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Addressing Risk in the Acquisition Lifecycle With Enterprise Simulation

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Preface & Acknowledgements

Welcome to our Ninth Annual Acquisition Research Symposium! This event is the highlight of the year for the Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) because it showcases the findings of recently completed research projects—and that research activity has been prolific! Since the ARP's founding in 2003, over 800 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 60 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

We generate this level of activity in three ways. First, we solicit research topics from academia and other institutions through an annual Broad Agency Announcement, sponsored by the USD(AT&L). Second, we issue an annual internal call for proposals to seek NPS faculty research supporting the interests of our program sponsors. Finally, we serve as a "broker" to market specific research topics identified by our sponsors to NPS graduate students. This three-pronged approach provides for a rich and broad diversity of scholarly rigor mixed with a good blend of practitioner experience in the field of acquisition. We are grateful to those of you who have contributed to our research program in the past and hope this symposium will spark even more participation.

We encourage you to be active participants at the symposium. Indeed, active participation has been the hallmark of previous symposia. We purposely limit attendance to 350 people to encourage just that. In addition, this forum is unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. Seldom will you get the opportunity to interact with so many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. In the words of one senior government official, "I would not miss this symposium for the world as it is the best forum I've found for catching up on acquisition issues and learning from the great presenters."

We expect affordability to be a major focus at this year's event. It is a central tenet of the DoD's Better Buying Power initiatives, and budget projections indicate it will continue to be important as the nation works its way out of the recession. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you're a practitioner or scholar, we invite you to participate in that research.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the ARP:

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- Program Executive Officer, SHIPS
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We also thank the Naval Postgraduate School Foundation and acknowledge its generous contributions in support of this symposium.

James B. Greene Jr.	Keith F. Snider, PhD
Rear Admiral, U.S. Navy (Ret.)	Associate Professor

Panel 3. New Approaches to Reducing Risk in Acquisition Programs

Wednesday, May 16, 2012	
11:15 a.m. – 12:45 p.m.	**Chair: Dr. Jomana Amara,** Associate Professor, Naval Postgraduate School ***Data-Driven Monetization of Acquisition Risk*** Katherine Morse and David L. Drake *The John Hopkins University Applied Physics Laboratory* ***Capability and Development Risk Management in System-of-Systems Architectures: A Portfolio Approach to Decision-Making*** Navindran Davendralingam, Muharrem Mane, and Daniel DeLaurentis *Purdue University* ***Addressing Risk in the Acquisition Lifecycle With Enterprise Simulation*** Doug Bodner, *Georgia Institute of Technology*

Jomana Amara—Dr. Amara, PhD, PE, is an associate professor of economics at the Defense Resources Management Institute at the Naval Postgraduate School in Monterey, California and a Fulbright Scholar. Dr. Amara worked with Shell Oil before joining the Naval Postgraduate School. She currently researches and publishes on international economics, defense economics, health economics, and the economics of the public sector. She has addressed various national and international academic organizations, institutions and conferences. Dr. Amara is the author of the forthcoming book *Economic Development and Post Conflict Reconstruction and* co-editor *of Military Medicine: From Pre-Deployment to Post-Separation.* She has published in numerous peer-reviewed journals. Dr. Amara is a member of the American Economic Association (AEA) and the International Institute of Strategic Studies (IISS). [jhamara@nps.edu]

Addressing Risk in the Acquisition Lifecycle With Enterprise Simulation

Doug Bodner—Bodner is a senior research engineer in the Tennenbaum Institute at the Georgia Institute of Technology. His research focuses on computational analysis and decision support for design, operation, and transformation of enterprise systems. His work has spanned a number of industries, including automotive, electronics, energy, health care, military acquisition, paper and pulp, semiconductors, and telecommunications. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and the Institute of Industrial Engineers (IIE), and a member of the Institute for Operations Research and Management Science (INFORMS). He is a registered professional engineer in the State of Georgia. [bodner@gatech.edu]

Abstract

Defense acquisition is characterized by significant levels of risk throughout the lifecycle. Risk, of course, may result in undesirable outcomes. Deriving from many sources, both technical and organizational, risk is inherently a sociotechnical phenomenon in enterprises such as acquisition. As such, it is difficult to address. At the same time, fiscal pressures are causing decreased funding and increased expectations for acquisition performance. This points to the importance of risk characterization and mitigation. Our previous work has focused on using simulation to model and analyze acquisition processes and incentives in order to understand how they can be designed to improve outcomes. Traditional simulation analysis is not well suited to modeling the sociotechnical complexities of risk in a systematic way, though. This paper presents a decision/event network construct implemented within enterprise simulation models to represent the complexities of risk over time. The F-35 Joint Strike Fighter program is analyzed with respect to risk and potential outcomes using this enterprise simulation framework that accounts for sociotechnical phenomena. Risk mitigation strategies are identified and presented.

Introduction

Defense acquisition is characterized by significant levels of risk throughout the lifecycle of new system development, production, and sustainment. Fundamentally, risk results from the combination of an uncertain future (probabilities) and its potential bad outcomes (magnitudes). Classic risk drivers in acquisition include immature technologies, overly optimistic baseline cost and schedule estimates, overly stringent requirements, poorly understood implicit requirements, and changing missions and environments. Increasingly, risks come from new sources, such as fiscal pressures on government spending and transformative initiatives in the acquisition enterprise.

