Improving Interorganizational Baseline Alignment in Large Space System Development Programs

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Abstract—This research uses a case study to explore leverage in reducing "disconnects" in baselines across multiple organizations in a large space system development program. Disconnects, latent differences in understanding that can negatively affect the program should they remain undetected or unresolved, can jeopardize program targets for cost, schedule, performance, and quality. In addition to case-study analysis, we constructed and analyzed a formal dynamic model of communication effectiveness across four organizations that rely on each other for requirements and deliverables. Findings to date refute common beliefs that disconnects result primarily from external stakeholders' requirements changes and that speeding up organizational processes will reduce disconnects. Instead, analyses suggest that the greatest leverage in reducing disconnects—and therefore mitigating program risks—lies in increasing expertise, improving communication clarity, and accelerating the pace of assessing impacts from changes in other organizations' understandings and actions—but *not* accelerating the pace of *acting* on those assessments.

1. Introduction

As applications benefiting from and relying on space technology proliferate, the expansion of user communities and multiple missions for equipment increases the complexity of space-technology products and the development programs that create them. Scholars and practitioners agree that, as a program grows in complexity—organizational complexity or technical complexity—so also grows the risk that the program will not be completed to the performance and quality specified, in the time frame originally planned, for the cost initially budgeted. Common qualitative and quantitative methods of managing and mitigating risk rely on decomposing, or partitioning, a program into components and taking actions to reduce risks within each component and across component and external boundaries. The majority of risk management methods focus on identifying and controlling technical risks to delivering products that meet performance expectations on time, on budget, and with high quality. Some research on managing large product development efforts (e.g., Cooper 1980; Ford and Sterman 1998) expands that focus to address adequacy of staffing, particularly early in the project, and adverse dynamics that can result from accelerating schedule, expanding scope, or understaffing. Addressing technical, staffing, and scoping issues becomes especially challenging when the people responsible for planning and doing the work and allocating resources to the work reside in different organizations (perhaps different societal sectors), which hold different values and objectives as well as employ differing methods for getting work done. Therefore significant risks to program cost, schedule, performance, and quality often lie not only in technical interfaces but also in interfaces across disciplinary, functional, and organizational boundaries. These risks are exacerbated when, as is often the case, the existing organizational partitioning of a program's work does not parallel the technical partitioning of the program.

Resolving issues that cross disciplinary, functional, and organizational boundaries often entails engaging the social, intellectual, and financial resources of multiple organizations as well as their technical expertise. Social interdependencies can constrain financial, human, physical, and knowledge resources. Some elements of project management and risk management methods acknowledge the difficulties of integrating and managing interdependent work, and recent attention to "systems of systems" underscores the challenge of creating and maintaining coordination among program components. In many project or risk management methods, however, only a single item with a generic name such as "project team" serves as an umbrella term to remind managers to consider issues posed by 1) the expertise of program team members; 2) the physical, technical, and organizational means to communicate with each other; and 3) the adequacy of the frequency, methods, and norms used to communicate about the program's interdependent work. Even when issues that cross disciplinary, functional, and organizational boundaries are identified specifically, there is little guidance on how to handle them effectively, since most project and risk management approaches focus on processes for identifying and prioritizing issues and on how issue resolution efforts will be assigned, monitored, and reported. They do not address which activities and tools for cross-organizational and cross-component conversations, collaboration, and coordination might be applied to reduce potential misunderstandings and disconnects, and mitigate the challenges of managing interdependent work in large programs.

To address this gap in program management practice and literature, this research endeavors to identify specific sources of program risk at organizational boundaries and to identify specific actions that can reduce those risks. Using a case-study approach to understand the "disconnects" in a large software-intensive space system program, we undertook the construction and analysis of a dynamic model to represent emerging disconnects across organizational boundaries and to explore possible actions and implications for reducing risk. A disconnect, in this context, is defined as a latent difference in understanding among groups or individuals that can negatively affect the program should it remain undetected and unresolved. These discrepancies in understanding needs, requirements, specifications, designs, and products among people working on the same program can result in decreased quality, decreased performance, late delivery, and costly overruns in human, material, and/or financial resources.

In the next section, we explain the methods and data we used. In the third section, we describe the dynamic model and discuss the analyses performed. In the fourth section, we summarize the findings and draw implications for reducing disconnects at organizational boundaries in large, technically and socially complex projects. We discuss the limitations of this research and describe future endeavors to build on the work reported here and, finally, offer recommendations on how to improve cross-organizational communications.

2. METHODS AND DATA

This research is based on work at a US federally funded research and development center focused on a large software-intensive space system program. The corporation assists with federal acquisitions, large research-to-order development by private contractors on behalf of the governmental user community. Part of this assistance includes serving with military personnel in the capacity of the System Program Office (SPO), responsible for planning, managing, and executing the development program. The presenting problem from the SPO that is the focus of this study was: "How does system engineering identify a 'disconnect,' and what do we do when we find one?" Members of the organizations involved agreed that a quintessential example of a disconnect was the scenario in which:

- The contractor doing development responds to a need for change;
- The contractor and SPO Integrated Product Team (IPT) responsible for that development agree to proceed with the change "at risk" until it is formally approved by the SPO's change review board;
- The IPT (a cross-functional team with responsibility for bringing focus to critical program issues as they arise) initiates the formal approval process;
- During the approval process, stakeholders revise the content of the change;
- When the approved change is negotiated with the contractor, the contractor objects to the "changed change";
- The contractor rejects the SPO's approved change.

The contractor then faces a dilemma; does it proceed with the current at-risk work, or revert to the state of development before the need for change was identified, or craft a revised approach to at-risk work and re-submit through the IPT a change that, it hopes, the SPO will approve without "changing the change"? As discrepancies (such as the example above) accumulate, the contractor's perception of its technical baseline diverges from the SPO's perception of the approved technical baseline, and eventually a disconnect crisis, or perhaps even a contract crisis, is recognized.

We approached the research as a case study for clinical research (Schein 2000). The case study approach is especially appropriate to this context, since very large projects are seldom repeatable in scale, scope, or content, and are even seldom consistent in personnel throughout the duration of the program. The clinical research approach is characterized by client-driven needs (here, to understand disconnects) and the desire to produce research findings that the organization can act on to address those needs effectively. Schein (2000) asserts that some of the best opportunities to gain clarity and actionable insights into organizations emerge when the people doing the work seek help from researchers. The subject/client has additional motivation to provide reliable and comprehensive data because the client's agenda drives the effort to decipher what is going on and because the subject/client provides data voluntarily.

In overview, our method consisted of data collection through interviews (Eisenhardt 1989; Merton, Fiske, and Kendall 1990), grounded theory-building (Glaser and Strauss 1967), and system dynamics modeling and simulation (Forrester 1961; Sterman 2000) to test the internal consistency of the emerging theory. Although we did not conduct formal group model-building (Vennix 1996; Andersen and Richardson 1997), we found that sharing the model representation and simulations was useful in stimulating additional data collection in second-round interviews and in confirming and disconfirming the face validity of the emerging dynamic theory of how disconnects are created and how they may be alleviated to mitigate program risk. In keeping with Eisenhardt's (1989) view of case studies and Glaser and Strauss's (1967) advocated method of grounded theory-building, we overlapped data collection and analyses. We then iteratively compared evidence of the SPO-contractor "system" behavior with evidence of the structures and behaviors comprising that system to identify useful constructs for investigation and to understand the "why" underlying apparent relationships. We also iteratively compared our emerging findings with conflicting and similar literature.

Data collection proceeded through 20 semi-structured interviews of individuals involved at various levels of technical and organizational responsibility in the SPO. Interviewees' years of experience in the SPO ranged from one to more than 20 years, and interviews lasted from 45 minutes to two and one-quarter hours. As analyses of the data proceeded iteratively, discussions of research-in-progress with individuals and small groups in the SPO stimulated individuals' providing additional data, which were then used to check, corroborate, disconfirm, and/or add depth to the emerging picture.

