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Taxonomy to Guide Systems-of-Systems Decision-Making in Air Transportation Problems

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The phrase *system of systems* has been in use for well over 10 years. As customers of the aerospace and defense industries began asking for broad capabilities rather than for single systems to meet specific requirements, the notion of a system composed of multiple independently operating systems has become more important as the way to meet the desired set of capabilities. This brings new challenges to system or systems-of-systems engineers and their ability to design and analyze alternatives for systems of systems. Because individual systems can operate independently within a system of systems, many engineering methods and tools used to design and analyze large-scale, but monolithic, systems do not appear to work for systems of systems. This paper presents a three-axis taxonomy that can guide design method development and analysis of alternatives for aeronautical systems of systems. Based on this perspective, two experiments in applying the methods are presented for system-of-systems problems that involve aircraft and/or air transportation.

Nomenclature

AR = aspect ratio
T/W = thrust-to-weight ratio
W/S = wing loading

I. Introduction

CURRENTLY, numerous system-of-systems (SOS) definitions exist (see, for example, [1]). The specifics of each definition vary somewhat, but most agree that a system of systems arises when a set of needs are met through a combination of several systems. Each system can operate independently, but each also must interact effectively with other systems to meet the specified needs [2].

While the *name* may be recent, the *notion* of a system of systems is not new. There have been (and still are) numerous examples of systems that rely upon the interaction of multiple, but independently operating, systems. These existed before the phrase system of systems entered common use, and they have been studied, in part, in several fields of inquiry. One overarching example is the air transportation system composed of the independently operating airlines, airports, airspace systems, and air vehicle manufacturing enterprises. The design, operation, and analysis of these systems have often occurred separately. Recently, more emphasis is being placed on the concurrent analysis and design of these interacting systems. This is an attempt to enhance the performance of the transportation system as a whole instead of improving the performance of any single system in this system of systems. At the same time, using a system-of-systems perspective for design has gained importance because of a change in procurement approach by government agencies and organizations (particularly the U.S. Department of Defense [DOD]). Where government customers once issued detailed requirements for a specific platform system, they now ask instead for a broad set of capabilities that are needed over a significant time span. As a result, the systems engineering (SE) process must determine the appropriate mix of both existing and yet-to-be-designed systems to provide these capabilities.

The original version of the U.S. Coast Guard's Integrated Deepwater System (IDS) provided an example of a more formally described system of systems. For this program, the Coast Guard described its 14 mandated missions and asked industry for the development of an optimum mix of ships, aircraft, and/or unmanned aircraft that would comprise the Integrated Deepwater System. However, fundamental system engineering failures forced the Coast Guard to restructure how they would develop this SOS. The original vision to develop this complex system of systems used lead system integrators (LSIs) to improve technical oversight and innovation by giving organizations with relevant technical background control of the SOS development [3]. LSIs are contractors hired by the government to generate requirements, develop systems, integrate systems, etc. For IDS, this resulted in cost overruns and schedule delays that the Coast Guard attributes to lax oversight on its part and too much management power for the contractors [4]. The U.S. Army's Future Combat Systems (FCS) was another example SOS; in its original version, it was to consist of 18 individual systems along with the communication network and the soldier [5]. The FCS would network existing systems, systems already under development, and systems yet to be developed. In 2009, the FCS program was cancelled: in part, due to cost and complexity issues. The required pace for technological advancements was underestimated, and beginning the system development and demonstration phase was deemed premature [5], suggesting a lack of understanding of the SOS nature. However, many of the FCS aims and major systems have become part of the Army's Brigade Combat Team Modernization program [6]. Attaining the desired performance and capabilities requires engineering methods for successful design, planning, integration, and operation of a collection of independently operating systems. The aforementioned examples (IDS and FCS) show that executing this for large systems of systems is difficult.

While aerospace- and defense-related examples illustrate a recent system-of-systems emphasis, systems of systems meet many of society's needs over many domains like supply chains and product distribution, health care delivery, electric power generation and transmission, and transportation. As society wants and needs increasing capabilities in these domains, the systems of systems grow to incorporate additional systems, which bring with them and/or result in additional requirements and stakeholders. When an important system of systems fails to provide the capabilities desired or needed from it, these failures often become widely publicized.

Unfortunately, nearly every instance of publicized shortcomings includes inflexibility in response to disruption (artificial or natural) or

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increased demand for service. Supply chains acquire excessive inventory and capacity if manufacturers and distributors ignore opportunities to collaborate on demand forecasts. The Boeing 787 program experienced the impact of such disruptors in 2007 when the supply chain created a program delay, because the company underestimated the extent of the fastener shortage [7]. Well-publicized transportation delays from overcapacity operations at major airports prevent passengers and cargo from reaching their destinations in a timely, productive manner. In 2008 alone, estimates indicate that flight delays caused by air traffic congestion at the three major airports in the New York metropolitan area were responsible for more than $2.6 billion in losses to the local economy [8].

The systems of systems encountered in civil air transportation provide services that are highly valued and critical to society. However, they have largely evolved into place; *they were not formally designed, planned, or even integrated holistically, as systems of systems*. A growing body of evidence indicates that the breakdowns and underperformance of these complex SOS arise more from insufficient attention to how systems interact and less from inadequate engineering of individual systems.

The challenge addressed in this paper is *the need for rigorous, repeatable engineering design methods that are appropriate for analysis of alternatives at different levels in an air transportation system-of-systems context*. The methods must address the SE complexities that result from a system of systems that incorporates multiple, often physically separate, systems that are capable of independent operations. These methods must also recognize that the SOS can be an amalgamation of legacy and new constituent systems that must be integrated and interact with each other to provide the necessary capabilities. Furthermore, development of an SOS can be expected to take considerable time and require spiral development, which implies a dynamic architecture that accommodates (continuous) changes.

Design is the process of developing a system to achieve a particular goal while managing constraints. It is the kernel activity within SE and culminates with analysis of design alternatives. For systems of systems, this activity entails making decisions to mold legacy systems, add new systems, and/or change the configuration of these. This requires both proper definition of the design problem and good analysis/synthesis. Architectures (constructed via abstraction of the SOS) describe form and function using several views pointed toward the operational objective. From the perspective of design, architectures are critical for problem definition. Design-oriented analysis is then needed to craft alternative instances of the system of systems and provide sensitivities in performance to parameter or system changes.

From a process point of view, there are similarities in designing a system of systems and designing a monolithic system. Requirement generation, synthesis, analysis, and evaluation are phases of the design process necessary for the development of both types of systems. However, the size (computational complexity) and the number of consequential interactions (internal complexity) in systems of systems may be extreme. While defense applications have led to improvements in architecting approaches, new methods are needed in design-oriented analysis and, further, in the interface between architecting and analysis. An SOS taxonomy may indeed provide this interface.

The overarching imperative for the research community is to develop SE decision-making tools for SOS problems, for which we recommend two stages:

1) Create a taxonomy to classify system-of-systems design problems (subsets of the complete range of possible architectures) properly and completely.

2) Develop and demonstrate repeatable, formalized, approaches (and solution patterns) leading to discernibly superior results when conducting analysis of alternatives (i.e., by comparing results of current approaches to approaches and solution patterns for SOS problems), so that subsequent SOS efforts can make use of these approaches.

