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System Earned Readiness Management for Defense Acquisition

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Abstract

Under Naval Postgraduate School funding, the Principal Investigators have conceptualized and are currently validating a system maturity scale called System Readiness Level (SRL). It combines the currently accepted Technology Readiness Level (TRL) with an Integration Readiness Level (IRL) to assess a whole system's developmental maturity and determine current and future readiness during the defense acquisition lifecycle. As a function of the TRL of the components and the IRL of the integrations, the SRL scale has been used by the PIs to develop system development optimization models that can maximize the SRL of the system subject to resource constraints or minimize the cost of development subject to attaining a pre-determined SRL value within a time constraint. This research builds upon these foundations to create a systems development lifecycle maturity management approach, which we define as Systems Earned Readiness Management (SERM). We envision SERM to be a suite of management tools which can be used to manage the development of novel high technology systems. Current research to date has produced a scheduling, monitoring and evaluation tool. In contrast with Earned Value Management (EVM), which focuses on cost and schedule, SERM addresses the earned readiness or maturity of system development as it equates to making strategic and programmatic decisions in defense acquisition. Future efforts will be directed towards complementing the scheduling and monitoring tool with additional methodologies such as Component Importance Analysis, management of Key Performance Parameters, and Interoperability to address issues associated with Multi-capability systems.

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1. Introduction

In an acquisition lifecycle there are many factors that impact the decision to: develop one system over another; supersede a new, more functional system over another; determine if a system or technology has become inadequate due to changes in other systems or technologies; and invest in the development of a new system or maintain existing systems. To examine these issues in engineering design and development it is a prescribed practice for project managers and systems engineers to use qualitative decision methods (Buede 1994). However, there is a continuous challenge in finding methods or approaches that produce the optimal allocation of any available resource to minimize development uncertainties (Dillon et al. 2005).

In project management the allocation of resources is frequently done with the purpose of creating individual tasks to maintain schedule and budget. This can lead to a focus on task-assignment to project scheduling (Salewski et al. 1997) even though the ultimate object of any project is to develop a product (or system) to satisfy a customer. Thus, disconnects often emerge between the priorities of the project manager and the systems engineer with respect to the optimization of the design during the acquisition lifecycle. Furthermore, additional challenges arise from the allocation of resources in medium to large-scale system integration efforts. (Chang et al. 2001). Salewiski et al. (1997) expressed this concern for complex interaction to minimize cost and solve a time-resource-cost tradeoff problem, but the focus was still on tasks/activities and not necessarily optimization of systems' developmental maturity. Dillon, et al. (2001; 2003) developed a decision-support framework for first guiding the design, not the resources, while quantitatively demonstrating the implications that constrained resources can have on critical engineering systems. Although, they explained that much of their work was focused on budget allocations that are made once at the onset of a project, new models are needed that allow for decision support on available resources throughout the lifecycle at key milestones (Dillon et al. 2005).

Fundamental to these challenges are that in project management, tasks are interdependent and coordinated in parallel; however, engineers cannot afford to wait for complete information, and are often forced to continue through the project lifecycle while coordinating design activities with preliminary, ambiguous, or subjective information (Pich et al. 2002). This creates a tension between the project manager and systems engineer (de Haes 2006). Unfortunately, subjective assessment techniques are human intensive and error-prone. Ideally, assessments should be based on system attributes that can be quantitatively measured using system metrics (Yacoub and Ammar 2002). Therefore, an approach that can combine the rigor of analytical resource allocation to the subjective assessment for system development metrics could provide potential solutions to this challenge.

To address this, the Principal Investigators (PIs) previously described a Systems Readiness Level (SRL) metric (Sauser et al. 2006; Sauser et al. 2008), an approach that incorporates the Technology Readiness Level (TRL) used by the Department of Defense (DoD) and an Integration Readiness Level (IRL) (Gove 2007; Sauser et al. 2010) to determine the maturity of a system and its status within the acquisition lifecycle. That is, if every technology is assessed using TRL and the system architecture is used to build an integrated representation of the system (e.g. physical architecture, context diagram) in which integrations are assessed using IRL, a metric that provides an assessment of a systems maturity against the acquisition lifecycle can be considered. The rationale behind the SRL developed by the PIs (Sauser et al. 2008) is that in the acquisition lifecycle, one would be interested in addressing the following considerations:

1. Quantifying how a specific technology is being integrated with every other technology to develop the system.

Note that this quantifier should be a function of both the maturity of the different technologies and the integrations between them (as dictated by the system architecture). That is, for each technology, this metric should be a function of both TRLs and IRLs. Thus, for technology i, one can view this metric (SRL_i), as "subsystem" measurement of this technology's integration within the system. In a mathematical representation: $SRL_i = f(TRL_j, IRL_{ij})$

2. Based on such a metric (SRL_i), SRL should provide a system level measurement of readiness.

Note that this new metric should be a function of the component SRLs of each technology or in mathematical representation: $SRL = f(SRL_1, SRL_2, \ldots, SRL_n)$ under the assumption that the system contains n technologies.

Thus, not only is SRL a quantitative measure of maturity, but the resulting SRL value has been correlated to qualitative defense acquisition practices (Sauser et al. 2008; Sauser et al. 2008; Sauser et al. 2008). From previous NPS-funded research, the PIs have developed models focused on the analysis of the costs associated with the drivers of the SRL so an SRL Optimization Model(s) could be represented. This has resulted in two models that have completed analytical validation: *Model SRL_{max}* (Ramirez-Marquez and Sauser 2008) which has the objective to maximize the SRL under constraints associated with resources (cost and schedule); and *Model $SCOD_{min}$* (Magnaye et al. 2010) which has the objective to minimize development cost under constraints associated with schedule and the required SRL value. Both can be solved using evolutionary optimization techniques such as the Probabilistic Solution Discovery Algorithm that has been developed by one of the PI's (Ramirez-Marquez and Rocco 2008). The mathematical representations of the models are presented below.

Model SRL_{max}

$$
\begin{aligned}
&\text{Max} \quad SRL(\mathbf{TRL},\mathbf{IRL}) \\
&s.t. \\
&R_1(\mathbf{TRL},\mathbf{IRL}) \le r_1 \\
&\vdots \\
&R_n(\mathbf{TRL},\mathbf{IRL}) \le r_n
\end{aligned}
$$

Model $SCOD_{min}$

$$
\begin{aligned}
&\text{Min}\, Cost(\mathbf{TRL},\mathbf{IRL}) \\
&s.t. \\
&SRL(\mathbf{TRL},\mathbf{IRL}) \ge \lambda \\
&R_1(\mathbf{TRL},\mathbf{IRL}) \le r_1 \\
&\vdots \\
&R_n(\mathbf{TRL},\mathbf{IRL}) \le r_n
\end{aligned}
$$

These two models allow for decisions to be made regarding the current and future developments of a system within the acquisition lifecycle. Specifically, both models identify the development path for the system such that the pre-specified strategy (i.e. maximize SRL or minimize the System Cost of Development) is satisfied. Thus, the solutions show which technologies and integration elements to mature at what point in time and at what costs. Given these global optimal solutions, the system development manager can then track the performance of the system during its acquisition lifecycle.

This research built on the foundation of the SRL and these optimization models based on constrained resources (as depicted in Figure 1) to develop a decision support tool that can enhance managerial capabilities and create an acquisition lifecycle maturity management approach, which we define as Systems Earned Readiness Management (SERM). Alternatively to Earned Value Management (EVM), which focuses on cost and schedule, SERM addresses the earned readiness or maturity of systems development as it equates to defense acquisition, so variances can be measured, evaluated and, when necessary, corrected, with the intention of providing answers to the following questions:

- What is the resource estimate for a development scheduled?
- What development has been accomplished?
- What is the resource estimate for the completed development?
- How much actual resources have been spent/consumed?