The research team constructed from interview notes an affinity diagram (Brassard 1989) that identified 103 areas of interest related to the dynamic problem of disconnects; the team then distilled from these areas of interest 11 variables believed to be key to the disconnect issue. From 10 individuals interviewed a second time, a behavior-over-time[1] graph for each of these 11 variables was elicited. The team found drastic discrepancies among individuals' perceptions of the behaviors-over-time of these key variables. Additionally, from interviews emerged themes of discrepant understandings in language critical to tracing issues across the organizations working on the program. The research team then developed a high-level semantic model representing the key language and traceability issues identified in transforming users' needs to program requirements, to specifications and to delivered products. Because of the wide discrepancies in individuals' perceptions of variables and language central to recognizing and resolving disconnect issues across the development life cycle, the research team chose to adopt a process for exploring the dynamics of creating and resolving disconnects that would build shared understanding of the complex baseline change process as the research progressed.

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[1] A behavior-over-time graph captures an interviewee's perception of how a variable has changed in the past as well as how it is expected to change in the future. (See Wolstenholme 1994; Sterman 2000.) These graphs often reveal implicit assumptions about trends playing out over a long period in the organization. We elicited behavior-over-time graphs of intangible variables (which we normalized on a scale from 0 to 1), such as management expertise, as well as tangible and easily quantifiable variables, such as the average number of pages to review for each change proposed to the SPO's change review board. Behavior-over-time graphs are sometimes referred to as "reference modes" because the model constructed to address the problem at hand should reproduce, in internally consistent and plausibly operational ways, the patterns represented in the reference modes at each point in the time frame specified.

The organization had little experience with system dynamics modeling, and this project was undertaken as a "pilot" of the system dynamics method's ability to provide insight, which would proceed by applying the method to address a persistent problem. Because of the research project's exploratory nature, and because we wanted the research process and product to provide an accessible bridge to further learning, we chose to create a small model that could be readily and rapidly understood by people with significant time constraints.

Therefore, we chose to construct a formal dynamic model focusing not on individual change requests but on a more abstract unit of analysis, that of the organization's (initially, the SPO's and the contractor's) collective understanding of the work-to-do. As with grounded theory, a formal model can be constructed by inferring from data some hypotheses about causal relationships that generate a particular pattern of behavior observed in the field (here, significant differences between the trajectories of the SPO's understanding and the contractor's understanding of work to be done). Model-building proceeds by representing hypotheses with connected elements of model structure, simulating the structure, comparing the simulated behavior qualitatively and in degree to the behavior observed in the field, and returning to the data to refine the hypotheses represented in the model by changing its structure. In this sense, a formal model grounded in data is a nontextual expression of a theory of the cause-and-effect relationships that systematically produce the patterns of behavior observed in the data (Black 2002). In this manner, we constructed a system dynamics model (Forrester 1961; Sterman 2000) of each organization's understanding of the baseline and its perception of the other parties' baselines—and how these perceptions are altered by requirements changes or by communication with other organizations on which its work depends. Thus, the modeling focuses not on particular events of requirements changes but on the constant flow of changes in each party's understanding of the work (which can give rise to subsequent events of requirements changes and contract changes). The model attends to the interactions among organizations as they seek to "get on the same page," since organizations cannot directly observe each other's understanding of the work to be done, even when that work is specified "in black and white." Focusing on each organization's understanding of the baseline makes explicit the research team's belief that integration of thought precedes integration of systems; in other words, people (either individually or collectively) cannot effectively implement work that they have not yet consciously conceived and considered.

The first version of the model represented the interactions of only the SPO and the prime contractor. The second version of the model represented the interactions of a four-level chain consisting of the SPO, prime contractor, subcontractor, and vendor. By conducting the model-building and validation processes "transparently," with frequent interactions with interviewees and other stakeholders in multiple organizations in the SPO, the research team helped stakeholders develop a common operational language to discuss the disconnect issue under study. Through the behavior-over-time charts of their perceptions and through responses to interview questions, interviewees provided estimates of parameter values for variables representing the level of collective expertise in each organization and the clarity of communication from one organization to another. The research team first validated the model's internal consistency through iterative simulation testing. We further validated the model by showing it and a range of simulations to members of the SPO (14 individual validation sessions were conducted).[2] These interviews with people who perform and manage the work of acquisition confirmed the face validity of both the causal relationships of the model structure and the simulated patterns in the variables of interest. Following that, analyses were performed on each version of the model. These analyses first focused on identifying the sensitivity of each variable and parameter to determine its influence on the organizations' shared desire for reduced number, magnitude, and duration of disconnects, and then focused on scenarios (including combinations of variables and parameters) that led to reduced disconnects, and their implications for risks to successful program completion.

3. Model Description

The first version of the model structure (shown in Figure 1) depicts the recursive interactions between the contractor (KTR) and the System Program Office (SPO). The stocks (portrayed as boxes) represent each party's accumulated understanding of the work to do, a baseline for the work to be performed by the contractor. The "flows" (portrayed as pipes with valves) indicate that the perception of the baseline work to be performed can change, with a variable rate, based on the influencing variables (connected via thin information links showing the direction of the influence).

Starting on the right side of Figure 1, one can read the diagram as follows: The SPO’s perception of the contractor's baseline will change based on the contractor's baseline, the clarity of the contractor's communication to the SPO about the baseline, the SPO’s own expertise level in determining what the contractor's communication means, and the delays the SPO experiences in attending to and re-orienting (figuring out "therefore what?") to the baseline change based on the contractor's communication. As the SPO’s perception of the contractor's baseline changes, the SPO may change its own baseline. The change in the SPO’s baseline is influenced by its perception of the contractor’s baseline, any requirements changes coming from users or other external parties, and the SPO’s internal delays in deciding how to respond to and then act on the changes it perceives.[3] The left side of the diagram replicates the same structure of influence from the contractor’s point of view, with contractor "requirements changes" emerging from the contractor's learning about how to operationalize the desired capabilities. The resulting picture of two organizations' cycles of perceiving, orienting, deciding, and acting is one of intertwined floating goals,[4] i.e., objectives that smoothly change through time as perceptions of the required work increase or decrease.[5]

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[2] Some researchers have argued that case study, “small n” data collection and ethnographic (also called participant-observation) studies cannot yield reliable, valid data. It is important to distinguish between these issues of reliability and validity. Reliability refers to the data’s representativeness of the population at large and therefore the researcher’s ability to generalize from the sample population or behaviors studied to the behaviors or population of the world in general. Validity refers to the idea that the information gathered from the sample population indeed represents the experience of that population, however narrowly defined, in the context of the issues under exploration (Bailyn 1977). In the system dynamics modeling effort for this work, we focus on the *validity* of the model. We reason that, in the context of this problem defined by the subject/client, identification of high-leverage variables and actionable recommendations need not be generalizable to all product development programs to be immensely useful to the acquisition work under study.

[3] This conceptualization of model structure is consistent with the Sense-Interpret-Decide-Act cycle of organizational decision and action, articulated in different terms by Boyd (1992), and more recently popularized by Haeckel (1999).

[4] For more on floating goals, see Forrester (1961), Appendix E, and Wolstenholme (1994), Chapter 13.

