Architectural Framework for Addressing Legacy Waste from the Cold War - 13611

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ABSTRACT

We present an architectural framework for the use of a hybrid simulation model of enterprise-wide operations used to develop system-level insight into the U.S. Department of Energy's (DOE) environmental cleanup of legacy nuclear waste at the Savannah River Site. We use this framework for quickly exploring policy and architectural options, analyzing plans, addressing management challenges and developing mitigation strategies for DOE Office of Environmental Management (EM). The sociotechnical complexity of EM's mission compels the use of a qualitative approach to complement a more a quantitative discrete event modeling effort. We use this model-based analysis to pinpoint pressure and leverage points and develop a shared conceptual understanding of the problem space and platform for communication among stakeholders across the enterprise in a timely manner. This approach affords the opportunity to discuss problems using a unified conceptual perspective and is also general enough that it applies to a broad range of capital investment/production operations problems.

INTRODUCTION

In the aftermath of the Cold War, the United States was left with a formidable legacy of radioactive waste, the byproducts of the creation of nuclear weapons and nuclear energy research. The cleanup of this waste is a challenging proposition, as the difficult, costly, and intensive technical process for disposition of nuclear waste is further complicated by regulatory, legal, organizational, and budget constraints. The challenge for the U.S. Department of Energy's (DOE) Environmental Management (EM) Program is to better understand the myriad processes, alternatives, and policy constraints of these operations from a system perspective, allowing them to better manage the system towards program completion and facility closure on time and within budget.

To address this challenge, we present a framework for the use of a hybrid simulation model to develop system insight into the DOE's responsibility for environmental cleanup of legacy nuclear waste. We use this framework for exploring policy and architectural options, analyzing plans, addressing management challenges and developing mitigation strategies for DOE EM. The sociotechnical complexity of EM's mission compels the use of a qualitative approach to analysis to complement a more a quantitative discrete event modeling effort. We use model-based analysis to drive scenarios for the model, pinpoint pressure and leverage points and develop a shared conceptual understanding of the problem space and platform for communication among stakeholders across the enterprise. This approach affords the opportunity to discuss problems using a unified conceptual perspective and is also general enough that it applies to a broad range of capital investment/production operations problems.

This framework employs a discrete systems level simulation model, referred to as the Systems Flow Model (SFM), to perform a quantitative analysis of operating facilities at the Savannah River Site (SRS). The SFM is used in conjunction with a qualitative, causal model of system influences, which provides social, managerial and regulatory context for the quantitative analysis. When used together, the quantitative and qualitative models can be used provide a system-level perspective of SRS performance,

Footnotes:
[1] This article represents the views of the authors and has not been subject to U.S. DOE peer review. It does not necessarily reflect the views of the U.S. DOE, and no official endorsement should be inferred.

cost, and schedule that spans organizational boundaries and looks at the total lifecycle of the EM mission at SRS. This hybrid approach to system analysis can be used to quickly develop insight into system level tradeoffs, greatly reducing planning time and helping to uncover unintended consequences before they are revealed by more detailed planning, or worse, in operation. With such a simulation model and analysis framework in place, the time for a true system level analysis can be reduced from months to as little as a week.

Background

The EM mission encompasses the decontamination and decommissioning of nuclear production facilities, the safe disposal of highly radioactive liquid waste stored in underground tanks generated from reprocessing excess Spent Nuclear Fuel (SNF), the retrieval of nuclear contaminated waste buried at sites that are threatening the environment, and the burial of nuclear contaminated material that meets legal standards for final disposition.

In 1998, EM developed a "projectized" approach to cleanup, which more fully defined the life-cycle scope and cost of the EM program [1]. The Paths to Closure document marked the evolution to a more discrete project management approach for over 350 projects at DOE sites. Four years later, a comprehensive review was published [2] recommending a renewed focus on completing projects with an appropriate sense of urgency. Program management reforms focused on performance-based contracts, comprehensive risk prioritization approaches and business processes focused on accelerated risk reduction and tighter controls on cost and schedule growth.

In September 2005, the House and Senate Energy and Water Development Appropriations Subcommittees requested the National Academy of Public Administration to conduct a management review of EM [3]. The study panel investigated how EM was organized and managed its human capital, acquisition, and project management operations.

