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Influence Strategies for Systems of Systems

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Abstract - *Distributed decision making has been identified as a source of managerial complexity for the SoS engineer. A new framework, AIR (Anticipation-Influence-Reaction), is proposed to capture the feedback relationship between the decisions made by constituents and those made by the managers of the SoS. AIR is then used to develop a five-member set of basic influences that can bring about changes in constituent behavior thus modifying the SoS. These influences, the 5 I's, are Incentives, Information, Infrastructure, Integration, and Institutions. AIR and the influences are demonstrated through qualitative application to real-world SoS and quantitatively through a simulation of an inter-modal transport network. It is found that cooperation between competing constituents can be quite fragile and sensitive to the SoS context. Careful, dynamic planning of influence strategies is needed to maintain SoS behavior in the face of constituents who are driven by self-interest and a limited, local perspective of the SoS.*

Keywords: Systems of systems; Influence; Management; Complexity; freight; Simulation; Transportation; Intermodal; Game Theory; Distributed decision making; Anticipation; Reaction

1 Introduction

Since the mid 90's there has been a growing interest in how systems come together to form systems of systems (SoS). These coalitions of independently operated and managed systems can meet unforeseen needs in a timely and cost effective fashion. A challenge for systems engineers is to design, develop and manage constituent systems that are capable of successfully operating within a SoS. Traditional systems engineering theories and approaches do not fully address the technical and managerial challenges caused by this problem. This research focuses on developing better strategies for coping with the managerial complexity caused by the dynamic interactions between constituent systems within an SoS. By understanding these interactions, systems engineers and managers will be better able to develop engineering and management strategies to influence an SoS.

Current interest in these SoS can be traced back to the 1990's with the work of Maier [1, orig. published in 1996]. Maier defines two independence properties characteristic of SoS that have subsequently been used by many author to define the class of systems termed SoS [a review can be found in 2]. These two properties, *operational independence* and *managerial independence* specify that both from a technical and a social perspective an SoS is composed independent yet interacting entities. This formulation has been extended and refined over time, e.g., Boardman [3] define several dimensions upon which SoS can be differentiated from traditional systems. More recently, Karcanias [4] echoed Maier's claim stating:

> "The multi-agent dimension of SoS has characteristics such as:
> *Autonomy:* the agents are at least partially autonomous
> *Local Views:* no agent has a full global view of the system, or the system is too complex for an agent to make practical use of such knowledge
> *Decentralisation (sic.):* there is no designated single controlling agent, but decision and information gathering is distributed." [4]

This third characteristic, distribution of decision making, is a core challenge within SoS engineering. The design and management of SoS is a problem of coordinating the parallel development and operations of the SoS with its constituents. Such coordination can be externally imposed such as in an enterprise [5] or arise as consequence of interaction between the constituents [6].

SoSE is a two-sided problem. On the one hand, it is a technical problem of the determination of the appropriate interfaces [1] between constituent systems in order to accomplish SoS objectives. On the other hand, it is a social problem of convincing those who control the constituents to actually implement such interfaces [7]. Both challenges are recognized gaps in the theoretical SoS literature and each has been identified as a key components to SoS community's research agenda [8, 9].

A variety of frameworks have been proposed to describe the structure, operation and management of an SoS [10, 11, 12]. Of particular importance is that each constituent is trying to satisfy a locally specified value proposition, i.e., they are free to make decision that ensure their local needs are met. The extent to which these decision support a broader SoS agenda depends upon the alignment of these local needs with the SoS goals mediated by whatever influences that the SoS authority brings to bear upon the constituents.[1] As described by Bjelkemyr:

> "Each system within a SoS is a self-interested node in a network. These system nodes try to maximize their own utility under the influences of and in competition with the other nodes. The global SoS behavior thus emerges as a result of the actions at the lower levels of the SoS, down to the system element level." [12]

