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Multi-Objective Optimization of System Capability Satisficing in Defense Acquisition

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Abstract

Previous research in this area has developed, tested, and implemented a system maturity measure, i.e. System Readiness Level (SRL); supporting optimization models; and an enhanced SRL hierarchy for multi-function, multi-capability (MFMC) systems. The later developments are predicated on what has become the accustomed challenge for managers and engineers to properly assess systems' development and acquisition to ensure the achievement of critical capabilities and functions while deciding amongst multiple technologies with similar functionalities but different maturity levels and limited resources. Building upon these developments, this research asked: ***How can we efficiently and effectively allocate available resources to ensure the maturity achievement of critical functions and capabilities in an MFMC system when facing competing technology alternatives?*** To address this question, this work developed a multi-objective optimization model and solution approach that can be used to evaluate systems' development maturity, track progress, identify component criticality, and form corresponding strategies for understanding trade-offs in technology and integration options.

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14. ABSTRACT

Previous research in this area has developed, tested, and implemented a system maturity measure, i.e. System Readiness Level (SRL); supporting optimization models; and an enhanced SRL hierarchy for multifunction multi‐capability (MFMC) systems. The later developments are predicated on what has become the accustomed challenge for managers and engineers to properly assess systems? development and acquisition to ensure the achievement of critical capabilities and functions while deciding amongst multiple technologies with similar functionalities but different maturity levels and limited resources. Building upon these developments, this research asked: How can we efficiently and effectively allocate available resources to ensure the maturity achievement of critical functions and capabilities in an MFMC system when facing competing technology alternatives? To address this question, this work developed a multi‐objective optimization model and solution approach that can be used to evaluate systems? development maturity, track progress, identify component criticality, and form corresponding strategies for understanding trade‐offs in technology and integration options.

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1. Introduction

Under the direction of the Principal Investigators (PIs) and with support from the Naval Postgraduate School (NPS) and government/industry partnerships, the Systems Development and Maturity Laboratory (SysDML) at Stevens Institute of Technology has developed the following:

a) A methodology for determining a system's development/acquisition maturity (i.e., System Readiness Level [SRL]; Sauser, Ramirez-Marquez, Henry, & DiMarzio, 2008; Sauser & Ramirez-Marquez, 2009b; NPS BAA 07-002);

b) Two optimization models for allocating resources so as to optimize cost, schedule, and maturity performance (i.e., SRL_{max} and $SCOD_{min}$; Ramirez-Marquez & Sauser, 2009; Sauser and Ramirez-Marquez, 2009b; Magnaye, Sauser, & Ramirez-Marquez, 2010; NPS BAA 07-002);

c) A methodology that combines items (a) and (b) into an approach called Systems Earned Readiness Management (SERM; Magnaye, Sauser, & Ramirez-Marquez, 2009; Sauser & Ramirez-Marquez, 2009; Magnaye, 2010; NPS BAA 08-004);

d) Models to determine which components[1] are sufficient, critical, or important to achieve a level of system maturity for the intended functionalities and capabilities of a system (Tan et al., 2010; NPS BAA 09-002); and

e) An enhanced SRL hierarchy that enables multiple architectural views in maturity assessment at the capability, function, and system levels and incorporates an Analysis of Alternatives (AoA; or trade-off) for technology and integration component adoption which impacts the system maturity, functionality, and capability (Tan, Sauser, & Ramirez-Marquez, 2011a, 2011b; NPS BAA 10-002).

It is important to note that throughout these research efforts, the SysDML has maintained an evolutionary development through which we have worked closely with industry and government to refine and implement our research in order to ensure its relevance and rigor (see Exhibit 1 for a summary). For example, current efforts funded by the Acquisition Research Program (ARP) are addressing some recurring issues that were revealed through conversations with our industry and government research partners. One issue of great interest to us is the following:

> *…with increasing development and acquisition of systems that are built upon open and flexible platform designs that accommodate multiple functions and capabilities as well as the ability for adopting future mission packages (e.g. modularity, system of systems), the decisions to trade-off among multiple alternatives that enable necessary functions and capabilities will be unavoidable.*

While the recent efforts in AoA are necessary and relevant to the understanding of systems maturity and alternatives comparison and prioritization, its application is limited in an acquisition situation where

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[1] *Components* are defined as the technologies and/or integrations of the system of interest.

in the procurement of a complex system there are many technology alternatives with the same functionality but different maturity states or different cost request for further maturation. Therefore, this research built upon the previous AoA research to propose the employment of multi-objective (MO) optimization models for the development of systems that can perform multiple functions and multiple capabilities (MFMC).

