Role of Humans in Complexity of a System-of-Systems

Daniel DeLaurentis

School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, USA
`ddelaure@purdue.edu`

Abstract. This paper pursues three primary objectives. First, a brief introduction to system-of-systems is presented in order to establish a foundation for exploration of the role of human system modeling in this context. Second, the sources of complexity related to human participation in a system-of-systems are described and categorized. Finally, special attention is placed upon how this complexity might be better managed by greater involvement of modeling of human behavior and decision-making. The ultimate objective of the research thrust is to better enable success in the various system-of-systems that exist in society.

Keywords: system-of-systems, complexity, human behaviors, connectivity.

1 Introduction

A system-of-systems (SoS) consist of multiple, heterogeneous, distributed, occasionally independently operating systems embedded in networks at multiple levels that evolve over time. While the *moniker* may be recent, the *notion* of a "system-of-systems" is not new. There have been and still are numerous examples of collections of systems that rely upon the interaction of multiple, but independently operating, systems. Ground and air transportation, energy, and defense are high profile examples. These existed before the phrase "system-of-systems" entered common use, have been studied extensively through several fields of inquiry, but rarely have been examined as a distinct problem class. In recent years, the formal study of systems-of-systems has increased in importance, driven largely by the defense and aerospace industries, where the government's procurement approach has changed. 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 system developers and contractors must determine the appropriate mix of systems and related interconnections to provide these capabilities.

As a result of the defense system heritage, perhaps the most active group discussing SoS is the systems engineering community. Several contributions in the recent literature from this community indicate a growing recognition that systems engineering processes are not complete for the new challenges posed by the development of SoS [1]. Thus, researchers are looking for new characterizations. Rouse, for example, describes implications of complexity on systems engineering approaches [2]. Sage and Cuppan present a working collection of traits for SoS that points to the possibility of a "new federalism" as a construct for dealing with the variety of levels of cohesion in

V.G. Duffy (Ed.): Digital Human Modeling, HCII 2007, LNCS 4561, pp. 363–371, 2007.

SoS organization [3]. We describe later in this paper an additional view with an angle toward structuring complexity in a SoS.

While defense-related applications have driven the recent emphasis on systems-of-systems, many of society's needs across diverse domains are met through systems-of-systems. Unfortunately, in many instances, an inflexibility in response to disruption (artificial or natural) or increased demand for service is observed. Supply chains acquire excessive inventory and capacity if manufacturers and distributors ignore opportunities to collaborate on demand forecasts. Healthcare networks experience breakdowns of information flows and lose continuity of care as patients migrate among autonomous hospitals, out-patient clinics, nursing homes, etc. Electric power blackouts illustrate consequences of emergent behaviors; modest breakdowns in some component systems of energy grids mushroom into major disruptions. Well-publicized transportation delays from over-capacity operations at major airports prevent passengers and cargo from reaching their destinations in a timely, productive manner.

We postulate that a common thread through all these challenges is the complexity that arises from their nature as a system-of-systems. Further, much of the effort towards development of effective approaches for system-of-systems is coming from the engineered systems community. "SoS solutions" are still conceived primarily as the appropriately organized mix of artificial systems. Less attention is being paid to the role of human behavior in these applications and to research areas such as the socio-technical systems approach, which addresses the complexities and uncertainties that result when human and technical systems interact.

Therefore, the goals of this paper are to describe the system-of-systems problem class, identify primary sources of complexity within this class, and highlight particular roles of humans in this context. It is hoped that this paper will spur interdisciplinary endeavors that link research threads from the human factors community (particularly digital human modeling) with those addressing system-of-systems problems from a complex systems engineering and design perspective. While the limited space in this paper does not allow for detailed presentation of design methodologies or analysis results from particular applications, several references will be given throughout to select methods and results.

2 Characterizing a System-of-Systems

A set of distinguishing traits for SoS problems have been proposed by Maier [4]. Maier's criteria are operational independence, managerial independence, geographic distribution, evolutionary behavior, and emergent behavior. The first three primarily describe the problem boundary and mechanics while the latter two describe overall behavior. Emergent behavior—the manifestation of behavior that develops out of complex interactions of component systems that are not present for the systems in isolation presents a particular challenge because it is unpredictable, is often non-intuitive, and can be manifested in a good manner (e.g., a new capability) or bad manner (e.g., a critical failure). A primary challenge in performing System-of-Systems Engineering (SoSE) with greater effectiveness is to understand the mechanism of emergent behavior, develop cues to detect it, and create a methodology for managing it intelligently. The one-sentence characterization for an SoS offered at the beginning of the introduction to this paper attempts to encapsulate these traits as well as additional aspects such as heterogeneity of component systems and multi-level structure.

