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JoAnn M. Brooks, John S. Carroll, Jon W. Beard

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JoAnn M. Brooks, The MITRE Corporation

John S. Carroll, MIT Sloan School of Management
and Engineering Systems Division

Jon W. Beard, The MITRE Corporation

{ jbrooks@mitre.org; jcarroll@mit.edu; jbeard@mitre.org }

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ABSTRACT

Engineering projects that support government enterprises face substantial challenges due to demands from diverse stakeholders and rapidly-changing technologies. In this paper, we present findings from analysis of five case studies of systems engineering projects for large government enterprises. We focus on what can be learned from systems engineers, their essential role, and their engineering practices. As they work to establish interoperability across pre-existing and new technologies—thereby evolving infrastructure—the engineers commonly face “agonistic” tensions between groups of stakeholders. Temporal pacing conflicts are especially prevalent, such as those between stakeholder groups concerned with fast-paced streams of innovation and stakeholder groups concerned with current operations. In response, many engineers are following an evolutionary approach, developing new capabilities for managing projects and individual professional skill sets. The engineers’ adaptive response can be understood as incremental modularization and re/integration of technologies and associated practices across organizational (stakeholder) boundaries. Additionally, engineers are developing new skills of influence to support these capabilities for addressing stakeholder tensions. We close by discussing implications of our findings for the management of infrastructure technology projects, emergent design and engineering of organizational infrastructure, and the changing role of systems engineers.

Introduction

Government leaders are increasing their reliance on new information technology as an occasion for coordinating and consolidating the efforts of multiple agencies into enterprises that share information and provide government services. By "enterprise" we refer to sets of organizations brought together to produce a product or service on a large scale. Rather than developing a single stove-piped system for a hierarchically-organized customer, as in traditional systems-building engineering, enterprise systems engineering projects confront multiple information and communication systems and technologies—many already in operational use—that must be somehow linked into a coherent infrastructure for diverse and competing stakeholder communities. For example, the military services (Army, Navy, Air Force, etc.) are now being pressured to collaborate as a single "Joint" force, at the same time they are undergoing the Department of Defense's version of business process reengineering (called "Transformation of Force Structure") and an ongoing transition toward "net-centric operations." These new developments in government enterprises can be understood as evolving from a technical focus on systems building to a multi-faceted sociotechnical process linking organizational practices, technical systems and social norms, both locally and globally (Edwards, Jackson, Bowker and Knobel 2007).

This paper reports on the results of a research study on social and organizational aspects of systems engineering for government enterprises. In the paper, we first discuss the nature of systems engineering work and summarize relevant work on infrastructure by Edwards and associates. We then describe our research approach and present results from our analysis of five case studies of large government enterprise system projects, revealing how systems engineers are adapting their engineering practices and themselves to meet the challenges inherent in the shift from systems to infrastructure. We find that systems engineers working at the enterprise scale are changing both their capabilities for managing projects and their individual professional skill sets. Next we discuss implications of these findings for the management of infrastructure technology projects, for emergent design and engineering of government enterprises, and for the changing role of systems engineers. We conclude with identification of some limitations of our work and some suggestions for future research.

Systems Engineering

Systems Engineering began as a sub-discipline of engineering during the late 1940s and 1950s when the development of weapons systems and aerospace systems was expanding beyond the scope and tools of separate engineering disciplines (Johnson 2003; Sapolsky 2003). By offering the label of "system," the focus was placed on the technical system being engineered, such as a missile or airplane, rather than on the component pieces that were the responsibility of discipline-based sub-teams and subcontractors. The major activities within systems engineering are systems analysis, acquisition and supply, project management, system design (requirements and specifications) and integration, implementation or transition to use, and technical evaluation (Martin 2000; Johnson 2003:36).

Traditional systems engineering methods for achieving interoperability and avoiding redundancies are predicated on long development cycles and emphasize formally structured requirements, specifications, and integration testing at the end of the project. However, in large enterprises with different systems and technologies evolving at different rates, component technologies must now be (continuously) integrated across different stages, and traditional approaches such as the waterfall method are no longer practical. The field of systems engineering has thus continued to evolve as more large-scale systems are developed in military and civilian applications. The term “system-of-systems” is routinely applied to distinguish more complicated systems engineering from typical systems engineering (Keating, Rogers, Unal & Dryer 2003; Farr 2008).

Yet experienced systems engineers have a growing sense that traditional systems engineering approaches and even systems-of-systems engineering are no longer adequate for meeting the challenges associated with engineering for large government enterprises. As one senior systems engineer commented on a recent engineering program: “[The complexity of the enterprise organization] broke a significant number of the traditional systems engineering practices that we depend on… [The state of the] practice didn’t apply, or we couldn’t impose it… one way or another it was undermined by the enterprise environment.”

With little availability of formal training on systems thinking and other necessary skills (Davidz 2006), systems engineers are adapting by developing ad hoc approaches through work experience. Our study examines these engineering challenges and the engineers’ adaptive response in detail, with the intent of capturing emerging enterprise systems engineering knowledge that can be useful for understanding and improving the management of such engineering projects.

Infrastructure Evolution

One theoretical perspective that sheds light on the difficulties faced by systems engineers has been developed by historian of science and technology Paul Edwards and his associates. They draw distinctions between technical systems and infrastructures, positing that infrastructures are comprised of networks and internetworks (Edwards 1998; Edwards *et al.* 2007). In their taxonomy, technical *systems* support a small number of basic functions, and are comprised of heterogeneous components and subsystems. Systems are usually built under centralized control as "stove-pipe" systems and can be changed only slowly. *Networks* meet a larger number of functions, and are pieced together from multiple heterogeneous systems using *gateways*, which are "technologies and standards" that "allow dissimilar systems to be linked" (Edwards *et al.* 2007: i, 8, 10). Networks are more often under distributed control; they also are reconfigurable and have shifting boundaries. *Internetworks* (also called webs) have a "near infinite number of functions" (Edwards 1998:21), are comprised of heterogeneous networks and rely on other infrastructures. Control of internetworks is weak; they are subject to widely distributed coordination. They are open, configurable, and continually being extended. *Infrastructures* are combinations of technical elements and social practices that "enable locally controlled and maintained systems to interoperate more or less seamlessly…. ubiquitous, reliable, and widely shared resources operating on national and transnational, scales" (Edwards *et al*. 2007: 12).