[5] People familiar with control theory representations may recognize the causal influences on each party's perception of the baseline as the common formulation for auto-correlated noise. Unlike many model implementations of noise, however, the variables associated with noise have

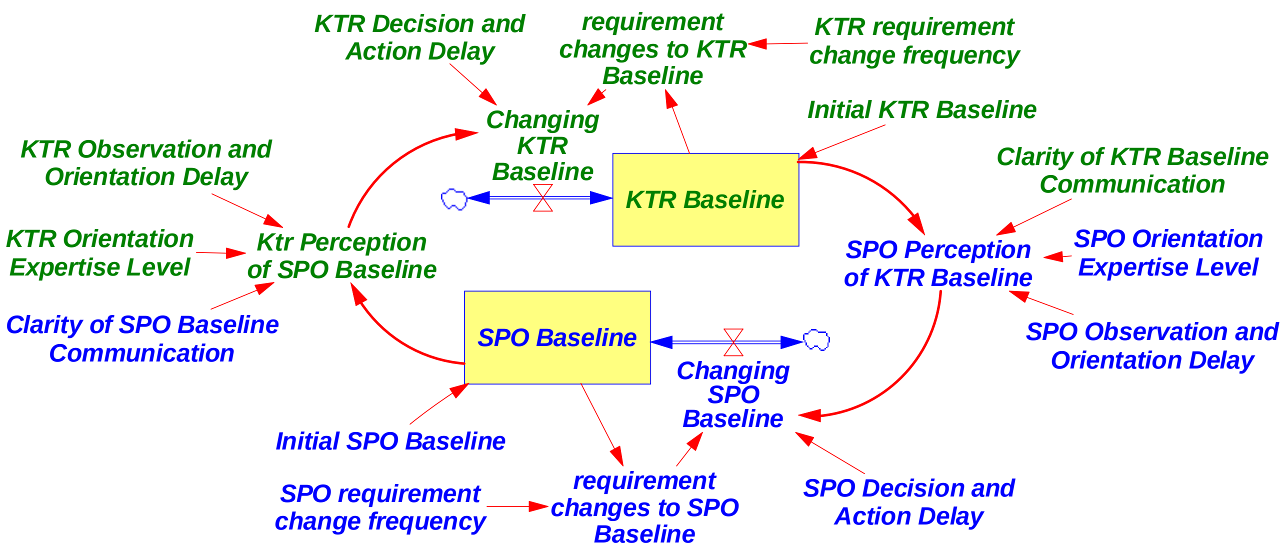

Figure 1: The SPO-contractor Model

The second version of the model replicated these structures for two additional players, a subcontractor (SUB) and a vendor (VEN), and linked them to the contractor and SPO. In this second version, the SPO interacts with the contractor as represented above; the contractor interacts with the subcontractor and the subcontractor interacts with the vendor in the same intertwined floating-goal structure. Because representing four organizations in a chain of intertwining floating-goal structures is visually unwieldy, Figure 2 shows the structure that is arrayed (with different parameters) for each of the four players. In Figure 2, one can imagine a "stack" of baselines, with the SPO on top, the contractor next, then the subcontractor, and last the vendor, with each organization interacting with the one or ones adjacent to it. The research team came to call this four-echelon structure the "intellectual-capital supply chain" indicating that members traffic, not in material goods, but in intellectual capital and the outputs of knowledge work.

In the model, each organization experiences "shocks" to its perception of the baseline, produced in the simulation by random-number generators based on normal distributions, with parameters for the mean, minimum, maximum, variance, and frequency of the shocks varying across the organizations represented. Although identical structurally (not numerically), we interpret the shocks differently for different organizations. The shocks experienced by the SPO, for instance, we represent as requirements changes, which, though infrequent, shift substantially the SPO's understanding of the baseline. The shocks experienced by the contractor, subcontractor, and vendor, on the other hand, we view as "learning," as these organizations try to construct an operational deliverable from the requirements and specifications. These small perturbations to each organization's understanding of the baseline take place much more frequently, as each one

real-world analogs here. We use "clarity of communication" as the (inversely related) standard deviation in the signal from one party to another, since clearer, more robust, and more specific means of communication reduce the variance between what is intended and what is actually communicated. We use "expertise level" (inversely related) as the min-max range of the random function associated with the variance in the signal, since high expertise can actively sift information and orient on the more relevant aspects of the information at hand. The "observation and orientation delay" is the correlation time in the noise function.

cycles through the weekly and monthly processes of getting work done. In each case, the parameters (summarized in Table 1) specifying the frequency and range and average of the "shocks" were synthesized from interview data about the frequency and magnitude of alterations and changes to the work emerging over time from each organization; the parameters and the model behaviors produced by them were then validated in second-round interviews. Because the purpose of this dynamic modeling is not to achieve precision in estimating each individual parameter or component but rather to examine and understand the dynamic behaviors that emerge from interrelationships *among* the components, the research team proceeded with these subjectively formulated parameter values, noting that interviewees validated them as consistent with their experiences and that the parameter estimates were fairly consistent across interviewees.

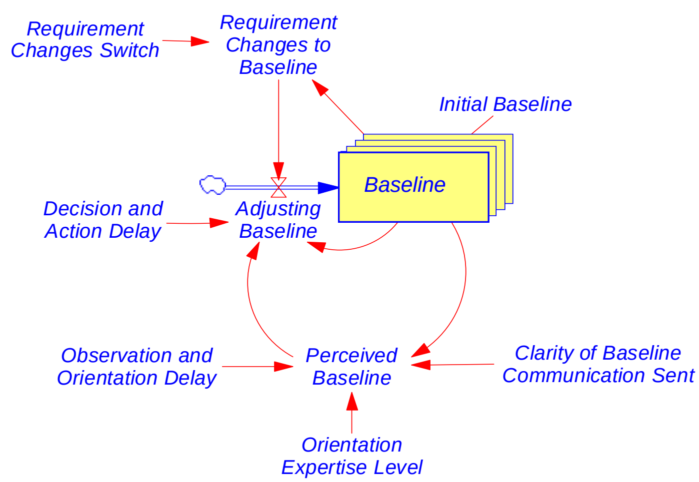

Figure 2: Representing (in array) four organizations in the intellectual-capital supply chain

As mentioned above, in the model, the SPO experiences shocks to its perception of the baseline as "requirement changes" from users, and these change the current perceived baseline value by an average of 10 percent with a frequency of every 18 months. In the model, the contractor and subcontractor experience changes to their respective perceived baselines as a result of "learning" when they try to construct operational deliverables from the requirements and specifications; these "learning shocks" alter their perceived baselines by, on average, 2.5 percent of their current baseline values with monthly frequency. The vendor experiences learning and baseline perception changes similarly to the contractor and subcontractor, except that the average change is 0.5 percent of the current baseline value, and changes occur once every 12 months. As stated above, these representations in the model reflect the research team's understanding, based on interviews, of the scope of work and frequency of "shocks" to each player's understanding of the baseline governing its work.

Given that this analytical effort is focused on dynamics across the intellectual-capital supply chain, the research team struggled to name the units of baseline understanding accumulated and altered through the course of inter-organizational interactions; eventually we settled on "widgets" in the model, not because it is especially descriptive but because it serves to denote numerically differences in understanding across players. We established the initial baseline values as 100, 80, 70, and 60 units of understanding for the government, contractor, subcontractor, and vendor, respectively; the initial values decrease down the chain, since each player begins with an imperfect understanding of its upstream customer's needs and expectations.

We simulated the base case using the following parameter values (also summarized in Table 1). The clarity of baseline communication sent was set at 0.6, 0.7, 0.7, and 0.8 respectively, reflecting the research team's assumption that greater focus and specialization (as one moves down the chain toward the vendor) yields clearer communication. Moderate expertise for each party is reflected in organizational expertise values of 0.5, 0.65, 0.65, and 0.75, respectively, which indicates increasing expertise as each organization increases in specialization further down the chain. From anecdotal data collected from and then validated in interviews, we parameterized the observation and orientation delays as 6 months, 6 months, 3 months, and 1 month for the government, contractor, subcontractor, and vendor, respectively, and the decision and action delays as 5, 5, 4, and 1 (months), respectively. The time horizon of the simulation is 60 months.