This paper presents an enterprise simulation approach to analyzing risk in major acquisition programs. This approach models interactions between forms and agencies within the acquisition enterprise, and it also includes a decision/event network that is issued to characterize the relationships of risk drivers to outcomes. The approach is used to model the acquisition of the F-35 Joint Strike Fighter, a large-scale acquisition program that has seen effects from risk. This program is currently in a combination of system design and development, and low-rate initial production.

The remainder of this paper is organized as follows. The next section describes enterprise simulation in the context of risk analysis. Then the F-35 program is discussed, with a particular focus on risks and current outcomes. An enterprise simulation model of the F-35 program is presented next. Risks within the model are analyzed and discussed. Finally, conclusions and future research are presented.

Simulation of Acquisition Programs

Computer simulation has traditionally been used to assess system performance during design and operation. One widespread use of simulation has been in manufacturing, as a means of predicting such metrics as throughput and cost for a factory system (Smith, 2003). Simulation enables the analysis of behavior and performance over time, taking into account probabilistic effects (Law, 2007). Simulation can provide analysis under different system design and operating scenarios, thus enabling possible system designs or modifications to be studied prior to adoption.

In recent years, simulation has seen application in a number of additional acquisition-related areas beyond manufacturing, including supply chain design and analysis (Kleijnen, 2005), software system development (Madachy, 2008), acquisition processes (Bodner, Rahman, & Rouse, 2010; Ford & Dillard, 2009), and fleet sustainment (Smith, Searles, Thompson, & Cranwell, 2006). While these are important constituent elements of a large-scale acquisition program, there are other important elements to consider, such as the enterprise nature of the public-private partnership that comprises the program. Increasingly, firms that develop and manufacture complex products and systems employ an enterprise paradigm that involves a large number of stakeholder firms (Bodner & Lee, in press).

The traditional use of simulation has been to study the technical aspects associated with acquisition program elements. These include work processes, quality, schedules, part flows, inventory levels, bottlenecks, costs, and lead times. While this type of analysis is quite useful, it does not capture the sociotechnical aspects of the enterprise, with its multi-actor collaborations, decision-making, and risks. Recently, two related types of simulation methods have come into usage—agent-based simulation (Hillebrand & Stender, 1994; Saam & Schmidt, 2001) and organizational simulation (Nissen, 2007; Prietula, Carley, & Gasser, 1998; Rouse & Boff, 2005). Agent-based simulation focuses on the interaction of different agents in an eco-system, where agents can represent individuals or firms. For example, it has been used to model supply chain actor interactions (Albino, Carbonara, & Giannoccaro, 2007). Organizational simulation seeks to model the behavior of people and firms in the context of a world model and organizational story. A world model represents the elements internal to the organization being modeled, as well as those relevant external elements. The organizational story represents a scenario being modeled. Organizational simulation has been used to model healthcare delivery, research and development, and electronics design (Rouse & Bodner, 2009). These two types of simulation are relevant to enterprise modeling needs in studying large-scale acquisition programs. Enterprise modeling has increasingly been incorporated in simulation (Barjis, 2011; Glazner, 2011).

Enterprise Simulation and Acquisition Risk Analysis

Recent work has extended the concept of organizational simulation to an enterprise simulation framework with an agent-based model for actors and a decision/event network to represent a risk-focused way of representing an organizational story (Bodner & Rouse, 2010). Agents represent organizations (e.g., firms or agencies) that participate in the enterprise. They can perform a variety of actions in the enterprise, among them are the following:

- communicate with other agents,
- react to incentives and information,
- accrue costs,
- change variables such as schedule targets or budgets,
- progress through processes and tasks,

- restructure a program, or
- terminate a program.

Figure 1 shows an example set of interactions in an acquisition context. The government program office interacts with the lead contractor, as well as with other agencies. The lead contractor manages the contractor network. Note that some contractors may be sub-contracted to multiple contractors. In a typical major program, of course, there are dozens of agencies, some outside the Department of Defense (DoD), and there are thousands of contractors.

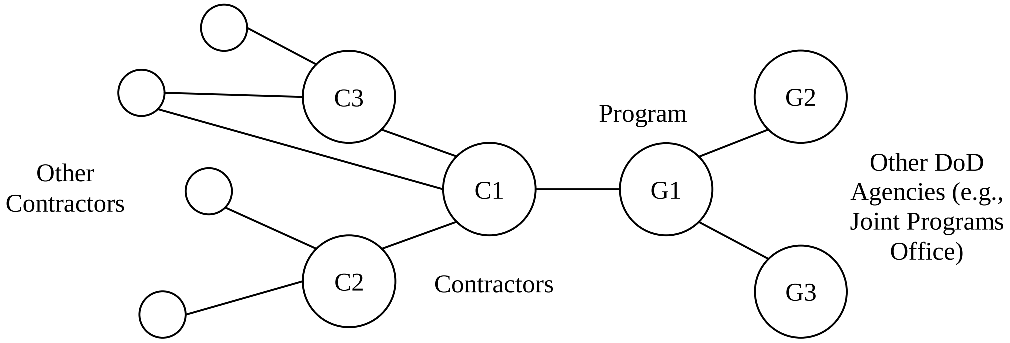

Figure 1. Example Interactions of Agents as Firms or Agencies

In terms of a risk-focused organizational story, this framework utilizes a concept from interactive drama and artificial intelligence, that of a drama manager (Roberts & Isbell, 2008). Interactive drama is a narrative implemented in computational form, similar to a game, in which a user interacts with a story. The drama manager interacts with the story flow to give the story particular characteristics (e.g., simplicity versus complexity). It does this through a construct known as a plot point model, which abstracts important events in the plot of the story. A plot point model is organized as a directed acyclic graph of plot point nodes, some of which may have precedence relationships between them (i.e., arcs), and some of which may be mutually exclusive. A precedence relationship from node 1 and node 2 (i.e., node 1 precedes node 2, or 1→2) implies that for node 2 to occur, node 1 must occur. Given precedence relationships from multiple plot points to a particular plot point, only one of the predecessor plot points needs to occur to allow the successor plot point to occur (i.e., an "or" relationship among the precedence relationships). A precedence relationship can be mandatory in that the predecessor must occur for the successor node to occur (i.e., enabling "and" relationships).

