Exploring the Synergy Between Industrial Ecology and System of Systems to Understand Complexity

A Case Study in Air Transportation

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Summary

Two objectives are pursued in this article. First, from a methodological perspective, we explore the relationships among the constructs of complex adaptive systems, systems of systems, and industrial ecology. Through examination of central traits of each, we find that industrial ecology and system of systems present complementary frameworks for posing systemic problems in the context of sociotechnical applications. Furthermore, we contend that complexity science (the basis for the study of complex adaptive systems) provides a natural and necessary foundation and set of tools to analyze mechanisms such as evolution, emergence, and regulation in these applications. The second objective of the article is to illustrate the use of two tools from complexity sciences to address a network transition problem in air transportation framed from the system-of-systems viewpoint and shaped by an industrial ecology perspective. A stochastic simulation consisting of network theory analysis combined with agent-based modeling to study the evolution of an air transport network is presented. Patterns in agent behavior that lead to preferred outcomes across two scenarios are observed, and the implications of these results for decision makers are described. Furthermore, we highlight the necessity for future efforts to combine the merits of both system of systems and industrial ecology in tackling the issues of complexity in such large-scale, sociotechnical problems.

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Introduction

Objective of this Article

Two primary objectives are pursued in this article. First, from a methodological perspective, we explore the relationships among the constructs of complex adaptive systems (CAS), systems of systems (SoS), and industrial ecology (IE). Although each carries distinctive perspectives and emerged from different histories, we find synergies and common themes when we focus at the application level, especially for treatment of large-scale, sociotechnical systems. Elements of these streams of inquiry are already being used to conduct systems analysis of challenging sociotechnical systems (Sverdrup and Svensson 2004; Ottens et al. 2005; Nikolic et al. 2007; Agusdinata 2008), with specific instances focused on air transportation (Lacroix 2001), an application expanded in this article. A primary difficulty that persists is how to deal with the complexity prevalent in such problems. Collections of heterogeneous, interacting systems driven by both complementary and competing objectives generate mechanisms that require increasing information to be described sufficiently for management. Therefore, we contend that complexity science (the basis for the study of CAS) provides a natural and necessary foundation and set of tools to analyze these mechanisms. In turn, IE and SoS present complementary frameworks for posing system analysis problems in this context. In particular, IE brings to the fore the notion of sustainability based on the ecosystem metaphor in a way that SoS has not. Conversely, SoS brings an emphasis on analyzing the underlying connectivity from interactions.

Illustrating the full complementarity among CAS, IE, and SoS is well beyond the scope of a single article (or even volume). Thus, our second primary objective in this article is narrower: to illustrate the use of two tools from complexity sciences to address a transition problem in an air transportation system (ATS) framed from the SoS viewpoint and shaped by IE to generate insight for decision makers. Donohue (2003) aptly describes the ATS as a complex adaptive system, and we have further characterized it as an SoS (DeLaurentis 2005). The distinguishing attributes that motivate the latter designation are highlighted, and their importance is explained. Along the way, we summarize evidence that supports the important juncture at which air transportation finds itself: A transition is needed to support increasing demand as physical capacity is constrained, yet it is unclear which particular strategies meet this objective in a sustainable manner. In generating sustainable transition strategies, we see the greatest impact of framing tools and approaches from IE, especially given that a CAS approach with a sustainability emphasis has been missing in large measure in this application domain. The computational model and simulation results presented here emphasize the use of complexity tools to treat some SoS traits and, although not nearly in a complete manner, expose some ways the IE perspective can more completely expand the model and shape system analysis.

Methodological Comparisons

Characterization of a Generic SoS

SoS problems often present distinctive traits, as shown in table 1. The first four are known as Maier's (1998) criteria. The first two (operational and managerial independence and geographic distribution) address problem boundaries and the mechanics of interacting elements, whereas the latter two (evolutionary behavior and emergent behavior) describe holistic behavior. Among these criteria, emergent behavior presents a particular challenge to both our intuition and our models because it is unpredictable and can manifest itself in a positive manner (e.g., a new capability arises) or a negative manner (e.g., a new failure mode is created). Dealing with emergent behavior by developing cues to detect it and crafting means to manage it intelligently remains a major challenge. The last three traits in table 1, introduced by us, have direct implications on modeling. In particular, we examine networks and heterogeneity further in the proof-of-concept application.

Although the term *SoS* and its intellectual underpinnings have a long history (see, especially, the work by Boulding [1956]), the increased attention it has received recently has been driven largely by a radical shift in some

Table 1 Distinguishing and important traits of system of systems (SoS) problems

Trait	*Description*
Operational and managerial independence	Constituent systems are useful in their own right; they can and do operate independently of other systems, managed by their owner or operator.
Geographic distribution	Constituent systems are not physically co-located, but they can communicate.
Evolutionary behavior	The SoS is never completely, finally formed; it constantly changes and has a "porous" problem boundary.
Emergent behavior	Properties appear in the SoS that are not apparent (or predicted) from examination of the constituent systems.
Networks[a]	Networks define the connectivity between independent systems in the SoS through rules of interaction.
Heterogeneity[a]	Constituent systems are of significantly different nature, with different elementary dynamics that operate on different time scales.
Transdomain[a]	(Proposition) Effective SoS study requires unifying knowledge across fields of study: engineering ∪ economics ∪ policy study ∪ operations management.

[a]We have identified these traits as important beyond the traits listed by Maier (1998) and sources cited in that work.

governments' procurement approach. Whereas government customers once issued detailed requirements for a monolithic system (e.g., an aircraft must survey a prescribed area in a specific time frame), they now ask, instead, for a broad set of capabilities that persist over a significant time span (e.g., ability to continuously detect and track air and ground movements). The SoS concept as applied to the aforementioned set of streams, dealing with more large-scale, sociotechnical problems in civil settings, is newer (e.g., Agusdinata 2008). But this ability to think beyond the "system," toward connected systems, to find superior problem solutions complicates the communication of problem boundaries, features, and so on, because an SoS involves multiple, heterogeneous actors with differing objectives. Our research experiences have thus pointed to the need for a common language in framing SoS problems.

