Systems Engineering Principles Applied to Basic Research and Development

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ABSTRACT

Systems engineering principles and processes have grown out of the need to effectively manage complex programs, many of them for the acquisition of operational military systems. These multi-billion dollar programs truly benefit from the application of structured systems engineering principles, and the supporting processes have been fine-tuned to maximize their benefit in a requirements driven environment. Research and development efforts, on the other-hand, have typically avoided application of structured processes, primarily due to a perception that such structure inhibits the creative processes that are so crucial to the discovery and development of new technologies. This paper proposes that systems engineering principles and creative discovery are not mutually exclusive environments, and that, in fact, appropriately tailored systems engineering processes can enable and enhance scientific discovery. An example of this concept will be presented for the principles of risk management, including application to basic research, applied research and development, and technology demonstrations.

1.0 Systems Engineering Principles

The origin of structured systems engineering lies in the development of large, complex, operational systems[1]. These programs are characterized by long duration (in many cases, decades), and large overall program budgets (typically in the tens of millions of dollars). For programs such as these, the stakes are high and the potential contribution for proper systems engineering is large. These programs typically have highly defined objectives and requirements. Research and development programs, in contrast, typically have only general goals, relatively limited budgets, and tend to emphasize creative discovery in all aspects of program execution. Application of systems engineering processes and procedures developed for the large, requirements oriented programs to smaller, exploratory programs usually produces poor results, if any. For an exploratory program to benefit from the knowledge embodied in systems engineering processes, an understanding of the basic principles is necessary. As an example, the principles and processes of risk management will be used for the remainder of this offering.

1.1. The Principle of Risk Management

The fundamental purpose of risk management in any program is to recognize, assess, and control the uncertainties that may result in schedule delays, cost overruns, performance problems, adverse environmental impacts, or other undesired consequences[2]. The principle of risk management can be decomposed into seven actionable elements. They include:

1. Identification of the potential sources of risk, and their drivers;
2. Quantification of risks, including the probability of occurrence and seriousness of impact, and an assessment their impacts on cost (including life-cycle costs), schedule, and performance;
3. Determination of the sensitivity of these risks to program assumptions, and the degree of correlation among the risks;
4. Definition and evaluation of alternatives to mitigate risks;
5. Assurance that risk is factored into decisions on program objectives and design alternative analyses;
6. Taking actions to avoid, control, assume, or transfer each risk, and document as appropriate;
7. Tracking risk items to ensure mitigation plans are effective, the potential impact on the program does not increase, and identify when risks become realized and become impediments to achievement of program goals.

For a process to fully implement the principle of risk management, it must address these seven elements. Risk appears in all phases of a program's evolution. A properly implemented risk management program will apply these elements at all phases of the program, and adapt them to the different issues associated with different technology maturity levels.

1.2. Types of Risk

There are four acknowledged types of risk. They each are present to varying degrees throughout the program life cycle, but each tends to dominate specific portions of the cycle. The four risks are:

> **Technical risk:** the possibility that a technical objective of the program may not be achieved. A potential failure to meet any objective which can be expressed in technical terms is a source of technical risk.

Cost risk: the possibility that available budget will be exceeded. Cost risk exists if the project must devote more resources than planned to achieve technical requirements or if the project must add resources to support slipped schedules due to any reason. Cost risk exists if changes must be made to the number of items to be produced or if changes occur in the national economy. Cost risk can be predicted at the total project level or for some element of the work breakdown structure. The collective effects of lower-level cost risks can produce cost risk for the total project.

Schedule risk: the possibility that the project will fail to meet scheduled milestones. Schedule risk exists if there is inadequate allowance for piece-part procurement times. Schedule risk exists if difficulty is experienced in achieving scheduled technical accomplishments, such as the development of software. Schedule risk can be incurred at the total project level for milestones such as deployment of the first unit, or can be incurred at a lower element of the work breakdown structure. The cascading effects of lower-level schedule risks can produce schedule risk for the total project.

