSE problems.
- SoS are complex, and analytical methods of game theory do not suffice.
- Best practice is based on simulation (mainly agent-based) and optimization.
- Future research: Mechanism design as a basis for synthesizing SoS.