Throughout this period of internal reforms, continuous improvement, and external oversight, EM has been evolving its management practices and business systems. EM has formalized these efforts with "Journey to Excellence" initiatives to institutionalize the evolution to best-in-class processes and practices.

Objectives

The EM program scope illustrates the complex system of systems nature inherent in large-scale government programs. The program spans a long time interval, with completion estimates extending out to the 2050 and 2062 timeframe [4]. Large investment in the billions of dollars are involved. The risks are very high. Cost escalation, delays and technical problems can undermine the financial feasibility, jeopardize its completion and lead to government inquiries. Problems in any single dimension can pose substantial management challenges. The challenge for EM is to better understand the myriad processes, alternatives and policy constraints of these operations from a systems perspective, allowing them to better manage the system towards program completion and facility closure on time and within budget while meeting performance measures.

To date, DOE has reduced the sites requiring cleanup from 110 to 18, which represents a reduction in the legacy footprint from 3125 square miles to 900 square miles [5]. Despite this progress, the remaining work presents unique management, technical and stakeholder challenges. Within this mission, the chief threat to the environment, health and safety is the radioactive liquid waste. DOE currently manages approximately 88 million gallons of highly radioactive waste in 239 underground tanks. Collectively, these tanks and downstream operations are the largest cost element in the EM program [5].

The EM program prioritizes [4] activities that are projected to reduce the most curies per volume (curie is a unit of radioactivity). These activities include (but are not limited to):

- The treatment and disposal of liquid waste stored in underground tanks;
- The receipt, storage and disposition of SNF; and
- The consolidation, stabilization and disposition of excess nuclear materials.

The paper presents the influence diagrams and the model structures that are currently being applied to address these objectives.

Influence Diagrams: A Unifying Structure for Qualitative Analysis

There is a large body of work on the application of system dynamics to project management. Lyneis and Ford [6] have surveyed published literature with a focus on single projects. Very large-scale capital projects in the public sector have been singularly analyzed in a case study format [7]. We have applied these and other causal structures to identify scenarios that the model might explore. While qualitative in nature, the influence diagrams capture the relationships between key variables and formalize the mental models of decision makers and engineers. This framework is extended with the SFM to perform a quantitative analysis of operating facilities at the Savannah River Site.

This paper presents an architectural framework for exploring policy options, analyzing plans, addressing management challenges and developing mitigation strategies. This framework makes it possible to see a complex problem on a single sheet of paper and affords the opportunity to discuss problems using a unified conceptual perspective. The framework is also general enough that it applies to a broad range of capital investment/production operations problems. The causal influences also identify those feedback loops that represent significant management challenges to DOE and can be generalized to large-scale operations in both the public and private sector.

What sets this framework apart from previous work is the system of systems scale and the joint operations/capital project dependencies and complexities. The production planning and operations of existing physical facilities need to be accomplished in an efficient, timely and cost-effective manner. The physical characteristics of excess nuclear materials stocks and radioactive waste streams are dynamic and often require investments in new technologies for safe disposal.

Project outcomes need to be viewed in the context of their impact on ongoing and future operations. Today's decisions have to be evaluated in the context of a common framework that can be translated into a model to generate reliable performance measures and outcomes.

Collectively, these structures are combined into an influence diagram [8, 9]. The diagram identifies the key variables and policies, which are of particular interest to EM. At a more technical level it identifies the main features of the problem addressed by the model. We expand the influence diagram to illustrate generic operational structures at a key government site. Although the modeling activities are ongoing, the paper highlights insights gained from early results.

Qualitative diagrammatic modeling in the form of influence diagrams is used to communicate the model scope and describe the relationship between key variables in the model. Many of the key variables are explicitly modeled, however some emerge from the scenario analysis. The influence diagram is an overall system representation that can be used to design scenarios.

Physical Flow – The Route to Closure

One of EM's goals is to accelerate the cleanup and reduce the life-cycle costs of legacy materials. To achieve this goal, DOE uses legacy hardened production facilities to reprocess SNF, separate and treat waste products. There are cases, however, where new capabilities are required to treat the radioactive wastes and prepare them for final disposition. Figure 1 shows the investment and production chain associated with the transformation process. EM is responsible for dispositioning excess nuclear material stocks and non-proliferation stocks. Management allocates production resources by scheduling campaigns for these different materials. Each campaign has a distinct start and finish date and is organized into a master roadmap. With each campaign start, existing production capacity is committed for that purpose, temporarily reducing the available capacity for other campaigns. Capacity is subsequently freed when a campaign ends making Process Options available for other materials. This flexibility is shown by the influence from Available Capacity to Process Options in Figure below. Over the course of the campaigns, interim milestones mark periodic progress towards a final closure objective.