Because the players in the middle of the chain, the contractor (KTR) and subcontractor (SUB), experience bi-directional communication because of their roles in the chain, they then must choose to whom they will listen *most* about changes to the baseline. We referred to this decision as the "listening priority"[6] and assigned values to both of the middle players of 60% listening "up" (to their customer) and 40% listening "down" (to their subcontractor/vendor) in the base case. All the model's baseline parameters are summarized in Table 1.

[6] Briefly, the listening priority indicates whether organization *i* "listens to," or (in terms of this model) perceives the baseline of and receives communication from, organization *j*. In this model, the listening priority is represented by a matrix that sets parameters for bidirectional communication between organizations adjacent in the intellectual-capital supply chain. It also establishes for organization *i* the weight given to organization *j*'s communication relative to the weight given to, say, organization *k*, to which *i* is also "listening." This represents that organizational "listening" is a scarce resource; since no organization can listen more than 100 percent, it must allocate its attention among the entities to which it is attending. In the version of the model described in this paper, only the contractor and the subcontractor have the opportunity to "listen to" more than one organization. In an extension of the model representing the intellectual-capital supply chain as scaleable, with a reconfigurable network, each organization can potentially "listen to" (and therefore be influenced by) *n*-1 organizations, where *n* is the number of organizations represented in the model.

Table 1: Summary of base case initial settings

Variable/Player	**SPO**	**KTR**	**SUB**	**VEN**
Initial Baseline	100	80	70	60
Clarity of Baseline Communication Sent	0.6	0.7	0.7	0.8
Orientation Expertise Level	0.5	0.65	0.65	0.75
Observation and Orientation Delay	6	6	3	1
Decision and Action Delay	5	5	4	1
Min Requirement Change Pct	0.00%	0.00%	0.00%	0.00%
Max Requirement Change Pct	20.00%	10.00%	5.00%	1.00%
Avg Requirement Change Pct	10.00%	2.50%	2.50%	0.50%
Requirement Change Std Dev	0.45	0.35	0.25	0.05
Requirement Change Frequency	18	1	1	12
KTR listening priority to SPO		60		
KTR listening priority to SUB		40		
SUB listening priority to KTR			60	
SUB listening priority to VEN			40	

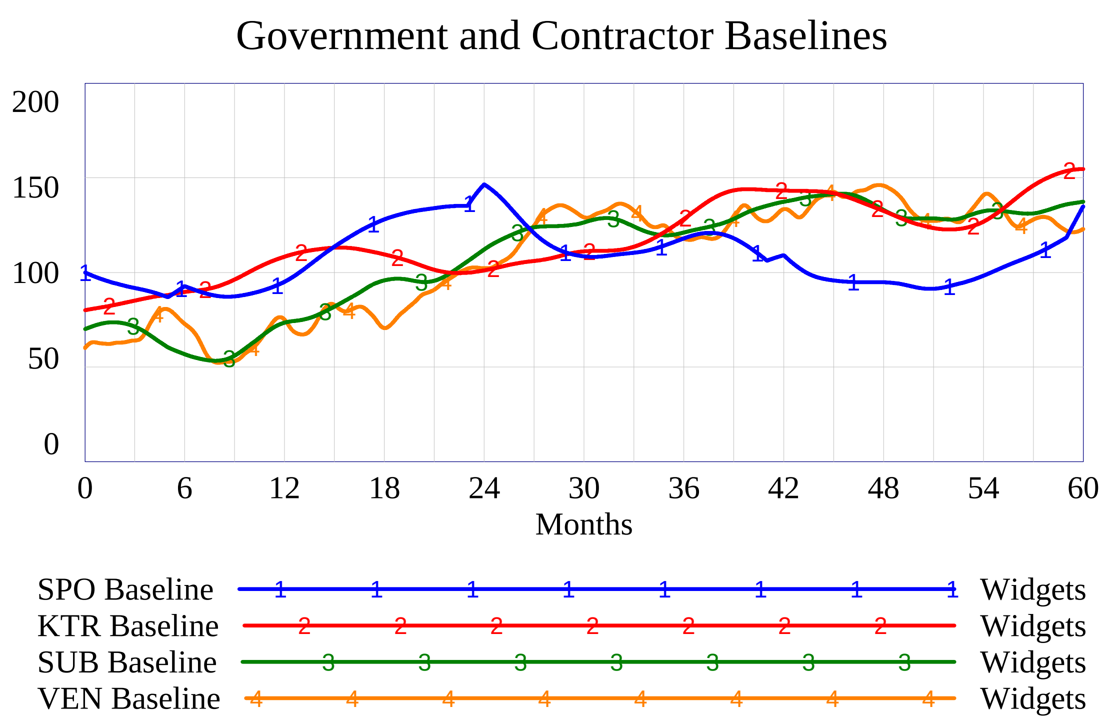

Figure 3: Base case simulation of disconnects in the intellectual-capital supply chain

The simulated interactions of the four-level model, based on the initial parameter values, produce the baseline variations shown in Figure 3. The "disconnect index" is the sum of the absolute value of the delta across the perceived baselines of communicating players over the entire simulation run.[7] The disconnect index allows us to assess the impact of one player's activity on all the parties in the chain, not merely the player with whom it is immediately interacting. Hence, efforts by one party to improve performance are measured not just by improvements for that organization but also for their direct and indirect partners as well. Figure 3 portrays that each party's understanding of the baseline varies from 50 to 150 percent of the SPO's understanding of the baseline throughout the 60 months of simulation and yields a disconnect index of about 2529.

4. Simulation Analyses

Scenario A: Turning off the "Requirements Grenades"

Many people interviewed expressed their belief that disconnects result primarily from changes in requirements made by stakeholders external to the development process. People sometimes referred to "requirements grenades," a metaphor that suggests that changes originate from somewhere far away and explode on the people who must accommodate and respond to the changes, leaving casualties and messes to clean up. The simulation model provided a way to test this commonly held belief. The resulting simulation output yielded behaviors negligibly different from (and slightly worse than) the base case scenario, with a disconnect index of 2542, compared to the base case's 2529.

The research team tested an even more extreme version of this scenario. In the simulation run shown in Figure 4, not only are all the requirements changes experienced by the SPO turned off, but also all of the "learning shocks" are turned off; in other words, no organization receives any kind of shock. Yet, the result does not differ significantly from the base case scenario. In the model, the divergence from the target baseline of 100 is endogenously generated by inadequate clarity of communication, imperfect expertise, and delays in perception, orientation, decision, and action. Thus, as reflected by the disconnect index of 2288 (a 9.5% reduction from the base case's 2529), removal of all changes does not materially reduce disconnects.

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[7] Mathematically the disconnect index is

$$\sum_{t=0}^{60} \sum_{i=1}^{3} | b_{it} - b_{(i+1)t}|$$

where t is time in months, b_{it} is the perceived baseline of the i^{th} organization at time t, and $b_{(i+1)t}$ is the perceived baseline of the organization one echelon upstream from i at time t.

