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

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Abstract

Systems-of-systems (SoS) are becoming increasingly common in more and more domains, spreading from the initial focus on government-controlled areas such as defense to open market industries. This implies that collaborative SoS are becoming more important, where the constituents need to be given incentives to join and remain within the SoS. Game theory has been proposed as a framework to model and analyze such SoS mechanisms. It aims at providing incentives to the independently operated and managed constituents. This paper presents a systematic literature review on the applications of game theory to SoS engineering, together with a synthesis aiming at capturing the best practices for doing such an analysis. The main conclusions are that game theory can be applied to SoS in a wide range of application areas, and deal with problems related to acquisition, design, and operations. In particular, the operational formation of SoS are well suited for this kind of analysis, and it often requires the use of simulation techniques. However, most results in the field lack a validation in practice.

Keywords: System-of-systems; game theory; literature review

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1. Introduction

Systems-of-systems (SoS) refer to a situation where independently operated and managed systems collaborate in order to achieve goals that cannot be reached by the systems individually [1]. SoS are becoming increasingly common as the digitalization permeats more and more areas of society.

While SoS were initially mainly a concern for government-related domains such as defense [2], where primarily directed or acknowledged SoS are found [3], the spread to commercial sectors is leading to increasing emphasis on collaborative SoS. In such situations, there is no strong central coordinator, but the constituent systems (CS) voluntarily choose whether to join and remain in the SoS.

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A business analysis is challenging for all SoS, and in particular collaborative ones. This has to do with the distributed and independent decision making that is at the heart of the SoS definition. Each CS will decide based on the value it expects to get from the different actions, and this can create complex dynamic effects that are sometimes counter-intuitive and where the most logical local decision by a CS actually leads to a situation with diminishing value for everyone. A core problem for SoS engineering (SoSE) is therefore to find mechanisms that give each CS incentives to act in a way that produces the desired emergent effects of the SoS as a whole.

The discipline of *game theory* (GT), introduced by von Neumann and Morgenstern in the 1940s [4], studies exactly the kind of distributed, independent decision making that appears in SoS. This theoretical basis tries to draw general conclusions from simplified archetypical situations, which can then be extended to handle more complex and heterogeneous situations that appear in SoS and other real-world applications.

The purpose of this paper is therefore to better understand how GT can be applied in solving more practical SoSE problems. The main contribution is thus a condensed description of the theory's usage in the SoSE literature that can be a starting point for researchers and practitioners that need to analyze SoS mechanisms. More specifically, the following research questions (RQs) are addressed:

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?

The remainder of the paper is structured as follows. In the next section, a brief introduction to GT is given, and this is followed by a description of the chosen research method, which is a systematic literature review. Then, in Section 4, the findings from literature are described, followed by a synthesis of best practices in Section 5. The results are discussed in Section 6, and finally the conclusions are summarized.

2. Game Theory

In this section, a very brief introduction to GT will be given. It is a vast subject, and the interested reader who wants details is referred to other sources (e.g. [5]), but here the objective is mainly to introduce a bit of terminology and a few key concepts that will be referred to later in the study.

GT deals with situations where a set of self-interested players act in order to maximize their own profit. The *utility*, or *payoff*, to each player is a function of the actions of all the players together, and hence a certain player can in general not control on his own what the benefit will be.

In the simple situation, where there a two players with a limited number of actions, the payoffs can be captured in a table[1], such as the one illustrated in Table 1. The game is called the *"prisoner's dilemma"*, and illustrates a situation where two criminals have made a pact to collaborate in committing a crime. However, they get caught and can now influence the duration of their time in jail by choosing to help the police (by ratting on their partner) or keeping the pact with the partner and say nothing. If they collaborate with each other, they will both get one year in prison. However, if one of them defects from the pact to help the police, he will go free and the partner will get three years in prison. If both defect, they both get a two year sentence. Each combination of actions of the two players thus yields a certain payoff, and the two values in cell of the matrix show the payoff to the first and second player.

The literature on GT often refers to simple games like the prisoner's dilemma, the *stag hunt*, or *pursuit-evasion*, and these are useful to illustrate fundamental principles. One such principle is the *Nash equilibrium*, which is a situation where no player would benefit from changing his chosen action, assuming the other players keep their previous choice. The Nash equilibria often represent stable points, but they do not necessarily exist. Also, it is usually the case that the best actions on an individual level do not lead to desired properties at a societal level.