Edwards *et al.* (2007: 7-11) identify several stages in the progression from systems to infrastructure. Two of these stages are of particular importance to us here. One is the *system building* stage, in which the designers of systems are considered "visionaries" and have a lot of control over what the final system will look like. This is the kind of engineering that the profession of systems engineering was developed to provide. The other is a *consolidation* phase, during which separate systems and/or networks are linked together – first in smaller area networks and then more globally. This is accomplished either by one system taking over, or more commonly through the use of gateways.

Agonistic Tensions

Perhaps most important for systems engineers facing the transition of their work from systems-building to infrastructure consolidation are what Edwards *et al.* (2007) refer to as "agonistic" tensions.

> Infrastructures of all types have encountered, and often provoked, a series of deeply felt tensions. Once established, infrastructures may hide or disguise such tensions, so that once bitterly-contested decisions and design choices appear as unproblematic or even natural features…. [But] infrastructures, especially those in the making, are what political scientists term *agonistic* phenomena: imagined, produced, refined, and occasionally reassessed in a stratified and deeply conflictual field. (Edwards *et al.* 2007: 24)

Edwards *et al.* identify several classes of agonistic tensions. The first is *interest and exclusion*, based on the observation that there are "winners" and "losers" in each infrastructure development effort. The uneven distribution of opportunities shapes and can redefine the roles that different stakeholders take on, along with their power to influence the evolution of the infrastructure. Their second category of tension, *ownership / investment*, refers to tensions anchored in funding mechanisms, policy options, and other external influences that play important roles in evolving infrastructure. After describing our research approach and cases, we will explain how an agonistic tension perspective informs our understanding of the major challenges faced by systems engineers on infrastructure technology projects.

Research Approach

Overview

Our research approach is grounded in case studies of five projects contracted between government enterprises and the MITRE Corporation, an organization that administers Federally-Funded Research and Development Centers (FFRDCs) involved in the technical design of large technical systems for government enterprises. We utilized cross-case comparative analysis (Eisenhardt 1989; Markus & Lee 1999; Friedman & Sage 2004; Yin 1994) to develop the results presented here. Our team was comprised of two researchers from MIT and several social scientists and senior engineer practitioners from MITRE (the exact number fluctuated over the three years of the project, Fall 2005 – Summer 2008). This combination of talents afforded a range of interpretive perspectives to make sense of the data we collected. Each of the five case studies was written by one or two of the team members.

Due to the nature of the research material, concerns about the possibility of disclosure of sensitive information related to government programs surfaced from several perspectives. The research process was reviewed and approved by both the MITRE Institutional Review Board (MIRB) and the MIT Committee on the Use of Humans as Experimental Subjects (COUHES). Unusually strong vigilance was required to protect the well-being of all parties involved, including interview participants and program managers, as well as the reputations of MITRE and its sponsors. Hence, we are not able to provide individual case summaries, but instead discuss aggregate data and analysis, so that results and quotations are never attributed to a specific case.

The Cases

All five cases were enterprise-scale projects with tens of thousands of users, some with hundreds of thousands.   Each represented a MITRE work program for government agencies, involving integration of new IT capabilities with legacy systems. As mentioned above, this paper uses aggregated data to safeguard national security, in addition to protecting the identities of the engineers, the programs, and the government agencies. Nevertheless, we can report that major technologies included a pair of operations planning tools; an integrated, scalable communications platform; a globally-dispersed operations intelligence information system; a multi-national command and control system; and a large-scale program coordination and development effort.   Projects ranged from a two-year effort focused on transforming a large globally-distributed legacy environment into a centralized service-based IT model, to a multi-year effort involving multiple cabinet-level agencies and industry sectors, and focused on guiding the evolution of a nationally-distributed operational environment. Three of the five cases studied were "Joint" (i.e. coordinated across all military services). Although several projects were less than ten years old, some of the legacy environments involved had been in use for several decades. Modernizing these legacy environments often required the consolidation of dozens of independent (and incompatible) databases, numerous external interfaces, a wide variety of both commercial-off-the-shelf (COTS) and custom-designed applications, and multiple systems at different stages of their life-cycles. Efforts were also dependent upon the willingness of stakeholders to move toward integrated, networked, available-on-demand environments.

All of the projects presented challenges to traditional systems engineering approaches—challenges which were more than strictly technical in nature. For example, one case involved an attempt to merge a legacy mainframe environment maintained through traditional systems engineering approaches, with a newer web-based system being developed with agile, rapid prototyping approaches. Another project addressed the challenge of consolidating formerly independent systems development environments across multiple agencies in order to achieve cost savings and ease data sharing, without stifling the creativity and innovativeness found in those locally-focused environments. A third effort was a long-term (i.e., more than a decade) project to build on existing technologies and capabilities by incorporating emerging technologies and the ability to integrate data streams from multiple sources across several agencies and sources, in order to manage an anticipated two-to-three-fold increase in system demand over the next two to three decades.

Data Collection

Senior engineer-practitioner members of the research team designed a semi-structured interview protocol. One pilot interview was conducted with another senior systems engineer and slight modifications were made to improve the protocol. The final version is included as an appendix. Senior managers overseeing each project provided researchers with the names of project leads who then identified qualified potential interviewees for each case study. For three of the cases, potential interviewees were sent a letter by their manager explaining the study and requesting their participation; all of these people agreed to be interviewed. For the other two cases, managers solicited volunteers more generally, and more people volunteered to be interviewed than in the cases where candidates were hand-picked.