This imperative and the proposed stages address recommendations from a recent workshop on SOS [9]: "There is a need to clarify the class of problems that should be defined as examples of SOS. Further, a taxonomy of SOS types is required if we are to eventually define the tools necessary to solve particular sorts of problems." The remainder of this paper addresses SOS analysis and design methods via a proposed taxonomy, with an emphasis on the air transportation domain. SOS from other domains (e.g., transportation and health care) that share the same taxonomy-based description may then call upon a similar set of design methods.

II. Behavioral Traits and Time Scales for SOS

Maier [2] has proposed a well-cited set of distinguishing traits for SOS problems: 1) operational independence, 2) managerial independence, 3) geographic distribution, 4) evolutionary behavior, and 5) emergent behavior.

The first three primarily describe the problem boundaries and mechanics of the interacting elements while the latter two describe overall behavior. Maier [2] contends further that the operational and managerial independence are key for creating a collaborative collection of systems, which may be the best distinction for an SOS.

Systems of systems display additional traits, such as the heterogeneity of component systems and a multilevel network structure. SOS also display emergent behavior that develops out of complex interactions among component systems that are not present for the systems in isolation; this presents a particular challenge. True emergent behavior is unpredictable, is often nonintuitive, and can manifest in a positive manner (e.g., a new capability arises) or negative manner (e.g., a new failure mode occurs). For many, the well-known phrase *unintended consequences* encapsulates the negative manifestation of emergence. Understanding the mechanism of emergent behavior in SOS problems, developing cues to detect it, and creating decision-support tools to manage it together constitute a tremendous challenge to methodology development.

Not all SOS problems will possess all of the aforementioned traits, and SOS problems may express the traits to varying degrees. Perhaps for some SOS examples, only a small subset of participant systems have operational interdependence. An effective taxonomy will account for these shades of possession with respect to the SOS traits.

Further, the traits may differ even for a particular SOS when examined at differing time scales. A variety of decision time scales exists for SOS. The *design time scale* is long and assumes an enduring SOS will exist. All the complications associated with long time horizons exist here, and the open system nature of SOS adds further complications. The *planning and implementation time scale* is shorter, but both deep uncertainty and imprecise knowledge of constituent participants still present challenges. While shorter in particular for individual component systems, it can be substantially longer for SOS because of the continuous evolution of the SOS and the interdependencies between systems, as documented in [10]. The *operational time scale* is real-time with short decision windows; the multiplicity of perspectives and the need for quick decision synthesis to exploit opportunities for surprise synergy are most vexing here.

Over its existence, a system of systems generally touches all of these time scales. Because of this, improved understanding of SOS features and characteristics relevant to the design, planning, integration, and operation time scales is needed. For example, the design of an air transportation system of systems must account for the multiyear time scales required for development of new aircraft, new air traffic control technology, or for the construction of a new runway that will impact the performance of the SOS. This long design time scale must also account for the development of new technology that could upgrade existing assets as frequently as every year. The planning and implementation cycles for an air transportation SOS account for transient seasonal variation in passenger demand and the more steady overall increase in passenger demand over time; the design of the SOS should also reflect this shorter time scale. Weather and unscheduled maintenance events greatly affect the daily (short) operations time scale of the air transportation SOS; similarly, the design of the SOS should consider the ability to respond to short term impacts. Enduring systems of systems other than air transportation will also require methods to design, plan and operate in a manner that provides the desired capabilities at the highest efficiency.

Alternatively, some systems of systems arise in a very rapid manner. Little time is available for planning or design studies to determine optimal or high-performance architectures when assembling an *ad hoc* system of systems in response to a specific, significant trigger event. In the aftermath of a severe weather event, one could envision an ad hoc disaster response system of systems assembled from readily available equipment. The literature in disruption recovery models for airline operations [11–13] is one example along these lines.

III. Taxonomy with Three Characteristic Dimensions

A taxonomy is a means of classifying entities according to their natural relationships. Our contention is that an important use of a taxonomy for a system of systems is to inform designers about which methods are appropriate to assist with decision-making in a system-of-systems context. The taxonomy here uses three characteristic dimensions or axes: 1) types of systems, 2) control of systems, and 3) connectivity of systems.

A. Related Work

Taxonomies for interacting system problems date back many years. For example, Jordan [14] proposed a dimension-based taxonomy of systems in which he identified three dimensions along which systems could be distinguished: rate of change (structural-static vs functional-dynamic), purpose (purposive or not), and connectivity (mechanistic or organismic). Although not a taxonomy, the concept of sociotechnical systems recognizes that system heterogeneity (human-technical systems) is a crucial aspect of modern endeavors. Large-scale sociotechnical systems is a term used in Hughes's system theory [15]. To avoid the lengthy acronym, Nikolik et al. [16] have proposed the term λ systems. "The term indicates a class of systems that span technical artifacts embedded in a social network, by which a large-scale, complex sociotechnical artifact emerges. λ systems include, for example, organizations, companies and institutions that develop around and sustain a particular industrial system, be it a single plant, industrial complex or set of interconnected supply chains."

Krygiel [17] proposed a form of taxonomy around the dimensions of autonomy, heterogeneity, and distribution to delineate a system of systems from a federation of systems, arguing that a federation has a greater degree of these three characteristics, implying more distributed, and less centralized, control. The work of Dennis et al. [18] proposed multidisciplinary design optimization (MDO) formulations of SOS problems based on the degree of control exerted by a central authority: inactive, guiding, mediating, and omnipotent. Dennis et al. postulate that decreasing the activity of the central authority, or increasing the autonomy of the subsystems, would allow larger instances of SOS to be posed and solved in an optimization problem. Essentially, this relates to the control-of-systems dimension in our taxonomy.

Beyond the engineering methods that are familiar in the design of aircraft and similar large, complex, monolithic systems, methods from areas such as operations research, complexity science, artificial intelligence, systems theory, competitive games, etc., can apply to some SOS problems. The application problems presented later in this paper document how the taxonomy describes and guides effective application of some of these to air transportation problems.

While taxonomy organizes features and behaviors as a prerequisite for appropriate modeling, a lexicon that articulates hierarchic structure and organization is needed to properly interpret outcomes of using a taxonomy. Reference [19] provides a proposed lexicon to frame the SOS taxonomy. The lexicon consists of two major structures: categories of systems and levels of organization. Table 1 shows four levels and four categories; however, there can be any number of levels and categories depending on the circumstance. Each category has a hierarchy of levels. To avoid confusion from ambiguous labels (e.g., is this a system, system of systems, or architecture?), the lexicon employs Greek letters to establish the hierarchy; α, β, γ, and δ indicate relative position within each category.

A β-level network comprises a collection of α entities and their connectivity. Likewise, a γ-level network is an organized set of β networks; this continues through the chain of levels. For many applications, there will be orders of magnitude difference between the numbers of α-level systems and β-level systems. This intuits an important point about SOS problems: *the physical manifestation may be most obvious at the α level, but the behavior of the SOS is dominated by the structure and organization at higher levels.* Relevant questions for SOS design might be the following: How does the preferred or observed behavior at the upper levels (e.g., γ level) affect the possibilities for alternatives at the lower levels (α and β)? How can one make design decisions at the lower levels (α and β) to improve a performance metric or meet constraints at the upper levels (γ)? Not coincidentally, the most consequential decisions usually arise at the upper levels. For instance, describing desired capabilities at the γ level can have great consequences on the design space at the α- and β levels, but these consequences are usually not obvious to one making a decision at the γ level.