This latter aspect especially indicates a need to characterize the structure of an SoS. For this, a lexicon has been formed [5]. Since many SoS problems have some interconnectedness in a hierarchical manner, the lexicon enumerates these interacting *levels* of various components with Greek letters. Starting from α, the levels proceed upward, leading to γ or δ or higher depending on the complexity of the problem and the depth of analysis desired. Further, a β-level constituent represents a network of α-level entities; a γ-level constituent represents a network of β-level entities, and so on.

In addition to these hierarchical labels representing levels of complexity, a set of scope dimensions are defined. These dimensions, or *categories*, highlight the trans-domain aspects of SoS. Specifically, not all entities within the levels are similar in their basic character; they can be made of entities or systems of different characteristics and representations. Thus, a framework is needed to classify the different components of each level. Further, these components can be categorized primarily into *Resources*, *Operations*, *Economics*, and *Policy*. Each of these categories independently comprises the previously described levels, thereby completing the SoS lexicon. The categorization of the levels lends clarity in dealing with the different facets of the problem while maintaining the lucidity provided by the levels. The relationship between the categories and the levels forms a pyramid, which is depicted in Fig. 1.

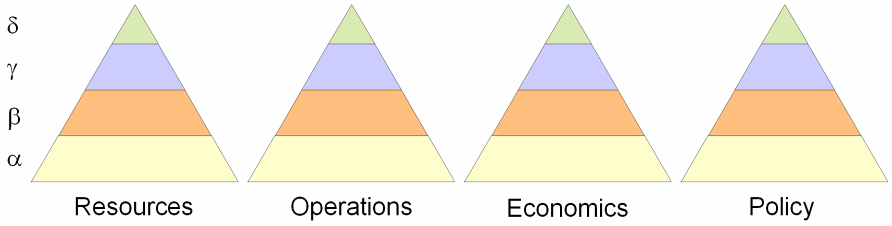


Fig. 1. Scope categories and hierarchy of levels: an unfolded pyramid unifying the lexicon

While a systematic representation of scope and structure is crucial, the ability to characterize SoS problems in the analysis domain is the next required step. Further, the SoS of interest must be defined in a way that exposes appropriate level(s) and categorical scope dimensions. Towards these objectives, a taxonomy has been proposed [6] consisting of a three-dimensional space characterized by system type, autonomy, and connectivity, illustrated in Fig. 2 below. Analysis methods must be appropriate for the **system types** *(S-axis)* that constitute the SoS. Some SoSs consist predominantly of technological systems – independently operable mechanical (hardware) or computational (software) artifacts. Technological systems have no purposeful intent; i.e., these resources must be operated by, programmed by, or activated by a human. Other SoSs consist predominantly of humans and human enterprise systems—a person or a collection of people with a definitive set of values. The second SoS dimension is the **degree of control** *(A-axis)* over the entities by an authority or the autonomy granted to the entities. This relates to Maier's discussion of operational independence and managerial independence of systems within an SoS. Emphasizing the importance of control / autonomy, others 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" [3]. Finally, systems involved in a system-of-systems are interrelated and **connected** *(C-axis)* with other (but likely not all) systems in the SoS. These interrelationships and communication links form a network. 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. These dimensions serve as a taxonomy to guide the formulation and analysis of the SoS design problem. A particular SoS can therefore be considered as a "point" or "region" in the three-dimensional space formed by the aforementioned dimensions as axes. Based on its location in this space, and other indicators of particular problem structure, the approach and methodology necessary for analysis and design can be more intelligently selected.