One can observe this challenge in real world SoSs. For example, peering disputes among the Internet service providers is an issue of choosing with which other systems one wishes to connect, i.e., with whom to collaborate. In October of 2005, Level 3 communications a Boston based tier 1 Internet service provider decided to terminate its peering agreement with Cogent communications, another tier 1 provider [13]. By refusing to peer with Cogent, Level 3 cutoff direct traffic flow between their respective networks. This forced routing via third-party network increasing congestion on those links. For some customers whose only connection was via Level 3, they were disconnected from those hosts whose only connection was via a Cogent network. The same was true in the other direction. After a few days, cooler heads prevailed and the peered connection was reestablished [14]. The underlying cause of the dispute was an imbalance in traffic flow between the two networks. Level 3 felt that Cogent was in violation of their contract when Cogent tried to make inroads into Level 3's market of selling access to Tier 2 providers. If a given Tier 2 provider, directly connected to Cogent instead of going through Level 3, this would might create a traffic imbalance to Cogent's benefit.

The essential difference between the decision structure in traditional SE vs. SoSE is one of alignment. The SoS architect may need to influence the constituent decision makers to behave in a manner that is not necessarily locally optimal for them but does serve the interest of the SoS. This relationship between the SoS architect and the constituent decision makers is a principal-agent problem [15].[2] In the SoS case, the principal is the central authority/SoS architect who wishes to effect some SoS behavior that they value via the actions of the agents, i.e., constituents. Given this framing, the central authority is referred to as an SoS principal. Note that constituents may be interacting with multiple such authorities at a given time (e.g. if they are participating in multiple SoS) and may also act as such an authority themselves with respect to other constituents such as in a collaborative SoS.

2 Anticipation–Influence–Reaction

The role of the SoS Principal (or Influencer) is one of coordinating constituent action to generate SoS behavior that the principal desires via influencing the constituents. This type of relationship is not new to the field of decision theory or organizational management. In logistics, for example, the problem is quite commonplace. Schneeweiss [16] extends the work done in logistics to more generic distributed decision making problems in organizations. The current work applies and extends his formulation to the SoS. While his focus was on the inter-organizational relationships, the current research also includes the connection between organizations and the systems they control. As a consequence, a broader selection of influence mechanisms are considered. While Schneeweiss, looks at direct incentives and information, the current research extends that to include technological and institutional mechanisms as well. Wernz [17] takes a similar approach in developing a theory of Multiscale Decision-Making.

To generate these influences (see Figure 1 for a visual description of the processes being described), the principal first observes current SoS behavior. This observation is used by the principal to capture the current state of the SoS and evaluate direct changes they could make to SoS entities under their direct control. Second, they anticipate constituent decision-making and interactions. The word 'anticipate' is used instead of 'observe' since, unlike system behavior, constituent decision-making process is not generally visible to the principal. As independent agents, constituents can make choices in private only revealing them through their actions. Therefore the principal must use their best estimate of constituent action in assessing influence strategies. Third, based upon observation of the systems and anticipation of constituent decision-making, influences are brought to bear upon the constituent with the aim of modifying their behavior.

Constituents respond to these influences in two ways. First, they take actions to modify the systems they control in response to the changes in their decision problem caused by the influences. If the influences were well-formed and

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[1] The situation is somewhat different in the case of directed SoS. The fact that a central authority has coercive influence on the constituents renders the problem of SoS and constituent alignment moot, however, it can also bring additional responsibility on the central authority to manage constituent needs.

[2] A classic example of this situation the the employer–labor relationship. In that case the employer, wishes to maximize the productive output of her firm. The output, however, is dependent upon the effort put forth by the employees. The employees wish to maximize their total wages while minimizing work hours. Each player, the employer and the employees, makes their own choices with regards to the variables they control.

the principal's understanding of the SoS and constituents accurate, then the effect of those changes in the systems will modify SoS behavior in an manner of value to the principal. The principal will observe the extent to which this has occurred (post-facto feedback). The constituents may also react directly to the influences, signaling their (dis-)satisfaction.

These three interactions, *anticipation, influence and reaction*, form the core social feedback mechanism between SoS principals and their constituents, and give the AIR framework its name.