Employing this lexicon, and with an eye toward understanding methodological needs for engineered SOS, there are three dimensions that serve as a starting point to characterize an SOS problem taxonomy. In a view similar to the spanning issues proposed by Rouse [20], we believe that (at least) three major dimensions of SOS problem characteristics exist. These are 1) type of systems, 2) control of systems, and 3) connectivity of systems. In each of these dimensions, a given SOS problem will have a (qualitative) value or measure. The location of an SOS problem in this three-axis space indicates how the problem might be cast and which method(s) might be best suited for use.

B. Types of Systems

Systems of systems are composed of numerous independent systems. Following Table 1, resources are the physical entities representing independent systems; stakeholders, the nonphysical entities. The design of an SOS requires that analysis methods be appropriate to the type of entities that constitute the system of systems. Some SOS consist predominantly of technological systems: independently operable mechanical (hardware) or computational (software) artifacts. Technological systems have no purposeful intent; i.e., these resources require operation by, programming by, or activation by a human or organization. Other SOS consist predominantly of

Table 1 Lexicon for describing a system of systems

Category	Description
Resources	Entities (systems) that give physical manifestation to the system of systems
Stakeholders/values	Nonphysical entities that give intent to the SOS operation through values
Operations	Application of intent to direct the activity of physical & nonphysical entities
Policies	External forcing functions that impact the operation of physical & nonphysical entities
Level	
α	Base level of entities in each category, further decomposition will not take place.
β	Collections of α-level systems (across categories), organized in a network.
γ	Collections of β-level systems (across categories), organized in a network.
δ	Collections of γ-level systems (across categories), organized in a network.

humans and human enterprise systems: a person or a collection of people with a definitive set of values/skills. While these systems are physical entities, they primarily act as operators of the technological systems, as service providers (both with and without the support of the technological systems), and/or as consumers of services.

Each SOS lies on a spectrum between wholly technological and wholly human enterprise. For example, the Army's initial vision for FCS was a mixture of $18 + 1 + 1$ systems [5]. The 18 systems are technological: stationary sensors, ground vehicles, and air vehicles. The first $+1$ is the network linking the entities and allowing information exchange; this, too, is a technological system. The last $+1$ is the solider: clearly, a human system. A health care SOS largely consists of doctors, nurses, lab technicians, and other health care practitioners, all of whom are humans or human enterprise systems. However, diagnostic equipment and information systems are also included, which are technological. The air transportation system (ATS) SOS embraces large numbers of both types of systems. The aircraft, airports, airways, information systems, etc., constitute the technological systems, while the aircraft designers, air traffic controllers, maintenance technicians, pilots, etc., contribute the human or human enterprise systems.

C. Control of Systems

The second SOS dimension is the degree of control of authorities over the entities or the autonomy granted to the entities. This relates to Maier's [2] discussion of operational independence and managerial independence of systems within an SOS. Emphasizing the importance of control/autonomy, Sage and Cuppan [1] refer to a collection of systems with operational, but limited managerial, independence as a system of systems and a collection of systems with little central authority as a federation of systems. This also follows from Krygiel's classification [17].

Theoretically, the military has a chain of command, and there is a single high-level set of objectives/capabilities/needs described by some high-level decision-maker for an SOS. The constituent systems in a defense SOS have independence (an air vehicle and a ground vehicle in the FCS operate without direct linkage to each other or without requiring explicit instructions for every move), but strategic SOS decisions are made at a high level. Ultimately, someone is responsible for directing the military SOS to provide the capabilities. The DOD system-of-systems engineering guide [21] helps here by identifying four types of SOS based on the degree of centralized management (in order from most to least centrally directed): directed, acknowledged, collaborative, and virtual. Most DOD SOS problems are acknowledged or collaborative. In air transportation, for example, each airline is seeking to make profit by providing air transportation, while following the requirements of safety imposed by regulations and policy; however, one airline cannot directly control or make decisions for another airline. The Internet, however, contrasts with the central authority exhibited by a defense SOS. Information exchange uses a set of protocols that most users agree upon, but no entity enforces adherence to these protocols. Individual computers connect into local area networks that have administrators, but the individual systems that comprise the Internet are very loosely connected, and there is no clear chain of command or central controlling authority. Arguably, this provision of autonomy (or lack of control) allows the Internet to successfully provide the services requested of it. Finally, the ATS application lies between the extremes of the defense and Internet examples. A subset of resources, mostly at the α level, is centrally controlled [an airline controls the operations (scheduling, maintenance, and crew assignment) of the aircraft in its fleet], whereas other systems, typically stakeholders at the β level and above, operate with a high degree of autonomy. Further, and perhaps most important, the intent of these stakeholders vary with time; both as individuals and societies, our motivations and priorities shift, often faster than existing SOS can respond.

D. Connectivity of Systems

The level descriptors in the lexicon of Table 1 highlight the importance of connectivity. Systems involved in a system of systems are interrelated and communicate with other (but likely not all) systems in the SOS. These interrelationships and communication links form a network. Furthermore, development of SOS implies the necessity for understanding programmatic connectivity that results in the development of network of systems as opposed to individual systems. A key focus for design methods research in an SOS context lies in analysis and exploitation of interdependencies (i.e., network topology) in addition to the attributes of systems in isolation [22–24]. Three overarching implications of connectivity are the ability to capture emergent behavior, the potential presence of positive emergent behavior, and the evolution of connectivity. An example of emergence due to connectivity is the reduced total capacity of adjacent airports like John F. Kennedy International Airport (JFK), LaGuardia Airport, and Newark Liberty International Airport; because of airspace intersections between the three airports, their total capacity is less than the sum of their individual capacities [25]. This became evident as air travel demands at these airports increased over time.

First, consequential interrelationships among independent systems lead to emergent behavior (i.e., SOS behavior not predictable from knowledge of constituent systems). The capture of emergent phenomena is an important requirement for design methods. Second, positive emergent behavior allows for robustness (as one independent system becomes incapacitated, another system alters its operations to accommodate). Finally, connectivity characteristics can *change over time*; thus, SOS models must posses evolutionary capability, so that independent systems can be removed, replaced, or upgraded over time. Performance measurement methods must respond, because time-varying (and possibly nonmonotonic) behavior is crucial in making design choices. In large measure, all of the SOS applications discussed in this paper, not just air transportation, exhibit significant connectivity, though perhaps a health care SOS would exemplify a lower level than the others. In the ATS, for example, operations at one airport can have a great impact on the operations at another (whether they are physically proximal or proximal in network connectivity). Flight delays at New York's JFK can hinder operations at Chicago O'Hare International Airport (ORD), because there are many daily flights between them. The March 2010 closure of one of the runways at JFK [26] led airlines like Delta Airlines and JetBlue to reduce the number of departures from JFK, stating that they prefer a four-month closure over the alternative, which was delays in the operations at connecting airports. The proximity of JFK to La Guardia and Newark, on the other hand, may result in capacity that is less than the sum of the capacities of the three airports if they were isolated [26]. Airlines, however, continuously change their network of operations; they create new

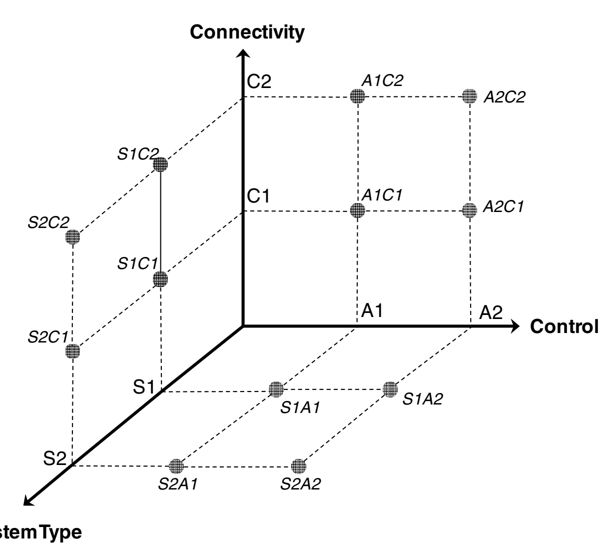


Fig. 1 Initial taxonomy: key dimensions and relative location of important SOS application domains.

routes between some cities or discontinue service between others. SOS models must capture these connectivity characteristics of component systems.

