TOWARDS A METHOD FOR IDENTIFYING COMPLEX SYSTEM CONSTRAINTS IMPACTING PERFORMANCE OF NASA AERONAUTICS MISSIONS

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ABSTRACT - Problems endemic to 21st century complex systems are inherently multidisciplinary and require more holistic approaches to address their high levels of uncertainty, ambiguity, and emergence. These holistic approaches must expand beyond a technology-centric focus. They must span the array of technology, organizational, managerial, social, policy, and political boundaries that influence analysis and solution development, impact solution deployment, and affect solution sustainability. For the NASA Aeronautics Research (ARMD) mission of safer, secure, efficient, and environmentally friendly air transportation systems; this suggests continually grappling with development of complex system solutions and their corresponding issues. Systems-based approaches offer insights into complex system problems. However, the literature shows that methods to support rigorous identification of multidisciplinary system issues affecting performance can be significantly enhanced from a more holistic grounding in systems theory. To identify complex system issues affecting ARMD, this research proposes the use of systems theory as a foundation for identifying metasystem pathologies as deviations from the ‘healthy’ status of systems. This paper presents the nature of complex system problems, limitations of current systems-based methodologies to deal with those problems, and outlines a research direction that aims to develop and deploy a method to identify and represent complex system pathologies.

INTRODUCTION

The aviation industry faces a daunting task of stewardship in transforming air transportation to maintain a safe, secure, efficient and environmentally friendly system. To meet this challenge, the industry must contend with diverse perspectives on the nature of transformation as well as the complexities embodied in the problem space, including: the complex views influencing how transformation should take place (e.g., political, commercial, national security, etc.), high levels of ambiguity and uncertainty (e.g., sustaining demand, terrorism threats), incomplete, incorrect, or nonexistent information and technologies, changing boundary conditions (e.g., use of Unmanned Aircraft Systems in the National Airspace System), and insufficient resources (e.g., funding) (Arnwine, 2012; Captain, Wald, & Hockenbury, 2011; National Research Council, 1998; 2003; GAO, 2010; Waggoner, 2011; 2012; Bourgeois, 2010). Against such factors, technology-based solutions appreciate technical elements of problems in the air transportation system. However, appreciation of non-technical factors, as well as their intersection with technical aspects affecting the air transportation system, requires a holistic view.

Consistent with literature, fulfilling NASA’s Aeronautics Research (ARMD) mission requires consideration of policy as well as technology issues. For example, Edgar G. Waggoner, the Director of Integrated Systems Research Program Aeronautics
Research Mission Directorate at NASA suggests that increasing use of Unmanned Aircraft Systems in National Airspace System requires significant change in policy that governs aviation (Waggoner, 2013). Additionally, Cosmas, Belobaba and Swelbar (2011) posit that there is need to change aviation policy to accommodate societal changes related to deregulation and globalization of the industry. For instance, they point out that the US policy restricting foreign airline operation and equity ownership may need to be revised since there is no difference between local airlines and foreign operators when it comes to national interests and customer care.

Furthermore, transformation of the air transportation system must consider contextual issues such as funding, availability of resources, environment, and the changing structure of aviation as a whole. For example, Robert A. Pierce, Acting Director of the FAA Next Generation Air Transportation System of Joint Planning and Development Office suggests that the present system was not designed to meet current changes and demands related to light jets, unmarked aerial planes, and meeting security concerns (Pierce, 2006). For NASA ARMD, this suggests the need to expand the boundaries to include multiple and diverse stakeholders (e.g., Departments of Defense, Homeland Security, Commerce, NASA, the White House’s Office of Science and Technology Policy, and industry leaders). Having an expanded boundary will enable better understanding and definition of relevant topics such as ‘defining RTSP (Required Total System Performance) levels of service’ for industry. Failure to include the breadth of stakeholders, by narrowing the boundaries too early, risks creating a solution space that will surely be challenged at inopportune times in the development process.