Programmatic risk: produced by activity external to the program. Programmatic risks can be produced by delays in authorization to proceed, by reduced or delayed funding, or by changes in objectives.

1.3. Technology Maturity

The technology maturity and maturation rate will drive the focus of the risk management activities. As shown in Figure 1, technology generally matures quickly compared to the overall life cycle of a program[4]. The early developmental phases, as represented by technology readiness levels (TRLs)[5] 1 through 6, occur (or, should occur) well before a system design is developed. For these early technology maturation

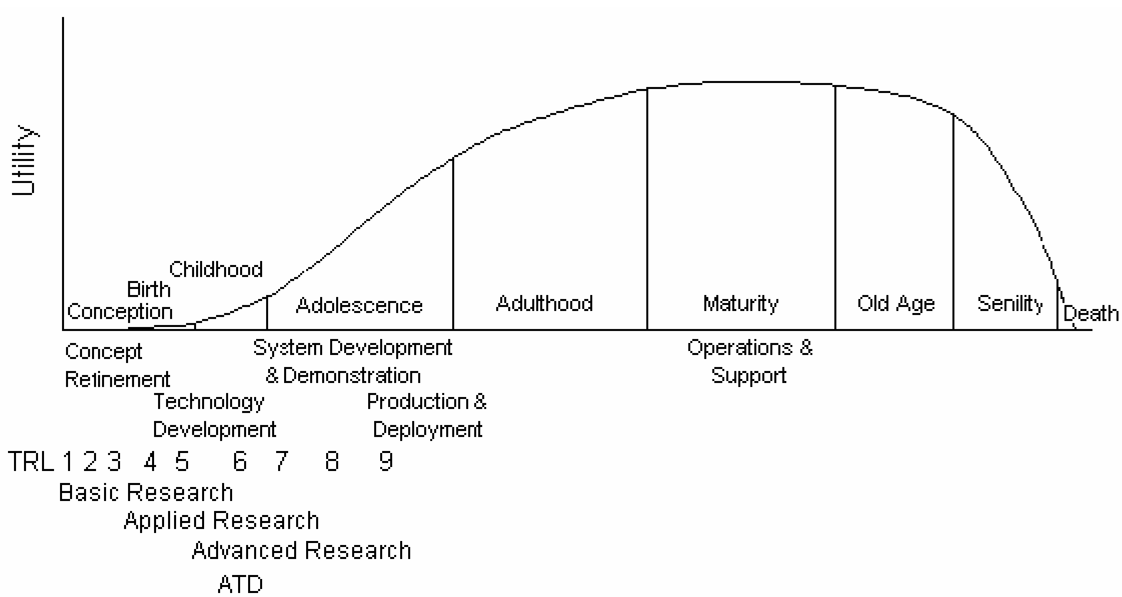

Figure 1. Program life-cycle 'whale' chart

efforts, one of the most important elements of knowledge is the rate of maturation. Many programs have failed because they lacked this basic information.

The technology development activities associated with these TRLs can be grouped into three categories. They are:

Basic Research – develop a fundamental understanding of select physical properties-TRLs 1-3

Applied Research – investigate application of physical properties to selected technical needs-TRLs 4-5

Advanced Technology Development – explore application of technology to assess military relevance (TRLs 6-7)

The remaining TRLs (8 and 9) are associated with technology and concept demonstrations, including formal test and evaluation (T&E) programs.

2.0 Risk And The Requirements Development Process

To address the requirements decomposition process it can be useful to consider questions relevant to each element. As shown in Figure 2, the systems engineering process for requirements development can be used to identify key questions to be addressed for successful completion of the process. Several of these questions address risk or the management of risk in a program. The ability to answer these questions evolves as the technology maturity increases, but the rate of maturation varies depending on the question. Table 1 describes, in general, how this knowledge can be expected to increase as a technology advances