Figure 1 offers a representation of the taxonomy that illuminates variations in system type, control, and connectivity within a system of systems. Subregions in the three spaces can be delineated (as shown) and used to describe and communicate a particular problem type. For instance, a problem at the origin consist of only technical systems that are independent of each other and under centralized control (i.e., not an SOS problem at all). A problem in the S2A2 region consists of mostly human/organizational systems that are independent of each other and decentralized in their control. An A2C2 problem has all technical systems whose interdependence is strong and whose control is distributed. Examples of systems of systems discussed in this paper are located in these three regions. Note that there very well may be coupling and dependency between the axis of the taxonomy, and appropriate modeling must be done to capture it. Additionally, if consideration of multiple SOS contexts is important to the problem at hand (e.g., programmatic and operational contexts), then they must be included and represented in the taxonomy.

IV. Taxonomy Guide Methods

We hypothesize that the location of an SOS problem within the space represented in Fig. 1 indicates which methods are appropriate for analysis and design: determining the appropriate mix of entities, including yet-to-be designed entities, in an SOS to provide a set of desired capabilities within a set of constraints. Subsequently, an assessment can be made concerning whether a) advances are required within a method domain to handle size and complexity of the SOS application, and/or b) advances are required to facilitate/enable interoperability between methods. Important areas of foundational methods include optimization, uncertainty modeling and management, dynamic system representation, decision-making and control, and interaction models.

A. Dynamic System Representation

Constituent systems are dynamic and uncertain to varying degrees. When the majority of systems are technological, differential equations are well suited to represent time-varying behavior or responses, and the most significant sources of uncertainty are operational. When there is significant heterogeneity or when the majority of systems are human-type, alternate methods to represent behavior are in order. For example, where human behavior is present or predominant, a multi-agent modeling approach employing a system of interacting agents is appropriate. Such an approach is commensurate with accepting the fact that the primary source of uncertainty in these systems is the way in which humans make decisions: not always predictable, not always rational, and usually without complete information. The fields or disciplines of control and reliability for technological systems have well established robustness methods. For example, the development of computers or computer components extensively applies reliability-based design and uses fault-tree analysis and reliability block diagrams. The inability to characterize the effects of human decision-making and its interactions with its environment and the inability of most robust/reliability methods to handle variables that alternate between controllable and uncertain limit direct applications of existing algorithms and/or methods.

As mentioned previously, a system of systems itself will evolve over time; this evolution will be more efficient and successful if methods exist to design the SOS over a time span that includes making decisions about when to retire existing assets, when to add new assets, and when to upgrade assets with improved technologies. Dynamic programming allows for a series of decisions; incorporation of the allocation of variable resources described above needs extensions of dynamic programming.

B. Decision-Making and Control

Decision-making and control methods span from centralized (or hierarchical) control in which all constituent systems have a higher authority and cannot act of their own accord, to hybrid schemes in which systems have limited decision-making ability, to a fully distributed approach in which every system contains the logic and authority to choose its own actions. In any of these, optimization plays a crucial role. However, the applicability of a particular optimization type (monolithic vs decomposition, gradient-based vs nongradient, global vs local, or single-objective vs multi-objective) depends on the level of decision-making, control span, and especially upon the degree of autonomy in a majority of systems. For example, decomposition-based methods appear applicable when autonomy and connectivity are low. Alternately, performing optimization for a system-of-systems design problem with a γ-level objective but with a majority of autonomous systems at the α level will likely be overwhelmingly difficult, due to both computational complexity from the large search space size and uncertainty in behaviors with exogenous inputs. Further, such SOS problems are often multi-objective, containing multiple stakeholders with possibly conflicting objectives.

In the γ-level decision problem with multiple α-level entities, optimization can prove useful to predict individual system behavior, which then feeds models for autonomous behavior at the higher levels. The implications of two autonomous systems interacting with each other can be understood via application of methods related to optimization: e.g., competitive games, cellular autonoma, and related methods. In cases of both cooperative and noncooperative situations, the ability to estimate optimal decisions among interacting players is crucial. However, the specification of outcomes may be difficult to accomplish computationally at the α level. Such decision games become more relevant at the β level and above.

C. Interaction Models

The degrees to which interactions between systems are present and are consequential influence the type of modeling required. When the number of systems is low and major effects can be aggregated, analysis of interdependencies as an SOS evolves can use systems of coupled (possibly uncertain) state equations. Applications of System Dynamics have sought to understand global behavior among various sources and sinks in a system of systems. Using causal loop diagrams and stock and flow dynamic models that aggregate behavior to capture key feedback mechanisms, system dynamic approaches attempt to determine policies offering optimal outcomes over time.

However, a single aggregated layer does not often confine all interaction models; i.e., interactions exist between the layers in Table 1. Interactions at higher layers, where an SOS provides capabilities (e.g., γ level), can have a more profound impact than lower level interactions. For instance, the γ-level policy that bans overland supersonic flight impacts β-level operations, which can only use supersonic aircraft on transoceanic flights. This impacts α-level decisions in aircraft design and the travel market. One could argue that a suitably quiet overland supersonic aircraft might be an economically viable enabler of faster air transportation and higher ATS throughput, but the current γ-level policy has prevented little more than research studies in commercial supersonic aircraft.

V. Recent Aircraft/Air Transportation Method Experiments

Two research projects undertaken by the authors provide experiments for the use of the taxonomy and associated methods to address SOS problems. The two projects provide an opportunity to describe how the type, connectivity, and control of systems are taken into consideration and how appropriate methodologies are used. The remainder of this paper presents these efforts, with the results mapped to the taxonomy dimensions in Fig. 1.

A. Simultaneous Resource Allocation with New Aircraft Design

References [27,28] present two experiments to commingle tools from operations research and MDO into a system-of-systems design method. The motivation to look for operations research and MDO tools in these applications follows the preceding discussions of SOS characteristics. The first experiment, concurrent aircraft design and resource allocation with new aircraft design for airline operations, seeks to determine the characteristics of a new aircraft for allocation along with an airline's existing fleet to meet passenger demand (providing transportation is a capability). The problem must consider the use of both new and existing/legacy aircraft along with the implications that this entails.