The engineer-researchers were first trained by the social scientists on appropriate methods for conducting objective and thorough interviews. Interviews were then generally led by one engineer-researcher, while at least two case writers with social science backgrounds took notes and interjected clarifying questions when necessary. An advantage of this approach was that the engineers being interviewed felt more comfortable talking about their experience in conversation with another engineer. Also, the engineer-researchers could then help interpret the interview notes that the social science researchers had recorded. Interviews were planned to take about an hour to complete; however, most took longer and many participants willingly gave ninety minutes of their time. Researchers also sought background information from various other media, including newspaper articles and archived project materials. Between three and six interviews were carried out for each case during the 2006-2007 timeframe. Some additional interviews were conducted in 2008, using revised methods. Altogether, a total of thirty-three interviews were conducted across the five cases.

Data Analysis

Analysis was performed in several phases. First, the primary author(s) of each case read through all typed data notes from the interviews on that case, and performed ad hoc coding to identify key themes. The team held weekly meetings to discuss the cases and emerging themes. The team also created a common case outline to ensure consistency across the studies, then authors adapted the outline somewhat for each case.

Each case was written as a detailed history of the specific engineering program, including a timeline of critical events, organizational charts, program accomplishments, challenges faced, engineering practices, lessons learned, and suggestions for further research. The narratives were developed weaving together the themes found in the data. After an initial draft of each case was prepared, its author(s) shepherded the case study through an extensive series of review/revise/release cycles, first with other social science members of the team, then with an engineer-researcher, next with the project interviewees, and finally with the project managers in charge of the relevant work program before the case was released internally within the company.

Roughly one year later, a second round of coding was performed by the principal investigator who reviewed all of the original interview notes, the five case studies and writings on the high level themes, and identified the cross-cutting subthemes developed in this paper.

Analysis

Challenges: Agonistic Tensions

In this section, we first describe the evidence we found for two types of agonistic tensions identified by Edwards *et al.* (2007), especially in those programs undergoing a consolidation phase (where technological convergence is easier than integrating social and organizational aspects). We then describe an additional type of agonistic tension not identified by Edwards and associates: regarding the *pacing* of enterprise change and the evolutionary *process* of infrastructure development itself (tensions developed by Edwards *et al.* 2007 mainly pertained to the distributional *structure of resources* and *outcomes* of the infrastructure development process). We close this section with a discussion of how the agonistic tensions are experienced by the engineers themselves, leading into the next section on their adaptive responses to the challenges.

The first set of tensions identified by Edwards *et al.* (2007), those concerning interest/exclusion, occurred so frequently during engineering requirements definition that they were sometimes referred to as "food fights" (suggesting that engineers would fling messy details of constraints at one another). Tensions also commonly surfaced in struggles around practicalities of designing technology gateways for bridging across different systems and networks. These tensions seemed unavoidable: although cooperation among stakeholders is essential to an enterprise, there are huge differences in language and philosophy between technologists, managers, policymakers, and members of the civil and military services (customers/users) (cf. Schein 1996). As one senior engineer noted, "Different groups have very different motivations, everyone has their own objectives – occasionally they align." And then the engineer added: "No, they don't align. They don't align yet, let me put it that way. If we're successful, they'll have to align."

We also found empirical support for Edwards *et al*'s (2007) category of ownership/investment agonistic tensions: "Applications have to be developed by industry in a netware environment; they can't be developed in isolation…. [and at the same time,] strategic partnerships (e.g. Microsoft) are not under our control." These tensions with external stakeholders also commonly surfaced around funding and budgetary arrangements:

“Congressional districts are among the stakeholders—How do you deal with the congressional politics?” “The … industry controls a large portion of … jobs in congressional districts.”

Engineers were well-aware that funding, policies and other external constraints were grounded in ownership/investment relations, and were significant sources of tension for their engineering projects. Interviewees described these tensions quite explicitly:

> … many programs that build platforms quite often choose control over the [gateway technology] to go inside or contract to have [gateway technology] built because it gives them flexibility …. When outsiders dictate which [gateway technology], you lose control and there’s higher risk.
>
> Originally, [military service experimentation lab] was controller of [prototyping technology]. They wanted to cut it and throw it to [acquisition agency]. And [acquisition agency] said no, [service research arm], this is yours. So [service research arm] took control of it. [Acquisition agency] will integrate it if possible. [Service research arm] wants to do all development and take all away from [acquisition agency]. [Acquisition agency] thinks doing fielding only is dysfunctional and wants to do development too.

Analysis also revealed that some of our cases exhibited significantly more conflicting customer groups and agonistic tensions than others. The government enterprise technology consolidation projects that the engineers considered successful were the only two whose member organizations had joined the enterprise voluntarily (benefits of cooperation appeared obvious). Thus these established government enterprises had relations between major stakeholder already worked out, the overall enterprise structures were relatively stable and there were policies in place to enforce compliance, all before technological consolidation was undertaken. On the other hand, the three projects using mandated technological consolidation as a means to establish a new government enterprise were comprised of organizational units that had traditionally competed with each other for funding and political recognition; these programs were considered by the engineers to be much more troubled (if not outright failures). Additionally, we found that the one effort to design technological gateways without formally addressing the issues associated with agonistic tensions, was not effective.

Tensions around Pacing

In reviewing the engineers' comments about the challenges they face, we were particularly struck by a prominent set of tensions not developed by Edwards *et al*. (2007), around differences in stakeholders' orientations to enterprise change, especially the pace at which it should proceed. As Ancona & Chong (1996) note in their work on entrainment, organizational entities may adjust or synchronize the pacing, cycles and rhythm of their activities to an external "pacer" – something in the environment with a rhythm that the organizational entity then assumes. When different organizational entities are working well with each other, their rhythms and tempos are normally in sync. In our cases however, clashes between organizations responsible for exploiting fast-paced streams of innovation and those concerned with slower-paced testing and integration into operational processes seemed omnipresent. As each organization struggled to entrain to multiple pacers, the resulting effect not infrequently seemed more like a war over which organization would submit to the other's pace, rather than the "dance of entrainment" that Ancona & Waller (2007) describe.