Moreover, the Governmental Accountability Office (GAO, 2010) notes that air transportation projects and operations can be impacted by lack of consideration of environmental and community issues such as reducing noise levels, controlling water pollution, reducing emissions, and using environmentally sustainable practices. This is consistent with the early suggestions of the National Research Council report of 1998 which recommended that maintaining and sustaining leadership in aviation requires understanding breakthrough technologies that enables reduction of emissions, reduction of perceived noise levels, reduction of aircraft accident rates, reduced air travel costs, increase design confidence and reduced cycle time, reduced travel time, and reduced cost to Low Earth Orbit (National Research Council, 1998). Over 20 years later, although some specifics and technology may have changed, the wisdom of the report calling for inclusion of multiple perspectives still rings true. Exacerbating the current state of affairs are the realities related to emerging crises stemming from manmade events (e.g., shutdown of the air transportation system following 9/11, security concerns that still keep many air travelers at home, security procedures that increase travel time, international conflicts, a downturn in the national and global economies, and the SARS epidemic) and natural phenomena such as extreme weather patterns (National Research Council, 2003).

The preceding discussion was purposely selected to illustrate the need for consideration of non-technical factors affecting a safer, more secure, efficient, and environmentally friendly air transportation system. This paper is developed to suggest that the future development of the air transport system will significantly benefit from inclusion of a perspective from the systems of systems problem domain (Keating, 2005).

The remainder of this paper is focused on first exploring the nature and role of systems-based methodologies. Second, a research structure is provided to suggest an approach to
better include non-technical aspects of the air transport problem. Third, the method application for inclusion of both technical, not-technical, and their intersection is explored. Fourth, the future research challenges to explore pathologies that impact development of metasystems is suggested. The paper concludes with an overview of the theoretical, methodological, and practical implications for this research.

SYSTEMS-BASED METHODOLOGIES

Characteristics of the system of systems problem domain are previously articulated in Keating and Katina (2011) and Katina et al. (2012) to include divergent (and potentially incompatible or politically driven) worldviews, abdication of long-term thinking in response to immediate perceived needs, and increasing complexity (due to interplay between technology, policy, and economic strategies). This set of characteristics is somewhat daunting at first glance. However, they are representative of the problem domain being faced by practitioners who must deal with complex systems development and implementation. To address the problems in this domain we quickly realize that there is no shortage of systems-based approaches enabling examination of complex systems and systems of systems. Table 1 provides a sample of systems-based approaches commonly associated with analysis and understanding system(s) under study. The purpose of such systems-based approaches is to enable systemic examination of complex systems problems and formulation of robust ‘solutions’ to issues in complex systems and systems of systems. For NASA ARMD this would entail examination of the air transportation system development for systemic issues impacting the ARMD mission of providing safe, secure, efficient, and environmentally friendly air transportation.

Despite the existence of systems-based approaches, we quickly discover that there is a paucity of thinking and methods to support formulation of systemic issues in systems of systems (Barot, et al., 2012). This has prompted researchers at the National Centers for System of Systems Engineering (NCSoSE) to develop methods and tools that enable systemic examination of systems of systems. There still exist a need to develop approaches to discover prevalent issues that cause deviation of a system from healthy functioning, potentially constraining performance and viability (Keating & Katina, 2012).

Table 1 Systems-based approaches for understanding complex systems

<table>
<thead>
<tr>
<th>Systems-based methodology</th>
<th>Primary literature/authors</th>
<th>Systemic issue identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organizational Learning (OL)</td>
<td>Chris Argyris and Donald Schôn (1978; 1996)</td>
<td>‘Diagnosing the organization’ Phase</td>
</tr>
</tbody>
</table>
### Systems Analysis (SA)
- Charles Atthill (1975); James Digby (1989); John Gibson et al. (2007)
- ‘Problem definition’ Phase

### Systems Engineering (SE)
- INCOSE (2011); Benjamin Blanchard and Wolter Fabrycky (2006)
- ‘Exploratory research’ Phase