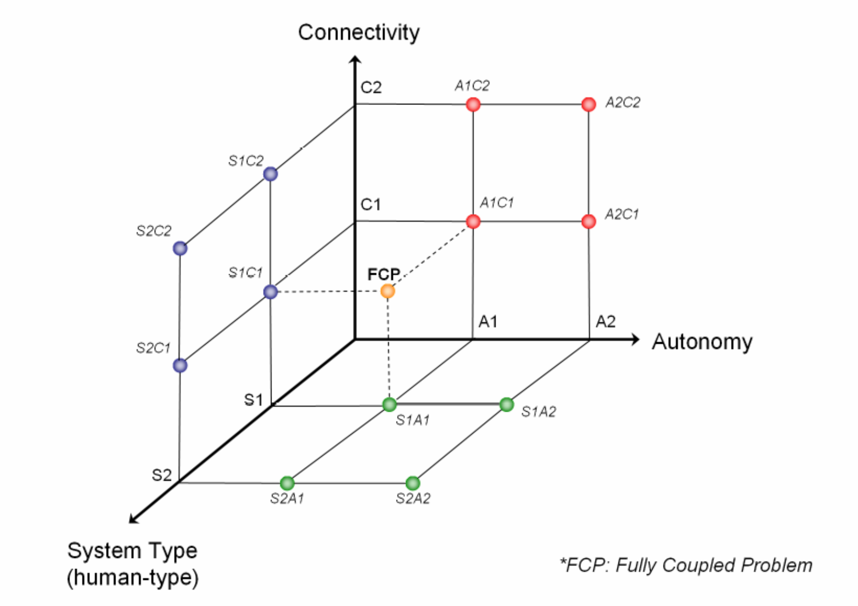


Fig. 2. Three key dimensions for system-of-systems

3 Role of Humans in SoS Complexity

3.1 General Sources of Complexity

Views of complexity include internal system complexity, external complexity, computational (algorithmic) complexity, etc. While complexity can be viewed in different manners, it is safe to say that complexity is always a comparative measure. A given system, at a particular scale and using a particular measure, can be more or less complex than another system examined at the same scale using the same measure. One particular view holds that complexity measures the amount of information necessary to describe a system [7]. More complex systems require greater information to define them. Complexity in an SoS stems primarily from the heterogeneity of its constituent systems, dynamic and uncertain connectivity that arises with operation at multiple levels, and the role of humans who bring "self-organization" and differing perspectives on operational context within an SoS. In this vein, sources of complexity in an SoS can be gleaned from their characteristics and placement in the taxonomy discussed. Further, in the face of these sources, representing the structure of organization is key to managing complexity in SoS.

The following notional example, depicted in Fig 3 and using the previously introduced lexicon, illustrates the manifestation of several of these sources of complexity in a system-of-systems. The α-level comprises the most basic components of the SoS. The result of the interactions at an α-level are felt at the corresponding β-level. Hence, emergence is evidenced at the β-level and higher. In addition, there is evolution at play in any given β-level during any interval of time. As shown in Fig. 3, the different α-level components are nodes in a β-level network and the connectivity may shift over time (t_1, t_2 and t_3). There is an undirected relation between 1 and 2 at time t_1 while there is only a one-way relation between them at time t_2. Also, new entities appear and existing entities depart over time. Due to these changes among different α-level constituents, the performance of the β-level entities is altered by both evolution and emergence. New configurations lead to altered interactions between the α-level constituents (emergence) and this emergence in turn affects the course of the future make-up of the β-level (evolution). Thus, evolution and emergence are mutually influential and are manifested at each level.

Relative complexity between two SoS may differ for each level. One SoS may have simplistic organizational structure (lower complexity) at β-level but its α-level systems are more complex than those of another SoS. This multilevel aspect is especially important from a computational complexity perspective. Integration of high fidelity analysis models across multiple layers of abstraction is impractical, and a more refined tact that is selective in which information is appropriate is required. This is well explained by Herbert Simon, who asserts that, "Resemblance in behavior of systems without identity of the inner systems is particularly feasible if the aspects in which we are interested arise out of the *organization* of the parts, independently of all but a few properties of the individual components" [8].