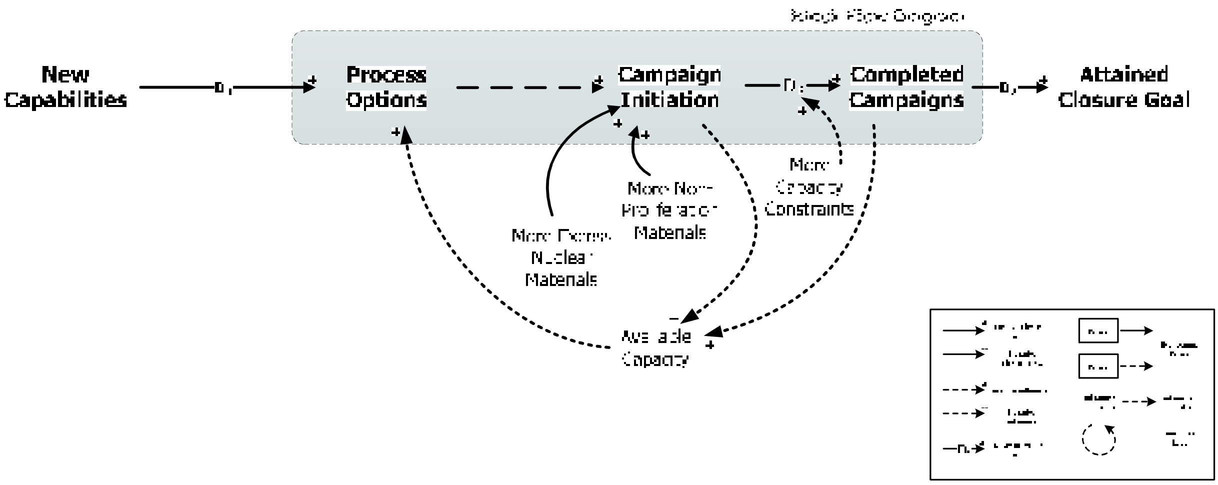

Fig. 1 Capital Investment and Production Campaigns

This planning process is straightforward for conventional materials that can be processed in existing facilities. However, unconventional materials often require capital investments with first-of-a-kind technologies. These investments can range from minor modifications to a major investment in a new facility such as the Salt Waste Processing Facility (SWPF).

Investment decisions are generally driven by production schedules and stakeholder commitments. This is more typical in the public sector in contrast to the private sector. Morecroft [10] presents three different approaches to evaluating capital investments: finance-driven, planning-driven and an operations-driven. EM typically focuses on the required capacity to meet regulatory commitment dates and projected benefits from accelerating milestones (operations-driven). This capital investment approach is a viable rationale, we simply point out that it is generally more appropriate for the public sector.

EM manages these investments to deliver performance objectives on time and within budget. Over the past five years, there has been a focus on accelerating the cleanup by compressing the roadmap plan while generally managing total program costs to a level funding profile.

Discrete Process Simulation: Building Blocks for Quantitative Analysis

While the influence diagram developed above is very useful for qualitative analysis at the system level, it requires a quantitative core that is able to translate a budget, policy and architectural alternatives into the performance of the system over a period of time. To complement the influence diagram developed for SRS, a modular, interconnected discrete event simulation was developed for site-wide operations. Key activities, ranging from nuclear material storage and separation to salt processing and vitrification were modeled at a level of abstraction that allowed the model to capture interdependencies across the system.

Each process was modeled as a modular block, which could be configured, modified, or removed in order to simulation different architectures for waste processing. Each block was modeled as a "black box" with a set of given inputs and outputs and a modifiable set of rules governing options and technological options.