For SoS, two structural features are prominent: hierarchical layered structure of networks, and enhanced scope, including categories such as economics, state or national policies and regulations, societal impacts, and so on. Researchers have made a number of advances to capture these features of SoS, and in this article we highlight a lexicon and taxonomy.

The lexicon (figure 1) was developed to aid the relative hierarchical "positions" of the different components according to their function and role in affecting a solution (DeLaurentis and Callaway 2004). The vertical "levels" are an abstraction of control among the network of

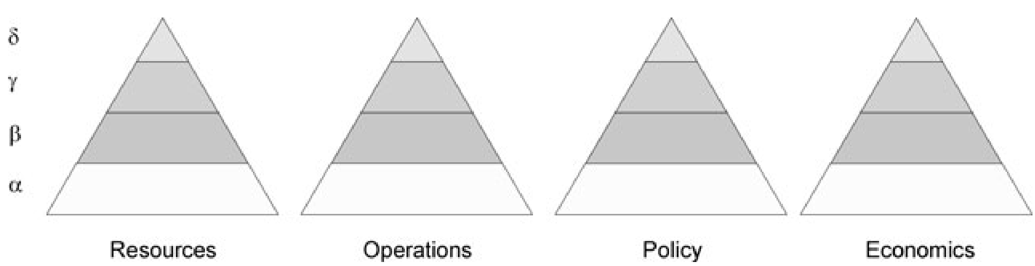

Figure 1 Lexicon: System of systems scope categories and hierarchal levels.

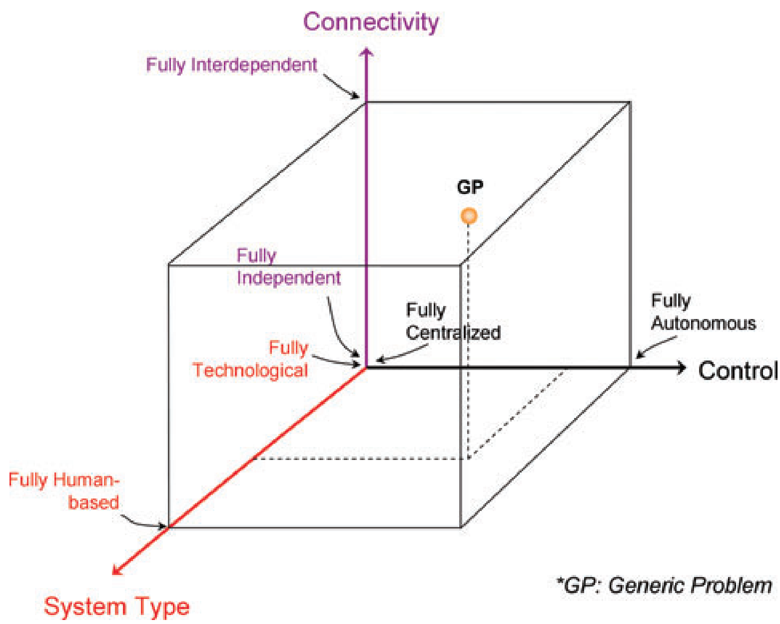

Figure 2 System of systems problem taxonomy.

components, starting from the lowest at alpha level (basic, most individual systems) and going all the way up to delta or higher, as the case may be; components at each level form part of the next level in a given category. The horizontal "scope categories" provide a basis for defining the scope of a component's role. Such categorization also brings forth couplings and interactions that take place between and across different levels in the SoS. A formal use of this lexicon to describe air transportation is available from DeLaurentis (2005).

An SoS problem need not satisfy all of Maier's (1998) criteria (see table 1). Furthermore, the extent to which a criterion is satisfied with regard to component heterogeneity, connectivity, and control or autonomy can vary. The taxonomy (see figure 2) was developed to appropriately characterize an SoS problem via its "location" in a three-axis space so that researchers could select the best suited modeling and analysis methods (DeLaurentis and Crossley 2005). For example, the U.S. Army's Future Combat Systems (FCS; U.S. Army 2008) is an SoS characterized by a high degree of connectivity, mostly centralized control, and high component heterogeneity. Hence, it would lie closer to the origin on the control axis but high on the connectivity axis when compared to a national ATS, which has far more autonomy and (at present) lower connectivity. Therefore, methods exploring the influence of stakeholder independence on system behavior are necessary for a study of the ATS, whereas tools such as systems dynamics are more appropriate for the more centralized control of FCS. Other researchers have pursued such a tack for the more general class of complex systems (Magee and de Weck 2004). Because problem behavior directly depends on its makeup, the taxonomy and lexicon can pinpoint the problem structure and guide selection of the solution method. Furthermore, the nature of an SoS may change with time (Sage and Cuppan 2001), and this is also a source of complexity, a topic we turn to next.