One might argue that these pacing tensions could be derived from the agonistic tensions initially presented by Edwards and associates (2007) – interest/exclusion and ownership/investment – because pacing tensions are closely aligned with funding and budgetary control issues. Yet across all of our cases, control over the pacing of change was the most prominent issue articulated by the engineers and apparently one of the hardest to resolve; we also maintain that it is theoretically significant (see below).

The most common version of such conflicts occurred between (on the one hand) government organizations that wanted enterprise evolution entrained to their visions for new capabilities enabled by technological innovation and (on the other hand) organizations tightly coupled with ongoing mission operations. The former were long-range planning or R&D organizations (often bearing names that included "lab" or "experimentation" in their title). The latter were government organizations either directly engaged in current operations, or responsible for the "acquisition" of technologies to meet the needs of users already working in the field (and therefore dependent upon situated combinations of legacy and innovative technologies).

In each case, senior officials concerned with "transformation" of military forces or "next generation" civil technologies had been advocating discontinuous change; whereas senior officials primarily concerned with ongoing operations and end-users out in the field displayed little tolerance for any change that was more than incremental. One such case of technology design was described eloquently by a manager via email:

> There were (and still are) deeply divided views regarding [this technology] within the [service branch]. There are loosely two camps. One camp … tend to emphasis leap-ahead capability. Their focus is on the [technology] to be fielded [ten years out]. The other camp … tend to emphasize more rapid fielding across the broader force (e.g., lower-cost, good enough capabilities). . . . [the technology championed by the first camp] has been a sacred cow within the [service branch], senior [service branch] leadership has generally supported the [first] camp. However, the cost, duration, and importance of [the war effort] has led many within the [service branch] to become vocal proponents for a relook at our … strategy (i.e., other camp).

Pacing tensions were aggravated by two factors. First, the institutional arrangements for "acquisition" (the contractual, legal, and regulatory arrangements for how new technological systems are to be funded, built, and fielded) are rigorous and proceed cautiously. This has been necessary because operational contexts often place many lives at stake; the risks associated with new software-dependent technologies must be carefully managed (Leveson 1986). Yet the qualitative increases in capabilities enabled by new technological innovations are emerging with increasing rapidity (correlating with Moore's Law), thereby creating inherent conflicts with acquisition and operational rhythms. One engineer noted: "The acquisition system doesn't support IT acquisition well, the testing process alone is too long." Another interviewee referred to inter-organizational tensions more directly:

> … there was conflict between the acquisition side, [which was] relying on historical understanding of what it takes to field a product in safe and suitable way, and a [rapid prototyping / agile] group who was trying to foster a leaner and new approach. Distrust, mistrust, second guessing, not best of relationship. … 'Us' vs. 'Them.'

Thus we found deeply-engrained oppositions between those organizations responsible for supporting the steady tempo of operations, and those responsible for the more discontinuous pulses of R&D endeavors.

Secondly, these differences are intensified by structural tensions impeding the ability of most large government bureaucracies to effectively manage change at all. While the leadership of government agencies can sometimes be of long tenure, technology projects are more often initiated by individuals who occupy their positions for only a two-to-three year period before moving on to other jobs due to political appointments or military rotations. This is enough time to plan for and start a transition or new program, but rarely enough time to complete it, leaving it for the next individual to bring things to a close. Yet the next individual brings their own agenda, goals, and new programs. Thus, there is rarely a single individual in charge of the entire enterprise for long enough to effectively mediate differences among the stakeholders or dictate final decisions. As one engineer described a resulting situation: "The program was already going, processes already in place. Then the new PEO was trying to put his new [plan] in place. Trying new architecture, requirements, specs. People were already building things. …Other things start clean. So, we're a little broken in my mind."

Furthermore, these recurring patterns of leadership turnover are set against a majority of personnel in both the civil service and military commands who are long-term (if not lifetime) employees enjoying considerable job security. These mid- and lower- level government employees, faced with pressure to change from the top, often find it most expedient to resist change by simply waiting for leader-initiated changes to "blow over" as leaders leave. Referred to as "slow rolling," this commonly occurs when rank-and-file members see no benefit to cooperating with transitory change efforts. This deeply entrenched pattern of resistance to change renders successful change efforts the exception rather than the rule. One interviewee made the point explicitly: "The culture is changing, but only because I think [the top two leaders] have stayed there long enough …. if people don't see the value, they will slow roll you."

Engineers' Experience of Pacing Tensions

Thus, systems engineers working to establish interoperability across pre-existing technological systems and networks continually face clashes in the temporal rhythms of the different organizations already using those systems and networks, in addition to the tempo of changes in the technologies themselves – regardless of a project's relative success or failure. And as with any professional group, the career aspirations of engineers are closely linked to perceptions of meeting professional responsibilities and establishing competent reputations (Van Maanen & Barley 1984). When the problems cannot be resolved technologically or at the organizational level, the engineers find themselves motivated to initiate changes at individual and project levels. In this section, we describe some aspects of the engineers' working context from their own perspective, in order to emphasize their motivation to develop adaptive capabilities and practices.

In engineering requirements, pacing tensions are so familiar that they have been given names such as "requirements creep" and "requirements churn." In some enterprise-scale projects, these become ubiquitous. One engineer described this trend in his project succinctly: "the only thing that is constant in our world is changing requirements." Another revealed a more humorous attitude – when asked "How does your program deal with changing requirements and constraints?" he responded with a sly grin: "Daily."

The traditional waterfall method for systems engineering – completing one stage before beginning the next – simply does not work for developing government infrastructure because the technologies that engineers need to integrate are at different stages of development. For example, one program integrating five separate sub-programs had each of those programs at a different stage. Another large integration project had "literally hundreds of smaller projects – all the way from implementation back up the chain to planning. Scattered – at any one time…at every stage."