To provide a useful and timely quantitative analysis capability, these blocks were assembled into an integrated simulation model of EM-related operations at SRS named the "Systems Flow Model." The Systems Flow Model simulates the flow of nuclear material across the SRS enterprise, from its original form to vitrified glass canisters in temporary onsite storage. The Block Flow Diagram, a depiction of these blocks and how they are interconnected at SRS, is show below in Figure 2. This is similar to the types of models described by Forrester in Industrial Dynamics [11]. The boundaries of the Block Flow Diagram are also shown in the shaded box in Fig 1., indicating where and how the discrete simulation model fits into the overarching influence diagram for system analysis.

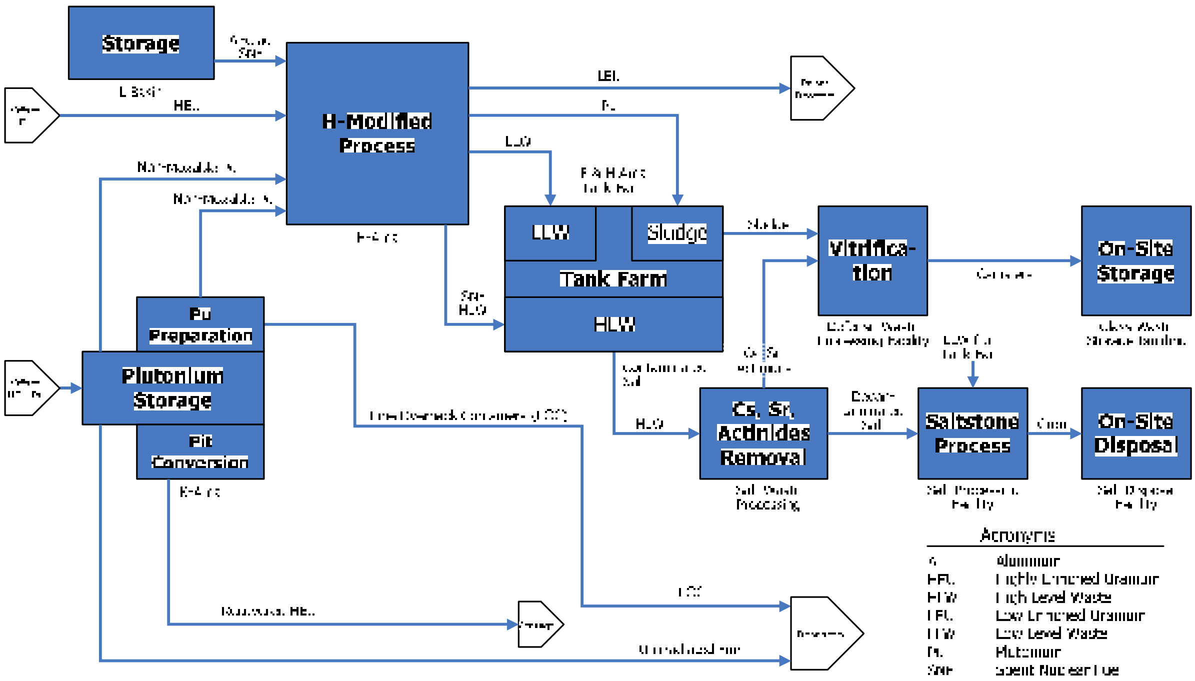

Fig. 2 Production Block Flow Diagram

Interactions among these blocks are extremely important to the performance of the system as a whole, and drive the need for an integrated system-level analysis over an analysis of the individual components. There is a very high degree of interdependency of the systems at SRS; the operations of any one of the blocks impact the performance of those of others around it. For example, the processing of salt waste to remove high level waste contaminates such as cesium and strontium establishes a systems-level dependency between salt waste processing facilities and the vitrification unit. Previous studies have associated technical design problems associated with impurity accumulation in recycle streams for new technology facilities [13]. Understanding these linkages in a complex system of systems is critical to achieving steady-state operations across the facility. When evaluating competing architectural alternatives for processing nuclear waste, these site-wide interactions must be closely modeled to understand not only how performance is impacted in the nominal case, but also to understand how the robustness of the system to failure or delay is impacted.

The activities in each of these blocks were modeled with variable resolution to ensure a balance between capturing system-level interactions meant to inform a lifecycle analysis with performance and execution speed. The simulation is not meant to replace higher fidelity operational models used on site for detailed analysis of performance. Instead, it is meant to provide responsive feedback while exploring options with SRS stakeholders, reducing "What if" analysis from weeks or months to hours or days.