Sources of Complexity in an SoS

From problem characterization via lexicon and taxonomy, we focus next on the multiple sources of complexity in an SoS. The simple illustration in figure 3 shows alpha-level entities (α_1, α_2, α_3, α_4 and α_5) interacting with one another within a beta-level (β_i) across time (t_1, t_2 and t_3). These can, for example, denote fleet

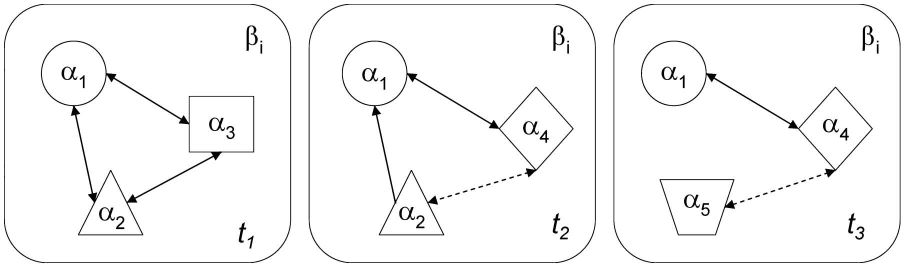

Figure 3 Dynamics underlying distinctive sources of complexity in a system of systems.

of aircraft (alpha-level) operated by an airline (beta-level). Note the change in composition of and connection in β_i with time (t). If some dynamic interactions are unknown or unexpected by participants, large uncertainties and emergent behaviors at the beta level develop, which makes it difficult to devise a solution. Complexity (the amount of information to describe regularities at a given scale; Gell-Mann 1995; Bar-Yam 1997) in the SoS can arise from various sources, such as

1. dynamic and uncertain connectivity
   a. between the levels of abstraction and across the scope categories (see figure 1)
   b. multiple time scales of operation and existence of components (see figure 3)
   c. unforeseen and unexpected interdependencies among components (emergence)
2. "porous" boundaries—changes in constitution of the SoS and the evolving nature of an "open system" (see figure 3)
3. heterogeneity of participants within and between human and technical systems and their impact on not only the problem but also the other SoS and the society in general (sociotechnical systems)
4. multiplicity of perspectives among participants.

The efficacy of a particular solution in complex systems is strongly tied to its ability to "accommodate" emergence (both good and bad). From the decision maker's perspective, the awareness of possible good and bad emergent outcomes over time generates valuable insight that may enable more robust and reliable solutions.

Relation of SoS to IE and Complexity Science

To relate SoS to IE, we first state that an SoS is a special kind of complex system consisting of multiple, heterogeneous, distributed systems embedded in hierarchical networks whose interactions evolve over time. These participating systems *can* and *do* operate independently in the course of their functioning. Heterogeneity implies participation of engineered and human—organizational systems, a clear resonance with the sociotechnical system concept. Our reason for being explicit about the nature of SoS problems and the sources of complexities is practical: We wish to (1) frame and formulate systems analysis problems in such a way that decision making in the SoS context is efficacious and (2) develop methods and tools that are appropriate for addressing the underlying complexities.

We can summarize that IE seeks to (1) understand how the industrial system works, how it is regulated, and the nature of its external interactions and, (2) by understanding the functioning of natural ecosystems, determine a restructuring that enables the industrial system to grow and behave like a natural ecosystem in correspondence with its environment (Erkman 1997; Lifset 1997; Allenby 1999; Van den Bergh and Janssen 2005). These two objectives attempt to frame and formulate an appropriate decision-problem.

SoS and IE are complementary in that they share the same general purpose of framing and formulating a problem, but they also bring unique emphases. The congruence between IE and SoS and the potential contributions that SoS can bring to the IE domain are shown in table 2. Although the list in table 2 is not exhaustive, we hypothesize that treatment of many systemic

Table 2 Congruence between industrial ecology (IE) and system of systems (SoS)

No.	*Central concepts of IE*	*Congruent concepts in SoS*	*Potential contributions of SoS and complexity science tools to IE*
1	Sustainability based on an ecosystem metaphor	Not explicitly treated	
2	Tracking of local, regional, and global flows of material and energy (Lifset 1997; Esty and Porter 1998; Schmidt 2008)	Networks of connections and interactions within and across different levels (lexicon)	Analysis of weights on links and nodal properties to understand flow of mass, energy, or information in the system
3	Product life cycle assessment (Van den Bergh and Janssen 2005; Lloyd and Ries 2006)	Scope categories Heterogeneity of SoS components	Analysis of economic and policy aspects that shape the evolution of a system's behavior and nature of interactions
4	Scales of industrial activity and their impact on natural systems (Allenby 1999; Van den Bergh and Janssen 2005)	Transdomain nature of SoS Managerial and operational independence of components Multiplicity of perspectives	Scalability studies of networks Simulation studies of agent actions and their impact on system behavior Conflicting objectives of stakeholders lead to compromises
5	Systems approach with adjustable boundaries (Allenby 1997; Van den Bergh and Janssen 2005) Understand and employ regulation in artificial systems Emergence	"Porous boundaries" Dynamic connectivity Lexicon and "taxonomy" to understand SoS construction Evolutionary and emergent behavior	Network theory tools to study connectivity and interactions between and across levels govern system performance and validate the assumptions of higher levels Analysis of system evolution via agent-based models and simulation

problems can benefit from a greater synthesis of IE and SoS supported by the tools from complexity science (encapsulated in figure 4). For example, IE brings in the notion of sustainability based on the ecosystem metaphor to help us understand the different states in which a system can be stably maintained. This is crucial, because large-scale systems exhibit multiple modes of performance under different conditions over time, and the understanding of which of these modes are favorable for long-term sustainability is the basis for appropriate policy decisions. Conversely, the strengths of SoS to analyze the connectivity among systems and shed light on their connectivity and interactions helps in identifying patterns of behavior of complex systems. Models and tools from complexity science transform information about the modes of behavior and their underlying causes to knowledge that significantly bolsters the decision-making process.

IE emphasizes the formulation of strategies to regulate an artificial ecosystem to make it sustainable. But, as can be seen from table 2, this concept is largely missing from SoS-based analysis.