Another interesting characteristic of the payoff matrix is the sum of each cell. If all cells sum to zero, it is a *zero-sum game*, where someone can only gain something if some other players lose.

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[1] In the GT literature, it is common to instead use a matrix for two player games, but this does not scale to more than two players, and the table form used here is therefore more generic.

Table 1. The payoff function of the prisoner's dilemma game.

Player 1 action	Player 2 action	Player 1 payoff	Player 2 payoff
Collaborate	Collaborate	-1	-1
Collaborate	Defect	-3	0
Defect	Collaborate	0	-3
Defect	Defect	-2	-2

To deal with more complex and realistic situations, variants and extensions to this simple scenario is needed. This includes the number of players that participate, and the number of actions they can take, leading to matrices of larger sizes and more dimensions.

Another type of extension elaborates on the possible *strategies*, i.e., the set of alternative actions available to a player. A *pure strategy* is when the choice of action is deterministic, whereas a *mixed strategy* includes an element of probability. This makes a difference since a player cannot base his choice on knowing for sure what the others will do. A *continuous game* is a situation where there is an infinite number of alternative actions available to the players.

The information available to the players is also important. In simple games like the prisoner's dilemma, everything is known, but in other situations, the players may have limited information on the payoffs, on the strategies of others, etc. Such games of private information are called *Bayesian games*.

The simple games like prisoner's dilemma are played in one step, but more advanced games can include several *sequential* choices. It can also include *repeated* playing of a simpler game, where the players can collect information about the other players and form an understanding of the information that was not known to them beforehand, such as the probability of a certain player picking a particular action.

In the simple games, all the players are typically competing against each other, but this can be extended into *collaborative* games, also known as *coalition* games. Here, the players are divided into groups, where the groups compete with each other, but collaborate within the group.

Sometimes, the game models a situation where several players are trying to control a system that is best described using differential equations, as is the case if the system is physical, and this is referred to as a *differential game*. This sub-field has close relations to control theory, but with the difference that it covers multiple controllers acting on the same system with possibly different objectives.

Going beyond basic GT, a topic that has some interesting connections to SoSE is *mechanism design*. Here, the problem is to define a suitable structure of the game, that leads to desired objectives. For this reason, it is also referred to as *reverse game theory*. It has been applied to situations involving negotiations and auctions, and the reason it is interesting in the context of this paper is because the rules of an SoS can be seen as a mechanism that controls how constituent systems interact during operations.

3. Research Method

In this section, the research method for systematic literature reviews is discussed. First, the method will be described in general, and then it will be detailed how it was applied in the study.

3.1. Overview of the systematic literature review method

A systematic literature review "is a means of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest. Individual studies contributing to a systematic review are called primary studies; a systematic review is a form of secondary study" [6]. It is a method which is very common in medicine, but which has been increasingly applied to other fields, such as software engineering, in order to make better use of existing evidence. The main steps of the method are:

1. Define research questions and review protocol.
2. Conduct search for primary studies.

3. Screen primary studies based on predefined inclusion and exclusion criteria.
4. Extract data using a classification scheme and data collection form.
5. Synthesize data and present results.

Ideally, this process is carried out sequentially, but in practice it is often necessary to go back and update previous steps as the researcher's understanding of the topic deepens.

3.2. *Application of method*

It will now be described how the above process was used in practice in this study. The steps in the process will be presented in each of the following subsections.

3.2.1. *Define research questions and review protocol*

The research questions have already been identified in the introduction to this paper. Based on those questions, a review protocol was prepared that described how to perform the remaining steps. The details of that protocol will be provided below in the steps where they apply.

3.2.2. *Conduct search for primary studies*

The identification of primary studies is decisive for the quality of results, and it is often difficult to ensure that all the relevant papers have been included. In particular, the selection of databases and the formulation of queries is important.

The search was conducted using the Scopus citation database, which is provided by Elsevier, and is claiming to be the largest such database in the world. Both literature [7] and prior experience of the researcher [2, 8] indicated that this database was likely to provide a large set of relevant papers for the topic of this study.