The graph is acyclic to disallow two or more plot points from simultaneously having precedence relationships among them. A terminal plot point represents an end to the story. The drama manager may influence the plot so that certain events occur (or are more likely to occur), or it may likewise prevent certain events from occurring. The particular path of plot points realized in an interactive drama reflects the instantiated plot.

Adapted to a simulation context, the plot point model (or decision/event network) is used to represent important events in the simulation that relate, for example, to risk in the unfolding simulation. Thus, the role of a drama manager (or simulation manager) in the simulation context is to guide the simulation through a particular set of decision/event nodes to reflect a certain risk profile. The outcome of the simulation can then be compared to the risk profile chosen. Figure 2 illustrates the relationships among the simulation manager, the plot point model, and the simulation. Certain events in the simulation model correspond to decisions or events in the decision/event network. However, many events and behaviors do not correspond to network nodes. Nodes 2 and 3 are mutually exclusive (only one at most may happen). Arcs 4→7 and 5→7 are mandatory precedence relationships, meaning that both nodes 4 and 5 must occur for 7 to occur.

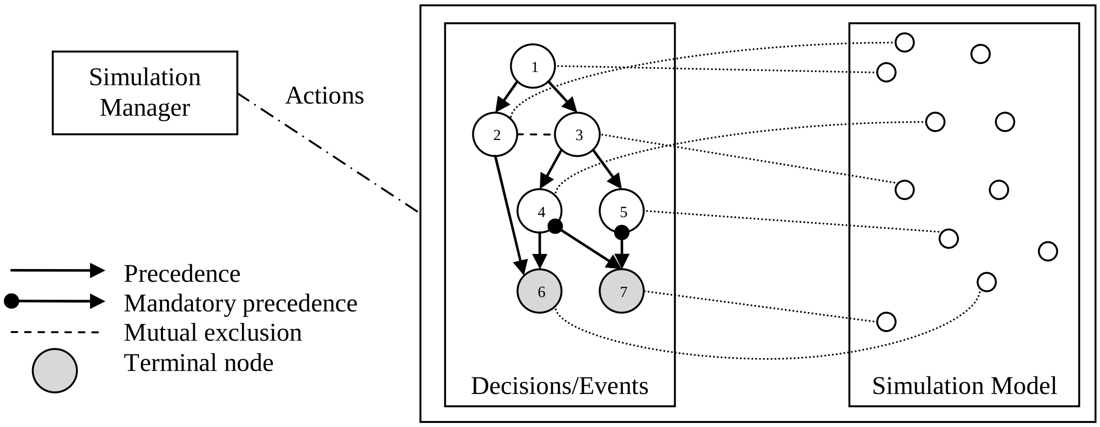

Figure 2. Simulation and Decision/Network Interaction

The decision/event network prescribes the relationships among decisions and events, not the outcome of a particular organizational story. An outcome is realized by a particular sequence of decisions and events. A valid sequence, or path, must conform to the precedence and exclusion constraints of the decision/event network, and it can have only one terminal node (at the path end). A particular decision/event network can generate many different paths. An example valid path from Figure 2 is 1→2→6, as is 1→3→4→5→7.

Given a particular decision/event network, the enterprise simulation framework conducts a pre-processing operation to determine the set of possible paths, and the result is returned in the form of a partial game tree. A game tree is a construct from game theory that defines moves that two players may make as alternating nodes in the tree. The simulation manager and simulation correspond to the two players in this context. Nodes in the decision/event network represent actions taken by the simulation (i.e., decisions and events). The simulation manager's actions are not represented in a path, as these actions are intended to influence the path followed for a particular simulation outcome. Hence, the set of paths is a partial game tree. The partial game tree for the decision/event network is shown in Figure 3.

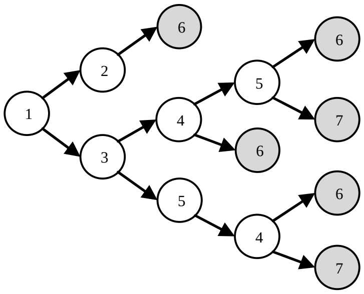

Figure 3. Partial Game Tree From Decision/Event Network in Figure 2

The simulation manager's actions are based on its evaluation function. This function is used to evaluate paths for selection of a next node in the decision/event network and a corresponding simulation manager action. For risk, the evaluation uses the expected value of a function of the program's schedule and cost outcomes for selection of the next node. This must be determined over the set of path remainders associated with each candidate next node, where a path remainder is the set of nodes comprising the rest of a particular path given a current node location.

For example, assume that the simulation has executed the partial path 1→3→4 in Figure 3. Nodes 5 and 6 are the two candidates to execute next. The possible path remainders are 6, 5→6 and 6→7. Node 6 is evaluated using simply the estimated schedule and cost values from the path remainder of itself. Node 5 is evaluated using a function of the schedule and cost values of the two other path remainders.