The categories into which inputs and outputs of the Systems Flow Model may be classified are given in Table I. While technical operational parameters (such as the length of time of an operation or the throughput of a piece of equipment) are used, the Systems Flow Model is notable in how many of its inputs are of a managerial nature: budget, policy, inventory, and project investments. Given a combination of inputs (i.e., a simulation scenario), the model can be simulated to return data documenting the simulated performance of selected parts of the system over the lifecycle of the program, as well as the overall cost of the program and its components, as well as the expected schedule for key milestones. This output data is shown in dashboards in the model and can also be exported for further analysis.

Table I Overview of Inputs and Outputs for the Systems Flow Model of Operations at SRS

Inputs	Outputs
• Available Budget • Policy Options • Technical Operational parameters • Project investment options (cost, performance, and anticipated start date) • Initial inventory of nuclear materials and liquid waste, and any future additions	• Performance (canisters vitrified, salt dispositioned, etc.) • Schedule (end of operations, milestone commitment dates, etc.) • Total estimated lifecycle cost

The inputs and outputs of the Systems Flow Model relate directly to the influences in the influence diagram of Figure 1—policy, budget, amount of material to disposition, and the start of new capabilities for disposition. In this way, the Systems Flow Model can be used to feed qualitative analysis of architectural alternatives within the framework provided by the influence diagram. With a quantitative backbone in the place, the full power of the influence diagram can be brought to bear to address budget impacts, the influence of policy, and project needs and outcomes.

Budget and Funding Levels

The cost components add an important strategic context to the Systems Flow Model and the broader framework for analysis. The ability to derive a total life-cycle cost makes it possible to monetize resources (labor, production assets and investment) for any scenario. This enables management to take corrective action based on simulated cost profiles, and to better architect possible alternative scenarios.

Figure 3 shows the funding policy decision and the process of allocating funds to operations and investment. The aggregate budget is primarily set by exogenous funding decisions. Annual appropriation bills establish the program budget. EM management can exercise some discretion to allocate expenditures between operations and investments. This provides leverage to accelerate prioritized closure activities to meet critical program objectives.

Production campaigns consume resources that are monetized in the model. A large proportion of these costs are direct labor operating expenses, much of which is fixed while facilities are operational. However, there are also incremental activity-based costs tied to discrete operations. When the campaigns are completed, funds become available for other purposes.

There is a parallel structure for investments. When major construction activities are completed, construction funding winds down, freeing resources for other activities. This should not be interpreted to mean that prior funding levels could be reallocated for other purposes. The funding policy usually restricts gross reallocation, but it may enable the capital project to transition to an operating phase. This is modeled as a state transition from an investment to an operating facility.

Policy Influences

The cost estimate for cleaning up the radioactive tank wastes is between $88 billion and $117 billion over the next 40 to 50 years [4]. With a planning horizon this long, there will be opportunities to accelerate tank closures with investments in new technologies and strategic operating decisions. The Accelerated Closure Policy [4] reflects this posture, making investments in new capabilities and increasing the excess nuclear materials production rate to accelerate the closure date.

A Proactive Non-Proliferation policy would have a similar effect, the main difference being the introduction of more non-proliferation materials from outside the DOE complex. New investments and more campaigns may be required to treat non-proliferation materials.

Another example is the identification of a long-term repository for high level waste. More important is the waste acceptance criteria adopted for the long-term repository that specifies the waste loadings that directly influence the number of high level waste canisters produced.

Needs and Project Outcomes

As policy decisions increase the stocks of Excess Nuclear Materials and Non-Proliferation Materials, the need for New Capabilities creates a Capability Gap that becomes the justification for new investments. These relationships form various feedback loops on the system that can be identified and studied. There are at least two feedback loops associated with capability gaps. The first is a reinforcing (positive feedback) loop, R_1: *Demand for Additional Capacity*. As more production campaigns are initiated, these activities tie up the process equipment, increasing the Capability Gap and the need for New Capabilities. New investments in production capacity may be required to eliminate the capacity shortfall. The implication is that life-cycle acceleration may become capacity constrained in the absence of new investment.