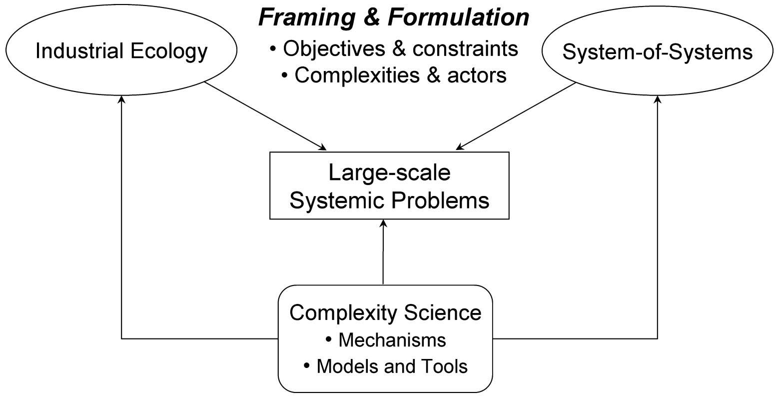

Figure 4 Synergies among system of systems, industrial ecology, and complexity science for analyzing large-scale systemic problems.

SoS studies have been biased toward capability generation—what additional things can be done with a network of systems—with less attention toward which strategies one must pursue to sustain the desired capability in a way that does not violate key objectives. But the articulation of the SoS concept via an ecosystem analogy by Polzer (2007) is an exception. Polzer describes how development programs to create an SoS must manage interfaces to ensure sustainability.

Considering ATS From an IE Perspective

The distinctive features of IE, combined with the SoS formulation, may produce a more comprehensive treatment of the complexities in the ATS. ATS is composed of different types of elements: physical infrastructure (airports), operational stakeholders (airlines), regulatory stakeholders (Federal Aviation Administration [FAA]), consumer stakeholders (passengers), logistics support (ground transport, electricity, water, waste disposal, etc.), and so on. Factors such as regional and national economics (fuel prices, etc.), geography (location of airports), and the nature of operations (regional or long-haul flights) drive the ATS. Furthermore, the ATS involves aircraft (and support vehicle) manufacturing, airline operations, maintenance (of aircraft and airports), and resale and disposal of those assets. In addition, each activity consumes energy and resources while producing waste, such as carbon dioxide and nitrogen oxide emissions and trash from aircraft and airports, which alludes to the fact that the ATS can also be analyzed via the IE perspective.

The emergent behavior in the ATS can affect these activities and flows. For example, retired commercial aviation aircraft generally assume the role of cargo transporters. Economic constraints in recent years created a huge market for such aircraft and added new variables to computing the life cycle costs of an aircraft. Additionally, the field had to rewrite policies and regulations regarding the use of aircraft to account for this unexpected development. This transformation of "waste" into "residual" (Allenby 1999) raises the issue of sustainability.

Other aspects of SoS are pertinent to both SoS and IE. The presence of multiple competing stakeholders creates a situation wherein each participant must not only thrive as an individual but also coexist with others. For example, overscheduling of flights at key airports—scheduling flights such that the number of departures or arrivals in an hour exceeds the airport's "perfect weather" capacity—although profitable for airlines, causes more delays in the overall network (Wang et al. 2008). These delays not only frustrate passengers but also generate more emissions (via taxi delays, holding patterns, etc.). Such conflicts demonstrate the SoS character of complex systems such as the ATS.

For illustrative purposes, this article focuses only on aircraft operations. The ATS has a wide geographical distribution and so affects a large

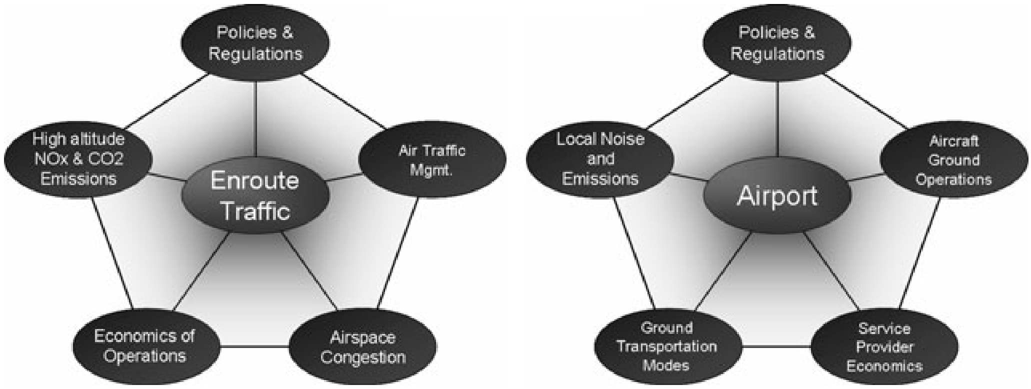

Figure 5 Aircraft operations: Analysis as an industrial ecology. NOx = nitrogen oxide; CO_2 = carbon dioxide.

population with its en-route impacts between airports and at the airports themselves (see figure 5). We argue that by adopting framing and formulation models from the SoS domain, with shaping from the IE perspective, and by integrating tools from the complexity theory domain (e.g., agent modeling and network theory), researchers can find preferred outcomes for both the overall network and the independent systems.

Proof of Concept: Transition in Air Transportation Networks

The proof-of-concept application presented in this article is focused on examining evolution in the ATS under differing behaviors of service (airline) providers (SPs) and infrastructure providers (IPs), using tools from complexity sciences. The following subsections describe our approach: motivating the analysis needed, formulating the problem from a layered network perspective, deploying tools from complexity science, and discussing the simulation results.