Of course, the simulation is stochastic, and the evaluation can only use estimates of schedules and costs. Another issue is the computational complexity associated with the evaluation over a large decision/event network. Thus, the look-ahead capability to analyze a path remainder can be limited to a certain number of nodes in the path.

The enterprise simulation modeling framework is implemented using AnyLogic™ with a set of Java class extensions for the agent models, the simulation manager, plot point models, and partial game trees. AnyLogic™ is a commercially available simulation product that supports multi-paradigm modeling using discrete-event, agent-based, and system dynamics simulation.

F-35 Program

One major acquisition program that is of interest with respect to risk analysis, and application of the enterprise simulation framework, is the F-35 Joint Strike Fighter (JSF) program. The F-35 program grew out of the need for a next generation tactical fighter fleet to replace the aging fleet of F-16s and F-18s. Due to the large size of these legacy fleets, the Joint Strike Fighter effort started as an ambitious, large-scale concept. As the program became more defined, Boeing and Lockheed Martin Aeronautics led consortia that developed concept aircraft in a competition for the system design and development (SDD) contract. When the Lockheed consortium won, the Joint Strike Fighter program entered into SDD in 2001. The initial planned procurement quantity was 2,852 planes.

The JSF actually consists of three variant aircraft (Gertler, 2012). The first (F-35A) is a conventional take-off and landing (CTOL) aircraft designed for the Air Force. The second (F-35B) is a short take-off and vertical landing (STOVL) aircraft designed for the Marines. The third (F-35C) is a carrier-suitable aircraft (CV) designed for the Navy.

The JSF program has used a transformative approach to acquisition of a major weapons system. In this context, transformation means a major change in the enterprise, moving from an as-is enterprise to a to-be enterprise, with specific intents (Kessler & Heath, 2006). The transformative elements of this approach include the following:

- Rather than the traditional command-and-control relationship between the lead contractor and its suppliers, the contract required a partnership model among three firms—Lockheed Martin Aeronautics, BAE Systems, and Northrop Grumman (Bennett, Kessler, & McGinnis, in press).
- The program was planned as a global effort, whereby design, development, and production activities would occur globally across an international consortium of firms, rather than primarily at one single site. Countries with firms represented in the consortium would be partners, agreeing to purchase F-35s (Kapstein, 2004).

- Modeling and simulation technologies have been used extensively in SDD, essentially to provide a “testing in software” capability. The confidence in this testing approach enabled substantial concurrency to be designed into the program between development and production so that production started prior to the completion of flight testing (DoD, 2011). The level of concurrency was higher than in similar programs.
- The program is developing three variants using a common platform targeting a high level of commonality of components across the three variants. The intent is to reduce cost (promote affordability) while providing aircraft to support three mission types. The three mission types require different high-level technical capabilities (stealth, STOVL, supersonic, and carrier capabilities) that historically have not been combined to this degree in a single craft or platform (Blickstein et al., 2011).
- The production supply network was planned for use by sustainment (Bennett et al., in press).

One of the first efforts in the SDD phase was to set up the global technology infrastructure needed to support the design of the F-35 among the different firms involved. This was a substantive and transformative initiative that required significant alignment among the enterprise leadership and major changes to processes among all stakeholder firms (Bodner et al., 2011). The technology requirements were challenging—providing real-time global access to the design database subject to myriad management and security constraints. The technical challenges turned out to be less difficult than the social and process changes needed. Overall, the setup of the technology infrastructure was deemed successful.

Nevertheless, such major transformative elements entail risk (Rouse, 2006), and there have been a number of less-than-desirable outcomes (and potential future outcomes) for the program.

- A reduction in planned purchases of 400 units occurred early in SDD, driving up unit costs (Blickstein et al., 2011).
- In the earlier part of SDD, there were weight and design issues that required significant additional effort to address (Blickstein et al., 2011).
- The weapons bay of the CV variant was redesigned for larger payload, resulting in the same redesign for the STOVL and CTOL variants. This redesign caused weight and stability problems for the STOVL (Blickstein et al., 2011).
- Due to schedule slippages and cost growth, the program was re-baselined in 2004 and 2007 (Blickstein et al., 2011).
- After the DoD’s Joint Estimating Team issued a report in late 2009 stating that the program would need an additional 30 months to complete SDD, the program was restructured (GAO, 2011), adding 13 months to the SDD schedule (as well as the needed funding), and withholding $614 million in award fees from the lead contractor. Three aircraft were also added to early production.
- In 2010, the program was found to have increased in cost over both the original baseline and the then-current baseline by enough that it was certified with a Nunn-McCurdy breach (Blickstein et al., 2011).
- Continued technical issues with the STOVL variant resulted in that part of the program being placed on a two-year “probation,” with its production schedule moved back (GAO, 2011).

- The U.S. government's fiscal situation has called into question whether the planned quantities of aircraft will be purchased. Already the U.K. government has reduced its planned purchases (Gertler, 2012).

Blickstein et al. (2011) conducted a root cause analysis of the Nunn-McCurdy breach and identified the following underlying risk factors as root causes:

- SDD was designed around a concept demonstrator rather than around a prototype that would have accounted better for producibility.
- The engineering strategy focused on developing the CTOL variant first, rather than tackling the more difficult engineering design and development of the STOVL.
- The original baseline was overly optimistic on cost and schedule due to assumptions on component commonality and technology integration.