In the field of this study, the terminology used is luckily quite well established, and therefore the query was simply "system-of-systems" AND ("game" OR "mechanism design"), where the last term was included due to the particular interest of mechanism design in the context of SoSE. The search was carried out in mid September 2018, and can therefore be assumed to contain most papers published in 2017 or earlier as well as some from 2018.

3.2.3. *Screen primary studies*

The selection of primary studies from the database search was based on the following inclusion criteria:

- Papers that explicitly discuss GT in the context of SoS.
- Papers in journals, conference proceedings (peer reviewed), and reports of normal academic standard.

In addition, the following exclusion criteria were applied:

- Papers that just mention SoS or GT as an important aspect, but do not analyze it.
- Papers that use terms in a different meaning, e.g. game as in "computer game", or as part of an expression, e.g. "game changer".
- Papers that are not accessible in full text from the normal research libraries or could be obtained in other ways.
- Preliminary reports, that were later followed by an extended version; typically this would be a workshop paper that later expanded into a journal article, and in that case only the latter was kept.

The initial search resulted in 99 papers. After screening based on title and abstract, 44 papers remained. These papers were read in full, and while doing so, a few papers that appeared relevant from the abstract were in fact not. Also, some papers were extensions of previous versions already in the set, and after removing the earlier versions, a final set of 31 primary studies remained.

3.2.4. *Extract data using a classification scheme*

The identified papers were classified based on the following scheme:

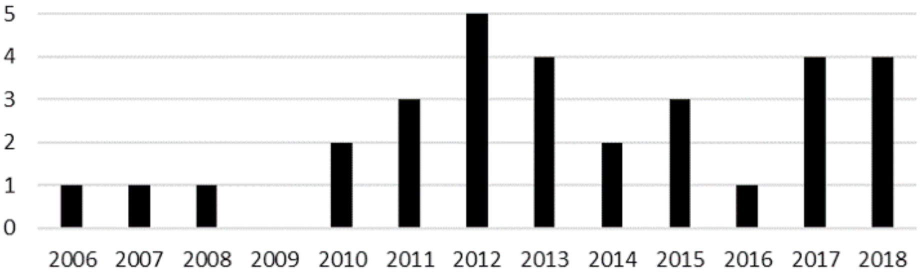

Fig. 1. Papers per year.

- Administrative information: Paper ID; Title; and Brief summary.
- Publication characteristics: Authors; Year; Venue; Country.
- SoSE characteristics: Application area; problem; life-cycle stage.
- GT elements used.

A data collection form was used consisting of a table with one column for each category, and one row per paper. Each cell in the table contained the data for that paper and category.

3.2.5. Synthesize data and present results

The data was synthesized by cross-reading the papers by column to identify the data that provides input to each research question. In some cases, the data was grouped into subcategories based on what was actually found. This will be illustrated in the next section, where the results are analyzed.

4. Results

Based on the identified literature, we will now present findings related to RQ1. The presentation will start with an overview of some statistics, and this is followed by a summary of some conceptual and theoretical papers. Then, we proceed with characterizations of the application domain, SoSE problems, and SoS lifecycle phases addressed. Finally, the concepts from GT are enlisted, together with the analysis approaches used in the papers. At the end of each section, a short summary of the findings are provided.

4.1. Overview of the literature

In the selected set, there are some papers published every year from 2006 to 2018, except 2009 when there were no publications. The frequency per year is illustrated in Figure 1, and as can be seen there is no clear trend.

The authors mostly come from the US, with no less than 22 of the 31 papers having authors from that country. This is followed by the UK (6 papers), China (3), Austria (2), and Italy, Norway, and Sweden (1 each).

The most common publication venues are the IEEE Systems of Systems Engineering Conference (7 papers), IEEE Systems Journal (5), and the IEEE Systems Conference (4), but many papers are also scattered in other places.

Summary of findings: There is a small, but steady, interest in the application of GT to SoS, but despite the apparently good matching, it does not appear to be increasing. It can be speculated that this is because GT is perceived as hard to grasp, and as the name implies being theoretical. There is thus a need for hands-on guidance in making it useful for more practical applications.

4.2. Conceptual papers

A few of the papers are primarily conceptual, and do not provide so much input to the specific research questions. However, they do contribute to a general understanding of the field, and are therefore retained in the set of papers, and summarized here for the sake of completeness.