Practical Motivations: Developing Scalable and Sustainable Air Transportation

The activity in ATS is growing. Total passenger traffic increased by nearly 7% (RITA 2008) in the United States and by nearly 30% in Europe during 2000–2006 (EUROPA 2008). Tam and Hansman (2002) identify the direct relationship between gross domestic product (GDP) growth and demand for air travel. As a result, despite the increased availability of alternative mechanisms (e.g., collaborative video communication technologies for business interactions), due to the spread of globalization and more populations participating in larger GDP shares, the accelerating demand for air travel will most likely remain. But in mature markets, such as the United States and Europe, constraints on operations (e.g., congestion at hub airports, outdated technology and procedures) are causing more delays.

Policy-shaping bodies have been formed on both sides of the Atlantic in response to these challenges. The Joint Planning and Development Office, with its NextGen plan (Arbuckle et al. 2007), in the United States and the participants of the SESAR plan in Europe (EUROCONTROL 2007) have the charge to plan the transition of ATS to a more scalable state (with respect to demand). But this is occurring amidst deep uncertainty about what policies and technologies provide the best strategies for an ensemble of plausible futures (Lempert et al. 2003). Additionally, increased attention is being paid to the impact of noise and emissions from aviation on the environment. In Europe, the European Union (EU) passed legislation requiring non-EU airlines to pay the EU to offset their contribution to emissions and noise (EurActiv.com 2008; Kanter 2008). Thus, transitions to accommodate growth will increasingly be challenged by stress on reducing environmental

Table 3 Networks in the air transportation system

Network	*Node (N) and link (L)*	*Time scale of change*
Demand	N: Homes/businesses L: Demand for trips	Months/years
Mobility	N: Origin/destination locations L: Actual passenger trips	Days/weeks
Transport	N: Airports L: Service routes	Days/weeks
Operator	N: Aircraft, crew L: Missions	Hours/days
Infrastructure	N: Way points and airports L: Air routes	Months/years

impacts—creation of a scalable and sustainable system. The recent text by Janić (2007) addresses modeling in these settings for ATS with a sustainability focus, although not from a complex systems (nor SoS) perspective.

Problem Formulation—Addressing Dynamic Connectivity

An abstraction of the multiple networks in the ATS, inspired by Holmes (2004), is shown in table 3 (DeLaurentis et al. 2008). Each layer or network topology is unique in its makeup and time scale. For example, the *operator network* has its nodes as aircraft and crew and its links as flight missions, over smaller time scales than the other layers. How these network topologies actually interact, evolve, and respond under disruption are key aspects of ongoing research, of which this article forms only a small part.

In the research summarized in this article, we focus primarily on the evolution of the transport network with service providers at the gamma level and its link to drivers of demand in the mobility network through simulation. Such multidisciplinary approaches for transportation that link domains are gaining wider interest (Wieland et al. 2002; Conway 2004).

Analysis—Leveraging Network Theory and Agent-Based Modeling

Dynamic interactions between components, influence of different scope categories (policy, economics, operations, etc.), and the shortcomings of point solutions make the study of SoS problems a challenge. We have adopted network theory and agent-based modeling (ABM) to facilitate exploration of complexity sources and SoS characteristics. Network theory models are useful to describe and quantify the interconnectivity of components. Agent-based models allow investigation of emergent behaviors by mimicking stakeholder inputs and responses.

Network Theory and Mappings to Transport Network

We used network theory as a means of representing connectivity among airports in the transport network. Founded in graph theory, network theory deals with extracting and analyzing the statistical properties of network topologies to study their behavior. Holmes (2004), Conway (2004), and DeLaurentis and colleagues (2008) have applied network theory to conceptual modeling and analysis of air transportation networks. A glossary of the network theory metrics is presented in Table S1 of the Supplementary Material on the Web; a comprehensive analysis of this subject is available from Barabási (2002) and Newman (2003).

In this article, we present results related to delays in operations and their implications for network evolution under actions of service providers. We applied network-theoretic characterizations to the ATS networks in table 3 to generate germane metrics. Data for instantiating the transport network were obtained from the U.S. Bureau of Transportation Statistics (BTS) for U.S. carriers

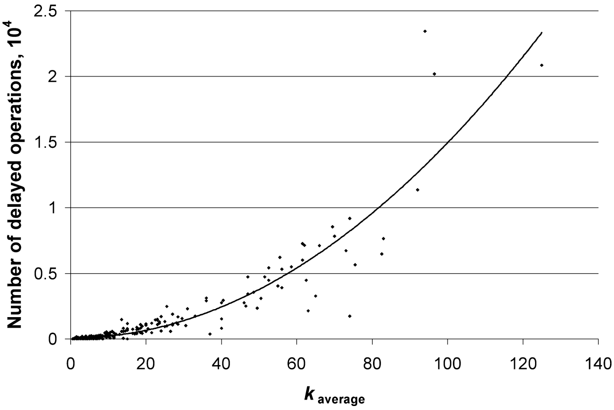

Figure 6 Relationship between degree and average delay operations.

in the domestic segment (BTS 1992). The relationship between nodal degree (k) and number of delayed operations was analyzed (see figure 6); a delayed operation is a flight that is 15 minutes or more behind schedule. The relationship between delay and nodal degree was surprisingly well represented by a simple regression model (equation 1) with a good coefficient of determination ($R^2 = 0.95$).

$$\textit{Number of delayed flights per year} = 1.4944k_{average}^2 - 0.7448k_{average} + 83.596 \quad (1)$$

We developed these correlations for operations and delay to estimate nodal/airport capacity—the upper limit on the throughput of an airport. The combination of capacity at all nodes heavily influences the ability of the ATS to process traffic, although many other factors determine nodal capacity, such as airport layout, weather conditions, and air traffic control capabilities. Rather than individually estimating capacity for each of the more than 2,700 airports cataloged by the BTS, we evaluated capacity as a ratio of the number of delayed and total operations for a particular node, where both values can be derived from nodal degree. Finally, we defined a new measure of merit, called nodal saturation, that encapsulates capacity and delay (equation 2). The complete statistical analysis and synthesis of this equation are available in work by DeLaurentis and colleagues (2006).

$$\textit{nodal saturation} = \frac{\textit{current degree}}{\textit{max degree}} \quad (2)$$

ABM

Network studies can represent and measure the connectivity at multiple levels in an SoS. But the heterogeneity of components—operational, economic, and policy related—that generates this connectivity through applied preference should be modeled. Regarding preferences, it is important not just to study the influence of human preference on design but to explicitly include human preference and behavior patterns in products and systems to be designed. In this regard, we have found ABM to be an appropriate tool.