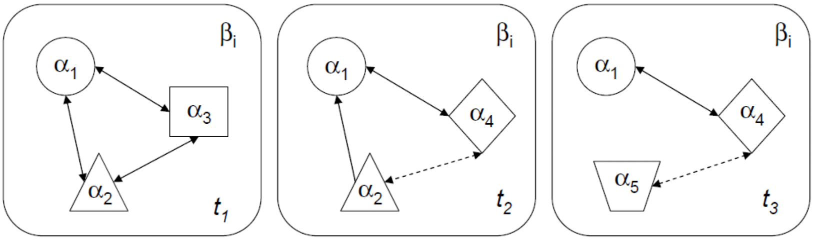


Fig. 3. Notional example of a system-of-systems

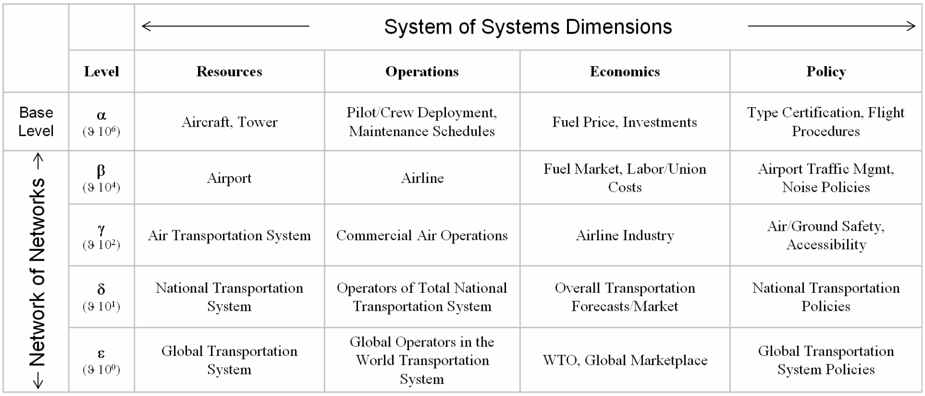
3.2 Role of Humans

When the taxonomy indicates that a particular SoS has heterogeneous system type which may imply significant role of human behavior (e.g. S1-S2 along S-axis in Fig. 2), an SoS-oriented approach will be most challenged by complexity sources peculiar to these human behaviors. This is also when such an approach is most needed in order to uncover the complicated interactions between entities that emerge at the higher levels of abstraction. Along these lines, the recently released study conducted by the U.S. Air Force Scientific Advisor Board entitled “System-of-Systems Engineering for Air Force Capability Development” [9] identified the role of the human as critical for the successful implementation of SoS in the field. Quoting from their summary:

> “Whenever the Air Force generates a system-of-systems, interaction among the systems often includes human-to-human interactions. If the machine-to-machine aspect of SoS is weak, then it falls upon the humans to achieve the interaction. This can, and often does, create a very challenging environment for the human; sometimes leading to missed opportunities or serious mistakes. The lack of sound Human System Interface designs can exacerbate this. Coordinated situation awareness is difficult to manage if the individual systems miss or convey confusing or conflicting information to their operators.
>
> Assuming there are sound human systems interfaces for individual systems, the Air Force can greatly reduce the burden on the human-to-human coordination if effective inter-system interoperation is established. It is the objective of our study to suggest ways for improving intersystem interoperation at the hardware and software level while keeping in mind that sometimes the human-to-human interaction is the appropriate interface. An effective system-of-systems will promote collaborative decision-making and shared situation awareness amongst the human operators. This occurs by addressing the need for common, consistent human-system interfaces.”

To more explicitly tie together the concepts of human behavior and sources of complexity in an SoS, we introduce a tangible example. The information presented in Fig. 4 describes air transportation as an SoS using the lexicon introduced earlier in this paper. This figure is adopted from our work in seeking to forge robust architectures that could transform air transportation from its current strained state to one that better scales to shifts in demand and disturbance.

Human values and the organizations in which they participate influence the SoS through application of self-interests and perspectives (via operational and managerial independence). Dynamics from this influence take place at multiple levels and under multiple time-scales. For example, humans can operate and implement policies for α-level systems. In air transportation, these roles include pilots, maintenance crew, inspectors, etc. Further, actions at these lower levels of hierarchy tend to evolve on a short time scale; they typically are near-term actions of a practical variety in response to the situation at hand and are operational in nature. Complexity may arise here from ambiguous instructions, differing skill levels in distributed teams [10], goals and