These in turn drove other issues that resulted in the eventual breach. Getting the high-level technical capabilities across the variants was more technically challenging than anticipated, involving extensive trade-offs. The initial weight problems caused redesign, and these design changes had to be distributed throughout the enterprise of collaborators. Due to the large number of suppliers, this process delayed test and production and hence drove up costs. Delays also resulted in work being done with higher labor rates.

The issue of concurrency has been raised as a cause of the program's cost and schedule issues (DoD, 2011). Historical analysis has indicated that concurrency has not been a major cost and schedule risk driver (Congressional Budget Office [CBO], 1988). However, this type of analysis likely does not account for the complexity of the JSF program.

At present, the program is entering a fifth low-rate initial production (LRIP) increment that is a fixed-price contract with risk sharing between the government and contractor (Gertler, 2012).

Simulation Model

An example enterprise simulation model and associated decision/event network for the SDD portion of the F-35 program (and overlap with low-rate initial production) is now presented. This model mainly addresses the U.S.-funded portion of the JSF program. Foreign partner purchases are treated as exogenous effects.

The outcomes of interest in the simulation model relate to schedule and cost. Let i be an index for fiscal years since the start of SDD in October of 2001. Thus, $i = 1$ corresponds to FY2002, $i = 2$ to FY2003, and so on. Let j likewise be an index for fiscal years. Let k index the variants, with $k = 1$ representing the CTOL, $k = 2$ representing the STOVL, and $k = 3$ representing the CV. Finally, let l be an index for program milestones, with $l = 1$ representing preliminary design review (PDR), $l = 2$ representing critical design review (CDR) for the CTOL variant, $l = 3$ representing CDR for the STOVL variant, $l = 4$ representing CDR for the CV variant, $l = 5$ representing flight test start for the CTOL variant, $l = 6$ representing flight test start for the STOVL variant, $l = 7$ representing flight test start for the CV variant, $l = 8$ representing flight test finish for the CTOL variant, $l = 9$ representing flight test finish for the STOVL variant, $l = 10$ representing flight test finish for the CV variant, $l = 11$ representing start of the first LRIP increment, $l = 12$ representing start of the second LRIP increment, $l = 13$ representing start of the third LRIP increment, $l = 14$ representing start of the fourth LRIP increment, $l = 15$ representing start of the fifth LRIP increment, and $l = 16$ representing start of production ramp-up.

The following state variables for the program's schedule and cost targets are defined. Note that the target values can change from year to year, which occurs, for example, when the schedule targets or planned purchases are moved back.

C_{ij} = cost target in year i for development costs in year j ($)
Q_{ijk} = planned quantities in year i for procurement in year j of variant k (number of craft)
U_{ijk} = per-unit cost target in year i for procurement in year j of variant k ($)
S_{il} = schedule target in year i for milestone l (number of months since SDD kick-off)
L_l = contract cost for LRIP increment l (l = 11, 12 … 15)

State variables for program status are needed. Let q refer to the original target for the status variable, r to the current target, s to the current progress, and t to the current time (since beginning of SDD). Finally, let u denote an index for capabilities, with u = 1 being stealth, u = 2 being supersonic speed, u = 3 being STOVL capable, and u = 4 being carrier capable. The following variables are defined.

G_q = original target for completion effort of global design capability = 100%
G_{rt} = current target for completion effort of global design capability at time t (% of G_q)
G_{st} = current progress toward completion of global design capability at time t (% of G_q)
D_q = original target for completion effort of engineering design files = 100%
D_{rt} = current target for completion effort of engineering design files at time t (% of D_q)
D_{st} = current progress toward completion of engineering design files at time t (% of D_q)
K_q = original target for completion effort of software = 100%
K_{rt} = current target for completion effort of software at time t (% of K_q)
K_{st} = current progress toward completion of software at time t (% of K_q)
F_{kq} = original target for completion effort of flight testing for variant k = 100%
F_{krt} = current target for completion effort of flight testing for variant k at time t (% of F_{kq})
F_{kst} = current progress toward completion of flight testing for variant k a time t (% of F_{kq})
M_{kqu} = original target for completion effort of capability u for variant k = 100%
M_{krut} = current target for completion effort of capability u for variant k at time t (% of M_{kqu})
M_{ksut} = current progress toward completion of capability u for variant k a time t (% of M_{kqu})
P_{lq} = original target for completion effort of LRIP increment l (l = 11, 12 … 15) = 100%
P_{lrt} = current target for completion effort of LRIP increment l (l = 11, 12 … 15) at time t (% of P_{lq})
P_{lst} = current progress toward completion of LRIP increment l (l = 11, 12 … 15) at time t (% of P_{lq})
W_{kt} = current weight of variant k as a percentage of the maximum weight target at time t (%)
E = level of concurrency designed into program
H_t = current level of component commonality among variants at time t (%)
A_t = SDD cost accrual rate at time t ($ per time unit)
V_t = cumulative SDD cost accrued through time t ($)
B_{lt} = cost accrual rate for LRIP increment l (l = 11, 12 … 15) at time t ($ per time unit)
X_{lt} = cumulative cost for LRIP increment l (l = 11, 12 … 15) through time t ($)

Note that G_q is a constant and reflects an original completion effort level of 100%. The actual work to be done for completion, G_{rt}, may increase (or decrease) over time. The percentage toward actual completion is thus G_{st}/G_{rt}. The same model is used for engineering design files, software, capability achievement, flight testing, and LRIP completion. It should be noted for the capability completion variables that variables exist only for valid combinations of variant k and capability u (i.e., there is no variable for the CTOL having a carrier capability).