ABM is suitable for analyzing complex systems because (1) it can capture emergent phenomena, (2) it provides a natural description of the system, and (3) it is flexible (Bonabeau 2002; Axelrod and Tesfatsion 2006). To mimic behaviors in SoS operation, we incorporate the logic (rules of behavior and adaptation) reflecting stakeholder behavior in the model via autonomous decision-making entities called agents. Thus, agent-based models employ a collection of agents that act and interact with one another and the environment. The mathematical representation of agent rules is often quite simple, but the resultant systemwide behavior is often complicated, unexpected, and thus instructive. The ultimate goal in employing ABM is not to prove an outcome but to understand the processes and patterns that may appear in complex systems. Although there have been other applications of ABM in air transportation (Niedringhaus 2004), our application is unique for its scope, its linkage with

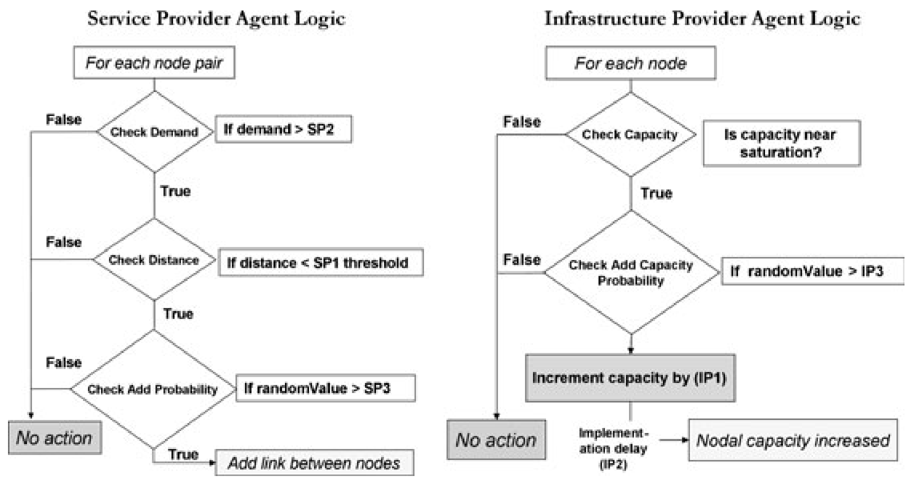

Figure 7 Stakeholder agent classes. SP = service provider; IP = infrastructure provider.

network topology analysis, and its use within an SoS framework.

Stakeholder Agent Models

The evolution of transport network is determined by gamma-level stakeholder agents making choices based on simple rules of self-interest. In general, these include such choices as alternative modes of travel (e.g., water, road, or rail transport) and network 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 (SPs; i.e., airlines) and infrastructure providers (IPs; i.e., the FAA and airports). The simplified logic for both classes is provided in figure 7. The goal of the SP agent is to meet as much demand as possible within its market niche; the model includes both a long-distance and a regional-type SP. The goal of the IP agent is to minimize delay by maintaining adequate capacity in the network. The following paragraphs describe the variables in these logic rules (**SP1-3**, **IP1-3**). It is important to note that these agents are probabilistic in construction, so the simulation is stochastic.

Simulation

The framework for the integrated simulation is shown in figure 8. Stakeholder agents (SPs and IPs) act to evolve an initialized service network under various scenarios that can be tailored by the analyst. Each agent employs its logic to guide its decisions and actions and updates its decisions in response to changes in the network environment in subsequent time steps. As this process unfolds, the magnitude and shape of the mobility network (see figure 5) also change, and agents respond to this by manipulating the transport network topology. Thus, we created a family of new network topologies over time and evaluated their structure and performance using network theory. Over an ensemble of scenarios, patterns in network structure and agent rules that lead to preferred outcomes can be identified. Furthermore, the evaluator can function as the search direction generator if the study involves optimization.

The simulation was initialized with baseline settings for the agents, an initial network topology, and scenario-specific parameters. Baseline settings for the SPs and IPs are shown in tables 4 and 5. The number of parameters was intentionally kept small, as appropriate for an exploratory model that examines issues at the gamma level. If a study has to be conducted at the beta level or below, clearly, more sophisticated models of SP and IP logic are in order. The initial network used the BTS data from 1990 for the U.S. domestic ATS overlaid on a 16 × 25 cell map that simulates the geographic proportion of the