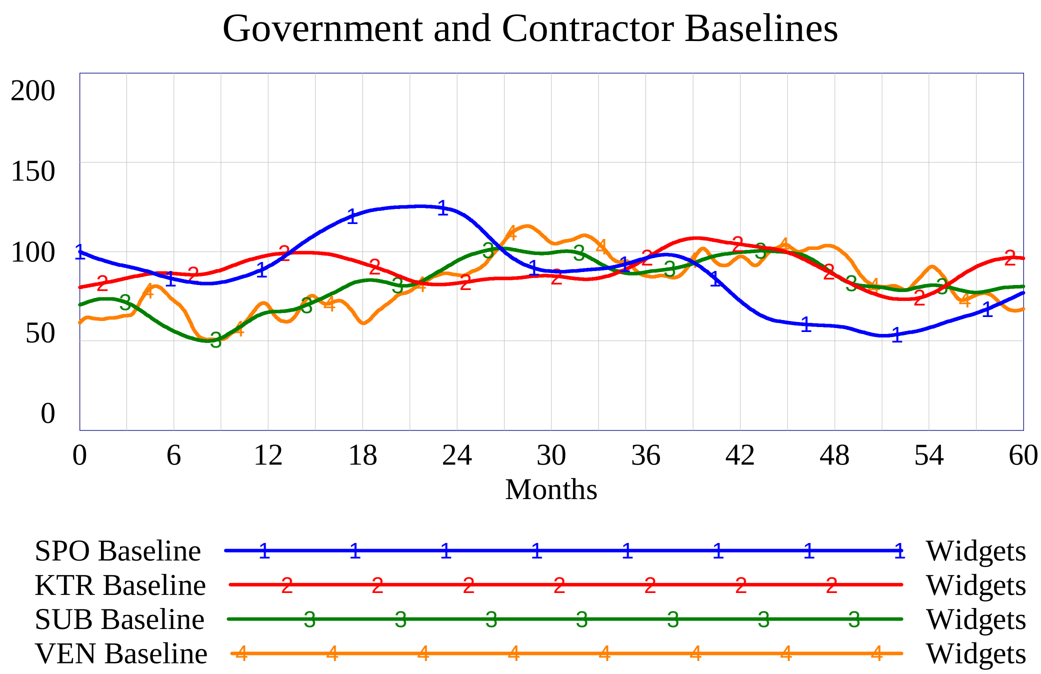

Figure 4: Turning off "requirements grenades"

Scenario B: Speeding up Decision and Action

Another commonly held belief that emerged from interviews was the notion that, if the SPO could make decisions more quickly and accelerate acting on those decisions, then fewer disconnects would result among the intellectual-capital supply chain players. In this scenario of model experimentation, we reduced the SPO's decision and action delay from 5 months to 1 month. The result, shown in Figure 5, portrays no improvement and even shows mildly worse performance (as measured by the disconnect index of 2635, 4.2% worse than the base case).

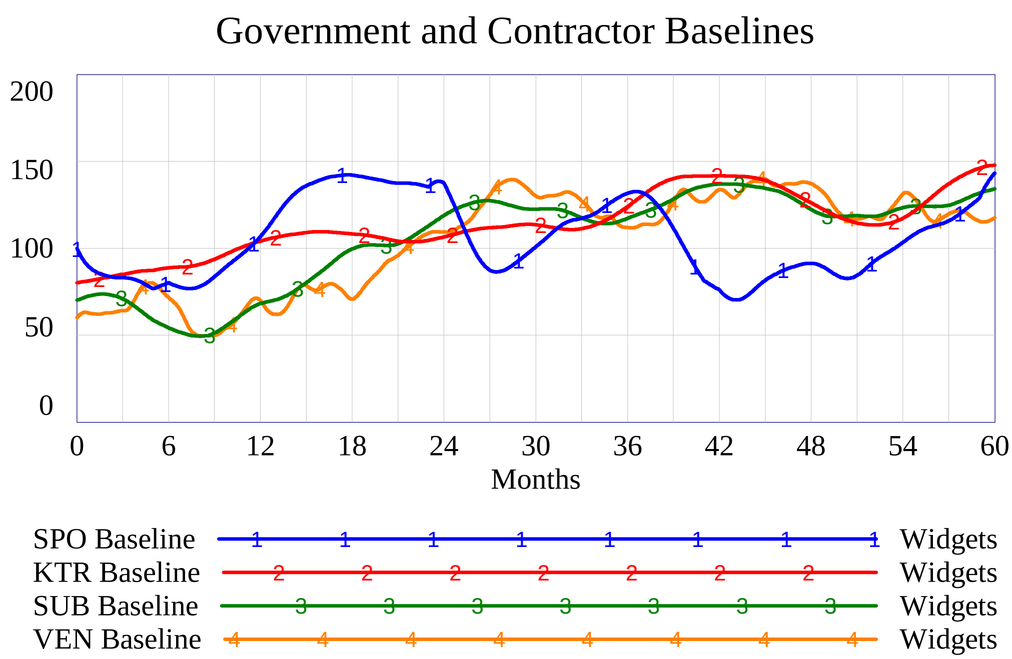

Figure 5: Speeding up decision and action

Although faster decision and action does not improve synchronization of the baseline perceptions, other simulation analyses revealed that, all else being equal, if the SPO observes and orients quickly (at a 1 month, versus the current 5 month, interval) but decides and acts relatively slowly (at the current estimate of 5 months), disconnects are reduced; that simulated scenario yielded a disconnect index of 1918, a 24.1% improvement over the base scenario. The model simulations suggest that the key to improving organizational performance—here, keeping pace with the other players in the chain—is to reduce the sense-making delay for observation and orientation relative to the rate of change in the organization's operating environment (see graphical results in Figure 6).

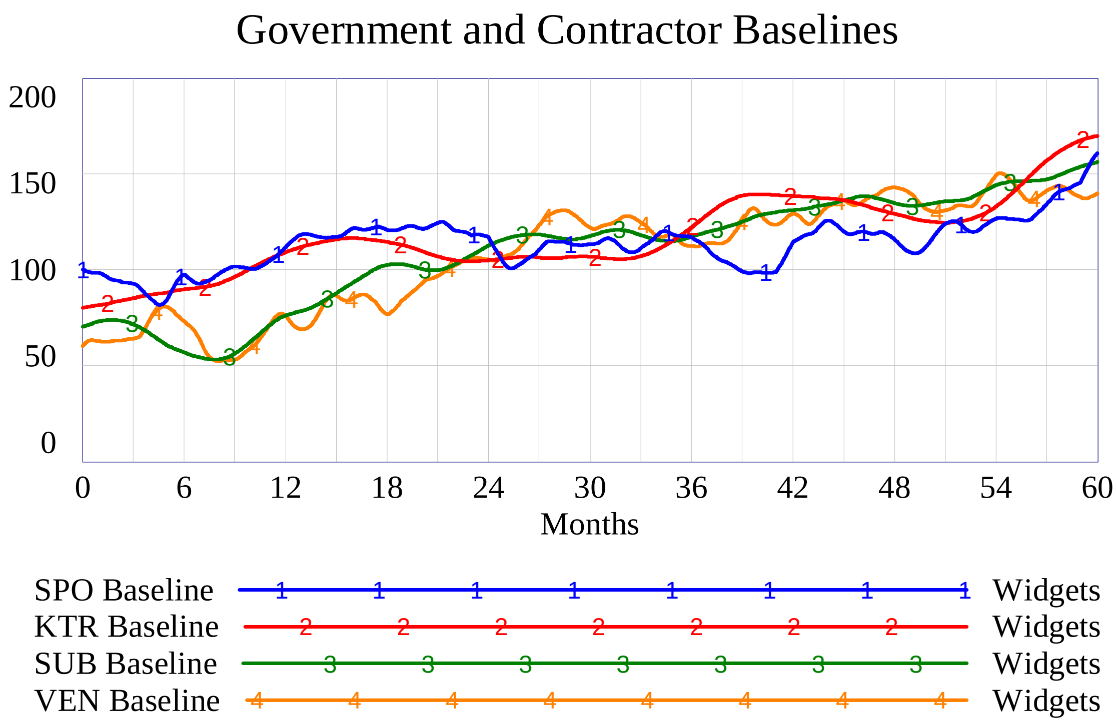

Figure 6: Fast observation and orientation and slow decision and action

Scenario C: Points of Leverage in Reducing Disconnects

We ran a series of simulations to identify points of leverage for the SPO for reducing disconnects in the intellectual-capital supply chain. We found that improving the SPO's clarity of communication (from 0.6 to 0.9) and increasing its orientation expertise level (from 0.5 to 0.75) yields a disconnect index of 1717, a 32.1% improvement over the base case (see summary graph in Figure 7).