A relief strategy can be seen in the balancing (negative feedback) loop, B_1: *Early Completion Mitigates Capacity Constraints*. Completing Campaigns frees up capacity, closes the Capability Gap and may obviate the need to expand capacity. The challenge is to develop a life-cycle campaign strategy that strikes a balance between these two feedbacks in such a way they minimize investment and maximize production flexibility. The underlying model is designed to explore this trade space. This approach is consistent with recommendations to prioritize cleanup work to achieve the greatest technical risk reduction at an accelerated rate [2].

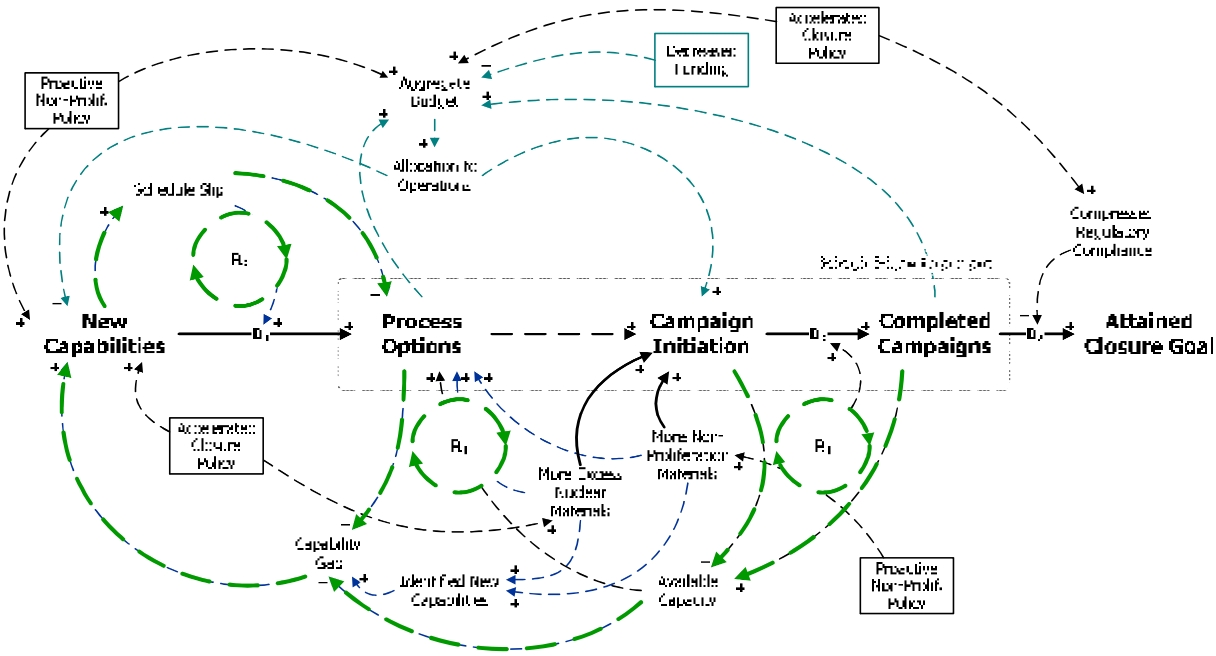

Fig. 3 Identifying and Delivering New Capabilities

<u>Feedback Loops:</u>
R_1: Demand for Additional Capacity
R_2: Schedule Slip Exacerbates the Capability Gap
B_1: Early Completion Mitigates Capacity Constraints

Project outcomes affect new capabilities. The reinforcing loop: R_2: *Schedule Slip Exacerbates the Capability Gap*, illustrates how delays in the delivery of new capabilities prolong the Capability Gap, putting pressure to resolve the problem with stopgap measures and acceleration strategies. While Figure 5 only illustrates the effects of schedule slip, a similar reinforcing loop for cost and performance outcomes can cause a project to spin out of control. For example, a performance shortfall can also fail to narrow the capability gap and in the worst case could require a follow-on project to address the deficiency. The diagram exposes the life-cycle consequences of large-scale projects that fail to deliver in any combination of the three outcomes: cost, schedule and performance.

The full influence diagram shown in Figure 3 can be used together with the quantitative Systems Flow Model to generate performance metrics such as the quantity of high level waste canisters produced, projected lifecycle completion dates, tank closure milestones, waste disposition progress, operating and capital investment profiles. The system-of-systems modeling architecture provides meaningful insights into operating unit interdependencies, key operating interfaces, recycle behaviors, pinch points and operating campaign risks and opportunities.