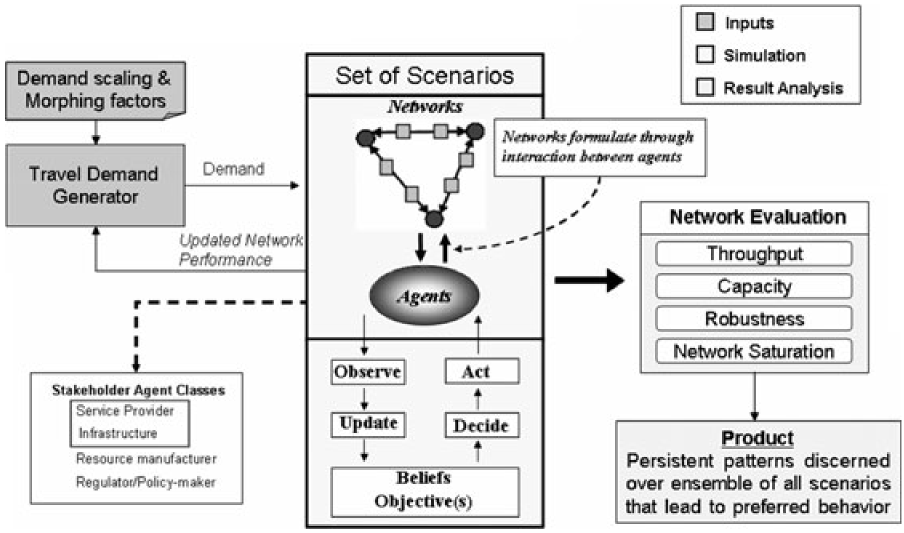

Figure 8 Simulation framework.

continental United States. The system was built with information about the characteristics of each cell based on U.S. census data, origin destination matrices and node initial capacities based on BTS data, and, finally, the demand structure based on work by Lewe and colleagues (2006).

Table 4 Service provider agent settings

Parameter	*Baseline settings*
Link add probability	Long dist. **SP3L** = 0.2
	Regional **SP3R** = 0.8
Link delete probability	Long dist. **SP3L-D** = 0.2
	Regional **SP3R-D** = 0.5
Link add threshold	Long dist. **SP2L** = 40
	Regional **SP2R** = 20
Link delete threshold	Long dist. **SP2L-D** = 30
	Regional **SP2R-D** = 15
Minimum length threshold	Long dist. **SP1L** = 200 miles
	Regional **SP1R** = 0 miles
Maximum length threshold	Long dist. **SP1L** → none
	Regional **SP1R** = 340 miles
Type	Air carrier

Note: dist. = distance; SP = service provider.

Simulation Results

Scenarios

To understand critical features such as evolution and emergence, researchers often tailor simulation studies to uncovering the most important factors driving complexity mechanisms rather than seeking a single, deterministic, optimal solution. Maps of parameter spaces that exhibit sharp transitions in behavior, for example, can help decision makers to wisely choose the best option among the multitude of future paths. We generated such maps as part of the simulation for two scenarios:

Table 5 Infrastructure provider agent settings

Parameter	*Baseline settings*
Nodal capacity add probability	**IP3** = 0.95
Nodal capacity delete probability	0.0
Capacity add threshold	100 units
Average time to implement	**IP2** = 45 time steps (∼ 1 year)
% change	**IP1** = 0.1

Note: IP = infrastructure provider.

For the first scenario, BASE, demand structure of the ATS based on the model from Lewe and colleagues (2006) was used as the initial point; demand grows evenly within this structure at a rate sampled from a uniform distribution from 1% to 5%.

For the second scenario, POPSHIFT (with 2004 as the reference year), the *structure* of demand in the mobility network was changed dramatically from the second year (2005), with significant urban–urban demand shifting toward small and medium regions. This mimics a situation in which demographic shifts result in more dispersed population requiring distributed transportation. This is also significant for exploring the relation between regional economies and air travel (Tam and Hansman 2002), although this aspect is not addressed in this article.

Results and Implications

We first used the simulation to generate a solution space map focused on the infrastructure provider (IP), relating the capacity added by the IP (augmenter of current node capacity, **IP1**) to the time to add this capacity (several weeks, **IP2**) while measuring average nodal saturation (equation 2). A set of simulation runs varying **IP1** and **IP2** was performed. Each simulation run was composed of 100 iterations of agent-logic and network updating. One data point in the solution space represents the end status of network saturation for a single run. The results for the BASE scenario indicate that, indeed, a flexible and timely capacity management capability is critical (see figure 9a). Lower is better for saturation, as indicated by the legend bar. Results for the POPSHIFT scenario were generated in a similar manner (see figure 9b). A pattern emerged across both scenarios, indicated by the line of demarcation separating acceptable and unacceptable regions for saturation.

Hence, healthy additions of capacity (high **IP1**) in a rapid manner (low **IP2**) are required of the IP to moderate network saturation and, thus, minimize delay. Furthermore, particular ratios of **IP1** to **IP2** delineate acceptable and unacceptable regions. The primary implication is that agility is needed to shape the capacity network: The IP must add or move capacity quickly and inside the action time of SP decision loops (how quick is just as important as how much). Results in figures 9a and b also indicate that, aside from the acceptable region, there are some "pockets" of useful policies, indicated by blue and hues of blue in the unacceptable region. This is not unexpected from a stochastic simulation. Although these appear to be viable options for adding more capacity, it should be noted that because they are surrounded by regions of unfavorable options, they are unlikely to be robust solutions. In contrast, if an option from the acceptable region is chosen, saturation does not degrade dramatically when moderate schedule slips occur (increasing IP2). These observations not only describe the importance of "solution spaces" but also reiterate the importance of practitioners and decision makers seeking strategies that are resilient to disruptions while trying to improve the system's capability. In the recent history of U.S. air transportation, the U.S. Department of Transportation Inspector General has found that such attention has not been paid in sufficient degree, which has resulted in numerous programs spiraling out of relevance due to developmental delays (GAO 2003).

We explored a second case to investigate the consequences of differentiated activity among the two types of service providers (regional and long-range service). In particular, the probabilities of adding a link, if thresholds are met for both long-distance (**SP3L**) and regional service (**SP3R**), were varied. Here, the measure of goodness (see figure 9c) is the average clustering coefficient, a surrogate for network robustness and, to a lesser extent, efficiency. Higher is better for the clustering coefficient value, as direct routings reduce the propensity for delay in more centralized (hub-and-spoke) topologies. Furthermore, this implies that there will be more direct routes, which can ultimately reduce fuel consumption per passenger and, thereby, the total aviation-related emissions. This case was simulated for the BASE scenario. Clarity in the solution space result in this case, however, was not as high as in the prior case, although low activity levels of the long-distance provider appeared to increase the systemwide average (and, thus, the systemwide robustness).