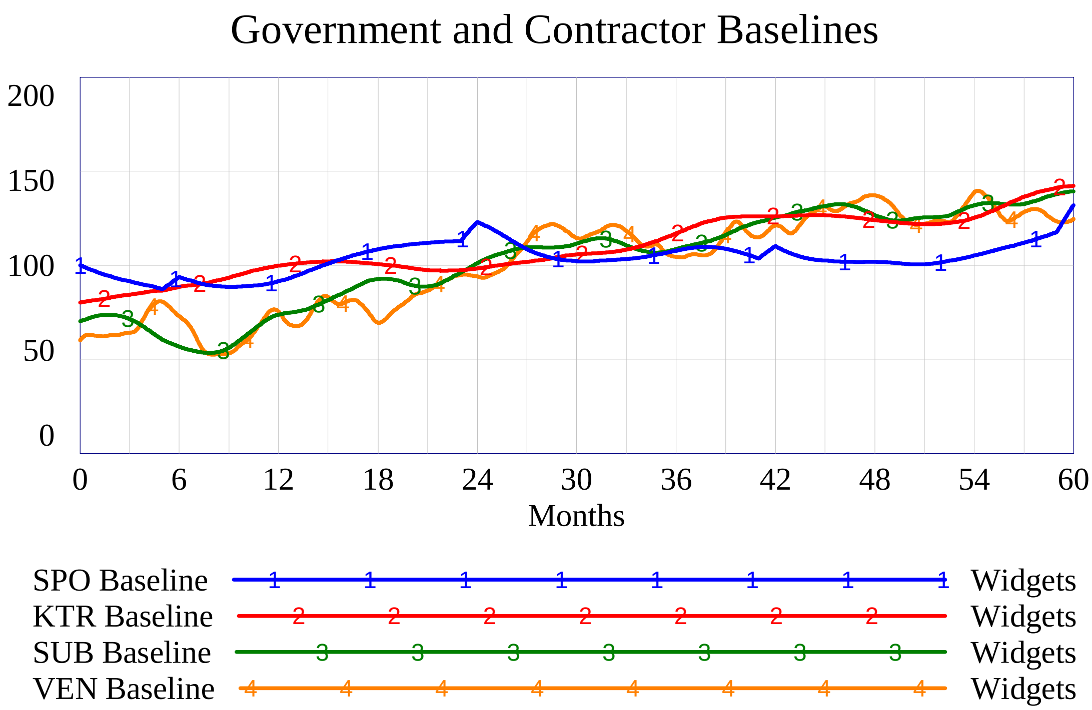

Figure 7: Higher expertise and greater clarity of communication in the SPO

If, in addition to increasing the clarity of communication and raising the expertise level of staff, the SPO also reduces its observation and orientation (sense-making) delay from 5 months to 1 month, the result is a disconnect index of 1409, a notable 44.3% improvement over the base case (see the graph Figure 8).

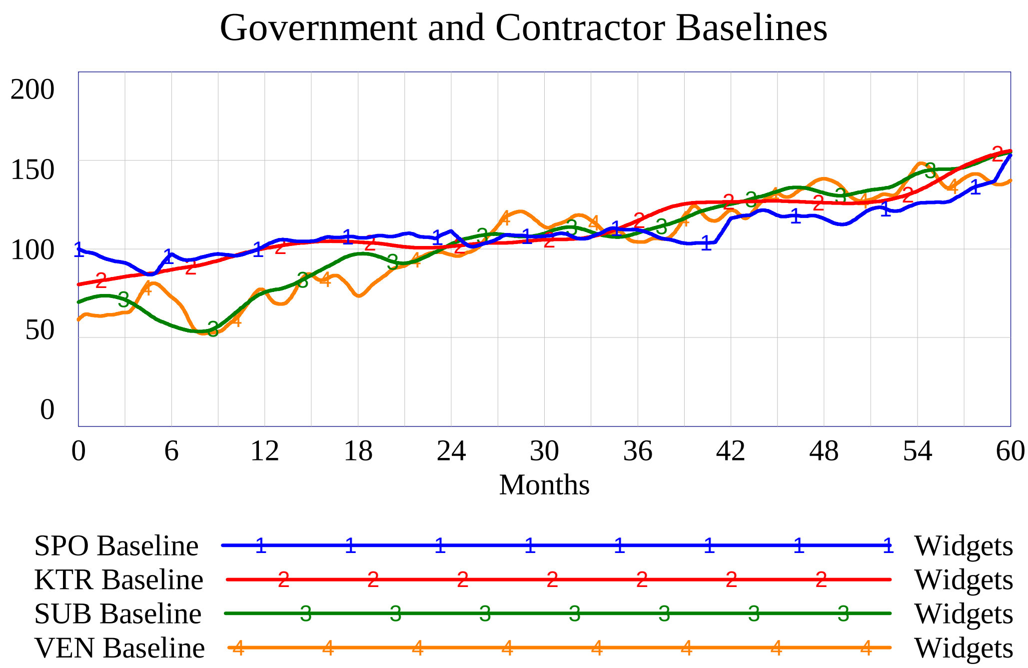

Figure 8: Greater clarity of communication, higher expertise, and faster observation and orientation in the SPO

5. Findings and Implications

Table 2 summarizes the changes to the disconnect index from the scenarios simulated.

The research to date suggests several implications for reducing disconnects and improving baseline alignment across organizational boundaries in large, complex programs. First, we must face the fact that the inter-organizational communication, coordination, and collaboration required for large development programs is a social, as well as a technical, problem. Next, interdependence among organizations means that success or failure comes to the collective, and we can proliferate misperceptions as well as good ideas as we strive to communicate. Indeed, communicating the "right things" may depend as much on the timing as on the substance of the communication. Finally, in the model, expertise is the highest point of leverage, a finding that many of us may not dispute. Considering, however, that organizational policies and practices and market dynamics may actively prevent developing and retaining the highest levels of expertise in the space system industry, we must consider alternative paths to improving communication and reducing disconnects in large programs. These alternative paths are the topic of the final section in this paper.

Table 2: Summary of effects on the disconnect index

Scenario	**Representation in Model**	**Disconnect Index**	**Percent change in Disconnect Index from Base Case**
Base case	See Table 1	2529	--
Turning off the "requirements grenades"—*including turning off "learning shock"*	SPO receives no external changes in requirements	2288	-9.5% (improvement)
Speeding up the SPO—*accelerating decision and action*	SPO reduces decision and action delay from 5 months to 1	2635	+4.2% (deterioration)
Speeding up the SPO—*accelerating observation and orientation*	SPO reduces observation and orientation delay from 5 months to 1	1918	-24.1% (improvement)
Reducing disconnects—*increasing the SPO's expertise and clarity of communication*	SPO increases its orientation expertise level from 0.5 to 0.75 and its clarity of communication sent from 0.6 to 0.9	1717	-32.1% (improvement)
Reducing disconnects—*increasing the SPO's expertise and clarity of communication and accelerating observation and orientation*	SPO increases its orientation expertise level from 0.5 to 0.75 and its clarity of communication sent from 0.6 to 0.9 and reduces observation and orientation delay from 5 months to 1	1409	-44.3% (improvement)

A "Wicked Problem"

In focusing on disconnects across organizational boundaries, we found that a large development program meets the criteria of a "wicked problem" (Rittel and Webber 1973), in which social and technical issues are intertwined and cannot be addressed separately. In a wicked problem, so many stakeholders care about the problem that addressing it is a fundamentally social, rather than technical, process. Some bellwether characteristics of wicked problems include: the problem results from an evolving set of interlocking constraints; people have trouble definitively stating the problem; and one comes to understand the problem only through the process of trying to solve it. If a software-intensive space system development effort is a wicked problem, then multiple interdependent factors may contribute to "a problem" (and people may not agree on the name, nature, or even the existence of the problem); furthermore, generating the needed multiple-dimension solution must proceed by effectively engaging many stakeholders' perspectives on the dynamic interlocking constraints. In this context, program management efforts can succeed only by representing explicitly the social as well as technical interdependencies of the program and analyzing the dynamic consequences to both the social and technical dimensions resulting from any changes to the program. Traditional organizational charts and unidirectional process flow diagrams must be augmented by tools that help stimulate productive conversations to manage social as well as technical interdependencies. These include, for example, project management tools that address dynamic resource allocation, roles and responsibilities matrices (e.g., RACI charting), and "soft" methods such as meeting and organizational change facilitation.