Contrary to the single-objective optimization models developed in previous research, this effort addressed the MO problem and provides potential solutions to assist managers with flexibility in the planning of system acquisition and further system maturation. Thus, this research addresses a fundamental question:

> ***How can we efficiently and effectively allocate available resources to ensure the maturity achievement of critical functions and capabilities in an MFMC system when facing competing technology alternatives?***

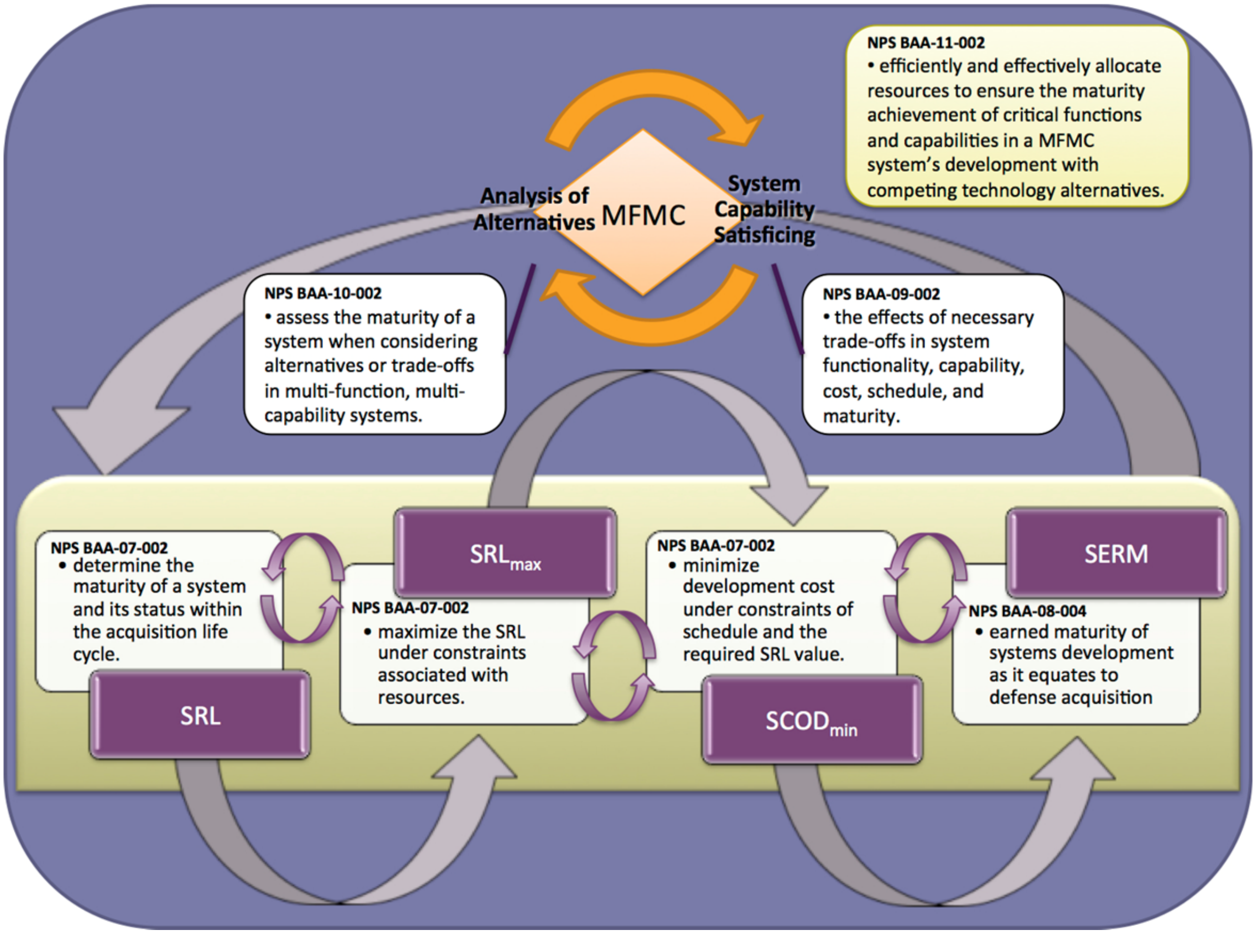


Exhibit 1. Evolutionary Development

2. Purpose and Focus of Research

Over the past six years, the SRL scale and supporting methods have undergone continuous development and have been accepted as a valid metric to measure the readiness of a system throughout its development lifecycle within various organizations (e.g., U.S. Navy-PMS420, U.S. Army Armament Research, Development and Engineering Center [ARDEC], Lockheed Martin, National Security Agency, and Northrop Grumman). However, to date, this scale has focused on the management of systems intended to perform a single function. Today, even the most basic weapons such as assault rifles have become multi-functional. As such, during the development process, these systems may be called upon to deliver some of their capabilities even as others are still several phases behind. Often, this requires an AoA among technology choices and architectures to take advantage of those that are already mature, though not originally intended for use in the development of the desired function. This, in turn, requires a thorough understanding of the technical aspects of the components but, more significantly, the relative importance of each choice on the readiness of the system *vis-à-vis* its desired capability.

In practice, a system evolves with time from a single capability of a specific function to a more complicated one that affords multiple functions and ensures the operational performance of a function by having several backup capabilities. Moreover, in order to ensure the success of the development or acquisition of a system, even for a specific function, it is common to have one or several backup capabilities. In addition, in the evolution of systems development, the advancement of technology options is progressing faster than the systems themselves. In this process, the following questions may arise: Will a new, more functional system or technology supersede the old? Has the system or technology become inadequate due to changes in other systems or technologies? Is it more effective to invest in the development of new technology or system? Has the system or technology lifetime been shortened by recent development? What is a robust methodology that can effectively and efficiently analyze, compare, and trade-off technology alternatives?