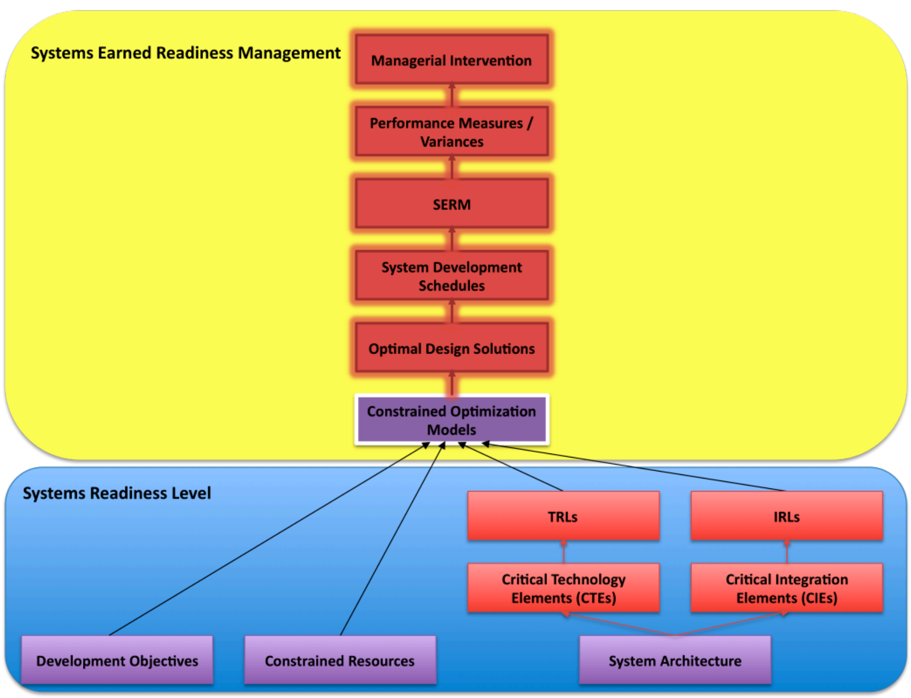


Figure 1: Current and Proposed Research

2. Purpose and Focus of Research

Early indications suggest that conceptually, both optimization models – *Model* SRL_{max} and *Model* $SCOD_{min}$ – can provide considerable insights into quantifying current levels of accomplishments, the impact of current and future technology choices and resource allocation on the development process as well as their implications on system performance during acquisition. Although, we still need to understand the validity and value of their application. Therefore, the first research question is:

> ***Q1:*** *Can the SRL scale and its implementation in the optimization models lead to a more informed allocation of resources such that greater system readiness levels can be achieved at the lowest possible cost and earliest feasible time?*

With the optimization models validated, some arrangement of both can be employed against existing system development plans to measure the degree to which development program objectives are being met at certain points in time. Such a measurement can be executed using the proposed System Earned Readiness Management (SERM) methodology. As a management tool, SERM can also be used to adjust the amount of effort applied to the development of each of the components of the system so milestones can be met and an estimate of the variance in developmental maturity can be calculated. While EVM evaluates planned, actual, and budgeted cost and schedule, SERM will evaluate planned, actual, and budgeted systems development levels (i.e. maturity) and use the allocation of resources as a means to make developmental planning decisions. To establish its validity, research question two states:

> ***Q2:*** *Can SERM be used to measure the development status of a system and calculate the impact of alternative budget allocations on system readiness and thus lead to more efficient distribution of resources for development?*

3. Research Approach

The development path for SERM proceeded in a spiral manner. Each spiral served as a foundation for the development of more complex concepts while also transitioning knowledge, information, and tools to a practitioner community. Likewise, each spiral was also closely linked to the previous in order to further develop the proposed concepts. For example, the determination of the validity of SRL research becomes the basis for the development of the optimization models. In turn, examining their validity provides insight towards the development of SERM. During the development, verification and validation of SERM, it is anticipated that there may be a need to go back to the preceding spirals for refinement; thus, creating feedback loops to calibrate the concepts and tools more accurately. Our research questions and the development cycles that flow from them are reflected in the approach for this research that will consist of these five spirals: *Spiral 1 – Validation of Optimization Models, Phase 2 – Development of a Scheduling and Monitoring Tool (SERM), Spiral 3 – SERM Verifications, Spiral 4 – SERM Validation*, *and Spiral 5 – Methodologies for Multi-capability Systems.*

3.1 Spiral 1 – Validation of Optimization Models

As previously stated, just as we have verified the SRL with the acquisition lifecycle, we must also validate the optimization models against real systems that are currently under development within the acquisition environment. Therefore, Spiral 1 was a 4-month activity that applied the optimization models to real systems from Northrop Grumman (Bethpage, NY) and U.S. Army Armament Research, Development and Engineering Center (Picatinny, NJ).

3.2 Spiral 2 – SERM Development

Step 2 in Spiral 1 became the basis for Spiral 2 and provided valuable insight into the development of a *scheduling and monitoring tool* System Earned Readiness Management (SERM). While the optimization models are unavoidably mathematically involved, SERM itself is envisioned to be a parsimonious management tool. It will measure in aggregate terms the level of accomplishment of the system development process. When compared to the development plans and factoring estimates that have been prescribed for a particular system under development, management can make conclusions on its status and suggest necessary adjustments to correct any significant deviations that will impact acquisition cost and schedule (as they relate to developmental maturity). Thus, Spiral 2 was a 4-month effort that integrated the optimization models into a unified evaluation of systems development to determine planned, budgeted, and actual developmental maturity; and determine how SERM could be used to better understand the resource implications on the acquisition lifecycle.

3.3 Spiral 3/4 – SERM Verification and Validation

The success of implementing these models depends on consistent and continuous definition of needed capabilities and the maturation of technologies that lead to disciplined development and production of systems that provide increasing capability towards a material concept. A fundamental challenge to defense acquisition is that the ultimate functionality cannot be defined at the beginning of the program. Only by the maturation of the technologies, matched with the evolving needs of the user can they provide the user with capability. These final two spirals were an 8-month effort that would verify and validate SERM with their associated solution techniques.

3.4 Spiral 5 – Methodologies for Multi-capability Systems (Future Research)

SERM as presently configured applies directly to a single capability system undergoing a single-step development process. All the concepts associated with it must be re-examined in order to determine if they would also be applicable to multi-capability systems undergoing an evolutionary development process. This re-evaluation is necessary when we consider that evolutionary acquisition is the adopted policy and that most systems under development are multi-functional. This portion of the research started in 2010 with NPS support and funding.

The approach to the development of SERM is illustrated by the diagram in Figure 2.