And while technological innovation continues to accelerate, there is a corresponding increase in challenges around managing the integration of innovative technologies with those already in operational use. One engineer noted the challenges of working on "many moving parts, [which] constantly move." Another referred to difficulties in planning: "operationally, it is difficult to predict… the network could be really shaken up in the future because you don't really fully know how it's going to be done." Sometimes the pace of innovation is faster than that of integration altogether: "a version is out of date before it hits the street. … evolution is moving beyond requirements too quickly to keep up." Engineers expressed this kind of experience in three out of our five cases: "Too much too fast." "We knew it was unreasonable under the timeline that was planned – that was plainly obvious to folks." "Original requirements were very ambitious from [the agency] – do everything for everyone and in a short time frame. Had such good top-cover that no one could say ‘the Emperor had no clothes’.”

Pacing tensions also result in challenges to testing and fielding the newly developed technologies. One engineer spoke about needing to temporarily suspend innovation in order to finish what had already been started: "…discovery was allowed to continue and is still ongoing now. We're still receiving and responding to it. There's an expression that General [X] has been saying…   'at some point, we need to snap the chalk line'." Thus the local environment for engineering government infrastructure is often quite messy, and frequently not conducive to finishing quality engineering products.

Given the extent and experience of these challenges, systems engineers are adapting in response to what they perceive as sheer necessity. Some of the engineers we interviewed indicated that they are responding to the challenges of agonistic tensions facing their projects by following an evolutionary approach. Denning, Gunderson & Hayes-Roth (2008) posit than an evolutionary approach which involves "continual adaptation to the environment" through "successive releases" of new technology and/ or survival of the fittest technology is necessary to reverse the increasing rate of failure in large system projects. While our findings are generally consistent with their proposal, we find that the linking together of large, pre-existing strove-piped systems already in operational use (developing infrastructure) requires additional capability beyond self-organizing communities of like-minded developers. In infrastructure evolution, the environment is not simply technical, but is fraught with agonistic (political) tensions between stakeholder groups with conflicting interests, and which prevent straightforward consensual agreements about how development should proceed.

In the next section, we describe capabilities and skills that systems engineers are developing for evolutionary development within environments characterized by rapidly changing requirements – both technical and organizational. Drawing on organizational perspectives in addition to engineering knowledge, we argue that the adaptive engineering management practices developed by systems engineers can be understood as developing capabilities of incremental modularization and re/integration across organizational boundaries -- complemented by a new set of interpersonal skills -- to address the stakeholder tensions; in the next section we describe some of the more prevalent adaptations.

Developing Capabilities: Changing Engineering Management Practices

Modularizing Technologies

One capability being developed by engineers is modularizing technologies to support separability and combinability of components (Salvador 2007). Systems engineers are modularizing large systems and networks into smallish "chunks" and then working to recombine them in different ways at later times. In addition to facilitating the reconciliation of interoperability constraints, smaller chunks of technology afford increased fluidity through or around the lumbering bureaucracy of traditional acquisition. They thus facilitate the approval and acceptance process, easing the tech transfer stage of infrastructure evolution (Edwards *et al.* 2007). As one engineer explained:

> One of the most fundamental modularization practices is breaking existing large systems and networks into smaller chunks of technologies… For information systems, take on acquisitions that you can do within a year - completed within lifecycle - longevity of requirement. You basically evolve systems, pick off bite size increments. Try things and take risks and if it doesn't work, throw it out and start again.

These shorter project timelines help to avoid requirements creep and help to deal with changing constraints and policies. Sometimes this is done serially, segmenting feature development temporally into stages; other times multiple aspects are developed concurrently. And increasingly, systems engineers are willing to cancel or change projects and shorten completion times as adaptive strategies. More projects are operating on “task order” contracts which support multiple exit points where they can decide whether to renew the contract, thus allowing them to adapt to changes more readily.

Increasingly, COTS products can meet many of the government needs at lower cost and within a shorter time frame. Reliance on prototypes also helps with shortening the time-frame from requirements through development to fielding. “Prototyping is key … it is used to better capture user requirements and to validate as early as possible man-machine interface, etc.” Furthermore, prototypes and/or COTS tools may simply be re-categorized to move them into the hands of operational users in a timely fashion, circumventing the slow formal acquisition process. “Many [user groups]…are pursuing alternative interim solutions – they use the term ‘interim’ to get it approved.”

Integrating across Actors in Conflictual Fields

Once technologies and programs have been modularized, a different set of challenges emerges as the modules must be integrated back into new arrangements. The complexity of technical modules alone challenges bounded rationality; for example one of the information system cases involved consolidation of 140 different types of databases into 5 large database systems. Yet technical challenges are compounded by agonistic tensions and disagreements over how re-combinations should be accomplished; consequently engineers are developing a second set of capabilities for re-integrating modules into a coherent whole (infrastructure) that interfaces with affected organizational practices, and thus eases the agonistic tensions.

One basic integration practice involves redrawing boundaries around collections of legacy and engineering programs to forge new program identities. “Part of the strategy is naming. People get used to a name and what it means and its scope and how to communicate in their … environment.” For example, one program that had already been in existence for 4-5 years was being renamed to reflect a change of scope from an exclusive focus on military capabilities to one accommodating interoperability with other governmental elements. The new name would then support changes in the conceptualizations and practices that people associated with the system.

Engineering management practices for integration generally rely on agreements represented in schedules and documents and other boundary objects (Star 1989; Carlile 2002). Documents are commonly used for coordinating across higher-level (i.e., more “abstract”) interdependencies. For example, a Concept of Operations document (“CONOPS”) spells out the processes in which a required technology is expected to be used; and a Performance Requirements Document (“PRD”) is a written specification of what the technology should be able to do once it is built / delivered. At the lower levels, which involve tracking many more details (such as managing changing requirements and risks), interdependencies are more often coordinated with spreadsheets or databases; the Dynamic Object-Oriented Requirements System (DOORS) is one such tool.