### Systems Dynamics (SD)
- Jay Forrester (1961); John Sterman (2000)
- ‘Problem structuring’ Phase

### Total Systems Intervention (TSI)
- ‘Creativity’ Phase

### Viable Systems Model (VSM)
- Stafford Beer (1979; 1981)
- ‘System purpose’ or ‘Systems in focus’ phase

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**RESEARCH STRUCTURE**

The lack of clarity and consistency as to how problem identification is accomplished and what it produces for systems-based approaches prompts a need for a formal systematic method for identification of issues impacting performance and system viability. This is necessary in the systems of systems problem domain due to the complexity associated with understanding behaviors of complex systems. Déry’s (1984, p. 14) original position that the analyst is often uncertain of his/her actions and may not even “understand the object of such pursuits” still appears to be the present day case for systems of systems problems. The introduction to this paper establishes the need for systemic identification of issue(s) affecting performance and viability of the air transportation system (as an exemplar of a system of systems). In such a case, failing to ‘articulate the issues’ correctly, can create the conditions for solving the wrong problem precisely in the most efficient way possible; otherwise known as Type III error (Mitroff, 1998).

Effective problem identification ensures articulation of the right problem based on understanding of the problem domain as an initializing activity (Crownover, 2005). For example, Peter Checkland’s Soft Systems Methodology is a systemic approach developed to deal with real-world problematic situations that are ill-structured (Checkland, 2000). This approach requires implementation of seven activities for learning, for exploring problem situations, and for suggesting helpful and feasible changes based on the elicited concerns from stakeholders (Checkland, 2000; Jackson, 2003).

For a systems of systems type setting, Adams and Meyers (2011, p. 164) posit “framing of the problem” as an initiating phase for Perspective 1 of the System of Systems Engineering Methodology and proposes nine execution elements for the methodology to enable systemic problem identification. These eight elements include: (1) generalize the wide context for the system under study, (2) characterize the system under study, (3) characterize the complex nature of the system under study, (4) present the system domain as characteristically complex, (5) frame the SoSE problem, (6) define problem statement and objectives, (7) conduct stakeholder analysis, and (8) conduct contextual analysis. Each of these execution elements is associated with a set of goals, inputs, outputs, methods, techniques, and tools that enable holistic understanding of a complex situation (Adams & Meyers, 2011). Regarding current methods for identification of systemic issues, the following points of critique are offered:

(a) There lacks a coherent set of assumptions, concepts, and values for practitioners to enable ‘issue(s) identification’ in the systems of systems setting.

(b) There is a lack of rigorous research-based methods to identify systemic pathologies at the metasystem (system of systems) level.
The current state of research indicates an opportunity to make a significant original contribution to the systems body of knowledge. This contribution can be centered on development and deployment of a method for identifying and representing systemic pathologies in systems of systems. This research is not intended to be a ‘reinvention of the wheel’ for problem identification in complex systems. On the contrary, it is supportive of the ongoing mission for NASA ARMD by suggesting a complementary approach for identification and representing systemic issues that threaten to hinder air transportation system transformation with respect to performance and viability. A starting point could be Baer’s (1995) suggestion for a three-step process rooted in systems analysis methodology:

1) Conducting exploratory analysis on vexing issues in the aviation system.

2) Running sessions to examine issues identified (options for the aviation system).

3) Identifying the promising options and scenarios as well as assessing their impact on performance.

Conducting exploratory analysis into the air transportation system enables the discovery of deep systemic issues and their impact on aviation missions and objectives (Baer, 1995). These deep systemic issues are what we have referred to as metasystem pathologies, which are defined as: “A circumstance, condition, factor, or pattern that acts to limit system performance, or lessen system viability, such that the likelihood of a system achieving performance expectations is reduced” (Keating & Katina, 2012, p. 253). The metasystem pathology concept exploration lies at the heart of the ongoing research. Figure 1 shows the structure (purpose, objective, and questions) of proposed research.