The second experiment, concurrent aircraft design and resource allocation with new aircraft design for operations of a fractional management company (FMC), also seeks to determine the characteristics of a new aircraft for allocation, but demand is uncertain and is expressed as a probability distribution of trips between city pairs. Further, the fractional operator has the option to hire charter aircraft to complement its fleet capability to satisfy demand. FMCs use this option to cover demand when the owned aircraft are unavailable due to unscheduled maintenance events or when demand is so large that owned assets are insufficient. In fractional operations, aircraft owners purchase shares of business jets starting at shares as small as one-sixteenth from FMCs based on the aircraft type and yearly number of hours the owner perceives to best fit his/her needs. The FMCs manage and operate the aircraft to satisfy the flight/trip requests of the shareowners. A fractional aircraft ownership operation is unlike airline operations in many ways. Airlines decide the flight schedule several months in advance, while FMCs must schedule their aircraft on a few hours' notice. While airlines must decide which routes and frequency of flights on those routes are most profitable, fractional operators must respond to the demanded flights and frequency of its customers. To book a flight, a share owner makes a request, with as little as 4 h notice, to indicate the desired departure time, departure location, destination location and number of passengers traveling with him/her. This makes the FMC allocation problem highly uncertain. Ensuring that all owner requests are satisfied, and doing so while maximizing profits or minimizing costs, is a complex problem of resource allocation and scheduling.

The solution, for both problems, seeks to minimize direct operating costs as a surrogate for maximizing profit (providing the operator with profit is also a capability, or profit could be a measure of the effectiveness for providing the transportation capability). These problems reflect the intent of the airline's and FMC's management. Both problems consider only one β-level entity (the airline or the FMC) that consists of several α-level entities (airplanes, both existing and yet-to-be-designed, and routes).

Solutions to these two problems give insight into the implications of approaching this type of problem as an SOS problem. In the airline example, the mixture of new and legacy aircraft captures the implications of how existing assets along with allocation impact the aircraft design. In the FMC problem, uncertainty of demand and the option to use charter aircraft accounts for the possibility of unexpected behavior (i.e., the charter aircraft are used differently from current practices).

By posing these as a simultaneous allocation and new aircraft design problems, optimizing the β-level metrics (here, minimizing fleet direct operating cost) directly drives decisions about the new α-level entity (here, the design variables describing the new aircraft). While aircraft designers do seek to improve the operators' key metrics, they traditionally do so indirectly, by optimizing an aircraft-specific performance metric that relates to the operator's key metric, rather than optimizing the key metric directly.

1. *Time Scales*

The decision time scales for an SOS include the three components previously mentioned: design, planning, and operations. Time scale is not one of the axes on the taxonomy diagram (Fig. 1), but it might influence the interpretation of the problem and/or the choice of methods.

As posed in [27,28], the combined allocation/aircraft design problems focus upon the longer time scales: predominated by the design and life cycle of the new aircraft. The airline currently operates (and allocates) a fleet of aircraft, and it plans to continue to do so with the addition of the newly designed aircraft; the same is true for the FMC. The problems must therefore consider the use of legacy and new systems along with its implications on the choice of methods, for the airline problem, and the use of charter aircraft and newly designed aircraft under uncertain trip demand for the FMC.

This formulation allows a look at how the new aircraft design problem may be tied directly with an allocation problem. For the airline problem, while fleet allocation is often a planning time-scale activity, the problem formulation does not address features of growing average demand over time. At an even finer time scale, the daily schedule of arrival and departure times represent an operations time scale. With its strategic focus, the airline problem does not consider the operations time scale. For the FMC problem, on the other hand, the problem formulation addresses the variability of demand by expressing the trip demand as a random selection of city pairs. While not directly including the operations time scale and growth in average demand, the FMC problem captures variations in demand and the implications that this has on the planning time scale. Decisions regarding the characteristics of a new aircraft must consider that demand is uncertain and that solution to the allocation problem must ensure that all demanded trips are served, with the yet-to-be-designed aircraft and/or charter aircraft.

2. *System Type*

In the airline problem, the airline can use up to seven existing aircraft types as well as the yet-to-be designed aircraft, and it must provide service on 31 different city pairs, or routes. To provide service, aircraft and routes are not sufficient. The airline must engage in planning to coordinate the operations of its aircraft on the available routes. Operations (the plan by which the airline allocates aircraft to routes, schedules aircraft departures, and schedules aircraft maintenance) is a highly technological system. This represents the aircraft and crew scheduling, revenue management, etc., arm of the airline. With the strategic focus of this problem, this is abstracted here to be just the allocation problem; along with the aircraft and routes, it represents the technological systems of this SOS.

The FMC problem formulation is somewhat different. The FMC must decide the number of yet-to-be-designed aircraft that it will own and the number of charter aircraft that it will use to satisfy demand between uncertain city pairs. As with the airline problem, the allocation problem, the aircraft, and city pairs represent the technological systems of the SOS.

In the airline problem, by treating the passenger demand on predetermined routes as static, the passengers do not have a direct impact on the airline. This is an assumption, because passenger demand does fluctuate, but with this assumption, the airline SOS consists solely of technological systems. In the FMC problem, however, trip demand is uncertain. The city pairs (and therefore the trip distances) are randomly distributed. Therefore, the FMC problem also includes human systems that introduce uncertainty to the planning process. While increasing the complexity of the allocation problem, this aspect makes possible observation of unexpected outcomes that result from the uncertain nature of demand.

3. *Control*

The problems view the airline and the FMC as the sole top-level entities. Because of this, centralized control exists; the airline's management can make decisions about which aircraft types and how many of each type to assign to each route and the FMC's management can decide how many aircraft to own, how many charter flights to use, and how these aircraft will fly the demanded trips. Centralized control implies that the management has objectives that it wishes to minimize or maximize. There may be many objectives, but the location of the airline and FMC SOS on the control axis implies that optimization is applicable to formulate the problems (as opposed to when only satisfaction or equilibrium are applicable when there is high autonomy).

4. Connectivity

While the airline is not establishing new routes and the existing route structure is fixed, the FMC faces different routes each day. For the airline, this means that there is little coupling between the routes and the individual aircraft; aircraft must have sufficient range to be assigned to a given route. Coupling does exist, however, between the passenger capacity of the new aircraft and the allocation problem. Passenger capacity of the aircraft is a variable in the aircraft design problem and is influenced by the allocation problem, which assigns aircraft to routes based on their cost as well as passenger capacity. Furthermore, between various aircraft, the only coupling is that the total capacity deployed on a given route meets or exceeds demand; e.g., if one aircraft does not provide sufficient capacity, a second aircraft is needed on the same route.

For the FMC, on the other hand, coupling is stronger. Uncertainty in demand means that the lengths of demanded trips greatly impact aircraft design: namely, design range. The distance between any two city pairs will dictate the design range of the aircraft, for example, or force the FMC to use charter aircraft with longer design range. Because the FMC uses only one type of aircraft, the coupling between aircraft is that the design range of the newly designed aircraft and the range of charter aircraft must be large enough to ensure that all demanded trips can be served.

In both problems, however, the operator does not have the option to turn down demand; it must serve all passenger demand. While airlines turn down demand through overbooking, this generally ensures high load factors and does not drive the selection of which aircraft type to use on a given route, nor does it keep the airline from providing service on the route. Hence, while the allocation problem serves as an evaluator of a given aircraft, the aircraft characteristics cannot, in themselves, influence demand. This limited (unidirectional) connectivity between the constituent α-level systems and its basis on the flow of information (i.e., the aircraft design problem needs to know the length of the longest route, and the allocation problem needs to know the aircraft passenger capacity for the airline problem and the design range and velocity of the aircraft for the FMC problem) implies that a decomposition strategy may be employed.