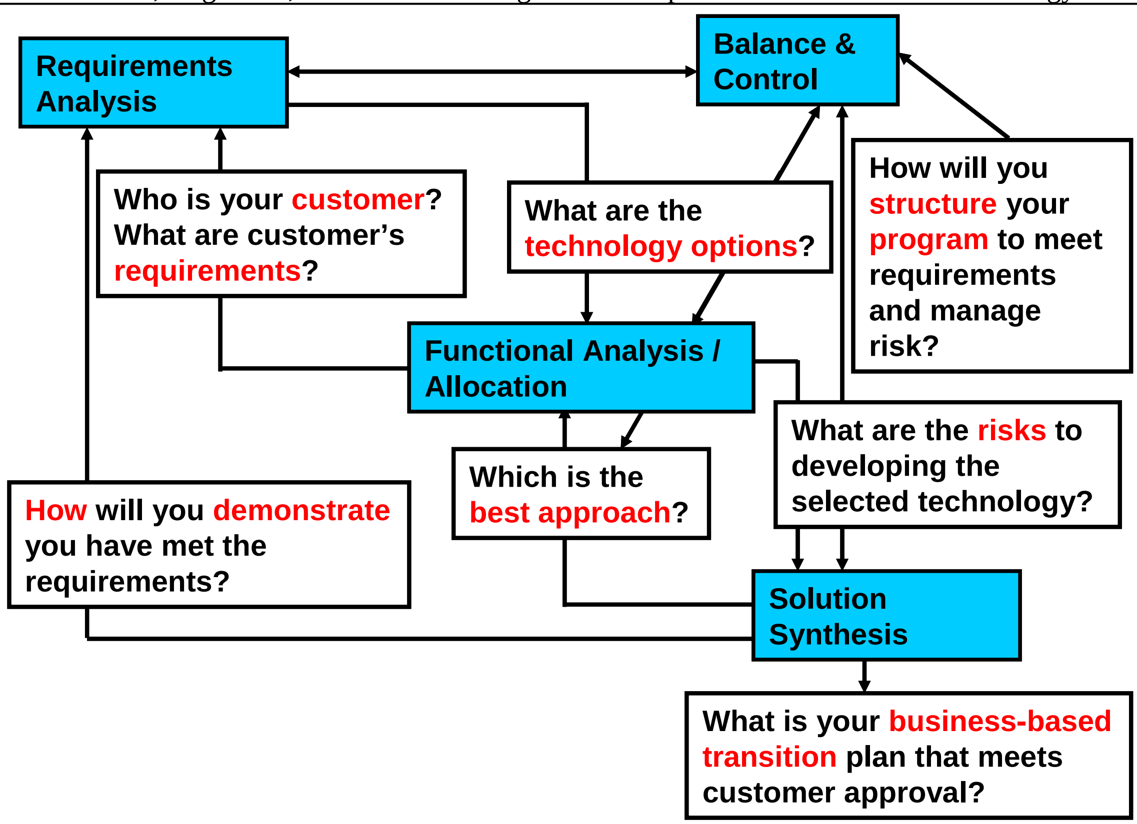

Figure 2. Requirements Development Cycle with Process Questions

from basic research to advanced technology development.

Table 1. Technology Development and Application Phases

Key Questions	Basic Research	Applied Research	Advanced Tech Dev
Who is the customer?	P	N	C
What are customer's requirements?	P	P	N
How you will demo you've met requirements?	P	P	N
What are the technology options?	L	N	C
What is the best approach?	L	N	C
What are the risks to developing the technology?	P	P	N
How to structure the program to meet requirements and manage risk?	P	N	C
What is your transition plan?	L	P	N

Table 1 key:
L – Limited/no knowledge
P – Partial knowledge
N – Nearly complete understanding
C – Complete understanding

In this model of the knowledge maturation, complete or nearly complete knowledge exists by the completion of advanced technology development and the attainment of TRL 6. Some questions start with very limited knowledge and mature quickly, while others start with some level of knowledge but mature much more slowly. This wide variance in maturation rate can be most efficiently addressed by tailoring the risk management process to each phase of technology development.