		← System of Systems Dimensions →			
	Level	**Resources**	**Operations**	**Economics**	**Policy**
Base Level	α ($\vartheta\ 10^6$)	Aircraft, Tower	Pilot/Crew Deployment, Maintenance Schedules	Fuel Price, Investments	Type Certification, Flight Procedures
← Network of Networks →	β ($\vartheta\ 10^4$)	Airport	Airline	Fuel Market, Labor/Union Costs	Airport Traffic Mgmt, Noise Policies
	γ ($\vartheta\ 10^2$)	Air Transportation System	Commercial Air Operations	Airline Industry	Air/Ground Safety, Accessibility
	δ ($\vartheta\ 10^1$)	National Transportation System	Operators of Total National Transportation System	Overall Transportation Forecasts/Market	National Transportation Policies
	ε ($\vartheta\ 10^0$)	Global Transportation System	Global Operators in the World Transportation System	WTO, Global Marketplace	Global Transportation System Policies

Fig. 4. Air transportation system-of-systems description

strategies and detection [11] and diagnosis of system failures [12] in a network context. Humans can also participate as managers of α-levels systems, or parts of organizations at even higher levels. In air transportation, these roles include airlines, air traffic regulatory bodies (e.g., Federal Aviation Administration, FAA), labor unions, etc. Actions of these human-based entities tend toward the longer-term influence based upon considered assessment of organizational goals; these decisions may establish well-intentioned policies that unintentionally restrict the existence of promising solutions.

The interactions of humans and human enterprises at various levels of the SoS exhibit the same kind of self-organizing behaviors described in the previous section on complexity. In order for human engineered/operated/managed systems interact, they must form "convergence protocols" [9] which enable interoperability. Driving the need for these protocols is the multiplicity of perspectives which arise from "institutional frames of reference and associated operational context scope that system users and system designers implicitly assume in their behavior and their designs" [13]. These perspectives form a backdrop for the operational assumptions adopted for the given system and enable (or prohibit) its integration with other systems in the system-of-systems. When systems come together (to exchange mass, energy, or information), the perspectives under which they were instantiated may conflict and require human intervention to resolve. These so-called "trigger events" force a reorganization of the convergence protocols, assumptions under which the systems operate, the context in which they interact, or some combination of these. This reorganization is nothing more than a manifestation of the self-organization of a complex system. Humans effect this restructuring of the SoS to resolve this interoperability challenge, but require additional information (about unstated assumptions, perspective, and so forth) in order to respond effectively. As a result, this increase in information also increases the complexity of the overall SoS.

Capturing these interactions with humans at various levels of organization in the SoS has been undertaken by some researchers in the SoS community in an effort to improve the understanding of SoS dynamics. For example, in the air transportation domain, traveler preference models (an α-level behavior) have been modeled by Lewe et. al [14] and Trani [15]. Further, models of β-level entities have been developed, such as MITRE's JetWise model of airlines [16], and higher level dynamics in DeLaurentis et. al [17]. Some of these studies have used agent-based modeling (ABM) to mimic the human factors and influences on the system-of-systems. 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. The mathematical representation of agent rules is often quite simple, but the resultant system-wide behavior is often more complicated, unexpected, and thus instructive [18]. One major limitation of this method involves the simple-rule-based models that represent human behaviors and organizations. ABM is a modeling tool for the study of Complex Adaptive Systems [19], which represents a problem class with many of the same dynamic behaviors of SoS problems (e.g., emergence). For air transportation, Donohue has specifically called for a CAS approach [20]. Recent advancements in analyzing complex networks also provide useful tools for addressing the global connectivity of a given SoS problem without reliance on low level interactions [21].

However, a need remains for an increased ability to understand and replicate the complex human factors involved in a human-technical system-of-systems. This includes more than simply the behaviors of individuals in the SoS, but also the representation and scope assumptions issues discussed in the previous paragraphs.

4 Summary

A brief introduction to system-of-systems problems was presented, especially crafted as an entrée into dialogue with researchers in human system modeling. The sources of complexity related to human participation in an SoS were briefly introduced, couched in a lexicon and taxonomy for the problem class. We observe that these sources reside at multiple levels and across different scope dimensions. In particular, each human participant brings a unique perspective, and thus interpretation, to information in an SoS. A challenge for effective design in a system-of-systems context is to make these perspectives transparent during interactions. Finally, a better understanding of the mixing between short and long-term time scales for human influence on an SoS must be obtained.