SYSTEM ANALYSIS USING THE FRAMEWORK

The stepwise building of the influence diagram introduces problem complexities systematically and logically through a gradual process that effectively captures the causal structure of dynamics. Each step focuses on a different dimension, can be used as a platform for communication with a diverse set of stakeholders. By initially breaking down the problem and then reconstructing the dynamics iteratively, a series of individual mental models are honed into a more complex series of system interactions that establishes a level of understanding that sharpens initial perceptions.

The influence diagram is intended to be used as a starting point to identify and explore scenarios and alternative architectures for processing using the simulation model. Many of the scenarios are “what-if” experiments that explore the consequences associated with the timing of certain key decisions and events or the rethinking of key processes and technologies. While the influence diagram may appear to be too general to address feedback loops, leverage points, and more complex system integrations at the operational level, the simulation model permits more detailed investigations, driven by the insight developed by carefully thinking through the causal structure of the system. Experience has shown the benefits from summarizing the results by referring back to the high-level interactions in the influence diagram.

The qualitative model forces rigorous thinking to guide analysis, and should not be overlooked or seen as superfluous. In a letter to system scientist Russell Ackoff, noted business professor Peter Drucker stated that “Your example and your worked showed us… that quantitative analysis comes after the thinking—it validates the thinking; it shows up intellectual sloppiness and uncritical reliance on precedent, on untested assumptions and on the seemingly ‘obvious’…” It is necessary to avoid “descending into mindless ‘model building’… sloppiness parading as ‘insight.’”[14]

After developing policy or operational scenarios, or developing alternative processing architectures, the model can be used to investigate their impact on system performance, cost, and schedule. A common way this occurs in by investigating the system impact of introducing a new capability and different points in the system’s lifecycle.

For example, consider the case of the process of actinide removal at SRS. There are many different technologies available to perform this task, and each has its own efficiencies, throughput, and cost. In order to meet stakeholder commitments for tank closure, one or more technologies may need to be employed. However, each technology has different requirements, and may not be available until certain future dates. Different architectures, comprising of different designs for actinide removal, can be compared using the simulation model, and the lifecycle cost of each architecture can be compared along with its impacts on meeting stakeholder requirements for schedule and performance at reducing the radioactivity of salts.

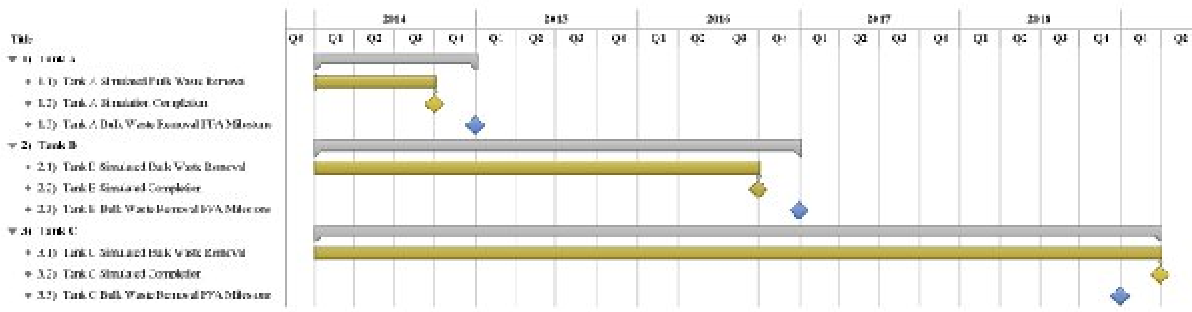

Fig. 4 Simulated Tank Bulk Waste Removal Dates (for illustration purposes only)

Figure 4 shows how schedule might be visualized for a single architectural alternative against a baseline. In this figure, key processing dates are shown as milestones in a typical Gantt chart view. Blue milestones can be seen as a target, commitments with stakeholders, or as a baseline of performance. An example is the tri-party Federal Facility Agreement (FFA) between DOE and the South Carolina Department of Health and Environmental Control and the Environmental Protection Agency concerning the closure of waste sites. The yellow milestones are the corresponding dates under an alternative scenario as produced by the simulation, allowing stakeholders to see how the proposed architecture performs in this dimension against its requirements.