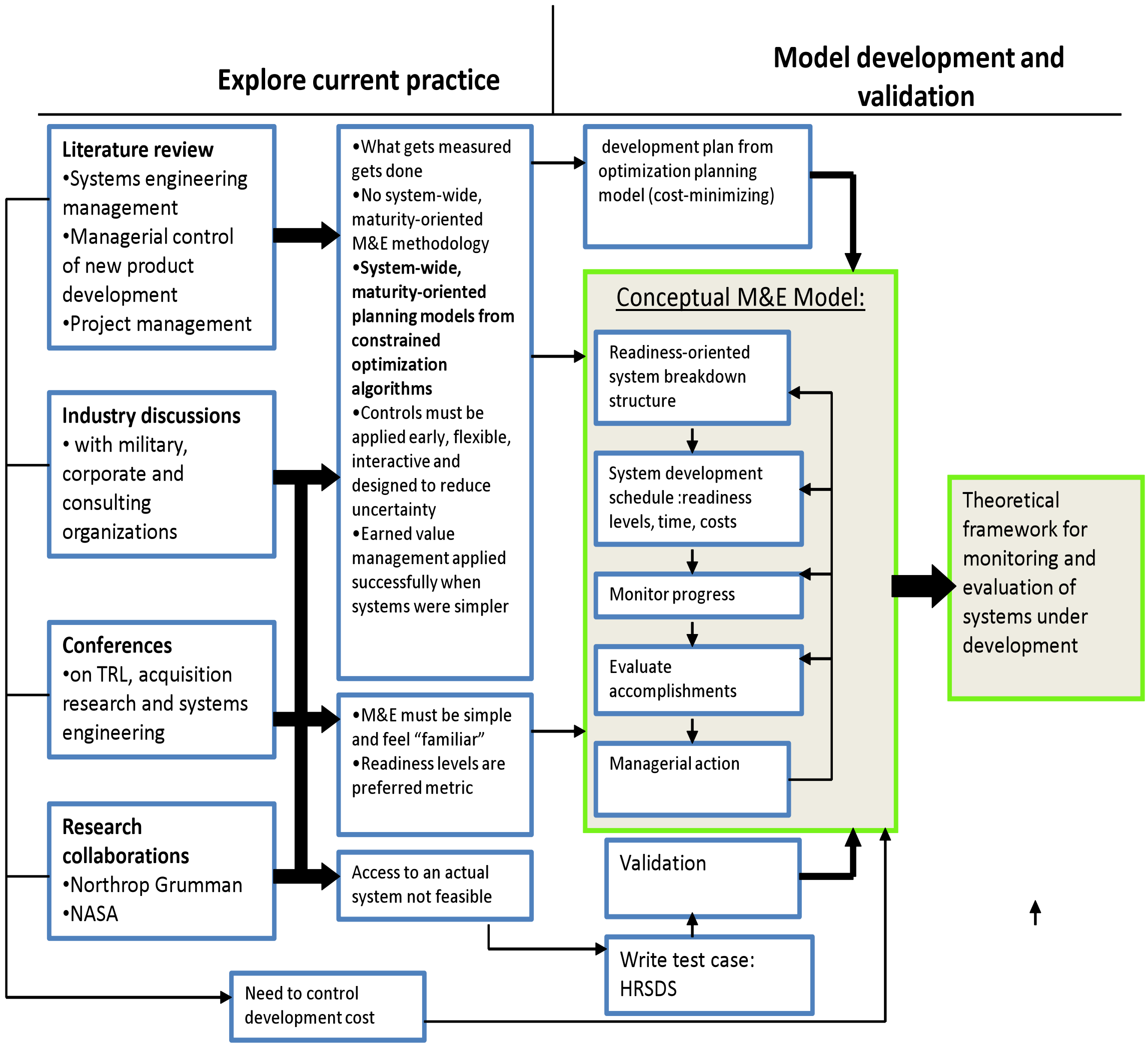


Figure 2: Methodology for Developing SERM

Current practices and gaps were determined using literature review and discussions with practitioners through meetings, conferences and research collaboration. A review of the literature on the management of systems development was used to identify the gaps in the current body of knowledge with regard to scheduling, monitoring and evaluation. The review is also used to determine if methods used in similar disciplines, especially project management, can be used as potential foundations for any new methodologies. The results from the review of the literature were validated through conversations with people who are actively involved in the development of high novelty systems involving high to very high technological components. In addition, the discussions with practitioners was used to determine if any cutting-edge approaches are currently being considered or used by the industry.

Similar information was also sought during six conferences that were attended. Finally, while participating in research collaborations with U.S. Navy, U.S. Army, Lockheed Martin, Northrop Grumman Corporation and NASA covering efforts related, albeit not entirely, to this research, attempts were made to gather information on how systems are being planned, monitored and evaluated with a view to controlling costs.

The assessment of current practices was followed by a selection of a system or case study, which can serve as a platform for the development of a new methodology for system scheduling, monitoring and evaluation. Such a system must be novel, involving new high technology components, but have a manageable number of critical components and integrations (7 plus or minus 2) to keep the discussions simple. A development planning model $SCOD_{min}$ (Magnaye et al. 2010) was applied to the case to identify a cost-minimizing optimal development plan. When a development plan has been determined, the scheduling, monitoring and evaluation approach was formulated.

4. Development of Systems Earned Readiness Management

4.1 SERM Background

The review of the literature on the management of systems development showed that many tools and methodologies have been and continue to be developed (Magnaye 2010). The planning aspect was addressed in the seminal work by Ramirez-Marquez and Sauser (Ramirez-Marquez and Sauser 2009) through the maturity-based model SRL_{max}. When it comes to containing costs, at best, this model can be used indirectly to set cost targets provided the temptation to develop the system faster than it needs to be is avoided. This can be accomplished by limiting the availability of resources allocated for each development period. This is easier said than done. Owners of systems under development have a tendency to see their products completed sooner than necessary. For example, in one meeting with personnel from the U.S. Navy, it was observed that there is not one program manager who would not want to maximize system readiness. This is probably true when the programs fall behind schedule. In order to avoid a tendency to spend more than necessary to catch up, there is a need to develop a methodology that is more directly targeted at formulating a system development plan that can be used to minimize the cost of developing a system.

To address this, Magnaye, et al. (2010) suggested a similar model called $SCOD_{min}$. This model was used to formulate a system development plan which can identify which components of the system should be matured to a certain level during a given time period. To monitor and evaluate the progress of a system under development in a logical manner, the plan must be translated into a system development schedule.

The need for a scheduling, monitoring and evaluation method is supported by the review of the literature on new product development. It observes that in order to be successful, managerial control (which begins with setting out the development plan, schedule and how a program will be monitored and evaluated) must be applied in the earlier stages of new product development (Bonner et al. 2002). The ability of managerial control to positively influence the success of the enterprise is also reinforced when it is applied in an interactive, flexible and responsive manner (Iansiti 1995; Bisbe and Otley 2004). Davila (2000; 2009) identified a couple of roles that managerial control plays: 1) the role of promoting goal congruence among team members and 2) the less traditional role of reducing uncertainty (resulting from novelty and high technological content) by enhancing coordination and learning through the creation of an information infrastructure. This is most important during the design and planning stages of the development of new complex products or systems. This need for control through coordination and learning using timely gathering and fast dissemination of information becomes critical to success.

Among the information that are needed are changing market or user requirements, technological improvements (from within the development organization and from competing efforts elsewhere) and the realities of systems integration. To exercise control, knowledge that is generated during systems development has to be reckoned against the original design and development plans.

Herstenstein and Platt (2000) observed that mechanisms to control the development process can be classified into 3 categories: 1) the position of product development in the organization, 2) the product development process and 3) the performance measures applied during the process. To be successful, it has been observed that the product development team must be positioned such that it is permanently headed by a heavyweight manager who reports directly to a senior executive (Cooper 2005) (Clark et al. 1987; Clark and Fujimoto 1991) Furthermore, the product development process must be well planned and articulated and, along with the performance measures, must be linked to the strategy of the enterprise (Cooper and Kleinschmidt 1987; Cooper and Kleinschmidt 1993; Brown and Eisenhardt 1995; Cooper and Kleinschmidt 1995).

Finally, when the system under development is very complex and has high levels of uncertainty due to their novelty and high technological content (Shenhar and Dvir 2007), the development process must be in the optimizing level - the highest level of process maturity as defined by Karandikar, Wood and Byrd (1992). At this stage, there has to be a high degree of control over the process and the major focus is on the application of process metrics and lessons learned in order to identify quickly the problem areas and be able to respond promptly.

The literature on new product development cited above suggests that to have success during the development of systems, the process must be flexible and responsive to changes in technology and requirements. This can be facilitated through an interactive managerial control system that promotes goal congruence and enhance learning through the creation of an information infrastructure with process performance metrics that are linked to the strategy of the enterprise.

Using project management tools, especially Earned Value Management (Barr 1996; Brandon 1998), as the foundation of management control makes sense because they are already widely accepted in this field. However, they are inadequate for complex systems because they are primarily focused on completing tasks, which have been derived from engineering development plans where requirements and designs have already been frozen. At best, project management tools, when used carefully, can measure very precisely the accomplishments and evaluate them against the tasks that were designated for completion at a particular time. However, they cannot be used to manage the readiness of a new technology, let alone a complex system composed of many new technologies or sub-systems where the concern is whether or not the new technologies or system are maturing as required.

With regard to measuring the maturity of new technologies and systems, process metrics or performance measures for systems development are not yet fully developed (Suomala 2004). Currently available tools and techniques - such as budgets, Quality Function Deployment (Hauser and Clausing 1988), Pugh's Concept Selection Process (Pugh 1991), Kasser's (Kasser 2004) First Requirements Elucidator Demonstration (FRED), Integrated Design Model (Vollerthun 2002), Subsystem Tradeoff Functional Equation (Shell 2003), Design for Manufacturability (Whitney 1988), Design-Build-Test Cycle (Clark and Fujimoto 1991) and Periodic Prototyping (Wheelwright and Clark 1992), Cost as an Independent Variable or CAIV (Brady 2001) and Lean Product Development Flow (Oppenheim 2004) - for controlling complex product development are fragmented and not used consistently throughout the process (Pawar and Driva 1999). More than an unwillingness to bother with such measures, perhaps system engineers or program managers do not use them consistently because they find them to be irrelevant or unable to address the needs of complex high uncertainty products. In particular, these tools focus only on measuring specific performance aspects of the system, such as task completion or cost, which may be important to some stakeholders but are unable to show if the system is maturing adequately over the development life cycle. Furthermore, concentrating on the measurement of these variables can lead to a wrong focus in terms of which activities are prioritized. Humans tend to apply more attention to activities that are being measured and rewarded (Shuman 1995; Chiesa et al. 2008; Blackburn 2009). "What gets measured is what gets managed" (Schmenner and Vollmann 1994). Therefore, it follows that when traditional project management tools are applied to assess the completion of tasks, a program manager will concentrate on meeting costs and schedule targets. Unfortunately, in the case of high novelty and high technology systems, achieving favorable cost and schedule performances alone do not guarantee that the system is maturing as planned. This is because when the technology development tasks were identified, there was no certainty yet that they will lead to the development of the novel technology. They were scientific educated guesses. What may happen is that by focusing on the project tasks and ensuring that they are achieved on time and within cost, the program manager will not know whether or not the required readiness has been achieved until much later. That is, he may discover that some of the tasks have to be repeated using a different approach or materials. Gaining this insight on a timely manner is crucial to containing costs because applying fixes later is always more costly. Such an assessment is most important during the earlier phases of the development life cycle when uncertainty is still high but corrective actions are still manageable. To encourage a system-wide view of the development process, the program manager must use system-wide maturity measures.