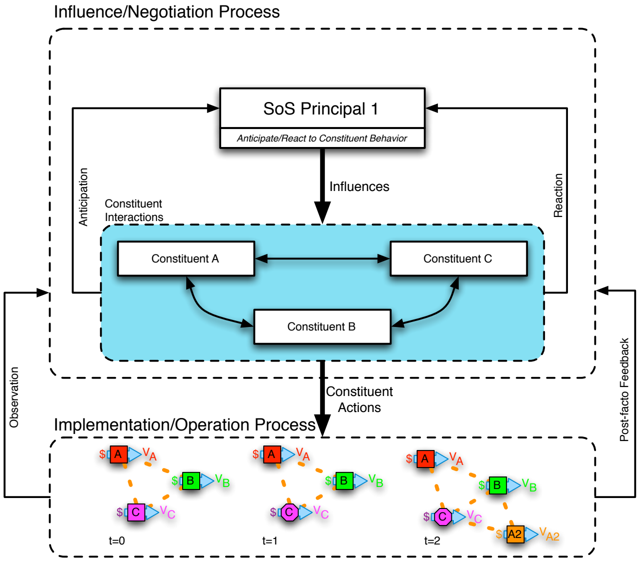

Figure 1. An SoS principal influences constituents to take action that modify SoS behavior such that the principal's objective are met. The upper portion of the diagram represents the *social* interaction between the constituent decision makers and the SoS principal, while, the lower portion represents the *technical* interaction between the constituent systems in the SoS. Constituent action are changes made in the constituent systems by the constituent decision makers causing the SoS to change over time.

To illustrate this approach for a collaborative SoS, the AIR framework is applied to GEOSS, the Global Earth Observation System of Systems. GEOSS is an effort to combine and coordinate the collection, dissemination and exploitation of earth observation data[3]. A multinational effort, it is coordinated by the Group on Earth Observation (GEO), an intergovernmental organization with membership from 80+ countries. Each country contributes its own local data and expertise. As the assets that produce this data are all locally managed and operated, GEOSS is an SoS. It is also a federation of systems as defined in [18]. One area of focus for GEO has been the establishment of data sharing standards to allow reuse of data collected by various GEOSS constituent systems [19]. Khalsa [20] describes a pilot program by which GEO is establishing an information system (of systems) for data sharing. A key challenge in building this SoS has been been diversity of needs of the end-users combined with the distribution of decision making amongst globally (and, therefore, culturally) dispersed constituents [21]. GEO met this challenge by implementing a service-oriented architecture (SOA) for data sharing. The SOA allowed each constituent to chose which data they published and specified a common repository that served as a catalog for these data sources. The process by which this repository was established is a good example of the different pieces of the AIR framework in practice. The constituents are the data providers. These same providers formed a working group that serves as the SoS influencer or principal.

As described in Khalsa [20], the data interoperability pilot program proceeded in phases. In the first phase, recognizing, that in many cases, constituents were already exchanging data, an effort was made to document the *de facto* standards under which these exchanges took place. This is the observation process from Figure 1. In the next phase, communities of potential users were formed to examine what new data exchange/normalization requirements needed to be developed to harmonize the de facto standards from the first phase. This is the anticipation step within which the influencer attempt to envisage how the constituents will respond to various influences and thereby find the influences that best induce the desired behavior of the SoS as a whole. In this case, the working group identified the new standards and protocols needed to enable the desired use-cases of the GEOSS members. The influence in this case is the offering of these new standards for adoption by the constituents. In the third phase, they will implement a demonstration version of the new data exchange service repository, thereby creating a opportunity for the users to try the new approach before broader deployment. This is a form of reaction, wherein private information to the constituents, i.e., the effect of the new standards upon them is revealed to the influencer through the constituents' participation in the demonstration.

3 Five basic influences (5 I's)

The SoS principal or influencer is trying to effect the choices being made by the constituents. Therefore, a natural starting point for developing strategies are the constituents' decision problems. Proposed below are five distinct ways that the influencer can exert influence upon the constituents' decision problems. Each influence mechanism impacts a different part of the constituent's decision problem. They are outlined in Figure 2 and are identified by an 'I' word and are collectively known as the 5 I's. They represent a basis set of strategies and may be used in combination to create the desired effect.

Incentives reward or penalize constituents for particular behavior that they would not do otherwise. For example, one may contract a commercial communication network to carry SoS related traffic in addition to their normal operating load.