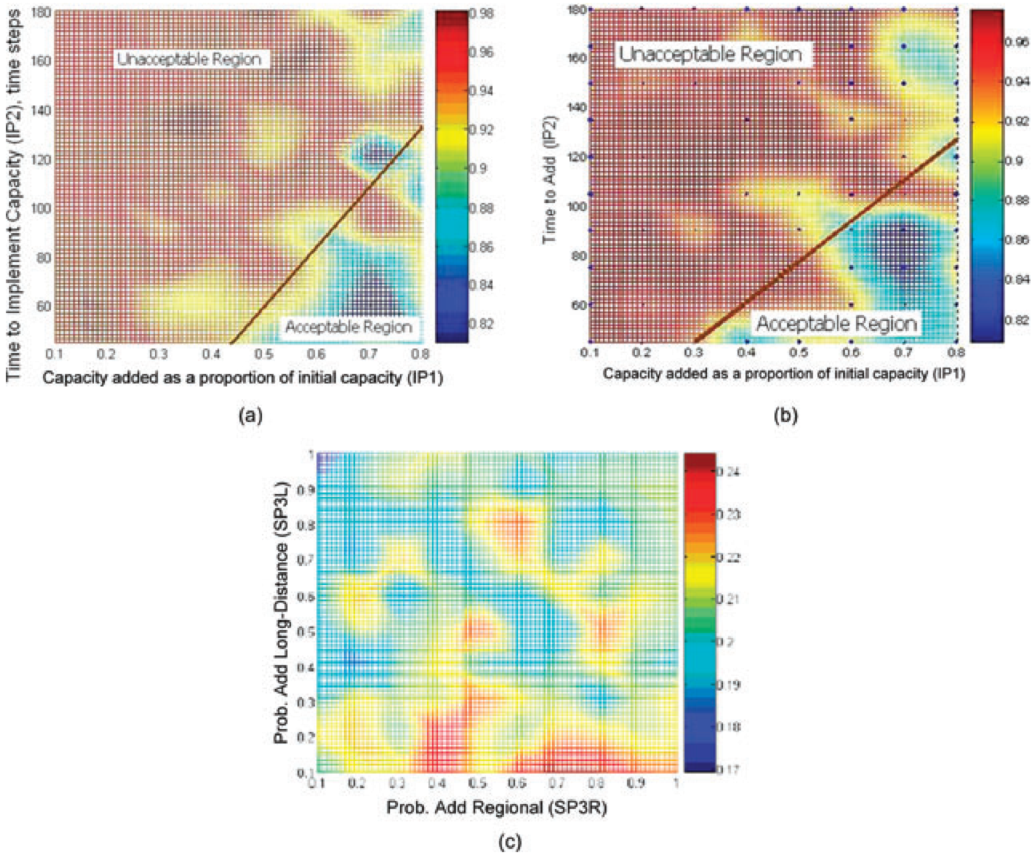

Figure 9 Simulation results: (a) average nodal network saturation under infrastructure provider behaviors—BASE scenario; (b) network saturation under infrastructure provider behaviors—POPSHIFT scenario; (c) average clustering coefficient under service provider behaviors—BASE scenario. IP = infrastructure provider; SP = service provider; Prob. = probability.

Conclusions

IE seeks to explore and explain the complex interactions between industries and the environment in which they operate, with the objective of sustainability. Our conception of SoS involves, at its core, the shaping of interactions among often independently operating systems to generate new capabilities. Although IE and SoS present distinctive perspectives and have different origins, we found synergies and common themes when we focused at the application level, especially for treatment of large-scale, sociotechnical systems. We documented these commonalities in the context of problem framing and formulation and presented a case for combining them with analysis techniques and tools from the complexity science domain to study transition in an ATS. We focused on the interaction in evolution between the transport network (network of service routes) and the infrastructure network (network of airports) driven by two stakeholders in the ATS and presented an approach to study the aspects of dynamic connectivity in these networks. We found that network theory and agent-based modeling were effective in developing our models and discussed a case study wherein the competing interests of two stakeholders in the transport network—the airlines (SPs) and the FAA and airports (IPs)—were analyzed under two demand scenarios. The results illustrated emergent behavior from combined actions of the SPs and IPs in terms of utilizing available resources to meet the demand: The IP must not only add capacity to the network but should do so at a particular rate to avoid nodal saturation, indicating that how quick is as essential as how much.

Future Work: Integrating Environmental Metrics

Our focus in this article concerns the particular problem of network saturation due to unbalanced demand growth and capacity enhancement resulting from competing and often conflicting interests of the different stakeholders in the ATS. The intent of this article is to present the similarities between the ATS as an SoS and its strong characteristics of an IE, with the hope that researchers will increasingly adopt the concepts and tools from IE to address this problem. This hoped-for outcome will likely be spurred by the increased prominence of the issues of aviation-related noise and emissions, which occur locally at and near airports as well as globally in the upper troposphere (primarily carbon dioxide). These environmental impacts are increasingly of concern, especially as the number of aircraft operations is growing significantly (Waitz et al. 2004), and must be monitored and regulated in an equitable manner—all hallmarks of IE.

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Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Appendix S1. A description of the layered structure of Air Transportation Systems (ATS), applications of agent-based models to ATS, and stakeholder interests in ATS.
Figure S1. Layers and time scales in air transportation system networks.
Table S1. Glossary of network theory terminology.

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