The actor model is relatively simple and consists of a government agent and a contractor agent. The government agent oversees the program, and the contractor agent executes the work. The government can make decisions such as program restructure or program cancellation. The contractor has parameters that govern its progress rate toward completion of the various efforts needed for the program (e.g., software). The contractor also has an alignment parameter that reflects the extent to which its executive leadership and technical management across the enterprise are aligned with a strategy to stand up the global design technology infrastructure. This parameter affects the rate at which that capability is achieved. In future versions of the model, the contractor agent will be replaced with multiple agents representing different contractor firms, and the alignment parameter will be refined so that individual firm alignments with enterprise strategy are modeled.

The decision/event model is shown in Figure 4. On the right side of the figure are various program milestones (e.g., design reviews, flight testing, and production). The left side focuses largely on decisions made by the government and contractor agents that influence program execution (e.g., program design), as well as on exogenous events (e.g., reduction in planned foreign partner purchases). The decisions on the left side reflect a number of risk drivers in JSF acquisition.

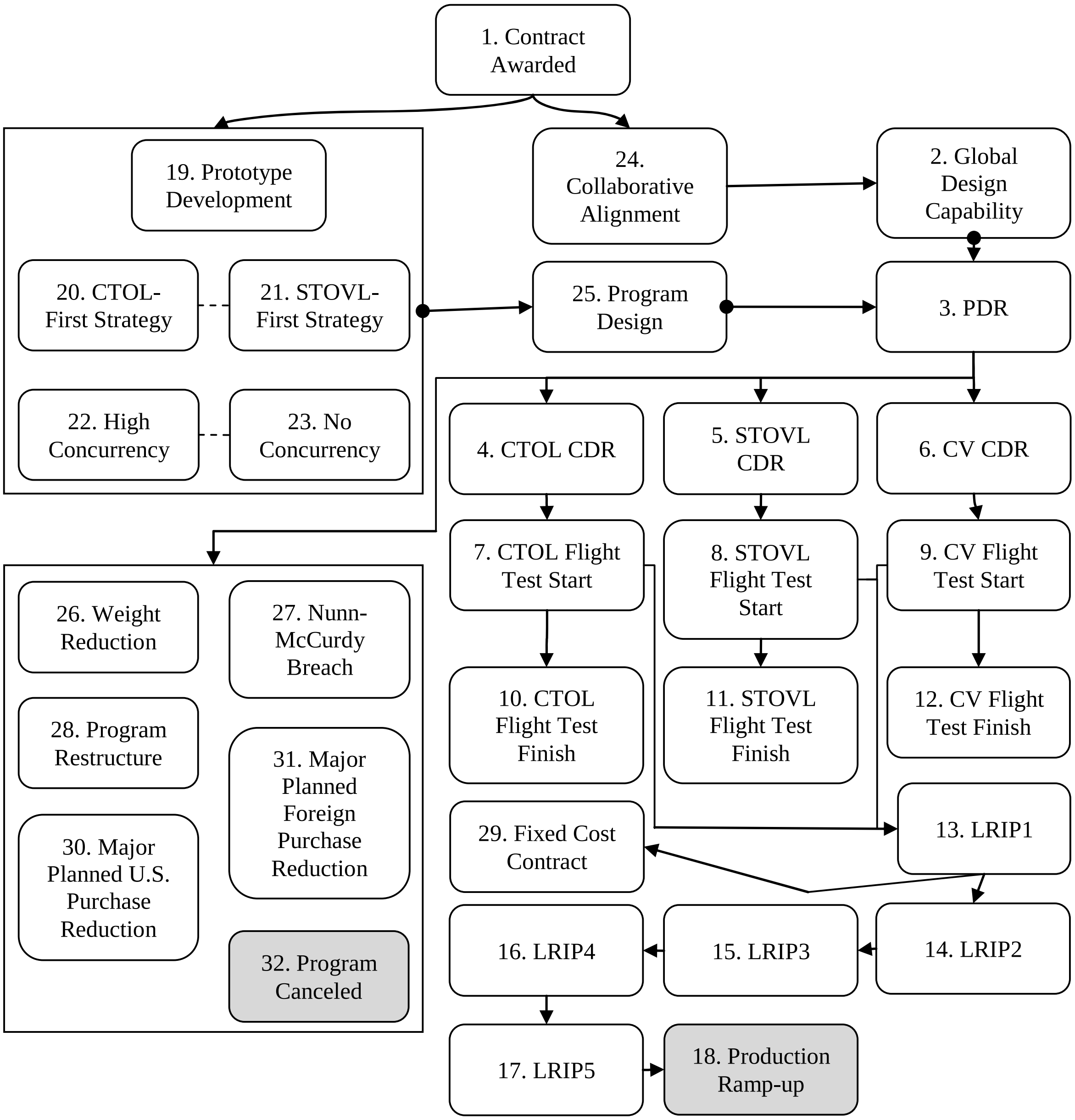

Figure 4. JSF SDD Decision/Event Network

Nodes 19–23 represent program design decisions, and they are grouped to reflect that they must be preceded by contract award, and that they precede preliminary design review (PDR). The mutual exclusion constraints mean that only one of nodes 20 and 21 and one of nodes 22 and 23 would occur to enable node 25. Nodes 26–32 represent post-PDR program management decisions. Except for node 29 (which cannot occur until after the first LRIP), they are grouped to reflect this. Table 1 describes the various plot points in more detail.