Scales that measure readiness levels have been proposed in the literature (Sauser et al. 2006; Sauser et al. 2008; Sauser et al. 2008; Sauser et al. 2008; Sauser et al. 2009, July). These scales – TRL, IRL and SRL – have gained some acceptance in the field of systems engineering (Cuellar 2009; Forbes 2009).

The review of the literature indicates that a properly constituted managerial control that is focused on the maturity of technologies, integration elements and the system as a whole is important to the success of new systems development. To exercise proper control, there must be a development plan to serve as the foundation for a scheduling, monitoring and evaluation method. This method must be interactive and encourage learning.

4.2 Discussions with Industry Representatives

During scheduled meetings with members of the industry who were directly involved with managing the development of systems, the response to the question of which methodologies they use for planning, monitoring and evaluation ranged from "Nothing" to "Earned Value Management (EVM)". However, the latter was immediately followed by the observation that EVM is "inadequate and cumbersome". Upon further probing, they revealed that EVM may determine if the tasks are being accomplished and at what costs but it does not yield any concrete information as to whether or not the system was maturing at an acceptable pace. At best, they can only hope that since the tasks were done, the system has matured accordingly. Often, this was not the case because the technologies and the system itself are so new and technologically advanced that no one really knows for sure how much maturity has been earned for the system under development, accomplished tasks notwithstanding.

These discussions were a strong indication that there is a desire to have a planning, scheduling, monitoring and evaluation tool specific to systems development which highlights system readiness.

4.3 Feedback from Conference Presentations

- Technology Maturity Conference 2007 and 2008 – this has been the primary venue for the exchange of ideas regarding the development and application of TRL. It is usually well attended by representatives from service units and postgraduate academic institutions of the Department of Defense (DoD), the Department of Energy (DoE), Department of Homeland Security (DHS), GAO and the private sector. During both conferences, some of the observations that were gathered were the on-going attempts to refine TRL, use it to manage systems development, but also the clear inability of TRL to measure the maturity of integration links and systems.
- Acquisition Research Symposium 2008 and 2009 – SRL and the planning, scheduling, monitoring and evaluation methodology for systems under development were presented during these DoD-sponsored conferences. The remarks received during and, more significantly, after the presentations were very positive and reinforced the observations that were gathered from the industry representatives, as mentioned earlier.

4.4 Conceptual Model

With the results of the research in mind, the conceptual model that we formulated has the following steps and represented in Figure 3 by the shaded areas:

1. Assign costs to each element and its readiness levels
2. Identify the optimal development plan
3. Translate the plan into a system development schedule
4. Establish a readiness management baseline
5. Track progress
6. Evaluate performance
7. Apply corrective measures (as required)
8. Identify, disseminate and apply lessons learned.

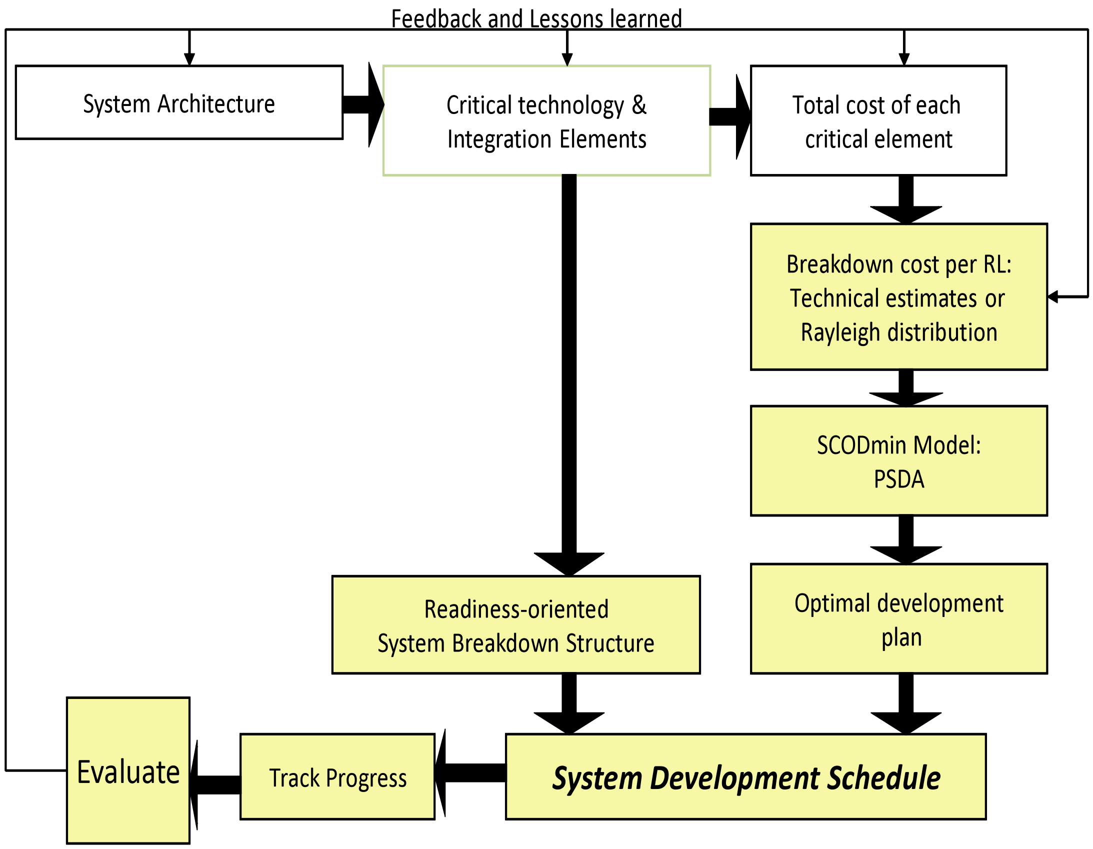


Figure 3: Conceptual Model

The cost of maturing each and every element of the system throughout the development process must be estimated. The readiness of the elements is determined using the technology readiness level (TRL) and integration readiness level (IRL) scales. The data on cost per readiness level for each element of the system is the main input to the SCODmin model (Magnaye 2010) whose solution yields an optimal development plan. This can then be broken down into the individual readiness levels, their readiness-oriented work packages, and then arranged into a *system readiness breakdown structure* (SRBS).

1. System Under Development

    1.1 Critical Technology Element 1

        1.1.1 TRL 1

        1.1.2 TRL 2

        1.1.3 TRL 3

1.1.x TRL x

1.2 Critical Integration Element 1

1.2.1 IRL 1

1.2.2 IRL 2

1.2.3 IRL 3

1.2.x IRL x

:

Figure 4: Abbreviated System Readiness Breakdown Structure

An abbreviated sample is shown in Figure 4. Level 1 is the whole system, Level 2 indicates its critical elements and level 3 represents their readiness levels, which have to be accomplished. Additional details can be incorporated to show the work packages that are required in order to achieve the readiness levels.

Using the SRBS as a guide, a *readiness management baseline* can be established. This show the tasks, when they should be achieved to reach each and every readiness level and how much they would cost. A work package is awarded an earned readiness value if the targeted readiness level has been achieved, as determined by an independent assessment process, which the organization prescribes. The *performance measurement baseline* is the Budgeted Cost of Readiness Scheduled (BCRS). Actual Performance is represented by the Budgeted Cost of Readiness Achieved (BCRA) and its cost as Actual Cost of Readiness Achieved (ACRA). These SERM concepts, their relationship to each other and how they compare to similar Earned Value Management measures are illustrated in Figure 5.