Summary of findings: In a series of papers [9, 11, 12], a theory for SoS based on games is developed. It regards the constituent systems as the players, and uses scenarios to describe the consequences of events in the environment. It also uses these concepts to identify classes of SoS, including natural vs. engineered, and unstructured vs. centrally coordinated. Sub-classes exist related to if the SoS is goal-driven or scenario driven. It also describes various coordination strategies.

4.3. Application domains

A clear majority (20 papers) mention an application area, and in many cases also use concrete examples from that area to illustrate or evaluate the proposed approach. However, the cases are all quite simplified, and it is rare to see papers where the analysis is actually implemented in practice. Very interestingly, a handful of quite different domains appear, indicating that this is a broadly applicable technique.

4.3.1. Power and IT infrastructure

Five papers cover critical infrastructures. This includes energy, where one concrete application is wind energy systems [13] and another is related to smart energy grids [14]. Several papers by mostly the same authors consider critical infrastructures on a more abstract level, exemplifying with cloud computing and energy [15–17].

4.3.2. Space and earth observation

Four papers relate to space applications, including earth observations. Two of the papers, by mostly the same authors, discuss the Global Earth Observation System of Systems (GEOSS), which is an international, voluntary collaboration for exchanging satellite data [18, 19]. Another application is federated systems where many smaller satellites collaborate [20], and the final one deals with an SoS of satellites and ground stations to improve situational awareness related to debris in low earth orbit [21].

4.3.3. Transportation

Four of the papers relate to transportation, and they cover a wide range of applications within that field. On the road side, one paper covers truck highway platooning SoS [22], and another deals with the planning of dangerous goods transportation [23]. Intermodal goods transportation, using both trucks and railways is considered in [24]. Finally, air transportation is considered in [25].

4.3.4. Defense

Four papers are within the defense domain. Abstract views of defense acquisitions are analyzed in both [26] and [27]. A counter air mission data loop is used as an example in [28], and a ballistic missile defense system is the topic in [29].

4.3.5. Crisis management

Two papers by mostly the same authors deal with crisis management by government extended enterprises. The first one is focusing on counter-terrorism [30], whereas the second one takes a broader perspective and includes also public health services' response to disease outbreaks and evacuation in the event of natural disasters [31].

4.3.6. Climate control

A solitary paper addresses international negotiations around climate policies as an SoS that tries to deal with global warming [32].

Summary of findings

The application of GT to SoSE is not specific to an application domain, but it has been shown to be useful in several different sectors. However, the results are mainly theoretical, and the link to practical applications is still missing.

4.4. SoS engineering problems

A number of SoSE problems are recurring in several papers, and often in different application domains. The most prominent ones are described next, with a focus on explaining how the problem can be seen as a game.

4.4.1. *Formation and dissolution*

The problem of attracting constituents to an SoS, and keeping them, is the most frequent topic in the study, accounting for 12 papers [14, 18–22, 30, 31, 33–36]. A common approach is to see the SoS as a game, where each constituent system is a player. Each of the players can choose to join or not join the SoS. The problem to analyze is how to provide strong-enough incentives for the constituents to collaborate, in order to reach the SoS goals. The strategies of the players can be modelled in various ways. In [30, 31], the willingness to collaborate is based on forces such as sympathy, trust, fear, and greed. A more theoretical analysis is presented in [35], that compares strategies such as always cooperate; different versions of mimicking opponent behavior (a.k.a. tit-for-tat); or randomly choosing. The alternatives of focusing on payoff maximization or risk minimization is studied in [20], whereas the cost-benefit balance is considered by [22]. In the smart grid example studied in [14], the problem is how much control over consumption the consumers are willing to transfer to the producers in order to optimize production, and what incentives are necessary to attract the consumers to the SoS. In the GEOSS application [18, 19], the satellite data provided by the participants becomes almost like a public good, and the issue is then that free-riders may use the data without contributing, thus making it less attractive to contribute.

4.4.2. *Security*

Security is analyzed in four papers, all from the power and IT infrastructure domain [13, 15–17]. The players of this game are typically an attacker and a defender, with the latter being the owner of the SoS. The analysis tries to find how different patterns of attack and response will affect important emergent properties of the SoS, and use that to design the most cost-effective defense strategies.