Figure 1 Proposed research purpose, objectives, and questions

METHOD APPLICATION

In order to formulate knowledge claims regarding a system, a method is needed (Sousa-Poza, Kovacic, & Keating, 2008). A method must provide systematic procedures to generate knowledge claims through application. Therefore, the proposed research suggests three phases corresponding to the
research questions: (1) exploration and conceptual model creation for metasystem pathologies, (2) development of a method for metasystem pathologies identification, and (3) application of the method in an operational setting. Phases 1 and 2 are inductive in nature. They have the primary purpose of establishing a link between system performance and viability to the larger field of Systems Theory, and based on that research developing the method to identify and represent systemic issues. Phase 3 enables the validation of the model and the method for identifying metasystem pathologies in real world settings.

Preliminary NCSoSE research indicates that Systems Theory can be used as a foundation to identify systemic pathologies constraining system performance and viability (Keating & Katina, 2012). Using systems theory (i.e., principles) and the functions of a metasystem as described in the viable systems model (Beer, 1979, 1981), Keating and Katina (2012) have developed a first generation articulation of an approach enabling discovery of systems pathologies (i.e., particular impediments to the healthy function of a system of systems). They stipulate that the derived pathologies offer a starting point for systemic inquiry into the underlying sources of deviations. An example of a systems principle and its implication for design is shown in Figure 2.

The principle of sub-optimization (Hitch, 1953) suggests that if each subsystem, regarded separately, operates with maximum efficiency (optimal), then the system as a whole will not operate with utmost efficiency (suboptimal). Application of this principle informs design, redesign, and strategic system development in two ways:

1) Care must be taken to ensure that there is a balance between the autonomy accorded to subsystems and the integration necessary to maintain system performance (viability).

2) Membership in a system of systems requires member systems to surrender a level of autonomy in support of integration into the system of systems.

Lack of consideration for sub-optimization would be indicative of a current system that is perhaps operating in an overly ad hoc fashion (i.e., lacking coordination and purposeful design). It also suggests a potential imbalance between autonomy of productive elements and integration of the whole system.

For NASA ARMD, the principle of sub-optimization, in relationship to the metasystem as depicted in the Viable System Model, suggests the need for continuous assessment of the air transportation system to ensure an appropriate balance between autonomy of subsystems and integration of the whole. This precarious balance can be the source of an underlying metasystem pathology that might only be observable as superficial manifestations of symptomatic conditions. For example, while Unmanned Aircraft Systems (UAS) are increasingly being used for firefighting, land and crop monitoring and surveying, border protection, emergency management, etc., they need to be integration into the National Airspace System (Waggoner, 2013). Such challenges are consistent with NextGen UAS Research of creating an integrated communication system, coordinated air transportation system, governance of unmanned aircrafts, and consideration of the new role of human element (Joint Planning and Development Office, 2012). Waggoner’s (2013) position of how the integration will take place and its impact on missions of UAS or NASA ARMD could certainly benefit from analysis that considers the sub-optimization principle.

While the approach taken by Keating and Katina (2012) offers insights into diagnosing system performance and viability of metasystems, it is a first iteration and as such needs to be further developed and subject to rigorous challenge from both the scholarly and
practitioner perspectives. Moreover, it does not offer an explicit linkage to system performance (i.e., mechanisms used to produce desired system behavior).

**Figure 2** Systems principles in relation to pathologies (adopted from Keating & Katina, 2012)

**FUTURE RESEARCH**

The current line of proposed research has been adopted as my emerging dissertation research topic area. The current aim is to develop and deploy a systematic mode of inquiry (i.e., method) for identifying and representing systemic pathologies at the metasystem level in systems of systems. This research is not meant as a ‘reinvention of the wheel’ for problem identification in complex systems. On the contrary, it supports systems-based research by suggesting a complementary approach for identification and representing systemic issues that threaten to hinder systems of systems performance and viability. This proposed research thrust is distinguished by the pathologies and corresponding method which is grounded in systems theory and underpinned with systems philosophy.