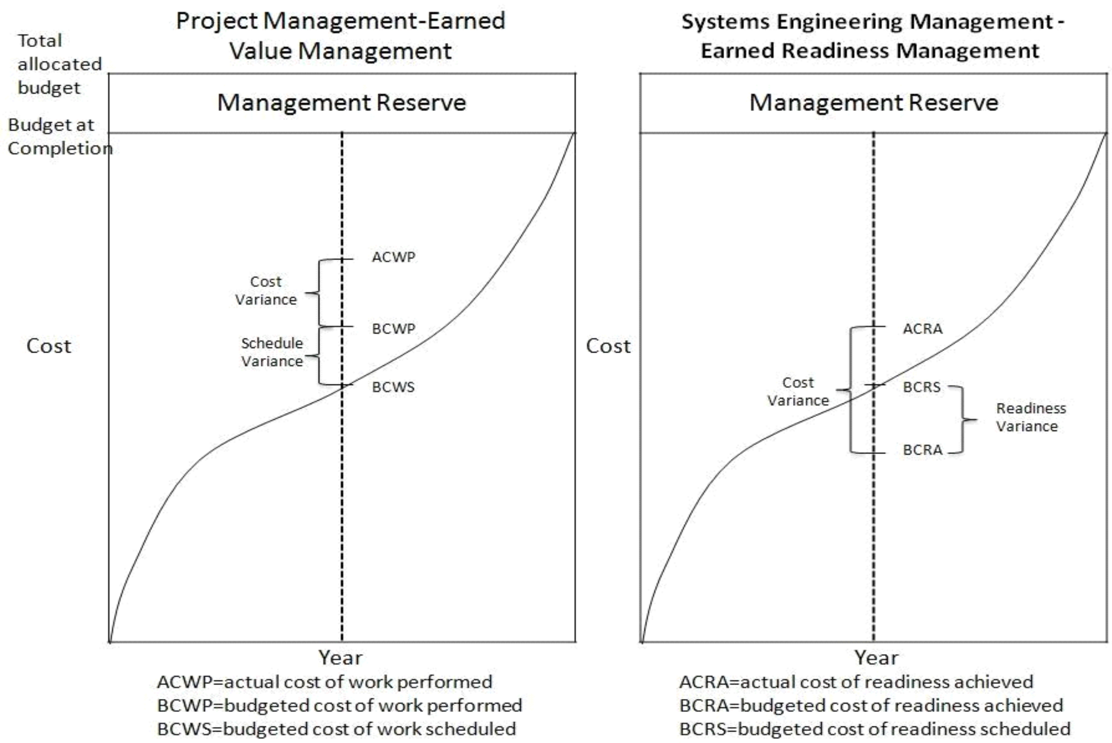


Figure 5: System Earned Readiness Management Concepts Compared to Earned Value Management

5. Illustrative Example

To show how the conceptual model of SERM can be used, we applied it to a system under development. We developed a case around the sample system that was used by Magnaye et al(Magnaye 2010) and added additional data as required. This case was based on a space robotic system that was developed by NASA but was later aborted in favor of an alternative manned approach. The paper assumed that this aborted system has been revived and the development scenarios were laid out using publicly available information.

5.1 Background

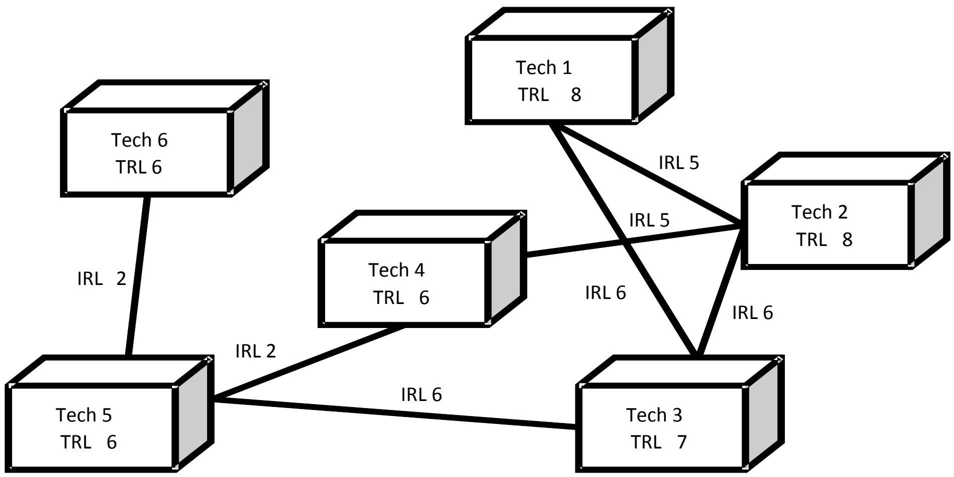
The test case that was written – *Robotic Servicing Mission for the Hubble Space Telescope* - presented the actual development of the robotic servicing system that was estimated to cost $1.3 billion. The Hubble Robotic Servicing and De-orbit System (HRSDS) was worked on extensively during fiscal year 2004 and fiscal year 2005 at a cost of $700 million. Over 1,000 persons from Goddard Space Flight Center of NASA, Lockheed Martin, MDRobotics and several other contractors completed enough activities such that the program went through a very successful Preliminary Design Review (PDR) in March, 2005 (Whipple, 2009). The servicing mission was estimated to have duration of 73 days of which

51 days will be the actual servicing of the observatory. However, later that year, it was cancelled after it was deemed that a manned servicing mission using the Space Shuttle was safe enough and had a greater chance of succeeding. The servicing mission (SM4) was completed in May, 2009.

The following presents a backgrounder, a rationale for reviving the system and hypothetical scenarios for its development.

> *The component upgrades and replacements to the Hubble Space Telescope (HST) that Servicing Mission4 (SM4) installed in May, 2009 have degassed and the observatory successfully underwent post-SM4 Servicing Mission Orbital Verification. HST is scheduled for de-orbit and retirement in 2014. The successor to the HST – the James Webb Space Telescope (JWST) – is proceeding and it is expected that the system will be launched in 2014. However, the scientific community expressed some doubts as to whether or not the HST should be retired at all. One concern stemmed from the fact that the JWST can only capture and send images in infrared wavelengths. On the other hand, the HST operates in visible, ultraviolet and near-infrared channels. The community saw advantages in having all modes available. The other concern of the scientific community was that without HST, any delays in the launch of the JWST will lead to a period when a gap in the transmission of exploration images from space can occur.*
>
> *A series of consultations within NASA and between the agency and the scientific community led to the conclusion that an observatory capable of handling visual and ultraviolet images such as the HST must continue operating alongside the JWST. Given the current economic climate at the time, developing and launching a new observatory to replace the HST was not approved. Instead, in January, 2010, Congress authorized NASA to send another servicing mission to maintain or even upgrade the HST by 2014.*
>
> *However, it was noted that the Space Shuttle Program on which the HST servicing missions have relied will no longer be in operation after 2012. Sending another manned servicing mission before then was also not feasible because the manifests for the remaining flights were already full and the new space shuttles of the Constellation Program would not yet be available by 2014.*
>
> *To solve this problem, the administrator instructed the director of the Goddard Space Flight Center (GSFC) to put together a plan to revive and complete the development of the Robotic Servicing Mission (RSM) which was originally considered for the SM4.*
>
> *In late August, 2009, the director of Goddard Space Flight Center (GSFC) and the manager of HST Servicing Mission Operations, Keith Walyus, submitted an updated plan to proceed with the development of HRSDM for use in Servicing Mission 5 scheduled for May, 2014. Based on consultations and collaboration with the original program participants or their successor entities, the plan retained the original technologies and architecture of the system* (see Figure 6*) but also incorporated the latest engineering advances. The plan estimated that incremental costs to mature the technologies from 2010 to 2014 will amount to $77.17 million*

while integrating them into the system will cost another $188.57 million for a total cost of $265.74 million (see Table 1).



Tech 1- Remote Manipulator System (RMS); Tech 2 - Special Purpose Dexterous Manipulator (SPDM); Tech 3 - Electronic Control Unit (ECU); Tech 4 - Autonomous Grappling (AG); Tech 5 - Autonomous Proximity Operations (APO); and Tech 6 - Laser Image Detection and Radar (LIDAR).