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[3] See http://www.earthobservations.org/geoss.shtml

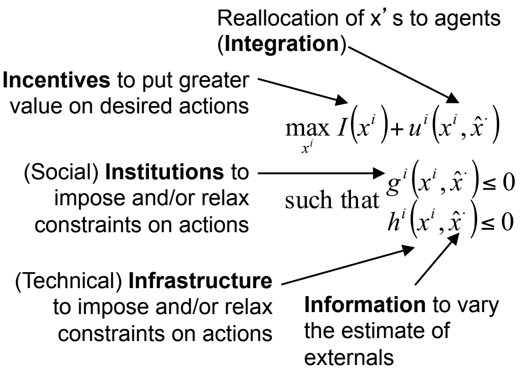

Figure 2. Changing the constituent decision problem via influences. u is the constituent's utility function, x their decision variables and $\hat{x}$ the decision made by others that affect them and so must be estimated. Constraints have been split into two groups, g and h reflecting those that arise from social and technical concerns respectively

Information can be provided to constituents to modify decisions made under uncertainty. For example, interface specification documents provide potential SoS constituent advance notice of the necessary interfaces needed for future SoS participation.

Integration is the re-assignment of particular SoS components to different constituents. A common example would be combining two systems into one.

Infrastructure refers to introducing new technology into the SoS. An example would be a new high-speed data network to facilitate higher bandwidth inter-connection between constituents and thereby encourage the formation of new interfaces.

Finally, *institutions* refer to the rules and regulations that constituents follow. An example of this would be allowing collusion between ordinarily competing constituent to ensure more efficient allocation of shared resources.

The 5 I's can strategies can be applied to the Internet peering dispute described earlier. Level 3 had several options available to it to resolve its peering dispute with Cogent. Using the influence mechanism of incentives, Level 3 could have renegotiated peering agreement to Cogent require compensation from Cogent in the event that traffic is imbalanced. In terms of integration they could buy Cogent's business (or sell their business to Cogent). They could exchange additional information with Cogent, e.g., traffic data and projections to better allow planning by both parties and possibly avoid traffic imbalances. They could have modified their technical infrastructure to selectively reduce the quality of service for Cogent customers traversing the Level 3 network. This would encourage those customers to find alternate transport thereby reducing the traffic imbalance. Finally, they could use dispute resolution institutions provided for in a typical peering agreement. Each of these approaches has side-effects and one may leave Level 3 in a better position that another, however, they do demonstrate the variety of strategies available.

4 Case study: Intermodal Transport

To demonstrate the AIR framework and 5 I's, they are applied to the problem of intermodal freight transport. Driven by both increasing demand and increased concern for externalities such as environmental damage and noise, one area of focus is making more efficient use of transportation networks. In terms of overland transport, there is much interest in greater use of intermodal transport [22]. Intermodal transport refers to transportation solutions that, from an origin point to a destination, use two or more transport modes. For inland transport in particular, research into rail-truck intermodal has revealed that combining rail with truck can lead to significant cost savings when compared to using trucks alone. This is a consequence of the greater efficiency of rail over long distances and carrying large loads. In addition, using modern locomotive technology, rail can generate less pollution than trucks for the same move [23]. On both these accounts, increasing the use of rail via intermodal links to the trucking system appears to be a beneficial policy objective. The objective of the case study, therefore, is to apply the AIR (Anticipation-Influence-Reaction) framework to look at the influence strategies in an intermodal transport network. While the overall context being described in the case study is manufactured, the behaviors of the constituents are rooted in real-world examples.

4.1 Anticipation Phase

Recall that the anticipation phase consists of the SoS principal attempting to understand the behavior of the constituents (and by extension the SoS) so that he may look at potential influences. Most SoS are far too complicated to describe in a deterministic fashion. As such, building a predictive model is impossible.[4] Rather, the SoS principal should seek to understand the key behaviors of and interactions between the constituents and include those in a simplified model that can be used to better understand the dynamics that emerge when all the pieces interact. This type of 'behavioral' model is much easier to produce. Using concepts from the models proposed by Fernandez [24] and Gambardella [25], the following local (constituent-level) decision makers (DM) are identified: (1) Shippers; (2) Road operators; (3) Rail operators; (4) Terminal operators. SoS-level decision makers are (1) Coalitions of mode/terminal operators who offer intermodal service as a door-to-door offering as perceived by the shippers and (2) external influencers (aka SoS principal) who provide incentives. For this study, the SoS design problem is framed from the perspective of an external influencer who wishes to increase rail usage.