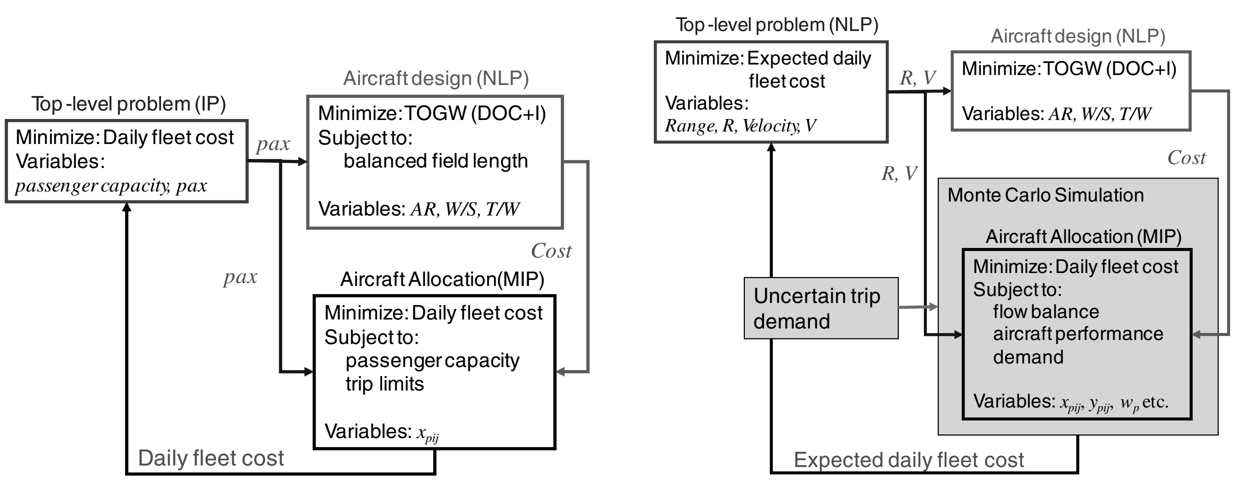
5. Problem Solution Strategy

Given that an optimization approach seems applicable for the concurrent aircraft design and aircraft allocation problems, and the nature of the connectivity, [27,28] pose these as mixed-integer nonlinear programming (MINLP) problems. The optimization seeks to minimize the expected daily operating cost of the FMC while determining the optimal aircraft design (e.g., design requirements and aircraft characteristics) and the optimal operations (e.g., aircraft assignment to routes and number of aircraft to be owned and operated). However, the size of the MINLP problems is such that solving all but the most simplistic versions is impractical. Because connections between the constituent systems are few, a decomposition approach allows solution to these problems. For the airline problem, the aircraft design and aircraft allocation problems are solved as a nonlinear programming (NLP) problem and an integer programming (IP) problem, respectively, (Fig. 2a); the results are used as function evaluations in a much smaller top-level IP problem (IP because passenger capacity is the integer variable). A similar approach solves the FMC aircraft design and aircraft allocation problem. However, because demand is uncertain and is expressed as a distribution, a Monte Carlo simulation is performed for every function evaluation of the top-level NLP problem. The top-level problem is an NLP problem, because the multidisciplinary design variables are continuous variables for the FMC problem: namely, aircraft design range and cruise velocity (Fig. 2b).

In one example application for the airline problem, using a 31-route structure and an existing aircraft fleet consisting of seven different aircraft types, the optimization strategy via decomposition resulted in a new aircraft design and its allocation along with existing aircraft that reduced the airline's daily operating costs by nearly 13%. The new aircraft had a capacity of 250 passengers, AR of 9.5, W/S of 135 lb/ft^2, and T/W of 0.31.

Similarly, in an example application of the FMC problem, serving demand between 10 (uniformly) randomly selected cities, the optimization resulted in the design of a new aircraft that, when allocated in concert with charter aircraft, reduced the daily expected cost of operations by nearly 1% with respect to operating an existing aircraft on the routes and using charter aircraft. The new aircraft had a design range of 1549 n mile, a cruise velocity of 438 kt, AR of 7.51, W/S of 44.8 lb/ft^2, and T/W of 0.464. The design range of the new aircraft was shorter than the longest demand trip (1600 n mile). As a result, the newly designed aircraft would not be able to serve all demanded trips, but the FMC must rely on charter aircraft that have longer range to satisfy all demand.

FMCs currently use charter aircraft on a regular basis, generally because owned aircraft are unavailable or because a spike occurs in the daily demand; this is the only way to satisfy demand, so the lowest cost solution includes these aircraft. Here, allowing charter aircraft in the problem formulation leads to a result that suggests a change in operations, where the FMC plans for the use of charter aircraft on the long, but infrequent, trips and uses the owned aircraft for the shorter, more frequent trips. The taxonomy guided an optimization problem formulation, and the formulation tried to not dictate β-level decisions (e.g., ensure that the new aircraft must fly all possible routes and only use charter aircraft to address unavailability or abnormally high demand). While not exactly emergent behavior,



a) Airline problem decomposition **b) FMC problem decomposition**

Fig. 2 Decomposition strategy in airline and FMC application problems.

this is an unexpected result that points to the ability of this problem formulation as an SOS to capture potential emergent behavior and changes in the component systems of the SOS because of design decisions of other, interdependent, systems.

The decomposition approach to allocate a yet-to-be-designed resource is not limited to the airline or FMC application. An analog may be seen in a production line application in which a company (one β-level entity) is seeking to design new workstation tooling to improve not only the performance of the workstation but that of the entire manufacturing plant. If the role of humans in the plant is largely supervision of automated tooling, the SOS here is mostly technological systems. With one β-level entity, the manufacturing plant's management exerts centralized control, and the problem may be posed as an optimization problem. With fixed production demand, the new workstation or tool is loosely connected to other tools, and decomposition may be possible. A method using a small top-level problem to coordinate the decomposed tool design and job allocation problems may have promise, because this application shares many features of the airline problem.

B. Transformational Modeling of Air Transportation

Reference [29] presents a second air transportation design study that was guided via the lexicon and taxonomy. This problem concerns a means to assist decision-makers attempting to transform the ATS to a state that can satisfy growing demand with greater levels of efficiency. The methodology objectives of this problem are to generate a design solution space at a higher level of aggregation than the previous problem and to consider two distinct time scales. Further, as indicated from the lexicon (Table 1), an SOS approach for ATS considers not only the technical aspects, but it also incorporates policy, socioeconomic, and alternative transportation system considerations into one framework.

Because such an objective is overwhelmingly complex if pursued at the lowest levels of detail, a system of system modeling approach is necessary in order to model alternative air transportation architectures at appropriate levels of abstraction in a hierarchy. For problems focused on higher levels in the hierarchy, the individual systems models are basic enough to enable the higher level analysis to identify good solutions (e.g., simple airport models used to determine the best network topology, configuration of nodes and links). The final product of such an analysis is a concept consisting of a set of rules of behavior and network structure that satisfies the transportation goals. Further, the high impact rules (policies) that accomplish those goals are identified by allowing agents in the system to do the *right thing* naturally.

1. *System Types*

The problem combines human/organizational and technological systems with high degrees of connectivity and autonomy. The primary organizations modeled are an aggregate airline and an infrastructure/air navigation service provider. As with the first problem presented in this paper, the passengers are not modeled explicitly, but implicitly through the infrastructure provider's desire to minimize saturation in the network. These features place it in the most challenging region of the taxonomic space in Fig. 1.