4.4.3. *Governance and control*

This topic concerns how a coordinating participant can influence other constituents to act towards the SoS goals, and five papers clearly touch upon this. Governance in organizational systems is described in [37], which introduces four basic concepts, namely architecture, metrics, knowledge management, and awareness. In [24], a framework based on anticipation, influence, and reaction is presented, which identifies five types of influence: incentives, information, integration, infrastructure, and institutions. The need to provide additional information can lead to the introduction of a mediator that give constituents information that makes them act towards the SoS goals [38]. The aforementioned smart grid example [14] provides a case in which the provider wants to influence behavior of the consumers, and further examples of how a central coordinator should act are given in the GEOSS case [18].

4.4.4. *Acquisition*

As already mentioned above, acquisition is the topic of several papers related to defense applications, and this problem is unique to that domain in the set of papers. The players of games in this area are the acquirer and the suppliers, and they want to maximize the resulting SoS capability, and their business value, respectively. Although not explicitly mentioning any applications, [39] discusses acquisition with a focus on the organizational interactions that support the technical SoS, and outlines a unifying framework with elements of GT.

4.4.5. *Architecting*

SoS architecting is discussed in three papers. The game can be seen as that between a central decision maker, the SoS architect, and a number of decision makers controlling the design of the constituent systems [24]. In [27], it is in the context of acquisition, and the architect is here seen as the role that decides how funding should be allocated to different alternatives needed for a set of capabilities. A different view is taken in [36], where the architecture of the SoS is instead emerging as a set of modules that result from the connections the constituents choose to form, given certain constraints on how many links are possible.

4.4.6. *Policy design*

Two papers deal primarily with policy design. Common in this field is to consider multiple levels of games, such as in [32], where the international climate control negotiations are considered, or in [25] that deals with air transportation, and models travel demand by passengers, service providers, and infrastructure providers.

Summary of findings: GT has been applied to a large number of key SoSE problems, with a particular focus on formation. The usage of GT involves identification of the relevant actors, and their goals and incentives.

4.5. SoS lifecycle phase

A majority of the papers quite explicitly address one or several lifecycle phases of an SoS. As already mentioned, a few papers deal with the acquisition phase, but the larger portion of the papers relate to operations and design. Issues like formation and dissolution discussed above mostly relate to the operational phase, as do security and control, whereas architecture and policy is closer to design.

Summary of findings

An interesting observation here is that there is often an interrelation between the design and operations phases, that is not so often treated. Evolution is a key characteristic of SoS [1], meaning that design and operations go on in parallel, and the design can be regarded as a game where the actors are the organizations behind the constituents negotiate the mechanisms to use in the operational game [24].

4.6. Game types

When considering the types of games used in the primary studies, the picture becomes quite diverse. A few papers rely on the archetype games often presented in the GT literature, such as the prisoners dilemma [20], the stag hunt [30, 31], or pursuit-evasion [33]. However, most papers do not fall back on these standard types, but instead formulate specific games for the situation at hand. This is probably because the standard type games are simplified as far as ever possible in order to highlight a certain aspect of GT, whereas the real SoS situation is much more complex.

Among the considerations in designing a game, a number of examples end up with non-zero-sum situations [13, 30, 31, 34]; repeated games [21, 30, 31, 35]; continuous or differential [14, 32, 33, 39]; or bayesian or random games [26, 36].

The notion of Nash equilibrium plays a fundamental role in GT. However, only 9 primary studies make at least an attempt to analyze Nash equilibrium [13, 15–17, 20, 24, 33, 36, 38]. Four other papers mention the concept but without any analysis [21, 30, 34, 39], whereas the remaining 18 ignore it completely.

Summary of findings: There is no clear pattern on what games to use, but it depends on the situation. However, it is evident that the simple school-book types do not suffice due to the complexity of an SoS, involving many players with many different options, that interact over extensive periods of time. Nash equilibrium is not considered very often, possibly because the rather complex games that result when studying SoS make this analysis difficult, or less meaningful.

4.7. Analysis approach

Due to the rather complex games studied in the papers, simple analytical approaches do not suffice. Instead, many of the authors resort to different simulation techniques, whose importance for SoS decision making is discussed in [10]. An overview of the strengths and weaknesses of alternative modeling and simulation techniques when applied to SoS is provided in [28]. The most common approach is different variants of agent-based simulations [22, 25, 29, 32, 34, 36]. Also commonly used are variants of Monte Carlo simulations [21, 33], or the two in combination [30, 31]. Network-based simulations is another option [24, 35]. Certain papers rely on optimization techniques or numerical analysis [13, 20, 23], including evolutionary programming [27].