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[4] This can be due to complexity, scale of the SoS, limitations on available data to characterize past behavior and, conversely, inability to use past data when consider novel SoS forms.

For this case, an island transportation system is specified in which goods flow from two origin points to two destination points. Connecting these are a network of road and rail links with intermodal terminal between rail and road Figure 3. Traffic is simulated upon this network for a period of 15 years.

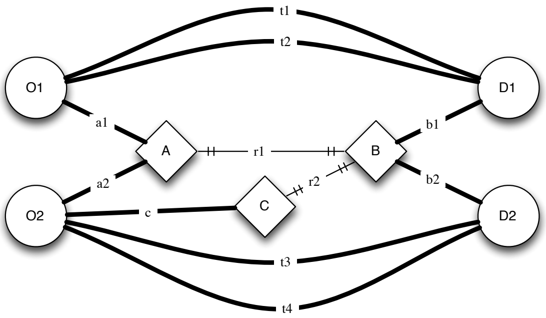

Figure 3. A simple intermodal network

The model represents the interaction between two types of agents – shippers who wish to use the transport network to manage the stock of a good at the destination point and carriers (railroad operators and truckers) who provide transport service between point on the network. The overall flow of the model is shown in Figure 4.

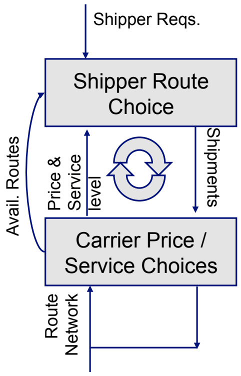

Figure 4. Overall transportation model flow

For the shipper model, shippers are assumed to use trigger-fixed quantity reorder inventory management strategy. Each quarter they attempt to find the transportation solution that minimizes their total logistics cost [26]. There are 50 shippers each of whom move 2000 TEU (twenty foot container equivalent units) per quarter. Rail pricing and operations (train frequency is the only operational variable considered) is modeled as profit maximization problem with exponential forecasting used to estimate future behavior of other actors (e.g. prices of competitors). This is inspired by the pricing approach used by BNSF as described in [27]. Pricing and service frequency is re-evaluated each quarter. For truck carriers the Owner/Operator Independent Driver Association[5] cost model is used. Again, prices are set quarterly to maximize profits and exponential forecasting is used. Terminals are assumed to be fixed time delay transfers between transport modes incurring a fixed cost per container moved. In the baseline case, shippers form routes using a forwarding company to contract with the relevant carriers forming a complete chain from their desired origin to destination. The forwarding company as modeled is a simple monetary pass through to the carriers.

Baseline results are shown in Figure 5. After a brief period of variation, the market eventually settles to an almost even split between traffic going on long haul truck and traffic using an intermodal route.

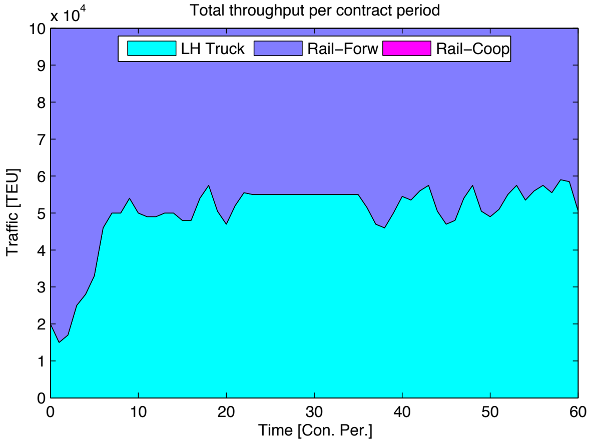

Figure 5. Baseline case: Traffic allocation by mode – Aquamarine long haul truck; Purple road-rail intermodal with routes formed via a forwarder

4.2 Influence phase

Two different influences are considered with respect to intermodal terminal. The first provided a subsidy to offset the additional cost borne by shippers when going through terminals, while the second posited an infrastructural improvement in terminal throughput [28]. Neither terminal improvement nor subsidy had a significant impact on shipper mode choice. The reason for this seems to be that, for the situation as modeled, terminal costs do not represent enough of a share of total logistics cost to cause a shift in shipper behavior, and, shippers compensated of higher (and more variable) transport delays by increasing inventory. As inventory costs are increased, these influences begin to have an effect, however, quite large costs shifts (more than 40% of per TEU value per TEU held, on average, in inventory) are needed to see a change.