2. *Time Scales*

As currently posed, the problem involves time scales that are between the *Design time scale* and the *Planning time scale*. For this problem, a conceptual transportation model encompassing all four entity categories, ranging from the α- to γ levels, enables the generation, study, and analysis of alternative futures for the ATS. Included are models of the resources and the economic and regulatory drivers (via actions of stakeholders agents) that comprise the ATS, placing it near the middle of the system-type axis. In particular, each layer or network topology is unique in its makeup and time scale (Table 2). For example, the *operator network* has its nodes as aircraft and crew and links as flight missions, over smaller time scales than the other layers. How these network topologies actually interact, evolve and respond under disruption are focal questions in an SOS study. Prospects for a purely analytical solution to a system-of-systems problem of this magnitude are dim at best. A simulation-based approach using a variety of methods, including agent-based modeling, presents a better opportunity to obtain a solution.

Stakeholder agents at the γ level making choices based on simple rules of self-interest determine the evolution of a transport network. In general, these include such choices as adding capacity at airport nodes and route network growth and reconfiguration (e.g., spreading demand more evenly via point-to-point travel instead of hub-and-spoke). In the current study, we implemented only two stakeholder agent classes: service providers (airlines) and infrastructure providers (the FAA and airports).

3. *Control*

The control exhibited by the service and infrastructure providers (encapsulated in the operations, economic, and policy dimensions) must be addressed. To achieve this, it is necessary to employ modeling methods that reflect the competition and cooperation driving the stakeholder behavior and determine the implications of their interactions and manipulation of resources within the SOS. This represents a departure point from current design theory where the emphasis often lies only on representing the preferences of a user/operator, rather than including actual behaviors. SOS analysis must incorporate human preference and behavior patterns explicitly inside the problem boundary along with the yet-to-be-designed systems.

Agent-based modeling (ABM) has emerged as an approach of choice in this setting. ABM employs a collection of autonomous decision-making entities called agents imbued with simple rules of behavior that direct their interaction with each other and their environment. Agent functionality is quite flexible, with behavior types ranging from simply reactive (change state or take action based on fixed rules) to learning/adaptive (change state or take action after updating internal logic schema via learning). If a given environment has multiple, diverse agent types, it is described as a multi-agent simulation (MAS). However, it is good modeling practice to limit the complexity of a MAS to only that required to answer specific questions; as modeling complexity increases, so too does the effort of verification and validation.

Employing ABM for SOS problems in which distinct decision-making entities exert control has a challenge: how to validate that the agent models properly reflect real human/organizational behavior. This is a critical question aimed at the trustworthiness of simulation results. The literature on this subject within the ABM domain is growing [31–34]. The most common approach uses as much historical data as possible to validate the individual agent behavior models and to then trust that the emergent behavior from agent interactions will be realistic. In this air transportation example, calibration of the agent behavior rules relied upon historical airline

Table 2 Networks in the ATS (adapted from [30])

Network	Node	Link	Time scale of change
Demand	Homes/businesses	Demand for trips	Months/years
Mobility	Origin/destination locations	Actual passenger trips	Days/weeks
Transport	Airports	Service routes	Days/weeks
Operator	Aircraft, crew	Missions	Hours/days
Infrastructure	Waypoints and airports	Air routes	Months/years

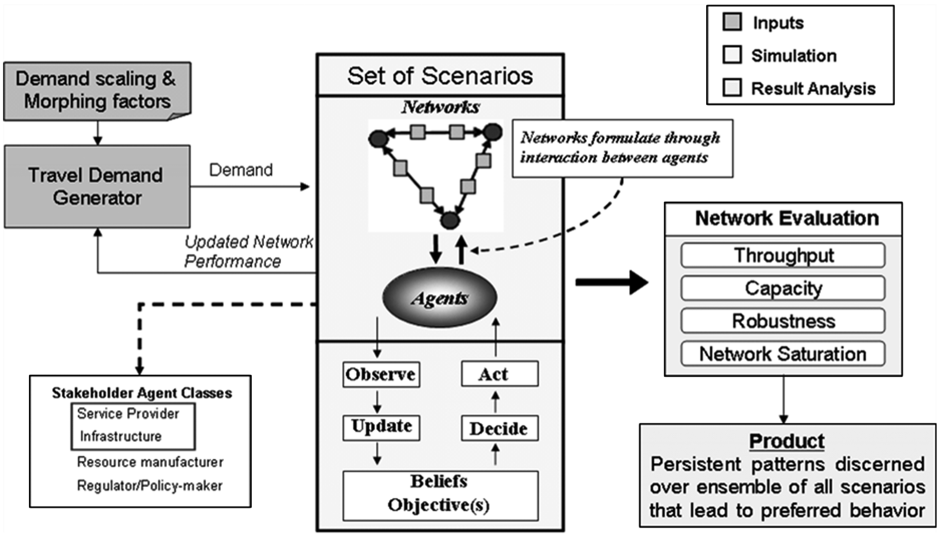


Fig. 3 Simulation environment for example problem.

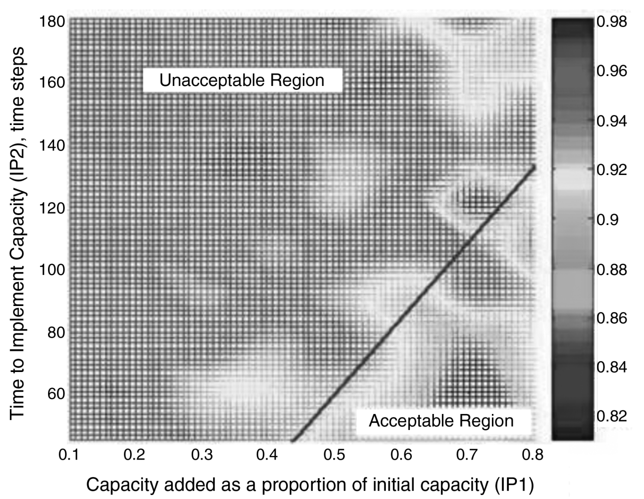


Fig. 4 Simulation results: average nodal network saturation under infrastructure provider behaviors (from [29]).

route selection data and the ability to increase airport and airspace capacity. The particulars of this calibration appear in [29]. Taken together, model validation for SOS problems that have especially high degrees of human/organizational behavior components must make best use of state of the art methods. Further, rather than a predictive mentality, the outcomes of ABM-type models should be exploratory in nature, seeking to understand distinct regimes of likely behavior, rather than identifying locally specific solutions with high predictive accuracy.

4. Connectivity

The connectivity aspect enters when examining how agents configure the transportation nodes (e.g., airports) and links (e.g., routes and aircraft). Among other approaches, the connectivity generated by interacting agents can be compared with preferred network topologies (determined via network theory methods) that display desirable traits such as scalability and robustness. Such an approach can determine the possible rules of behavior that lead naturally to desired performance of the ATS. Network science examines connectivity (links) between the entities (nodes) in a topology through various statistical properties. For instance, the degree of a node is the sum of all links associated with a node, and the degree distribution represents the topology of a network. Further, average shortest path reflects the efficiency of propagating information across the network, whereas average clustering coefficient measures a network's cohesiveness. These properties (and others) are highly relevant to understanding the robustness, vulnerability, and overall efficiency of the network of systems. A study of the properties of the networks can help determine preferred patterns of the connectivity in an SOS. The long-term intent is to build upon this knowledge base to create new integrated network topological measures and apply them as design objectives to manage and improve the performance of the SOS.