Table 1. Decision/Event Descriptions

Decision/Event Node	Description
1. Contract Awarded	SDD contract awarded to Lockheed Martin consortium. This initiates the organizational story.
2. Global Design Capability	The enterprise achieves capability to support JSF design via global technology infrastructure.
3. PDR	The program passes preliminary design review.
4. CTOL CDR	The CTOL variant passes critical design review. Note that CDR is a separate event for each variant.
5. STOVL CDR	The STOVL variant passes critical design review.
6. CV CDR	The CV variant passes critical design review.
7. CTOL Flight Test Start	The CTOL variant starts flight testing. Once again, flight tests are modeled separately for each variant.
8. STOVL Flight Test Start	The STOVL variant starts flight testing.
9. CV Flight Test Start	The CV variant starts flight testing.
10. CTOL Flight Test Finish	The CTOL variant finishes flight testing.
11. STOVL Flight Test Finish	The STOVL variant finishes flight testing.
12. CV Flight Test Finish	The CV variant finishes flight testing.
13. LRIP1	The first low-rate initial production contract is initiated. The details (cost and number of each variant) are captured in the simulation.
14. LRIP2	The second low-rate initial production contract is initiated.
15. LRIP3	The third low-rate initial production contract is initiated.
16. LRIP4	The fourth low-rate initial production contract is initiated.
17. LRIP5	The fifth low-rate initial production contract is initiated. The current model assumes only five LRIPs. In future versions, the number will be variable, with the simulation having the capability to generate LRIPs.
18. Production Ramp-up	Production ramp-up begins, ending SDD. This is a terminal decision/event.
19. Prototype Development	This represents the program enterprise decision to develop or not develop a prototype aircraft in addition to the concept aircraft that won the SDD contract. Note that an affirmative decision delays PDR.
20. CTOL-First Strategy	The program decides to design the CTOL variant first.
21. STOVL-First Strategy	The program decides to design the STOVL variant first. Note that this is mutually exclusive with the CTOL-first strategy.
22. High Concurrency	The program designs a high level of concurrency into the program. The baseline case assumes moderate concurrency.
23. No Concurrency	The program designs no concurrency into the program. Note that this is mutually exclusive with the high concurrency decision.
24. Collaborative Alignment	The enterprise achieves or does not achieve collaborative alignment on the changes needed to enable the global SDD technology infrastructure to be stood up. Achievement includes executive alignment among partner organizations, as well as technical management alignment. Achievement speeds up technology development over the case where

	there is little alignment.
25. Program Design	Program design is complete.
26. Weight Reduction	The program engages in a major weight reduction effort.
27. Nunn-McCurdy Breach	A Nunn-McCurdy breach is declared.
28. Program Restructure	The program is restructured, changing cost and schedule targets.
29. Fixed-Cost Contract	The contract moves from cost plus to fixed price. It is assumed that this cannot occur until after the first LRIP.
30. Major Planned U.S. Purchase Reduction	The U.S. decides to reduce its purchase quantity.
31. Major Planned Foreign Purchase Reduction	Foreign partners decide to reduce their purchase quantity.
32. Program Canceled	The government cancels the program.

Risk Analysis and Mitigation

Current work is addressing detailed analysis of risk in the JSF SDD phase using the enterprise simulation model. This section describes the analysis being done.

1. One set of analysis involves the effect of having a high degree of alignment among enterprise stakeholders for the strategy needed to stand up the global design technology infrastructure needed to support design efforts across the enterprise. Without alignment, this capability is delayed (thus delaying initial design activities) and may not be as effective as with better alignment, resulting in downstream design issues that must be addressed (causing increased cost and delayed schedules).
2. Another set of analysis involves program design decisions. High levels of concurrency can shorten the time until systems are produced and deployed, thus helping meet schedule targets. However, undiscovered issues may affect production and cause rework, thus negatively affecting cost and schedule. Low levels of concurrency on the surface extend the schedule beyond what is possible with higher levels, but have less risk from design issues. Similarly, producing a prototype system delays design of the real system. Is this compensated for by improvements in schedule and cost of downstream activities?
3. Finally, what is the effect of exogenous events such as major reductions in planned purchases? This tends to drive up per-unit costs, making future purchases more costly and less likely to occur.

Conclusion and Future Research

This paper has presented a novel enterprise simulation approach for analyzing risk in acquisition programs. Risk continues to be a major concern in acquisition, especially as program budgets are under increasing pressure from fiscal constraints. Simulation is appealing to use in risk analysis since it enables probabilistic analysis of system and organizational behavior and outcomes.

The enterprise simulation approach differs from traditional simulation in two important ways. First, traditional simulation approaches focus on analyzing the technical aspects of system and organizational behaviors. Increasingly, sociotechnical phenomena are important to the success and failure of large programs due to their nature as enterprises. For instance, the level of alignment among the JSF enterprise actors as to a strategy for standing up the global design technology infrastructure is an important sociotechnical behavior that influences the time needed for this activity, as well as the success of the outcome.

Second, the enterprise simulation approach explicitly models a decision/event network that can be used to link risk drivers with downstream program activities and outcomes. Traditional simulation approaches tend to model this implicitly, so that it may not be effectively modeled, and also so that the organizational story (path realization) is not explicitly presented.

Future work involves continued elaboration and validation of the model, as well as analysis of particular risks.