We recommend collaborative explorations between engineered system architects and designers with human system modeling experts in order to increase the effectiveness of system-of-systems that may involve significant human presence in their constitution as described via the proposed taxonomy.

References

1. Keating, C., Rogers, R., Unal, R., Dryer, D., Sousa-Poza, A., Safford, R., Peterson, W., Rabadi, G.: System-of-Systems Engineering. Engineering Management 15(3), 36–45 (2003)
2. Rouse, W.: Engineering Complex Systems: Implications for Research in Systems Engineering. IEEE Transactions on Systems, Man, and Cybernetics—Part. C: Applications and Reviews 33(2), 154–156 (2003)

3. Sage, A.P., Cuppan, C.D.: On the Systems Engineering and Management of Systems of Systems and Federations of Systems. Information, Knowledge, Systems Management 2(4), 325–345 (2001)
4. Maier, M.W.: Architecting Principles for System-of-Systems. Systems Engineering 1(4), 267–284 (1998)
5. DeLaurentis, D.A., Calloway, R.K.: A System-of-Systems Perspective for Public Policy Decisions. Review of Policy Research 21(6), 829–837 (2004)
6. DeLaurentis, D., Crossley, W.: A Taxonomy-based Perspective for Systems of Systems Design Methods. In: Proceedings of IEEE System, Man, & Cybernetics Conference, Hawaii, 10–12 October 2005, Paper 0-7803-9298-1/05 (2005)
7. Bar-Yam, Y.: Dynamics of Complex Systems. Westview Press (Perseus Books Group), Boulder, CO (1997)
8. Simon, H.: Sciences of the Artificial, 3rd edn. MIT Press, Cambridge (1996)
9. Saunders, T., et al.: System-of-Systems Engineering for Air Force Capability Development. United States Air Force Scientific Advisory Board, Report SAB-TR-05-04, Washington, DC (July 2005)
10. Caldwell, B.: Analysis and Modeling of Information Flow and Distributed Expertise in Space-related Operations. Acta Astronautica 56, 996–1004 (2005)
11. Patrick, J., James, N., Ahmed, A.: Human Processes of Control: Tracing the Goals and Strategies of Control Room Teams. Ergonomics 49, 12–13, 1395–1414 (2006)
12. Rasmussen, J., Rouse, W.B. (eds.): Human Detection and Diagnosis of Systems Failures. Plenum Press, New York (1981)
13. Polzer, H., DeLaurentis, D., Fry, D.: Multiplicity of Perspectives, Context Scope, and Context Shifting Events. In: Proc. IEEE SMC Society Second Annual International Conference on System-of-systems Engineering, San Antonio, TX , April 16–18, 2007 (2007)
14. Lewe, J., DeLaurentis, D., Mavris, D., Schrage, D.: Modeling Abstraction and Hypothesis of a Transportation Architecture. Journal of Air Transportation 11(3) (2006)
15. Baik, H., Trani, A.A.: A Transportation Systems Analysis Model (TSAM) to Study the Impact of the Small Aircraft Transportation System (SATS). In: 23rd International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005 (2005)
16. Niedringhaus, W.P.: The Jet:Wise Model of National Air Space System Evolution. Simulation 80(1), 45–58 (2004)
17. DeLaurentis, D., Han, E.-P., Kotegawa, T.: Establishment of a Network-based Simulation of Future Air Transportation Concepts. In: 6th AIAA Aviation Technology, Integration and Operations Conference (ATIO), Wichita, Kansas, 25–27 September 2006, AIAA 2006-7719 (2006)
18. Bonabeau, E.: Agent-based Modeling: Methods and Techniques for Simulating Human Systems. Proc. Natl. Acad. Sci. 99(3), 7280–7287 (2002) (accessed on 6 Feb 2006 from) http://www.pnas.org/cgi/reprint/99/suppl 3/7280
19. Waldrop, M.M.: Complexity: The Emerging Science at the Edge of Order and Chaos, 1st edn. Simon & Schuster Inc., NY (1992)
20. Donohue, G.: Air Transportation is a Complex Adaptive System: Not an Aircraft Design. In: AIAA International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio, 14–17 July 2003, AIAA 2003-2668 (2003)
21. Barabási, A.-L., Albert, R.: Emergence of Scaling in Random Network. Science no. 286, 509–512 (1999)