Risk management during the early development phases of a technology follows the same principles, and must address the same types of risk, as development of more mature technologies. The focus, however, is fundamentally different. Since there are seldom defined requirements during these early development efforts, the primary risk to be addressed is that of spending time and resources on a technology that will not make the transition into a useful application. The focus of risk management, therefore, should be on strategies that enable transition opportunities, and mitigate barriers to that transition.

3.0 Risk Management Approach for Basic Research

At the beginning of the technology maturation process, during basic research, there are too many unknowns to the potential application of the technology to develop firm expectations. Attempting to apply a traditional requirements-focused risk management process under these conditions can become an exercise in futility. Early development is very much a capabilities-based activity. To accommodate these unique properties, the primary purpose of risk management during basic research should be to define the development roadmap.

3.1. Basic Research Risk Management Focus

Risk management during basic research can most effectively focus on three activities:

- Development of cost estimates for advancement of technology to useful level
- Identification of development options and the relative difficulty of the options
- Maintenance of the budget within pre-defined boundaries

The information from the first two activities is necessary for a valid technology development roadmap. This roadmap defines the projected schedule and performance goals for the development program, as well

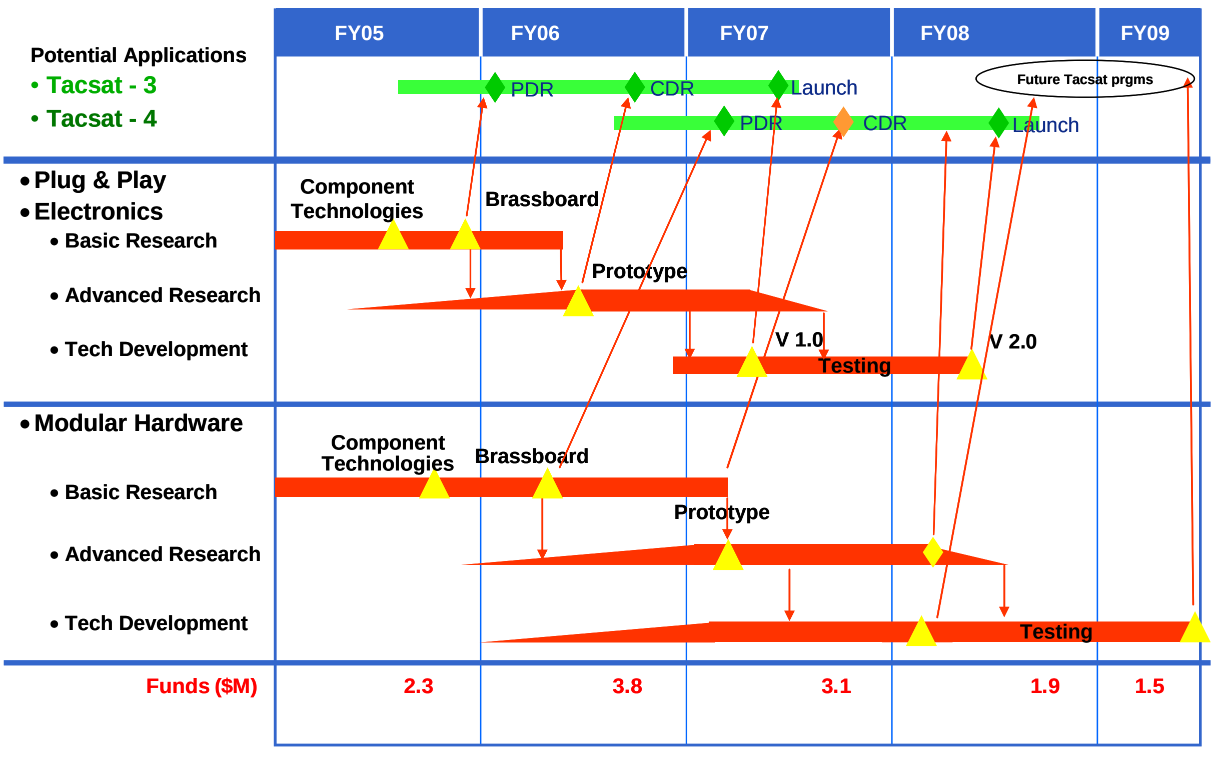

Figure 3. Example Technology Roadmap for Basic Research through Advanced Technology Development