References

Albino, V., Carbonara, N., & Giannoccaro, I. (2007). Supply chain cooperation in industrial districts: A simulation analysis. *European Journal of Operational Research*, *177*, 261–280.

Barjis, J. (2011). Enterprise modeling and simulation within enterprise engineering. *Journal of Enterprise Transformation*, *1*(3), 185–207.

Bennett, N., Kessler, W. C., & McGinnis, L. F. (Eds.). (in press). *Enterprise transformation—Manufacturing in a global enterprise*. Amsterdam: IOS Press.

Blickstein, I., et al. (2011). *Root cause analyses of Nunn-McCurdy breaches* (Vol 1). Santa Monica, CA: RAND.

Bodner, D. A., & Lee, I.-H. (in press). Organizational simulation in support of global manufacturing enterprises. In N. Bennett, W. C. Kessler, & L. F. McGinnis (Eds.), *Enterprise transformation—Manufacturing in a global enterprise*. Amsterdam: IOS Press.

Bodner, D. A., Medvidovic, N., Lane, J. A., Boehm, B. W., Kessler, W. C., Rouse, W. B., Edwards, G., Kirkland, K., Krka, I., Podar, A., & Popescu, D. (2011). Requirements management for net-centric enterprises—Final report (Technical report SERC-2011-TR-021). Hoboken, NJ: Stevens Institute of Technology, Systems Engineering Research Center.

Bodner, D. A., Rahman, F., & Rouse, W. B. (2010). Addressing cost increases in evolutionary acquisition. In *Proceedings of the Eighth Annual Acquisition Research Symposium* (Vol. 1, pp. 329–345). Monterey, CA: Naval Postgraduate School.

Bodner, D. A., & Rouse, W. B. (2010). *Final report for "A framework and tools for organizational simulation"* [Technical report]. Atlanta, GA: Georgia Institute of Technology, Tennenbaum Institute.

Congressional Budget Office (CBO). (1988). *Concurrent weapons development and production*. Washington, DC: Author.

DoD. (2011). *F-35 Joint Strike Fighter concurrency quick look review*. Washington, DC: Author.

Ford, D. N., & Dillard, J. (2009, July). Modeling the performance and risks of evolutionary acquisition. *Defense Acquisition Review Journal*, 143–158.

GAO. (2011). *Joint Strike Fighter: Restructuring places program on firmer footing, but progress is still lagging* (GAO-11-677T). Washington, DC: Author.

Gertler, J. (2012). *F-35 Joint Strike Fighter (JSF) program*. Washington, DC: Congressional Research Service.

Glazner, C. (2011). Enterprise transformation using a simulation of enterprise architecture. *Journal of Enterprise Transformation*, *1*(3), 231–260.

Hillebrand, E., & Stender, J. (1994). *Many-agent simulation and artificial life*. Amsterdam: IOS Press.

Kapstein, E. B. (2004). Capturing fortress Europe: International collaboration and the Joint Strike Fighter. *Survival*, *46*(3), 137–160.

Kessler, W. C., & Heath, R. D. (2006). Lockheed Martin Aeronautics: Restructure and transformation. In W. B. Rouse (Ed.), *Enterprise transformation: Understanding and enabling fundamental change* (pp. 431–464). Hoboken, NJ: Wiley-Interscience.

Kleijnen, J. P. C. (2005). Supply chain simulation tools and techniques: A survey. *International Journal of Simulation and Process Modelling*, *1*(1-2), 82–89.

Law, A. M. (2007). *Simulation modeling and analysis*. Boston, MA: McGraw-Hill.

Madachy, R. (2008). *Software process dynamics.* Washington, DC: Wiley-IEEE Press.

Nissen, M. E. (2007). Computational experimentation on new organizational forms: Exploring behavior and performance of edge organizations. *Computational and Mathematical Organization Theory*, *13*(3), 203–240.

Prietula, M., Carley, K., & Gasser, L. (Eds.). (1998). *Simulating organizations: Computational models of institutions and groups*. Menlo Park, CA: AAAI Press.

Roberts, D. L., & Isbell, C. L. (2008). A survey and qualitative analysis of recent advances in drama management. *International Transactions on Systems Science and Applications*, *4*(2), 61–75.

Rouse, W. B. (Ed.). (2006). *Enterprise transformation: Understanding and enabling fundamental change*. Hoboken, NJ: Wiley-Interscience.

Rouse, W. B., & Bodner, D. A. (2009). Organizational simulation. In A. P. Sage & W. B. Rouse (Eds.), *The handbook of systems engineering and management* (2nd ed., pp. 763–792). New York, NY: John Wiley & Sons.

Rouse, W. B., & Boff, K. R. (Eds.). (2005). *Organizational simulation: From modeling & simulation to games & entertainment*. New York, NY: Wiley.

Saam, N. J., & Schmidt, B. (Eds.). (2001). *Cooperative agents: Applications in the social sciences*. New York, NY: Springer.

Smith, J. S. (2003). Survey on the use of simulation for manufacturing system design and operation. *Journal of Manufacturing Systems*, *22*(2), 157–171.

Smith, V. D., Searles, D. G., Thompson, B. M., & Cranwell, R. M. (2006). SEM: Enterprise modeling of JSF global sustainment. In L. F. Perrone, F. P. Wieland, J. Liu, B. G. Lawson, D. M. Nicol, & R. M. Fujimoto (Eds.), *Proceedings of the 2006 Winter Simulation Conference* (pp. 1324–1331). Piscataway, NJ: IEEE.

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