5. Problem Solution Strategy

The combination of agent-based modeling and network theory provides the core of the air transportation SOS simulation. The method constitutes a nondeterministic approach, which means that it fundamentally asks and answers different questions than deterministic models. The nondeterministic method is necessary primarily due to the marriage of human systems with technological ones in a partially unknown set of future worlds. The goal is to simulate how the SOS, human, and technological components combined, evolve. Observing these simulations allows understanding of this process. The simulation makes significant use of actual data from today's transportation system obtained from the Bureau of Transportation Statistics. Once initialized, a validation exercise confirmed that the simulation could represent the reality of today's system, within the bounds on fidelity.

Table 3 Summary of SOS experiments

Problem feature	Airline and FMC resource allocation	ATS network evolution simulation
Time scale	Long, static	Long, dynamic
System type	Technological and limited humans	Technological and human
Representation methods	Differential equations and Monte Carlo simulation	Differential equations and multi-agent simulation
Control/autonomy	Centralized	Mostly distributed
Decision-making methods	Optimization	Agent satisfaction
Connectivity	Low	High
Interrelation modeling methods	Decomposition	Network models

The overall framework for the integrated simulation is as follows: stakeholder agents (e.g., service providers, infrastructure providers) act to evolve an initialized air transportation capacity network under various scenarios (Fig. 3). Each agent employs its logic to guide its decisions and actions. In subsequent time steps, the agent sees consequences from the environment and updates its behaviors. As this process unfolds, the magnitude and shape of the mobility network (demand) also changes, and the actions of agents must respond by manipulating the capacity network topology. Thus, a family of new network topologies is created over time, and their structure and network-theoretic analysis tracks their behavior. The key question is as follows: Do the evolved networks exhibit good performance in terms of capacity? To address this question, a network evaluator compares the evolved networks to topologies that do exhibit preferred behaviors. Using this method, the evaluator can function as the search direction generator for a design/optimization problem.

An example outcome from this simulation approach, presented in [29], appears in Fig. 4. This result indicates the average saturation of airport nodes in the network as both the amount of nodal capacity (x axis) and time needed to implement nodal capacity increase (y axis) are varied. For this study, the intent was to provide a visualization of the decision space so that a decision-maker(s) can consider options given the boundaries of behavior change. Selecting a singular optimum from this decision-space analysis was not intended here. If subsequently desired, the behavioral rules, connectivity structure, and engineered system capability can act as design variables to explore the generation of preferred outcomes over an ensemble of plausible scenarios. This particular result from the ABM showed that a distinct regime of desired behavior emerged from the interactions between the airline agents growing and restructuring their routes and the varying capability of the infrastructure agent to keep up via capacity addition.

VI. Broader Insights for Additional Experimentation

The SOS-relevant problems described above are only two types of air transportation-related examples. They help illustrate how considering the proposed three-axis taxonomy and time scales can inform a decision-maker about which tools and methods are appropriate for SOS problems. Table 3 attempts to summarize how considering the taxonomy influenced the tools and methods employed in the example problems.

The example studies actually took place at the same time as our understanding and articulation of the taxonomy was evolving. Thus, it is hard to unravel the degree to which the taxonomy drove the methods and the methods crystallized the taxonomy. Modeling is always an iterative process in which scope and technique are continuously evaluated in light of objectives. In retrospect, having the taxonomy in place before beginning these two problems would have shortened the iteration time by synthesizing the essence of the key modeling challenges and identification of analysis techniques in relevant regions of the SOS problem space. Additional experiments using the taxonomy are needed, preferably by a diverse set of research groups tackling a wider variety of problems. Insights from the two experiments in this paper could assist these additional studies.

System type is perhaps the strongest driver influencing model/method selection for design. The chasm between models for physics-based systems and human/organizational systems is large. As highlighted earlier in the paper, design methods for engineered systems have typically reduced customer/operator/stakeholder concerns to preference functions used in objective or constraint formulations. The degree to which this is acceptable depends, in part, on the time scales and connectivity. How important are human/organizational decisions on changing the *structure* of the SOS in a given time scale of analysis?

The control strategy is typically apparent in a particular SOS. Thus, the modeling approach is also straightforward. In the resource allocation problems, a centralized control over the aircraft allowed for decomposition of the problem to two levels, improving the ability to solve the problem in modest time and computational effort. In the ATS network evolution problem, distributed airline agents clearly were at play and thus distributing control to agents via a MAS model was appropriate. However, some problems may have as their objective the determination/decision of whether a switch between centralized control and distributed control should take place. This would require a more complicated, comprehensive model and simulation, as well as modified design problem formulation.

VII. Conclusions

System-of-systems problems present new challenges to system engineering. Important problems of this type exist in the aerospace domain; transformation of the air transportation system is certainly one of them. The challenge addressed in this paper is the need for rigorous, repeatable engineering design methods that are appropriate for analysis of alternatives at different levels in an air transportation system-of-systems context. A taxonomy consisting of three dimensions (system type, control, and connectivity) was presented and its use demonstrated. The demonstrations showed that SE complexities that result from a system of systems that incorporates multiple, often physically separate, systems that are capable of independent operations can be addressed. Although the examples explored here have civil applications, SOS problems in the military domain provided the original motivating stimulus for the taxonomy and thus clearly require attention as well (as indicated by the change in approach in the IDS and the cancellation of the FCS). A better understanding of the control dimension in the case of the IDS, for example, could have avoided the cost overruns caused by the failure of the LSIs and the restructuring of the acquisition approach.

In the examples presented here, modeling of the resource allocation problems as a system of systems suggested operating strategies that were not otherwise observable. For the FMC operations, the result was an aircraft design that directly impacted costs related to the FMC's operations and the identification of operational changes to take advantage of the new aircraft characteristics. Implementing this approach resulted in an aircraft with a shorter range and slightly higher cruise speed than a baseline business jet, and the allocation used charter flights in a manner different from how FMCs currently use charter aircraft. This is a nonintuitive result because business aircraft are typically designed to provide maximum performance, and that performance usually includes a large design range. In the second example, the combination of agent-based modeling and network theory provided an appropriate means to model an SOS problem that exhibited strong network evolution features driven by independent entities. The method constitutes a nondeterministic approach, answering different questions from those of a deterministic model in an attempt to bound the likely trajectories of the evolution. Distinct regimes of desired behavior emerged from the interactions between the airline agents growing and restructuring their routes and the varying capability of the infrastructure provider.

A comprehensive set of methods for design in a system-of-systems context does not yet exist, and improving decision-making for SOS problems requires development of more methods and/or combining various existing methods. The taxonomy for system-of-systems problems presented here, however, should help guide design method development and use and facilitate system integration and analysis of alternatives. The taxonomy emphasizes dimensions of system type, control, and connectivity; time scales also play an important role in identifying decision-making methods. Patterns that may emerge across diverse SOS application domains will allow for identification, combination and enhancement of tools and methods that have previously been associated with one domain.

The example problems/experiments highlight the fact that, for system-of-systems problems, there are likely to be multiple design or decision-making problems embedded under an umbrella problem, e.g., transportation or health care. The ongoing challenge will be to employ design and analysis methods that treat these subproblems within the holistic understanding of the upper levels of organization. For example, in the airline resource allocation problems the solution algorithms are well suited to provide the basis for service-provider agent models in the larger air transportation SOS problem. This interweaving of multiple methods, guided by the proposed taxonomy here, appears to have great potential to assist in the design and analysis of systems of systems.

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