These changes in boundaries, names and documentary objects must be linked with adjustments in complementary stakeholder practices to yield effective integration. We found that the most common approach involves a recurring series of meetings attended consistently by representatives from relevant groups, and focused on the associated boundary objects. These meetings occur at multiple levels throughout the enterprise and are comprised of representatives from various stakeholder and subject matter expert groups.[1] Depending upon the program and level of representative members, the groups may be called "boards," "integrated project teams" (IPTs), "working groups," or comparable terms.

It is in these recurring group meetings (which are usually co-present, though sometimes also use distance communication technology) that agonistic issues of inclusion/exclusion, ownership/investment, and temporal pacing arise and can be addressed through collective focus on and action involving relevant boundary objects. Agreements and decisions then represented in boundary objects can be likened to "knots in the web of infrastructure technologies and concurrent socio-institutional provisions" (Edwards *et al*. 2007: 36), tying together the different participants' orientations and technological trajectories. For example, requirements documents are important not only for managing changes to requirements, but later for traceability during testing. Similarly, architecture is "one of the key documents that can bridge the requirements to capabilities." Thus, relationships between different technological modules and temporal stages of development are bridged by "flow forward" and "trace back" of representations in the boundary objects and accountability pressures in the recurring group meetings. Across groups then, reliance on the boundary objects and upon representation in the meetings constrains and enables members of different organizational units to coordinate their practices with each other.

We found several variations of such enterprise-scale capabilities for integration. One example was called a "Capability Package." This approach unites financial, technical, and

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[1] Participants are likely to include some subset of those specified in the Prince 2 methodology (PRINCE 2009): line management, project management, resource manager, operational customer, support organization, transformation organization.

organizational dimensions of the enterprise in a single process that initiates funding and facilitates budget planning, placing financial responsibility within a single funding vehicle and a formal organizational process. It is initiated at the highest level of enterprise management, and progresses through consensual agreements to deeper levels or details; overall it is a slow process, but it generally results in consensual agreements about how to move forward with engineering decisions.

Another means for integrating a myriad of components and stakeholders is the "spiral development" model, which emphasizes iterative integration and operational testing as major linkages between technology development and fielding. This involves provisionally accepting large numbers of new candidate technologies, testing them against a baseline system in orchestrated field "experiments" involving up to hundreds of participants, and then moving forward with those technologies deemed successful. It is usually carried out incrementally and iteratively, as a process extending over multiple years with new technologies spreading out into use in managed increments according to CONOPS developed through the exercises.

And if all other integration efforts fail, a last resort strategy more in keeping with both military and traditional systems engineering approaches is to consolidate budgetary and managerial control in the office responsible for the systems engineering effort itself. The person at the head may be someone within government, called a Program Executive Officer (PEO), or JPEO (for Joint programs). Other times, a decision may be made to contract management out to a Lead Systems Integrator (LSI) or a Program Management and Implementation Contractor (PMIC). This helps to rein in divergent stakeholders; however, innovative improvisations are often still necessary, and the enforced formal hierarchy may only work for a limited time and to a limited extent before pacing tensions overtake it again.

Role of Systems Engineering Professionals: Skills for Influence

It should be apparent that developing systems engineering capabilities such as modularizing technologies and integrating re-combinations of the technologies across organizational actors with disparate viewpoints and interests requires more than technical skills. Because systems engineers on infrastructure projects work at the intersections of organizational and professional groups, they must have other skills to fill such a role appropriately. They can only lead others by example and persuasive argument, rarely with formal authority. And the skills for exercising influence are rarely taught, but necessary nonetheless.

Systems Engineers Play Ambidextrous Roles

Unlike most technical professions, systems engineers tend to be allied with, and even located within, one customer organization for a long period of time (Johnson 2003; Sapolsky 2003). Organizationally, it can be hard to distinguish the systems engineering organization from the customer organization: both could have people doing technical work and project management. Systems engineers are often located in government offices with military or civil service counterparts, and work together collaboratively with or even oversee them. They have long-term working relations, often eat lunch together and may joke about the only real difference being the appearance of their badges.[2] Some senior systems engineers talk about being "dual-hatted" which means they have one job title for their employer and another for their customer. "I am dual-hatted, I run the MITRE project that supports the JPEO and I also, from the government perspective, run the systems engineering organization for the JPEO."

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[2] As employees working on government projects, all participants wear badges indicating their personal identity and organizational affiliation.

Systems Engineers Cultivate Influence Rather Than Power

Although a few senior MITRE people are actually dual-hatted and have positions with authority in the client organization,[3] most systems engineers have individual contributor roles (presence on teams, liaison roles, etc.) within the client organization. Their influence therefore depends on their reputation and relationships rather than any formal authority. In one project, an interviewee referred to their program as an "office of influence. No budget, do not implement… no authority, but a lot of influence."

Sources of influence range from the more technical to the more interpersonal. On the more technical side, MITRE has generally been perceived by customers as objective, problem-focused, and technically-capable, and therefore trustworthy. As one interviewee said, "we do good analysis, we have good reputations so they come to us." Engineers have also generated influence through providing demos and technical "guidance."

But increasingly technical expertise is insufficient as a source of influence. "When I [first started], we did technical problem solving; now it's cultural problem solving." "Success of projects is about people. If you don't know [the right] people, you can work for a long time and not succeed." As a result, systems engineers finds themselves exercising influence and even leadership from a strategic position at the nexus of information and relationships, but without any explicit training or skill base. "I was put here [by my General Manager] for a reason and nobody is giving me a recipe. You have to do this by instinct, figure out a path to get what you want." "We try to be flexible… Listen, offer suggestions… Compromise, negotiation, alternatives… How do we go from nothing to a system of systems? Compromise is a big part of

[3] And these senior project leaders were overrepresented in our interviews.

it." MITRE systems engineers do have a significant resource in their access to information and people, and to each other: "These MITRE people at commands have a back channel, so MITRE people started hooking people up especially as doing technical design work… in trying to get command issues teed up ahead of time…"

Thus, even while systems engineers are developing new organizational capabilities which modularize technologies and contracting processes, and support integration across stakeholders in conflictual fields, the systems engineers themselves are also changing their individual roles and developing new sets of "people skills" – fairly radical for traditional engineers(!) These skills for exercising influence in a multi-stakeholder environment include listening, delivering persuasive arguments, role-taking, relationship building through competence and integrity, and negotiation (including compromising and finding win-win solutions).