Summary of findings: It appears reasonable that a complex SoS requires a combination of different analysis techniques. Simulation techniques make sense since the questions often relate to a dynamic behavior, and the agent-based approach is useful since there is a direct correspondence between agents, players of the game, and constituent systems, making the structure of the analysis clear. At the same time, elements of network-based simulations are useful, since they capture the critical relations between the agents. Also, Monte Carlo simulations and optimization have a place in this, in order to evaluate effects of different starting conditions, parameters, strategies, etc. that may be applied over a set of heterogeneous constituents. Most papers are not explicit on how they performed the simulations in practice, but it appears that many use standard programming languages to write the simulation models, and that ready-made tools are rarely employed.

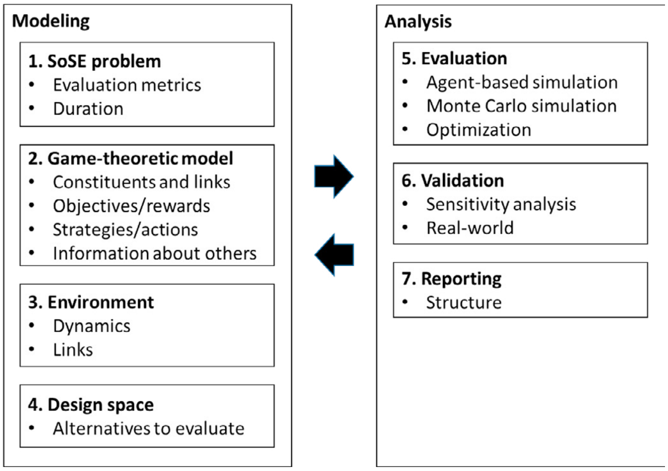

Fig. 2. Overview of best practice process.

5. Synthesis of Best Practice

Based on the findings presented in the previous section, and also on other information in the primary studies, we will now address RQ2 by trying to elicit a best practice for applying GT to practical SoSE problems in various domains. The method consists of two main activities, modeling and analysis, where the modeling aims at capturing the SoSE problem in GT terms, and the analysis uses that model to evaluate the alternative solutions to the problem. Often, an iteration between these activities is needed as a deeper understanding of the problem emerges.

An overview of the proposed process is given in Figure 2, and the steps are presented in more detail in the following subsections.

5.1. Modeling

The modeling consists of four steps, which describe the problem; the players; the environment they exist in; and the design space where solutions can be sought.

5.1.1. Problem

As a first step, it is essential to state what SoSE problem is being analyzed. In the papers, examples included formation and dissolution; security; governance and control; acquisition; architecting; and policy design. However, other problems involving the interaction between different systems are surely conceivable.

The problem statement should also include how solutions are evaluated, and often this will be based on a set of emergent properties of the SoS. Those properties need to be defined, including how to measure them.

The duration of the situation is also essential. Is it a short scenario that requires a single simple decision, or is it interesting to aggregate properties over longer periods of interaction?

5.1.2. Game-Theoretic Model

The next step is to identify the set of players in the game. Often, these are the constituent systems of the SoS, but they can also include external entities that interact with the SoS. An example of the latter is the attacker in a security problem, or surrounding traffic in a transportation SoS.

Related to this are also the possible links that can be formed between constituents, which can put restrictions on what information they have available and how they can influence each other. The description thus often involves a network structure.

Furthermore, each category of players will have their objectives and rewards, and these will need to be modeled as utility or payoff functions. The utility is not necessarily monetary, but can be of various kinds depending on the nature of the problem.

Also, the strategies, i.e. set of actions, that each player can take is essential to know.

Finally, it needs to be understood how much each player knows about each other, including internal states, strategies, objectives, etc.

5.1.3. Environment

In practical SoSE, an understanding of the environment that the constituent systems interact in is essential. Often, this environment contains physical elements, that both interact with each other and with certain constituents, and the dynamics of this must be understood. The payoffs can often be expressed in terms of attributes of this environment, and the model of the environment thus is essential in understanding the consequences of various actions that the constituents can take.