Across the EM mission, schedule performance often directly translates to lifecycle cost. Figure 5 shows a hypothetical financial comparison of several competing alternative architectures, perhaps representing different combinations of technologies and operational schedules. Costs should always be shown as a net present value to fairly compare the lifecycle cost of architectures that result in different closure dates, or result in different spending profiles over the mission life. In this way, comparisons that reflect the time value of money can be made among alternatives. While the relative difference between scenarios may appear small on a percentage basis, the lifecycle baseline is a much larger value, in the billions of US dollars. It is not uncommon to evaluate potential cost impacts in the hundred million dollar range.

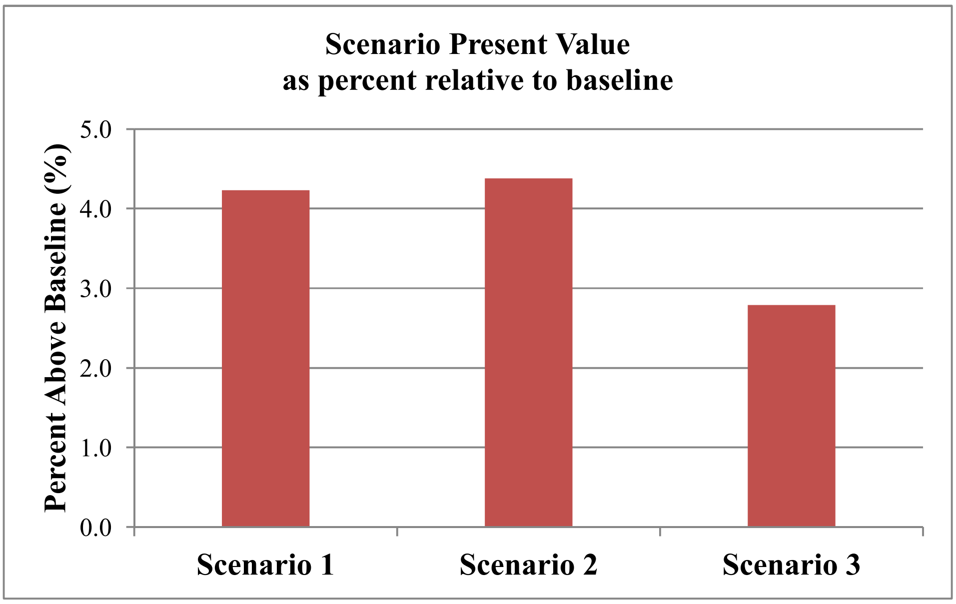

Fig. 5 Present Value Results (for illustration purposes only)

Analysis does not stop with a single number, however. The results of quantitative analysis must be considered in context of the qualitative influence diagram. Analysts must ask, “Given certain behaviors or outputs, what influence would this have on the qualitative aspects of the system, such as stakeholder satisfaction, nuclear non-proliferation, or the budget itself?” A full analysis places the results of the simulation in their proper context within the system, and will help decision makers understand the nuances of choices beyond basic lifecycle savings or schedule without regard for broader system performance on other dimensions.

CONCLUSION

This paper presents a hybrid framework for the architectural analysis of a very complex system: the DOE's Environmental Management mission at the Savannah River Site. By pairing a quantitative system-wide discrete event model with a qualitative model describing the feedback across the system, richer scenarios and alternative architectures can be developed and simulation data can be understood in its proper context to more effectively support decision making.

The level of aggregation in the qualitative influence diagram presented here masks some of the details; however, the advantage lies in the ability to analyze the problem from a high-level systems perspective. By probing the dynamic relationships between key model variables, the diagram effectively conveys the problem complexities in a way that can easily be understood by stakeholders. The stepwise progression through the diagram hones the collective mental models into a more cohesive whole and leads to a deeper understanding.

The analysis of feedback loops promotes the development of scenarios that can be evaluated in more detail with a simulation model. These model runs may test important subsystems, explore system resilience, identify leverage points or develop system plans that satisfy life-cycle criteria. The results of these runs can then be generalized in the context of illustrative planning scenarios using the influence diagram to summarize important findings and provide context for their impact on the wider system, beyond the boundaries of the simulation model and programmed.

With this hybrid framework for architectural analysis in place supported by a validated simulation model, system level lifecycle planning can be greatly accelerated and better communicated to provide stakeholders a dynamic view of their system, linking the qualitative with the quantitative.

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