In the case of road travel, Janic [23] claims that 20% of the total cost can be attributed to externalities. Conversely,

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[5] http://www.ooida.com/Education%26BusinessTools/Trucking_Tools/costpermile.shtml

in the intermodal case, only 6% of the cost is the from externalities. Upon imposition of the tax to cover this difference, there is a shift of traffic from the road to the rail intermodal as expected. However, that shift is small resulting in only 60% of the traffic going on rail. Better than the baseline, but not by much. Insufficient traffic is shifted to justify the railroad increasing capacity. The net effect was little shift in traffic in the long run and a large dead-weight loss to the shippers.

The final influence considered was an institutional change to allow the formation of cooperative routes through a negotiation between longhaul truckers and the railroad. This is also an example of integration as two entities that were separate are now acting together.Once formed, coalitions are kept in place for 4 contract periods (one year) and then re-negotiated (prices for these cooperative routes are re-evaluated every quarter to maximize the joint-profit earned by the coalition). Coalition formation is modeled using the Nash bargaining solution with service offering of non-involved parties forecasted as above. The results are shown in Figure 6. The influence was turned after 20 quarters had elapsed. There was an immediate and stark shift in traffic away from the truck (teal in Figure 6) to rail intermodal – both from coalitions (magenta) and via forwarding companies (purple). Though coalitions come and go as the other parties adjust prices to make them no-longer advantageous, for almost 30 quarters, truck traffic is kept to under 20% of the total flow..

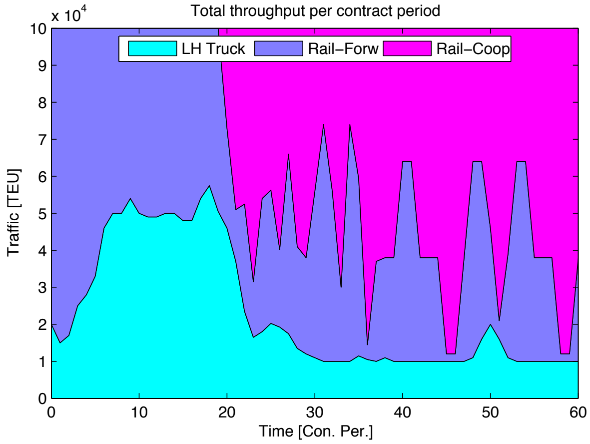

Figure 6. Cooperative routes allowed case: Traffic allocation by mode – Aquamarine long haul truck; Purple road-rail intermodal with routes formed via a forwarder; Magenta road-rail via cooperative agreement

4.3 Reaction phase

To look at reaction requires examining how each of constituent parties are effected by the influence mechanisms. Both the tax and cooperative routes resulted in shifting traffic from road to rail. However, the tax resulted in a significant cost increase (11%) that was passed on to the shippers. Either directly or through the carriers, they are likely to protest such price increases. The cooperative route on the other hand resulted in a net cost decrease to the shippers of 10%. Looking just at this it would seem that the cooperative solution is the best. However, the truckers suffer in that situation. Moving so much traffic to rail greatly reduces their profits by almost 2/3. They would likely object to such a move. Thus, in implementation, the SoS principal would likely have to balance the protests from the truckers while not placing to large a burden on shippers. This is representative of the types of trade-offs that can occur when influencing SoS with many interacting constituents.