The environment can also create indirect links between players, through the elements of the environment, and this extends the network structure described in the previous step.

5.1.4. Design Space

Having identified the problem, the players, and the environment, the next step is to understand what alternative solutions exist that should be analyzed. A very common question is what decision strategies the constituents should employ, but it can also involve what information should be provided to them. Each option usually has a different cost associated with it, so in the end this implies a trade-off analysis.

5.2. Analysis

In the analysis, the alternatives in the design space are evaluated, followed by a validation of assumptions, and a report of the results.

5.2.5. Evaluation

The exact approach to use for evaluating different options in the design space depends on the problem, but in many situations an agent-based simulation seems to be a good starting point. If a large number of parameters in combination need to be evaluated, Monte Carlo simulation is a good complement. If a clear objective function exists, optimization techniques can also be applied.

5.2.6. Validation

Based on the evaluation, different conclusions will be drawn about the pros and cons of the different options in the design space. However, in most cases these conclusions will depend on a large number of more or less arbitrarily chosen parameters, and hence the results need to be validated. In the best of worlds, this should be done in the real applications, but as a minimum, a sensitivity analysis of the assumptions should be carried out.

5.2.7. Reporting

The final step is to report results, and in doing so, it is highly recommended to clearly present how the different steps above were conducted, and make all considerations and decisions explicit. Otherwise, replication and extension of the studies become very difficult.

6. Discussion

In this study, we have investigated how GT has been, and should be, applied to SoSE problems. A large number of papers exist on the subject, reporting studies that have surely contributed to improving the understanding of a particular SoS among the researchers. However, the results of those studies are rarely validated in practice, so it is hard to say to what extent the approach really succeeds in improving operational SoS. One can suspect that simplifications are often needed, that may well lead to results that do not match reality, and for this reason, the proposed best practice in the previous section tries to deal with the complexity of real SoS.

One should also be aware that GT, even though it has been a very active area of research for three quarters of a century that has yielded several Nobel prizes, it is not free from critique. For instance, it assumes that decisions are rational, whereas there are many indications that human decision making is partly irrational. Hence, the modeling needs to move from idealistic assumptions on how decisions are made, and find SoS mechanisms that are robust to disturbances resulting from more arbitrary or random behavior.

In SoSE, one of the most fundamental problems is to define the rules that should hold in the collaboration, and those rules should guide the independent constituent systems towards a behavior that gives the desired emergent properties for the SoS as a whole. This problem is closely related to the concept of mechanism design, or reverse GT, that deals with trying to find incentives for players to act towards desired objectives. However, with the exception of [10, 26] mechanism design is not showing up in this study. This indicates that there is a large gap in the theories underlying SoSE, that needs further research.

Many of the papers deal with the dynamics of the operations, but less attention is given to the dynamics between the organizations during SoS design. This can be seen as a game, that results in the rules for another game, and is sometimes referred to as meta-game analysis. It is possible that more attention is needed here, in order to deal with even more rapidly evolving SoS in the future.

7. Conclusions

This paper has provided a systematic literature review in the area of GT applied to SoSE, and this contributes a starting point for researchers wishing to delve deeper into the area. It has also synthesized a best practice process for applying GT to more complex and realistic SoS problems, and this contribution is more towards practitioners.

The main conclusions are that GT can be fruitfully applied to SoS in a wide range of application areas, and deal with various problems related to acquisition, design, and operations. In particular, problems related to the operational formation and dissolution of SoS are well suited for this kind of analysis.

Due to the nature of SoS, that involve a large number of heterogeneous constituent systems that have a wide range of possible actions at their disposal, analytic techniques for evaluation do not suffice, but instead simulations are necessary. In particular, agent-based simulations are frequently used in the analysis. Unfortunately, the reported results from applying GT are not validated in practice in the literature, and there is still some way to go to properly ascertain the value of this as a practical SoSE technique.

As for future research, a few areas would benefit from attention. One is to lower the threshold of experimenting with modeling and simulation. This could require better tools, but it could also take the form of libraries for those who wish to retain the flexibility of ordinary programming languages. On the theoretical side, deeper investigations into mechanism design as a technique of synthesizing the rules of an SoS would be highly interesting, as would the application of meta-game theory to the engineering processes that result in the SoS.

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