Discussion

The intent of our research project was to capture the emerging knowledge among MITRE systems engineers about government enterprise engineering, in the form of capabilities, practices and skills. Our results inform knowledge in several areas: 1) the management of infrastructure technology projects, 2) emergent design and engineering of organizational enterprises, and 3) the changing role of systems engineering.

Management of Infrastructure Technology Projects

Many have noted the frequency of organizational conflicts around the development of information systems (Kling 1980, 1987; Feldman & March 1981; Orlikowski & Baroudi 1991; Latour 2005; O'Sullivan 2006). The infrastructure approach advanced by Edwards *et al.* (2007) highlights the prevalence of political tensions during the consolidation phase of infrastructure evolution – when stovepipe systems and networks are being linked together via gateways. These situations of infrastructure technology development, especially for government enterprises, require more than like-minded cooperative communities of developers as postulated by Denning *et al.* (2008). Our finding that capabilities of modularization and integration, coupled with skills for influence, are critical.

Our results extend Edwards *et al.*'s (2007) work on infrastructure development by detailing agonistic tensions which arise not just over the material and political resources comprising the infrastructure, but over the *pacing* of the infrastructure development *process* itself. It seems especially important that managers of infrastructure efforts approaching or at the consolidation stage pay attention not just to politics and budgets, but also to potential mis-matches in temporal cycles, especially between those attuned to ongoing operations, those concerned with streams of technological innovation and those emphasizing pulses of transformative change across the enterprise.

Further, our analysis revealed that agonistic tensions were more severe in cases where the differing stakeholder organizations had traditionally competed with each other, and were much more manageable when the component organizations had already established enterprise relations with each other so that the emphasis of consolidation was mainly on integrating technical systems. With respect to managing agonistic tensions in infrastructure technology projects, we would therefore expect to see significant differences between the kinds of pro-active planning ("strategy") that can be effective within mature enterprises, and the reactive, more nakedly-political strategies that arise during periods of infrastructure consolidation when enterprise leadership is contested and turbulent. In both situations, there is an increasing need to rely on modularization and integration techniques as well as to recognize the changing role of systems engineers.

Emergent Design and Engineering of Organizational Enterprises

Studies of large technical systems in situ (in organizations and enterprises) also show that it is virtually impossible to cleanly separate technical systems from organizational processes (Barley 1986; Orlikowski 1992; DeSanctis & Poole 1994; Garud & Karnoe 2003; Chae & Poole 2005; Kearns and Sabherwal 2007; Volkoff, Strong and Elmes 2007; Leonardi 2008; Rodon, Pastor, Sesé and Christiaanse 2008). Our results reinforce the findings of these studies: while it is important to plan/design for future changes, it is often not possible to predict or control the outcomes.

Our results suggest, however, that processes of emergent design and engineering can be supported through reliance on modularization and integration techniques. Modularization, such as partitioning existing legacy systems by architecture levels and application domains, facilitates recombination of technologies on a more rapid and ad hoc basis. And then, integration managed via recurrent meetings of boards, integrated project teams, and working groups focused on boundary objects at different levels enables representatives from different organizational units to communicate about interdependencies between infrastructure components and to hammer out agreements with each other that are then carried back to the different units. Continued reference to the boundary objects and representation at recurrent meetings support organizational members in staying coordinated after the agreements have been reached, as they modify pre-existing organizational practices.

Further, we suspect that pairing modularization and integration as complementary capabilities may facilitate a kind of meta-articulation at the meso-level. Together then, modularization and reintegration make it possible to reconfigure socio-technical arrangements in ways that ease the continual process of organizing and re-organizing the practices of users and developers, and their organizational units. By this we mean that constraints on change as well as agreements about it can be propagated both horizontally and vertically across multiple organizational levels, application domains, and technical dimensions on an ad hoc and relatively rapid basis, authorized through the recurring group meetings at different levels.

Because of the necessity to maintain confidentiality of case data, we do not step through a specific example of meta-articulation in this paper. However, we believe the mechanism described should be of significant scholarly and practical interest. Our view of meta-articulation is similar to Gasser's (1986) recurrently realigning lattices of constraints and relations, though ours emphasizes agonistic tensions at the enterprise level in evolving infrastructure and details specific mechanisms of alignment from an infrastructure engineering perspective. Our approach addresses issues regarding orientation and connection of stakeholders in complex engineered systems as does to Cutcher-Gershenfeld's "lateral alignment" (Cass 2005); though ours provides more detail about how this can be managed in infrastructure engineering cases. Our perspective on meta-articulation also shares the notion of hierarchical and lateral propagation of constraints with Leveson, Dulac, Marais and Carroll's (2009) systems approach to safety in complex systems, although ours privileges bottom-up practitioner-based participatory mechanisms through which design can emerge, rather than top-down designs employing formal modeling techniques.

Our work thus contributes to work on organizational design and engineering by specifying mechanisms through which components (both technological and organizational) can be modularized and (re-)integrated in order to meet emergent needs.

The Changing Role of Systems Engineers

As systems engineers are coming under increasing pressure from ever larger and more complex projects, they are grappling with agonistic tensions that prevent the kind of successful long-range planning that has traditionally been central to their discipline. They are instead developing evolutionary, adaptive capabilities for modularizing technologies and integrating them across conflictual fields of stakeholders. And at the same time, they are also learning to increase customer contact, to improvise, to influence, and to drive collaboration across sponsors.