Figure 6: System Concept Diagram

Table I: HRSDS Incremental (2010–2014) Development Costs

Component	Cost	Comments
Remote Manipulator System	9.00	
Special Purpose Dexterous Manipulator	7.65	
Electronic Control Unit	14.23	
Autonomous Grappling	21.50	
Autonomous Proximity Operations	11.87	
Laser Image Detection and Radar	12.92	
System Integration	188.57	
TOTAL	265.74	

Satisfied with the plans and cost estimates, the new NASA director, Dr. Bolden, informed the White House who promptly advised him to build support for the program in Congress. After meeting with the chairpersons of the relevant committees in both chambers, the director concluded that congressional support for HRSDM will be greatly enhanced if a more detailed multi-year budget tied to a technology maturation plan (as called for by the Government Accountability Office - GAO) could be presented during the supplementary budgetary hearings scheduled for late September. The director was also assured that by developing more confidence in the ability of NASA to launch HRSDM successfully in 2014, a waiver may be granted to forego rebidding of the program elements. In effect, the prior contractors will be retained and thus save considerable time in restarting the program. A more elaborate technology and system development plan for HRSDM could also serve as a model for future programs which NASA could *use to finally address the concerns of GAO as it continued to argue for the need for technology system metrics, higher maturity of technologies that go into NASA systems and better control of development costs.*

5.2 Application of SERM

The conceptual model for the Earned Readiness Management approach to scheduling, monitoring and evaluation of the development process was applied to this case. The first step was to breakdown the cost estimates from Table I to determine the incremental cost of maturing every element through each readiness level. These are shown in Tables II and III.

Table II: Incremental Cost to Mature Technologies (cost in millions, time in man-hours)

Technology	1		2		3		4		5		6	
TRL Level Effort	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1												
2												
3												
4												
5												
6												
7							$8.76	127	$4.67	280	$7.80	450
8					$6.89	476	$4.21	341	$5.31	236	$1.23	21
9	$9.00	349	$7.65	432	$7.34	299	$8.53	568	$1.89	48	$3.89	300

Table III: Incremental Cost to Mature Integrations (cost in millions, time in man-hours)

Integration	1,2		1,3		2,3		2,4		3,5		4,5		5,6	
IRL Level	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1														
2														
3											$4.53	200	$1.23	80
4											$5.81	400	$2.19	380
5											$7.21	658	$5.95	532
6	$1.00	140					$2.75	164			$9.00	700	$7.00	621
7	$1.75	180	$2.00	93	$5.0	25	$5.40	320	$3.45	324	$12.00	954	$8.08	862
8	$4.00	300	$4.00	165	$4.50	320	$6.32	432	$4.57	400	$14.32	1021	$10.03	997
9	$6.00	500	$6.50	389	$5.50	465	$7.45	690	$6.78	500	$17.65	1238	$11.10	1145

Next, we apply the SCODmin model to the data and obtained the solution or development plan shown in Table IV.

Table IV: Optimal Development Plan

Fiscal Year	Target SRL	TRL						IRL						
		1	2	3	4	5	6	1,2	1,3	2,3	2,4	3,5	4,5	5,6
2014	1.000	9	9	9	9	9	9	9	9	9	9	9	9	9
2013	0.896	9	9	9	8	9	9	9	9	9	8	8	5	7
2012	0.792	8	9	9	6	9	9	9	9	9	5	8	4	6
2011	0.688	8	8	9	6	9	9	8	8	7	5	7	2	4
2010	0.584	8	8	8	6	7	6	7	7	7	5	6	2	4
2010	0.480	8	8	7	6	6	6	5	6	6	5	6	2	2

From the optimal development plan, we prepared the system development schedule by showing the system readiness breakdown structure along the vertical, the timetable on the horizontal and the costs in the cells formed by their intersections. The schedule from 2004 to 2014 is shown as Table V. According to this, work on the Electronic Control Unit (element 3), Autonomous Proximity Operations module (element 5), the integration links between elements 1&2, 1&3, 2&3 and 5&6 are to resume in Fiscal Year 2010 requiring a budgetary allocation of $20.230 million. The elements and integration links that should be worked on for the succeeding years can also be identified from Table V along with their costs. Altogether, including the $700 million that was already spent for development from 2004 to 2005 followed by mothballing until 2009, the system under development will cost $965.74 million.

There are situations where the optimization algorithm suggested that work on an element of the system be put on-hold during some years and resumed at a later year. For example, the integration link between elements 2&3 is advanced to an IRL of 7 by 2010 but no work on it is called for during 2011. It is resumed only in 2012. Similar situations exist for the integration links between elements 3&5 and 5&6. This could mean that workers and equipment may be idle for a year. It is not a big issue if they can be diverted to other tasks. Otherwise, it represents opportunity costs (due to foregone revenues) and administrative ones associated with laying-off workers and re-hiring them later. This should be avoided unless there are genuine technical justifications for it.

Table V - System Development Schedule (Fiscal Years) and Costs ($Millions)

	2004-05	2006-09	2010	2011	2012	2013	2014	TOTAL
1. HUBBLE ROBOTIC SERVICING AND DE-ORBIT SYSTEM								
1.1 CRITICAL TECHNOLOGY ELEMENTS								
1.1.1 Remote Manipulator (Element 1)								
1.1.1.1 TRL=1								
1.1.1.2 TRL=2								
1.1.1.3 TRL=3								
1.1.1.4 TRL=4								
1.1.1.5 TRL=5								
1.1.1.6 TRL=6								
1.1.1.7 TRL=7								
1.1.1.8 TRL=8								
1.1.1.9 TRL=9						9.000		
1.1.2 Special Purpose Dexterous Manipulator (Element 2)								
1.1.2.9 TRL=9					7.650			
1.1.3 Electronic Control Unit (Element 3)								
1.1.3.8 TRL=8			6.890					
1.1.3.9 TRL=9				7.340				
1.1.4 Autonomous Grappling (Element 4)								
1.1.4.7 TRL=7						8.760		
1.1.4.8 TRL=8						4.210		
1.1.4.9 TRL=9							8.530	
1.1.5 Autonomous Proximity Operations (Element 5)								
1.1.5.7 TRL=7			4.670					
1.1.5.8 TRL=8				5.310				
1.1.5.9 TRL=9				1.890				
1.1.6 Laser Image Detector and Radar (Element 6)								
1.1.6.7 TRL=7				7.800				
1.1.6.8 TRL=8				1.230				
1.1.6.9 TRL=9				3.890				
1.2 CRITICAL INTEGRATION ELEMENTS								
1.2.1 Elements 1 and 2								
1.2.1.1 IRL=1								
1.2.1.2 IRL=2								
1.2.1.3 IRL=3								
1.2.1.4 IRL=4								
1.2.1.5 IRL=5								
1.2.1.6 IRL=6			1.000					
1.2.1.7 IRL=7			1.750					
1.2.1.8 IRL=8				4.000				
1.2.1.9 IRL=9					6.000			
1.2.2 Elements 1 and 3								
1.2.2.7 IRL=7			2.000					
1.2.2.8 IRL=8				4.000				
1.2.2.9 IRL=9					6.500			
1.2.3 Elements 2 and 3								
1.2.3.7 IRL=7			0.500					
1.2.3.8 IRL=8					4.500			
1.2.3.9 IRL=9					5.500			
1.2.4 Elements 2 and 4								
1.2.4.6 IRL=6						2.750		
1.2.4.7 IRL=7						5.400		
1.2.4.8 IRL=8						6.320		
1.2.4.9 IRL=9							7.450	
1.2.5 Elements 3 and 5								
1.2.5.7 IRL=7				3.450				
1.2.5.8 IRL=8					4.570			
1.2.5.9 IRL=9							6.780	
1.2.6 Elements 4 and 5								
1.2.6.3 IRL=3					4.530			
1.2.6.4 IRL=4					5.810			
1.2.6.5 IRL=5						7.210		
1.2.6.6 IRL=6							9.000	
1.2.6.7 IRL=7							12.000	
1.2.6.8 IRL=8							14.320	
1.2.6.9 IRL=9							17.650	
1.2.7 Elements 5 and 6								
1.2.7.3 IRL=3			1.230					
1.2.7.4 IRL=4			2.190					
1.2.7.5 IRL=5					5.950			
1.2.7.6 IRL=6					7.000			
1.2.7.7 IRL=7						8.080		
1.2.7.8 IRL=8							10.030	
1.2.7.9 IRL=9							11.100	
Total Annual Cost ($Millions)	700.000	0.000	20.230	38.910	58.010	51.730	96.860	265.740
System Readiness Level	0.480	0.480	0.580	0.690	0.790	0.890	1.000	
LEGEND:								
(black) - Completed Work								
(grey) - Program Mothballed								
0.000 - Work to be Completed after Program Resumed at the End of FY2009 and Cost								

To avoid this problem, the development team may be allowed to start such affected activities early to maintain continuity. For example, instead of waiting until 2012 as prescribed by the algorithm, work on reaching an IRL of 8 for the integration link between elements 2&3 can be moved forward to 2011. The program managers and the owners of the system must weigh the trade-off between incurring some expenditures earlier than originally planned versus the administrative and technical costs of putting the affected elements of the system "on-hold" until it can be re-started at the later prescribed date. The revised system development schedule is shown in Table VI.