Proliferating Misperceptions

As players in the intellectual-capital supply chain confront the noise in the communications they receive and generate noise in the communications they send, misperceptions are not only created but also re-created or passed on. Oscillations are apparent in each party's effort to meet the target baseline. Notably, in the model, noise in the chain is generated even when there are no changes external to the SPO or generated by other organizations' learning. We may observe here a form of the bullwhip effect commonly found in material supply chains (e.g., Lee, Padmanabhan and Whang 1997). In material supply chains, oscillations are amplified in parties farther down the chain, and, in this intellectual-capital supply chain, there is increasing variation farther down the chain. Acknowledging the proliferation of misperceptions yields two implications. First, recognizing that disconnects do not arise from "out there" (particularly in the realm of stakeholders external to the SPO) will help players recognize they have the power to engage the wicked problem of disconnects. Second, recognizing that the end of the chain experiences the greatest variation in the perceived baseline (in this case the vendor, when players are listening "up" to their respective customers) will help players develop policies to dampen those variations.

Collective Performance Gain or Loss

The intellectual-capital supply chain can lead to collective performance over time that is very poor (never achieving a collective understanding of the evolving target baseline) or excellent (developing a collective understanding that evolves to exceed the initial target baseline). It is possible for collective performance to exceed the initial target baseline because knowledge and perceptions are unconserved flows.[8] Whether performance exceeds, meets, or falls short of the initial target baseline actually results from how well or how poorly the supply chain players handle the propagation of the disconnects, or learning, up and down the chain. In other words, disconnects are good when they are recognized and dealt with constructively, and disconnects are bad when they fail to be recognized or are dealt with poorly. However, in interviews, we seldom found that people framed disconnects positively (as in, "We are collaboratively learning more about the development as we iterate from abstract requirements to actual details of construction"). More commonly, people perceived disconnects negatively (for example, "What we are saying in the contract and doing in development are different; the contractor is working at risk, and we are contributing to an organizational 'lie.'"). When the parties in the intellectual-capital supply chain recognize that discrepancies can be positive (i.e., that cross-organizational

[8] To understand the difference between a conserved and unconserved flow, consider the thought experiment in which one person teaches another; if knowledge were a *conserved* flow, then the teacher would "transfer" knowledge to the student, in the sense that the teacher would *lose* the knowledge, once the student had acquired it. Knowledge, ideas, and information are examples of unconserved flows.

communication is leading to learning) they can re-cast and re-direct some of their frustration in the face of "disconnects" into creative tension and collaborative problem-solving.

Faster Not Necessarily Better

Model simulations suggested that, all else being equal, accelerating the pace of decision and action does *not* improve performance of the intellectual-capital supply chain. This has profound implications for process design and even for people's conceptions of completed work, especially in engineering cultures where perfection is often prized. Faster iterations of sense-making[9] (Weick 1979), circulating ideas that are not perfectly understood and *not* acting on those ideas too quickly, can yield improvement over processes that strive (slowly) for perfection in each step. It is clear that deciding and acting quickly on erroneous information produces poor performance. The implication here, however, is that disconnects result, not necessarily from "wrong" information, but from “right” information at the "wrong" time, relative to other players in the intellectual-capital supply chain. The temporal aspect of disconnects suggests that getting all players on the same page, at the same time, is as critical to program success as being "right." The issue thus becomes one of how to represent complex in-process work in relatively low-cost, concrete, and speedy ways, so that people doing interdependent work can interact and discuss the constraints to, and consequences of, various possible decisions. This capability would enable more productive use of scarce resources to achieve the program's aims. Although interview data indicated that text documents are commonly used to communicate changes across organizations, text is not the most powerful tool to represent complex or dynamic interdependencies. Attention to the design and use of “boundary objects” (Star and Griesemer 1989; Henderson 1991; Carlile 2002)—a sociological term for concrete objects used to communicate and transform understanding across differences in expertise, organizational norms, and time frames—becomes a point of high leverage to increase the velocity of sense-making among the supply chain players.

Expertise as a Point of Leverage

In the model simulations, no single variable materially improved overall performance; rather, sets of variables working in concert are required to reduce disconnects significantly. That said, simulations revealed that *improving expertise* provides the single greatest point of leverage. This is not easily done, as personnel turnover and reductions in force often lead organizations to lose expertise rapidly, and, once lost, it cannot be regained either through hiring or on-the-job training at the speed at which it was lost. The personnel policies of the military and the market dynamics of the defense industry actively work against retention of collectively high levels of expertise, and the challenges of sustaining expertise through a single program phase are exacerbated when we consider how to support the development and maintenance of a long-lived space program. Strategies for hiring, training, and retaining staff—and also for distributing cognition (Lave 1988) among the tools, methods, and processes used—must compensate for the policies that prevent accumulation of expertise in individuals who do not have the chance to execute a given role throughout the development life cycle. In the final section of the paper, we discuss in more detail strategies for distributing cognition to raise the overall level of expertise brought to bear on inter-organizational communications.

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[9] Observation and orientation delay is the variable in the model that refers to the individual and social process of sense-making.

Reflections on the Research Process

During this research effort, we became aware of our use of the system dynamic model itself as a boundary object. That is, we became aware that members of the SPO began to look to the model-in-process as a concrete tool showing interdependencies in their work. As they posed questions and hypotheses that led us to alter the model structure and create scenario simuluations for analyses, they effectively transformed the model; and the resulting conversations about the model structures and behaviors in turn transformed the conversations about managing the interdependencies. We believe that keeping in mind the characteristics of a robust boundary object (representing muliple points of view, depicting interdependencies, being transformable by the people involved) during the modeling process offers a valid approach to generating insights for both the research team and the members of research site. The boundary-object approach to modeling may offer ground for fruitful exploration by people interested in using modeling to facilitate organizational change (e.g. Vennix, Akkermans, and Rouwette, 1996).

6. LIMITATIONS AND CONTINUING RESEARCH

The model and analyses described above represent an effort to understand the dynamics of disconnects in a large development program through grounded theory-building (Glaser and Strauss 1967) informed by research literature. The research findings to date are limited by the single-source case study; additional case studies could corroborate or disconfirm the emerging picture of disconnects presented here, and the research team anticipates gathering data in a second space system program in an effort to deepen this study. Furthermore, any model representation of a complex situation minimizes and/or omits contextual detail that might, given a more robust understanding of variable interactions, prove significant to understanding the behavior of the intellectual-capital supply chain. Using "perception of baseline" as the primary unit of analysis is problematic, since it is hard to measure, and since an organization's perception of a baseline is almost certainly not uniform and monolithic but diverse and fragmented across different parts of the organization.

Similarly, the model simplistically represents the organizational players by focusing on the SPO communicating with one contractor, one contractor communicating with one subcontractor, who in turn communicates with one vendor. More realistic (and possibly different) dynamics may emerge from a model representing more than one player in each role, with more complex communication patterns among them. The model also assumes that the intellectual-capital supply chain has sufficient resources (in personnel, finances, and time) to perform both the work originally intended and new requirements added by external users and the learning effects of the development organizations. Finally, the model is not calibrated to data of actual disconnects (initiated, pending, and eventually accepted or rejected changes to the baseline). The model portrays the disconnect issue at a level of abstraction that may prove challenging to calibrate, because the organizations represented in the model may not collect data at the level of aggregation of the variables used. That said, the duration of the disconnects shown in the simulations does accurately reproduce anecdotal data collected in the interviews.