4.4 Observations, Limitations and Extensions

From a transportation perspective, the case study results could lead one to hypothesize that external market interventions such as taxes and subsidies can be less effective that mechanisms that exploit self-interest such as allowing cooperation. The strong effect of cooperation is consistent with empirical studies of intermodal transport networks [29]. Of course such mechanisms may not always be available, but when extant, they should be carefully considered. As formulated, however, the case study model is quite simplified and so its results should be taken as behavioral and not predictive beyond showing potential trends. It can be extended to include a, larger, more realistic route network and more varied shipper and carrier populations such as in [30] allowing better characterization of the effectiveness of the proposed strategies. Costs of implementing the influences was not considered as evaluating the cost of a social change in way that is comparable to a technological change is difficult. Nash bargaining is only one approach to look at cooperation between constituents. Other game-theoretic approaches such as those developed in [31] could be particularly useful as they can be applied to modeling the participation/cooperation decision in other SoS.

5 Limitations of AIR and the 5 I's

The preceding sections provide a glimpse into how the AIR framework and the 5 I's could aide an SoS principal. There are several significant limitations and opportunities for extension. With respect to the AIR framework, one must keep in mind that AIR, on its own, is not sufficient for managing an SoS. It is best used in the context of broader framework such as those cited earlier. AIR only helps formulate strategies for changing constituent behavior. It does not aide in determining what the desired constituent behavior should be. That is the design problem of SoS and progress towards it has been made in [32]. Simulation and modeling of SoS is required for AIR. Progress has been made there by [33, 34, 35]. As developed thus far, AIR assumes a fixed constituent set. Changing this would require modeling a super-set of potential constituents and their respective life-cycles. In addition, scaling the agent-based modeling approach demonstrated in the case-study to very large numbers of constituents can be challenging. For such large numbers, constituents may need to be represented as member of a class whose behavior is characterized statistically instead of as individuals. Systems dynamics can be helpful in such a situation as was shown in [36] where multiple satellite operators were aggregated. Determining the costs associated with influence mechanism, especially those that are social in nature is quite challenging. Research from political and organizational science should be used in assessing such costs and managing trade-offs between constituents that arise during the reaction phase. Finally, influence strategies were discussed in isolation and were implemented as such in the case study. In reality, they will likely need to be used in combination to achieve the desired effect. How to form such combined strategies is another area of research.

6 Impact on SE practice

The AIR framework and 5 I's can have significant impact on systems engineering practice. They provide a simple, consistent representation of the key roles that in the stakeholder community that controls an SoS. At the highest level, these are those of the constituent and the influencer. While the notion of constituent is not new, the notion of an 'influencer' is novel. More often than not the system of systems engineer finds themselves in this influencing role that can only indirectly effect the systems within the SoS. Traditional systems engineering is predicated on the ability of the highest level stakeholder to proscribe requirements which determine decision making at the lower levels. Such an approach would not work in SoS when there was a conflict between the needs of the system of systems engineer and that of the constituents. Rather strategies that account for the local needs of the constituents are required. The 5 I's are a first steps towards developing such strategies.

As is demonstrated in the case study, counter-intuitive results can occur when attempting to intervene in systems of such significant decision-making complexity. Therefore modeling such as the agent-based approach used in the case is crucial to gaining a sufficient understanding of the dynamics of the SoS before intervening in the real world. Examples of this are replete in case studies of real SoS. When trying to modernize document production in the DoD, the need of for common standards was identified [6]. In implementing these standards, however, problems arose given the diverse areas in which the standards needed to be applied. Furthermore, making such changes without disturbing on-going operations was quite challenging. Even though the end-state was much better than the status quo, there was a need to ensure local buy-in to make the transitions happen. AIR and the 5 I's can help the systems engineer think through such issues systematically before making changes in already operating systems.

7 Summary

A key challenge in the management of SoS arise from the operational and managerial independence of the constituent systems. They are free to make decisions based upon local concerns. As these concerns may not align with SoS needs there is no guarantee that constituent decisions will benefit the SoS. To help mitigate this, SoS principals must use influence upon the constituents to make those actions that support the SoS the preferred actions of the constituents, i.e., to ensure incentive compatibility [37]. The AIR framework and 5 I's can help with this task. By anticipating how constituents will behave, understanding how influences change their behavior and ensuring that mechanisms exist for constituents to react, SoS principals can gain a deep understanding of both the social and technical dynamics within their SoS along with the levers available to them to change it. The 5 I's, incentives, information, infrastructure, integration and institutions provide a basis set of influences from which many aspects of constituent decision making can be changed.

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