The actual progress of the development process can be measured on a regular basis, compared to the original schedule and the readiness and cost performance measures using SERM can be calculated to identify problem areas and formulate remedial measures.

Table VI - Adjusted System Development Schedule (Fiscal Years) and Costs ($Millions)

	2004-05	2006-09	2010	2011	2012	2013	2014	TOTAL
1. HUBBLE ROBOTIC SERVICING AND DE-ORBIT SYSTEM								
1.1 CRITICAL TECHNOLOGY ELEMENTS								
1.1.1 Remote Manipulator (Element 1)								
1.1.1.1 TRL=1								
1.1.1.2 TRL=2								
1.1.1.3 TRL=3								
1.1.1.4 TRL=4								
1.1.1.5 TRL=5								
1.1.1.6 TRL=6								
1.1.1.7 TRL=7								
1.1.1.8 TRL=8								
1.1.1.9 TRL=9						9.000		
1.1.2 Special Purpose Dexterous Manipulator (Element 2)								
1.1.2.9 TRL=9					7.650			
1.1.3 Electronic Control Unit (Element 3)								
1.1.3.8 TRL=8			6.890					
1.1.3.9 TRL=9				7.340				
1.1.4 Autonomous Grappling (Element 4)								
1.1.4.7 TRL=7						8.760		
1.1.4.8 TRL=8						4.210		
1.1.4.9 TRL=9							8.530	
1.1.5 Autonomous Proximity Operations (Element 5)								
1.1.5.7 TRL=7			4.670					
1.1.5.8 TRL=8				5.310				
1.1.5.9 TRL=9				1.890				
1.1.6 Laser Image Detector and Radar (Element 6)								
1.1.6.7 TRL=7				7.800				
1.1.6.8 TRL=8				1.230				
1.1.6.9 TRL=9				3.890				
1.2 CRITICAL INTEGRATION ELEMENTS								
1.2.1 Elements 1 and 2								
1.2.1.1 IRL=1								
1.2.1.2 IRL=2								
1.2.1.3 IRL=3								
1.2.1.4 IRL=4								
1.2.1.5 IRL=5								
1.2.1.6 IRL=6			1.000					
1.2.1.7 IRL=7			1.750					
1.2.1.8 IRL=8				4.000				
1.2.1.9 IRL=9					6.000			
1.2.2 Elements 1 and 3								
1.2.2.7 IRL=7			2.000					
1.2.2.8 IRL=8				4.000				
1.2.2.9 IRL=9					6.500			
1.2.3 Elements 2 and 3								
1.2.3.7 IRL=7			0.500					
1.2.3.8 IRL=8				4.500				
1.2.3.9 IRL=9					5.500			
1.2.4 Elements 2 and 4								
1.2.4.6 IRL=6						2.750		
1.2.4.7 IRL=7						5.400		
1.2.4.8 IRL=8						6.320		
1.2.4.9 IRL=9							7.450	
1.2.5 Elements 3 and 5								
1.2.5.7 IRL=7				3.450				
1.2.5.8 IRL=8					4.570			
1.2.5.9 IRL=9							6.780	
1.2.6 Elements 4 and 5								
1.2.6.3 IRL=3					4.530			
1.2.6.4 IRL=4					5.810			
1.2.6.5 IRL=5						7.210		
1.2.6.6 IRL=6							9.000	
1.2.6.7 IRL=7							12.000	
1.2.6.8 IRL=8							14.320	
1.2.6.9 IRL=9							17.650	
1.2.7 Elements 5 and 6								
1.2.7.3 IRL=3			1.230					
1.2.7.4 IRL=4			2.190					
1.2.7.5 IRL=5				5.950				
1.2.7.6 IRL=6					7.000			
1.2.7.7 IRL=7						8.080		
1.2.7.8 IRL=8							10.030	
1.2.7.9 IRL=9							11.100	
Total Annual Cost ($Millions)	700.000	0.000	20.230	49.360	47.560	51.730	96.860	265.740
System Readiness Level	0.480	0.480	0.580	0.690	0.790	0.890	1.000	
LEGEND:								
(dark) - Completed Work								
(grey) - Program Mothballed								
0.000 - Work to be Completed after Program Resumed at the End of FY2009 and Cost								

5.3 Managerial Implications and Future Research

This report presented an approach which can operationalize the implementation of a system development plan such as the one obtained from the cost minimization optimization model ($SCOD_{min}$) proposed by Magnaye et al (2010). The approach – System Earned Readiness Management – provides program or system engineering managers with the tools to schedule, monitor and evaluate the completion of tasks aimed at achieving the planned maturity of the system as measured by SRL. This is the primary contribution of this paper. With SERM, it is now possible to exercise a more effective maturity-focused managerial control over the process of developing new systems as has been suggested by the Government Accountability Office and practitioners themselves. SERM also reinforces the ability of program managers to define and analyze the development of individual technologies that go into a system not as isolated projects but as critical parts of an integrated unit (Forbes et al. 2009).

SERM can be used in an interactive manner that can also be integrated with the learning processes of the development organization. This is important when the system involves a high level of novelty and technological contents. Such a system will undergo multiple designs, technology choices and cost estimates, generating valuable insights and lessons. These can be captured by an iterative application of SERM as the novel technologies, architecture and functionalities within the system become clarified and better understood. For example, new more accurate cost data can be entered into the SCODmin optimization model to generate a revised development plan which can then be translated into the system breakdown structure, schedule and so on. The same could be done with changes in technology choices, system architecture or capabilities.

In accordance with the wishes of the practitioners that we consulted throughout the research process, SERM is both simple and familiar. The system development schedule is in the form of a GANTT chart which is used routinely in project management. The system breakdown structure (Figure 4) is very similar to a project work breakdown structure (WBS) while determining readiness and cost variances using SERM is almost the same as in project earned value management (see Figure 5).

The effectiveness of SERM in facilitating better managerial control over the development of a novel high technology system will be greatly enhanced by a thorough verification and validation of the metrics which serve as its foundation. These are the TRL, IRL and SRL scales. They must be applied to a wide cross-section of technologies and systems across all the relevant domains which include, but are not limited to, strategic national defense, aerospace, software, energy, transport, environment and economic systems. The primary goal would be to determine which values of SRL correspond to which phases of the development life cycle for each domain.

SERM itself must be validated by examining its practicality when managing the development of a system. This would involve a longitudinal research study of a diverse collection of systems from beginning to deployment and disposal. Earned Value Management for projects did not become a mature concept until it was experimented with by the students and faculty of the US Air Force Institute of Technology (Abba 1997; Abba 2001). Perhaps SERM for systems should also be subjected to the same amount of scrutiny by the academic institutions and contractors associated with the Departments of Defense and Energy as well as NASA.

Our research showed that there is a desire among program and systems engineering managers to have a methodology for exercising managerial control over a novel, high technology system undergoing development. Such a methodology must be based on a system-wide view, focused on readiness or maturity of the system, which can be employed in an interactive and informative manner. Above all else, it must be simple and have a familiar feel or the practitioners will be reluctant to employ it.

Such a desire is justified by the conclusions that one can draw from the literature on managerial control of new product development. Our review showed that such a control mechanism is important to success so long as it is applied early in the process or life cycle, applied in an interactive manner and can enhance coordination and learning through the creation of an information infrastructure.

With these in mind, we crafted a methodology called System Earned Readiness Management that is patterned after tools that were generally accepted in the project management domain. What distinguishes SERM is that the information presented, analyzed and used for decision-making revolves around metrics on readiness or maturity of a novel high technology system, its critical technology elements and the integrations among them. We illustrated the use of SERM by applying it to a sample space system – the Hubble Robotic Servicing and De-orbit System – with actual but disguised data from 2004 to 2009 and hypothetical scenarios from 2010 to 2014.

SERM can be greatly refined and validated if it can be applied to actual systems that are about to undergo development. This calls for longitudinal studies, which we hope to initiate with the cooperation of a defense contractor and an oil services firm.