as an estimate of the cost to achieve each increment in capability. Figure 3 depicts a roadmap for a typical technology development program. Key milestones in the roadmap should be defined on a fiscally relevant cycle, typically 2 years for government research programs. Additional risk management activities should be developed to ensure that the budget to the next milestone is controlled, with capability at the next milestone the primary variable. For the four risk types, the emphasis of activities to manage risks during basic research should be (in descending order of importance):

- Cost
- Schedule
- Programmatic
- Technical

3.2. Basic Research Risk Management Structure

To manage the risks associated with basic research programs, there are a few procedural steps that can be taken:

- Establish knowledge incremental goals and exit criteria – incremental goals should be established for short intervals (less than a year), and should be knowledge building blocks to a better exploration of the technology's application. These can become elements of the roadmap milestones. Exit criteria should be established for the specific technical performance parameters. If the criteria can be stated as capabilities goals and thresholds, then technical risk management activities need only be developed if the threshold level of capability seems to be in jeopardy. This should provide a useful trade-space for the project manager.

For the example used in Figure 3, plug and play electronics, incremental technical goals might be to understand the costs associated with instantiating a single plug and play interface in a typical application, the potential cost savings over a custom interface, and the impact the interface might have in power, mass, or volume on a system design as compared to a custom solution.

- Estimate cost/time needed to achieve – once the incremental knowledge goals and exit criteria are established, the work breakdown and available resources will determine the cost and duration of each step in the roadmap. This is very much like any program planning and budgeting activity.

- Determine risks – Most risks will be associated with maintaining budgeted costs and schedule to provide a capability within the range of the threshold and goal technical capabilities. Focus should be on the uncertainties of maintaining project costs and schedule to achieve the most immediate technical increment(s) as defined in the roadmap. Only if there are risks that could impact achieving the threshold level of knowledge should technical risk management measures be developed.

- Track variances for periodic cost and schedule re-planning - The greatest failure in most programs during this early developmental period is caused by ignoring the dynamic nature of basic research and the impact of this feature on budget and schedule. If a new developmental avenue is explored that was not originally foreseen (and planned for), there could be serious program cost and schedule breaches. The baseline program budget and schedule is only valid for the tasks planned. A program manager should be diligent regarding basic changes in focus or exploratory paths by the science team. The changes may very well be necessary, but proper systems engineering of the process will require the goals, thresholds, budgets, and schedules be re-visited to provide reasonable program management metrics.

4.0 Risk Management Approach for Applied Research

Once basic research has been completed, there should be a better understanding of the technical issues that can drive the development of the technology. The technology development roadmap should be updated at this point, and a new set of incremental technical goals established for the applied research phase. This is similar to a program baseline update for an acquisition program at a major design review. The primary purpose of risk management during the applied research phase is to ensure sufficient understanding of the development process exists to allow a potential user of the technology to accurately balance cost and performance.

4.1. Applied Research Risk Management Focus

Risk management activities during the applied research phase are best focused on three key areas:

- Development of a technology into a repeatable engineering capability – Statistical significance is necessary to develop repeatable processes. This may require a structured, design-of-experiments[6] approach to planning the technical effort. Using the program described by the roadmap in Figure 3, this phase might focus on the development of a statistically significant confidence level in the metrics for the potential cost savings over a custom interface, and the impact the interface might have in power, mass, or volume on a system design as compared to a custom solution.

- Identification of the extent of applicability of a technology to military needs – Knowledge of the boundaries of applicability for the technology is crucial to its acceptance into future designs. To minimize the perception of risk in adopting this technology into new designs, it will be important to define the breadth of application. This might be done through modeling or simulation, but a well validated model, one supported with actual instantiations of the technology will be necessary for an acceptable confidence in the results.