There are thus significant findings on the *role* of systems engineers specifically, within infrastructure technology projects. Systems engineers are not often tied to one specific funder, but assumed to be available to whichever funders come out on top, which gives them some clout in helping (or hindering) competitions between funders. Concomitantly, the engineering profession experiences internal tension between coming up with the "right [technical] answer" and managing negotiation/collaboration processes with stakeholders. Systems engineers thus find themselves in a key leverage position for determining each next step in emergent organizing processes: they are technically savvy and familiar with many stakeholders while their training predisposes them to avoid taking political sides. Combining technical knowledge and familiarity with the role of honest broker across multiple stakeholders thus renders systems engineers in a position to be a “back door” for integrating across stakeholders, in ways somewhat similar to labor negotiators and international diplomats.

Systems engineers have traditionally had a professional responsibility and a unique role in terms of "systems thinking" -- trying to see the big, long-term picture primarily in terms of technical constraints within relatively stable environments. The current set of changes highlights their growing need to maintain a delicate balance between what will work technically, and what will work politically, along with what will satisfy the original basic intent of the engineering task. This requires that they listen to other viewpoints and respect other types of expertise.

Systems engineers working on government infrastructure projects therefore are developing a somewhat different skill set than the linear technical analysis of traditional systems engineering. Our results should have obvious implications for the professional training of (and curriculum design for) systems engineers, as well as for review and evaluation of their accomplishments, including the management of systems engineering programs. This suggests emphasis on new skills in role taking, conflict management, and systems thinking (cf. Sterman 2000; Davidz 2006; Atwater, Kannan & Stephens 2008). And to support these new roles and skills, there is increased need for thoughtful strategy about how systems engineering organizations can use their networks of connections to influence underlying professional organizations to build trustful networks ahead of the need for specific technological change.

Limitations and Future Research

Of course, our research is based on only five case studies within a highly constrained set of government sectors. Further, each case study is based on a small number of interviews, in most cases with only MITRE personnel rather than a sampling of stakeholders, including the users of these systems, with their various viewpoints. Thus, we have a very particular, and possibly cloudy, window into the world of systems engineers and systems integrators. We would like to see other researchers complement this work with studies of other enterprises and infrastructure technology projects.

What our study does not reveal is whether the new techniques that are being used are sufficient, assuming that systems engineers and/or others can develop the necessary skills. While clashes between organizational change and stability are commonly recognized by organizational scholars, we remain somewhat concerned that the extent of tensions between the hierarchical command-and-control culture of the military (on the one hand) and the creative destruction and fragmentation of accelerating innovation by vendors (on the other) may be stretching the limits of systems engineering and integration to the breaking point, especially in light of the path dependence that "locks in" effects of choices and can lead to dominance of inferior technologies over potentially superior solutions (Edwards *et al*. 2007: 17). Research on this would be especially important, if not also quite challenging.

Conclusion

In this paper we have leveraged practitioner perspectives to identify challenges facing systems engineers working on government infrastructure technology projects, and the capabilities and skills they are developing in response to those challenges. We found that agonistic tensions surface during the consolidation phase especially when stakeholder relations are not already well-established and, at least in our government cases, particularly with regard to the pacing of enterprise change and infrastructure development. In their adaptive response to the difficult experience of these tensions, systems engineers are developing capabilities of modularization and integration to facilitate more rapid and flexible organizing and re-organizing of combinations of technological and organizational components. Also in support of these changes, systems engineers are developing new relational skills, especially with regard to influence and functioning as a well-connected neutral third party. Whether these adaptations will be adequate to meet the challenges remains unclear at this time.

We see several possible paths forward. First, while systems engineers are not at the executive level, there may be advantages to raising their positional authority, at least of a chief engineer or project manager, and highlighting the importance of the role of "honest broker" to moderate agonistic tensions.

Second, the proliferation of agonistic tensions across the broader context within which engineering projects must be managed is a relatively new phenomenon for systems engineers and a challenge they are grappling with across many dimensions and only succeeding in some. Is there something else that should be done that isn't currently even on the menu? To what extent should changes in complementary roles, e.g., managers of systems engineers, project managers, stakeholder leaders also be evolving?

Third, perhaps more alarmingly, we note that all of these approaches can be expected to work only to the extent that there are consistent groups of stakeholders; problems remain when leadership changes in a shorter timeframe than changes can take root. Bearing in mind Ancona & Waller's (2007) work on "dance of entrainment," it is interesting to juxtapose our findings against work by Hobday, Davies and Prencipe (2005), who posit that systems integration is an organizing crux for networks of large-scale economic organization. What if a resonant frequency is being reached in tensions between innovation and integration, especially given leadership turnover in military commands and government agencies, so that agonistic fragmentation supersedes integration efforts, and large scale infrastructure crumbles? Like that of canaries in a coal mine, the experience of enterprise systems engineers may be forewarning of an uninhabitable environment. What would be our best intelligent response?

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Appendix A: Interview Protocol

Thank you for agreeing to participate in this interview. It is part of a joint MITRE-MIT research study that leverages social science to help define the discipline and advance the practice of "enterprise systems engineering." *[hand them copy of one page description of research project]* Enterprise systems engineering encompasses and enriches traditional systems engineering as it is practiced within a broader enterprise environment. <Program name> has been identified as good cases for this study. Your participation in this interview is voluntary. You may skip over any questions for any reason and you may stop at any time. Would you be willing to sign this consent form indicating you agree to participate in the interview? *[hand them consent form]*

A. Would you please tell me the name of the organization you now work for, your current position, and give me a brief overview of your role in the work of <program name>?

B. What is your Program Strategy? and what stage(s) are you in currently (planning, implementing, fielding, maintenance/evolution)? What is your development and fielding strategy and to what extent are you using prototypes, experiments, and betas?

C. What engineering processes do you use?
   How do you do requirements?
   How do you do software design?
   How do you do software development?

D. What is your program's organizational approach (including government and contractors)?

E. How does your program deal with changing requirements and constraints?

F. How do you work with your stakeholders? Please discuss your internal stakeholders, external stakeholders, and relationships with competitors and other programs.

G. If you had to pass this project off to someone tomorrow, what (one thing) would you want them to know?

H. Is there anything else you'd like to tell me/us about the program or its current context?