The need for this method stems from society’s continuing search for methodologies capable of holistically and systemically analyzing dominating issues of the 21st century (e.g., safer and environmentally friendly air transportation system). Since ‘issue(s) identification’ (i.e., framing the problem) is the first phase/activity supporting initial understanding of symptomatic manifestations of the deeper systemic issues affecting system performance and viability (Keating & Katina, 2012), a natural track of progression is developing a method that can identify and represent systemic issues. Literature suggests that this activity (i.e., issue identification) is at the foundation in any problem-solving endeavor (Baer, 1995; Crownover, 2005; Pyster et al., 2012; Minger & Rosenhead, 2004; Mitroff, 1998).

Extending the initial Keating and Katina (2012) work into the future research arena can focus on creating a conceptual model capable of linking metasystem functions to their corresponding pathologies and the underlying systems theory/principles. Generation of this understanding requires development of a formal method that can serve to (re)frame the system to produce alternative decision, action,
and interpretations that were not accessible independent of the method application. The value for NASA ARMD is in the application of the method to offer face validation in identifying and representing metasystem pathologies affecting the ARMD mission. The deep system pathologies are intended to support more rigorous understanding of the systemic issues in a complex system. The outputs of the method application can then be used to inform more holistic design, redesign, and strategic system development. The intent of the emerging research stream is to develop and test the method in different industries (e.g., air transportation, healthcare, etc.). Therefore, there is a tremendous opportunity to provide an approach to better understand and address some of the most complex issues society must face in the 21st century.

CONCLUSIONS
Dealing more effectively with 21st century issues will require robust methodologies capable of holistically addressing technical and non-technical issues. Systems-based approaches seem to offer insights; however, they do not offer clarity and consistency as to how ‘issue(s) identification’ is done and what it produces for a complex system problem domain. This does not deny that this activity is accomplished by practitioners who must confront these problems daily. However, adding to the practitioner’s “toolbox” with a purpose built method can be instrumental in improving effectiveness in dealing with complex problems. This paper calls for development and deployment of a method to identify metasystem pathologies impeding systems of systems performance and viability. The National Centers for System of Systems Engineering proposes the use of Systems Theory and the Viable System Model to identify pathologies affecting performance and viability of systems of systems. This research is certainly on the knowledge edge and will push the prevailing boundaries of the Systems Theory, Systems Engineering, and System of Systems communities. However, this is a first articulation and an invitation to engage a dialog that is necessary to propel our thinking and capabilities for dealing with complex problems that currently appear beyond our grasp to understand, let alone resolve.

The proposed research introduced in this paper has three major implications for the body of knowledge that can accrue from this effort:

- **Methodology** - the research provides a method for identifying and representing systemic issues by linking System Pathologies to Metasystems using Systems Theory/Systems Principles. This linkage is not available in literature or practice with the exception of Keating and Katina’s (2012) preliminary work. There are significant opportunities and implications for enhancing the systems body of knowledge and corresponding practices.

- **Theory** - the research provides a platform for including metasystem pathologies in systems of systems issue identification. This enables expansion of systems literature debate on how to identify systemic issues and clearly grounds this dialog in the related body of knowledge for Systems Theory.

- **Practice** - The research provides a deployable method that can be used by both practitioners and researchers to identify metasystem pathologies affecting system performance and viability in an operating environment. Application outputs can then be used to inform design, redesign, and strategic system development.

This is an exciting time and place in the evolution of society. While technology has brought unprecedented opportunity, so too has it pushed the boundaries of our capacity to address the problems that have been born from
the consequences of those technologies. At some level, we must acknowledge that our ability to deal with the consequences of technology deployment across human, social, organizational, managerial, policy and political lines lag technology. This research offers a step in the direction of better understanding the pathologies stemming from technology introduction. This is achieved by exploring a method to equip practitioners with an approach to better understand the source and systemic implications of pathologies in complex systems.

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REFERENCES