6. Project Accomplishments

6.1 Publications

6.1.1 Journal

Tan, W., J. Ramirez-Marquez, and B. Sauser. (2010). A Probabilistic Approach to System Maturity Assessment. *Systems Engineering* (accepted)

Sauser, B., R. Gove, E. Forbes, and J. Ramirez-Marquez. (2010). Technology Integration Maturity Metrics: Development of an Integration Readiness Level. *Information, Knowledge, Systems Management* (accepted)

6.1.2 Conference Proceedings

Tan, W., B. Sauser, and J. Ramirez-Marquez. (2009). Monte-Carlo Simulation Approach for System Readiness Level Estimation. *International Symposium of the International Council on Systems Engineering*. July 20-23, Singapore (**Brian Mar Best Student Paper**)

Sauser, B., E. Forbes, M. Long, and S. McGrory. (2009). Defining an Integration Readiness Level for Defense Acquisition. *International Symposium of the International Council on Systems Engineering*. July 20-23, Singapore (**Best Paper in Government Domain**)

Magnaye, R**., B. Sauser**, J. Ramirez-Marquez, and W. Tan. (2009). Using a System Maturity Index to Monitor and Evaluate the Development of Systems. *Acquisition Research Symposium.* May 13-14, Monterey, CA

Cuellar, R., and B. Sauser. (2009). Dynamic Multipoint Optimization Application to Corporate Portfolio Management. *Acquisition Research Symposium.* May 13-14, Monterey, CA

6.2 Presentations

"Systems & Change: Understanding System Maturity" General Dynamics Corporate Leadership Forum, Webinar (seminar), February 23, 2010 (invited)

"System and Integration Readiness Levels for Defense Acquisition." INCOSE Heartland Chapter, Webinar (seminar), November 3, 2009 (invited)

"Dynamic Modeling of Programmatic and Systematic Interdependence for System of Systems Acquisition." *National Defense and Industry Association Systems Engineering Conference*, San Diego, CA, October 29, 2009

"Linking Systems Engineering Artifacts with Complex System Maturity Assessments." *National Defense and Industry Association Systems Engineering Conference*, San Diego, CA, October 28, 2009

"System Maturity Assessment for Decision Support in Lifecycle Acquisition." INCOSE Chesapeake Chapter, Applied Physics Laboratory, Johns Hopkins University, October 3, 2009 (invited)

"Systems Maturity Assessment for Defense." National Security Agency Learning Seminar, September 9, 2009 (invited)

"System (of Systems) Acquisition Maturity Models and Management Tools." Office of the Secretary of Defense Software Collaborators Webinar (seminar), August 18, 2009 (invited)

"Defining an Integration Readiness Level for Defense Acquisition." *International Symposium of the International Council on Systems Engineering*, Singapore, July 21, 2009

"System Maturity Assessment for Decision Support in Lifecycle Acquisition." University of Alabama in Huntsville College of Business Administration, Huntsville, AL, July 7, 2009 (invited)

"A Review of Frameworks and Models from Maturity to Collaboration in Systems and System of Systems Engineering." Texas A&M University Department of Industrial and Systems Engineering Seminar, College Station, TX, June 29, 2009 (invited)

6.3 Awards

Best Paper in Government Domain
International Symposium of the International Council on Systems Engineering, Singapore, July 2009

Brian Mar Best Student Paper
International Symposium of the International Council on Systems Engineering, Singapore, July 2009

Note: From the potential four best papers given at the International Symposium of the International Council on Systems Engineering, we won two out of the four.

6.4 Knowledge Transfer to Industry/Government

6.4.1 U.S. Army Armament Research Development and Engineering Center (ARDEC)

We have built strong working relationship with the U.S. Army ARDEC System Engineering Director. This relationship has resulted in an effort to develop a guide and tool for determining a systems maturity readiness and potential for making efficient and effective life-cycle acquisition and operational decisions. In addition, an ARDEC employee will be utilizing our research outputs in a Six Sigma Black Belt Project in order to benchmark their utilization in program review processes.

6.4.2 Northrop Grumman / USN PMS 420

Northrop Grumman has worked in partnership with the US Navy's Littoral Combat Ship Mission Modules Program Office (PMS 420), to implement the SRL methodology across the Mission Modules development effort. Since its roll-out to the program in September of 2007, SRL's role has steadily evolved to become a vital component of both system technical development status monitoring and on-going resource allocation decisions. From inception, the Mission Modules Program has been chartered with leveraging a large number of existing DOD programs of record and COTS/GOTS equipment and integrating them together to provide enhanced capabilities and data sharing. Due to the inherently mature incoming system components, the need for analysis and monitoring of overall development maturity beyond the TRLs was acute. By quantitatively evaluating the maturity of the complex network of integrations in concert with the components they connect, the IRL scale and SRL methodology have proved to be invaluable. The scale provides a common dashboard view of true system maturity enabling decision makers better understand current status and mitigate emerging risks in the systems integration activity. The concept is also being expanded for use in analyzing future technology insertion options and program development costs. This work with Northrop Grumman and the U.S. Navy has resulted in the SD&ML begin directly funded by the U.S. Navy PMS 420 through the Systems Engineering Research Center.

6.5 Other Related Activities:

6.5.1 Systems Maturity Assessment Roundtable

On March 12, 2009, a Roundtable was held in Washington, DC with the purpose of providing system designers and developers, program and project managers, and researchers a platform to discuss and disseminate emerging knowledge in systems maturity indices (beyond TRL). The objective was to create a community of practitioners and researchers focused on new knowledge in system maturity indices and assessment.

For the first half of the day, presentations were made from stakeholders on the emerging challenges and potential solutions in systems maturity indices and assessment. For the second half of the day, breakout groups were asked to address these four questions with respects to the future of systems maturity assessment:

1. What are the real questions?
2. What do we know?
3. What do we need to know?
4. What could we do to learn that?

Copies of the presentations and a summary report of the outcomes can be found at http://www.SystemReadinessLevel.com, under SMA Roundtable.

6.5.2 Web Page

From the birth of this research, we have believed in an open academic model of sharing our research outcomes in the broadest sense possible. Thus, we have created a web site, http://www.SystemReadinessLevel.com, for the distribution of our research results. At this web site you will find: Research Overview; Publications/Presentations/News, Research Projects; and Contact Information.

6.5.3 Conferences Attended

- Systems Engineering Conference, National Defense and Industry Association, San Diego, CA, October 2009

- Acquisition Research Symposium, Monterey, CA, May 2009.

6.5.4 Student Research Supported/Supervised

Our funding from the Navel Postgraduate School as afforded us the privilege to support one Ph.D. student to assist in the execution of this research. But, it has also allowed us the ability to attract graduate student to pursue related and supportive research. These students are:

- Ana Lisbeth Conch*o. M.S. Student*. *"*Functionally Equivalent COTS for Optimal Component Substitution within System Evolution Planning*"*

- Romulo Magnaye. *Ph.D. Student*. *Robert Crooks Stanley Fellow*. "Using a System Maturity Scale to Monitor and Evaluate the Development of Complex Systems"

- Weiping Tan. *Ph.D. Student. NPS Supported*. "A Probabilistic Approach to System Maturity Assessment."

6.5.5 Student Projects Supervised

Within the School of Systems and Enterprises at Stevens Institute of Technology, students are encouraged to complete a 3-credit special problems project as part of their course requirements. Because of the success of this research, we have been able to attract a number of students to pursue projects related to SRL and related topics. Here is a list of those students and projects:

Sweeton, J. (2009). "Transitioning Innovations into an Agile System Analysis of Cost and Improving Communication." M.S. Special Problems in Systems Engineering.

Jumbo, L. (2009). "Evaluation of Selected DOD Systems Development Using the System Readiness Level (SRL) Concept" M.S. Special Problems in Systems Engineering.

Snow, G. (2009). "The Use of System Maturity Indices to Assess & Manage Risk in an Open System from Development through Production." M.S. Special Problems in Systems Engineering.

Lin, D. (2009). "Develop a Producibility Readiness Level to Complement System Readiness Level within Defense Acquisition Systems." M.S. Special Problems in Systems Engineering.

Van Nostrand, A. (2009). "What can Constellation Learn from Taking a Soft Systems View of the Reliability Success of Apollo?" M.S. Special Problems in Systems Engineering.

7. References

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Abba, W. F. (2001). "How earned value got to prime time: a short look back and glance ahead." The Measurable News.

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