While some project management methods acknowledge the importance of infrastructure for communication, few have identified it explicitly as a significant point of leverage in reducing project risk or offered explicit advice on how to improve communication. Research that builds on the findings described above will explore the design and use of concrete tools to iterate cheaply and rapidly through interdependencies at a wide variety of abstraction levels, and so create communication infrastructure to mitigate risks and improve the output of programs crossing multiple organizational boundaries. Additionally, further research will explore policies that will strengthen organizational expertise sufficiently to help the intellectual-capital supply chain learn collectively and effectively. Currently the research team is building on the work described above by extending the model to represent a more fully connected network among supply chain players and exploring the limits to "cognitive bandwidth" as communications increase; constructing deeper and more explicit representations of facilitative communication across organizational boundaries; and creating a more operational view of the cross-organizational processes that create and resolve disconnects in the large complex development efforts central to space-technology programs.

7. RECOMMENDATIONS

The simulation analyses suggest three points of leverage for reducing the number, magnitude, and duration of disconnects: increasing expertise; improving clarity of communication; and accelerating observation and orientation of other organizations' changes in understanding of the baseline. The simulations do not, however, provide insight into *how* to act on or exercise these points of leverage. To create actionable recommendations for the SPO based on these findings, we draw on additional research on individual cognition (Lave 1988) and knowledge-work in organizations (Leonard 1998; Nonaka and Takeuchi 1995; Carliile 2002). Below, we suggest that improving processes and boundary objects—elements in the distributed cognition of the SPO—effectively exercises these three points of leverage in reducing disconnects and thereby mitigating risks and improving performance in organizationally and technically complex development programs.

Increasing Expertise

We often think of expertise in terms of its collective inflows to, and outflows from, an organization—that is, to increase expertise, an organization can hire individuals with higher levels of skill, or it can retain the most skilled employees who are otherwise exiting. Lave's (1988) research on individual cognition, however, points out that cognition is not only "in our heads" but distributed across what we know intellectually, the activities we engage in as we "think," and the locations—including the tools and processes tied to a physical space—in which we do those activities.[10] Since the military's personnel rotation policies and the aerospace industry's consolidation may practically limit the customary human resource levers of hiring and retention available to the SPO, increasing expertise in the SPO may rely most on improving the tools and processes for managing not only the technical aspects but also the social dimensions of acquisition work. Readily available resources that can help accomplish this include more *visible* use of existing project management tools and resource allocation tools to draw attention, energy, and focus to complex cross-boundary issues; roles and responsibility charting, which depict the

[10] When cast in light of "distributed cognition," acquisition reform of the 1990s, which eliminated many processes and communication tools within the SPO and across the SPO-contractor boundary (and obstructed the SPO's visibility into development work of subcontractors and vendors), effectively *reduced the expertise* that the SPO could bring to bear on acquisition work.

nature of stakeholders' involvement (responsible, accountable, consulted, or informed) in work breakdown structure elements; and a wider and deeper repertoire of meeting planning, executing, and follow-up tools and facilitation skills.

Clarity of Communication

Increasing the clarity of communication relies foremost on building better boundary objects (Star and Griesemer 1989; Henderson 1991; Carlile 2002). Unfortunately, to date, no documented methodology for building robust boundary objects exists, though Carlile (2002) has identified the following characteristics of useful boundary objects: They *provide representations* of what people on either side of the boundary know about the issue at hand; they *depict dependencies* in the work across the boundary; and they *are transformable* by people on both sides of the boundary. One can consider blue-prints in home construction as playing the role of a robust boundary object; they represent the spaces the homeowner will occupy as well as the engineering, materials, plumbing, and electrical dependencies, which suggest both opportunities for and constraints to emphasizing certain physical or functional features of the actual physical dwelling. In contrast, a several-hundred-page *text* specification would provide a poor boundary object for the stakeholders in home construction. By studying project documentation and interview data and analyzing examples of successful and failed efforts to communicate across boundaries, the research team has generated some hypotheses, which it hopes to integrate, build on, and test in subsequent research that may culminate in a boundary object method. Those hypotheses are:

- A robust boundary object is useful because it is an impoverished replica (Lonergan 1992)—that is, because it *omits* information not salient to the interdependencies at issue.
- By omitting detail complexity and retaining interdependence complexity, a boundary object allows parties to manipulate and trade off the consequences of various interdependencies in a less costly abstract model, rather than experimenting in real time on the assets of the organization.
- When the dimensions of an issue remain constant across a boundary (for example, square feet, across the homeowner-builder boundary, or lines of code across the SPO-contractor boundary), a static boundary object can be sufficient to help the parties negotiate interdependencies across the boundary.
- When the dimensions of an issue change units across the boundary (for example, square-feet into cost dollars across the homeowner-builder boundary, or person-hours into lines of code, or cost dollars into weeks of schedule extension, across the SPO-contractor boundary), a dynamic boundary object, such as automated project management tools or other kinds of simulation, are needed to negotiate interdependencies across the boundary.

As a facilitator of complex cross-organizational development processes, the SPO can provide critical points of leverage in reducing disconnects in software-intensive space system acquisition programs by developing expertise in creating and using robust boundary objects in all parts of the intellectual-capital supply chain.

Accelerating Observation and Orientation

Robust boundary objects can also reduce the SPO's observation and orientation delay, if they are easily *accessible* to all parties and sufficiently *low-cost* (in time, as well as other resources) to permit iterative use. From hand-drawn diagrams showing physical or logical interdependencies (e.g., DeMarco 1979) to spreadsheet simulations and more sophisticated tools dynamically portraying at a variety of levels of abstraction the consequences of interdependencies (e.g., Koo 2005), effective boundary objects help people hear (observe) and assess the implications of (orient to) communications across organizational boundaries. By iterating through the implications of changes or new information *multiple times* using boundary objects *before* acting on that information, the SPO can improve its ability to assess quickly the "so what?" of communications as well as the effectiveness of its actions, through multiple scenarios, since orienting more effectively reduces the number of times it acts on erroneous information.

CONCLUSION

In software-intensive space system acquisitions, disconnects, or latent differences in understanding that can negatively affect the program should they remain undetected or unresolved, can jeopardize cost, schedule, performance, and quality targets. This research undertook a case study approach to building a formal dynamic model of communication effectiveness and delay across four organizations that sequentially and iteratively rely on each other for requirements and deliverables. After analyses through multiple simulations, findings to date refute the common beliefs that 1) disconnects are primarily the consequence of requirements changes from external stakeholders and 2) speeding up organizational processes will reduce disconnects and allow organizations to keep their respective understandings of the baseline synchronized. Instead, the analyses suggest that the highest points of leverage in reducing disconnects—and therefore mitigating risks to program cost, schedule, performance and quality targets—lie in increasing the expertise levels, improving communication clarity, and accelerating the pace of assessing the impacts of partner organizations' activities and understandings—but *not* accelerating the pace of acting on that information.

Through this research, we have come to believe that disconnects are caused by ineffective and slow social construction of solutions, *not* by changing requirements. Rapid program-wide sense-making of changes is critical because disconnects can become wicked problems when they are not quickly resolved. We believe that boundary objects are a significant point of leverage to enable improved collaborative performance.

While, in general, the research and development community has excelled at solving technical problems, historically it has placed much less emphasis and few resources on addressing problematic social aspects of technical challenges. Managing complex development programs across multiple organizations depends, however, on successful navigation of social, as well as technical, complexities, and programs must accept responsibility for how quickly and effectively they socially construct solutions. The research described here draws from diverse disciplines of dynamic modeling, sociology, and information systems, as well as from a variety of research methods. This may indicate that similar breadth of disciplinary tools and skills is needed to build more effective management methods for the socially and technically complex "wicked problems" of large-scale software-intensive space systems.

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