- Determination of the parameters that affect the cost to benefit performance of a new capability –Drivers to cost/benefit performance need to be identified during this phase, or adoption into systems will be considered to risky. Using our notional plug and play electronics program from Figure 3, variances might include range of software developers experience level (possibly captured through a capability maturity model), platforms used for development, or host operating systems impact on development of drivers.

For the four risk types, the emphasis of activities to manage risks during applied research should be (in descending order of importance):

- Technical
- Cost
- Programmatic
- Schedule

4.2. Applied Research Risk Management Structure

To manage the risks associated with the focus areas listed above, the following elements are useful:

- Explore range of application of technology – Budget and schedule should be assigned to exploration of the breadth of application of the technology, but the effort may be constrained by the total program budget available. A narrowing of application may be necessary to fit within program constraints.

- Refine development roadmap for specific applications – During applied research it may be necessary to update many of the elements of the roadmap. This phase of technology development can be very dynamic in cost, schedule, and capability expectations. It may very well be that the roadmap should be updated after each incremental step in the applied research process.

- Determine risks associated with achieving required performance at known cost/schedule – Throughout the activities in this phase of development, it will be important to capture the variances and the drivers for those variances of each of the metrics associated with the cost-benefit analysis. Data collection and analysis methods should enable this type of analysis – the development system itself can have metrics applied to generate this data.

- Identify issues reducing repeatability and define mitigation approaches - Analysis of development performance data created by the step above should be analyzed to determine the degree of variance and potential sources of variance.

5.0 Risk Management Approach for Advanced Technology Development

Advanced research and development programs have much in common with systems acquisition programs. At this stage of development, the technology is fairly well understood to the extent that its application is known. Performance requirements for the technology application have been established, to include parameter thresholds and goals. In some cases, programs at this phase are being utilized as concept demonstration activities. Therefore, the goal of risk management is very much like that used for acquisition programs. Risk management for these types of programs is covered in detail in current literature, and a full exploration of these methods is left as an exercise for the reader.

5.1. Advanced Technology Development Risk Management Focus

The primary purpose of risk management during the advanced technology demonstration period is to balance cost, performance, and schedule. Achieving this balance requires the program manager to focus on the programmatic aspects of the technology development process. The budget and schedule become risk drivers in the three traditional program management areas of cost, schedule and performance. For the four risk types, the emphasis of activities to manage risks during this phase should be (in descending order of importance):

- Programmatic
- Cost
- Schedule
- Technical

5.2. Advanced Technology Development Risk Management Structure

The following elements are useful for managing risk during advanced technology development:

- Link budget and schedule - Use program management processes such as earned value management to provide a level of vision and control.

- Establish a formal risk mitigation process - Risk mitigation can be defined through a risk management plan. Since this phase in development will produce items that may be directly implemented into operational systems, it will be necessary to include configuration control at the system and component levels as part of the risk management process.

6.0 Summary

While the philosophy of risk management is a constant through all phases of technology development and systems acquisition, the focus and application of supporting tools can vary drastically. Sometimes the focus is counter-intuitive. For each of the three phases of technology development, program management efforts should accommodate the following foci:

- **Basic Research**: Manage the investigation so that it creates the maximum knowledge return on a fixed investment of time and money.

- **Applied Research**: Use a fixed amount of money to investigate the boundaries of the potential application space. Schedule is generally not too important, maturing the technology to fit a potential application is key.

- **Advanced Research**: Use budget and schedule to develop an operationally significant capability that's ready for insertion into a designated application during a defined window of opportunity. Depending on budget or schedule, this may require incremental or spiral development.

Risk management during technology development is necessary, but can have a fundamentally different focus than traditional acquisition programs. By focusing on the primary risk of technology development– failure to provide sufficient knowledge of the application of a technology to enable its transition into a functional design – and developing solutions to that key risk, a greater likelihood of technology transition can be realized.

7.0 References

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