With an ever-increasing complexity of the systems that are being developed and realized, multiple functions and capabilities are common to the development of most systems, which raises the need to balance development objectives when facing multiple component alternatives. As a result, managers require metrics that enable the assessment of MFMC system developmental maturity to manage the potential risks posed by the previous questions (Volkert, 2009).

For example, Forbes, Volkert, Michaud, Gentile, and Sondi (2009) have described a system with six capabilities that are realized by six threads of components. The architecture of this system is represented in Exhibit 2. As described in their paper, this system had undergone a system maturity assessment with summary charts also depicted in Exhibit 2. The initial system architecture represented in Exhibit 2(a) resulted in an assessment with an overall SRL of 0.60 (see MP SRL in upper right box); the identification of an insufficiently mature technology and supporting integrations (circled); and analysis of the technology-integration maturity of all the system components (horizontal line at bottom of diagram). An alternative systems solution based on a trade-off (see Exhibit 2(b)) considered replacing a single technology (i.e., MVCS) with another two technologies (i.e., DLS OB; DLS RMMV). This alternative does not significantly improve the overall SRL value (increase of only 0.04), but it does improve the technology-integration maturity of all the lagging system components (horizontal line at bottom of diagram). While this analysis may seem sufficient in increasing systems maturity toward an effective acquisition decision, it does not consider many of the IMs related to an AoA and their influence on the system’s current or future maturity. Thus, a decision made purely on an increase in maturity may be insufficient. This described research intends to address this concern by enhancing the SRL approach to take into account the multiple system functions and capabilities which allows for the opportunity to better understand an AoA in technologies and integrations to more effectively manage system maturity and acquisition.

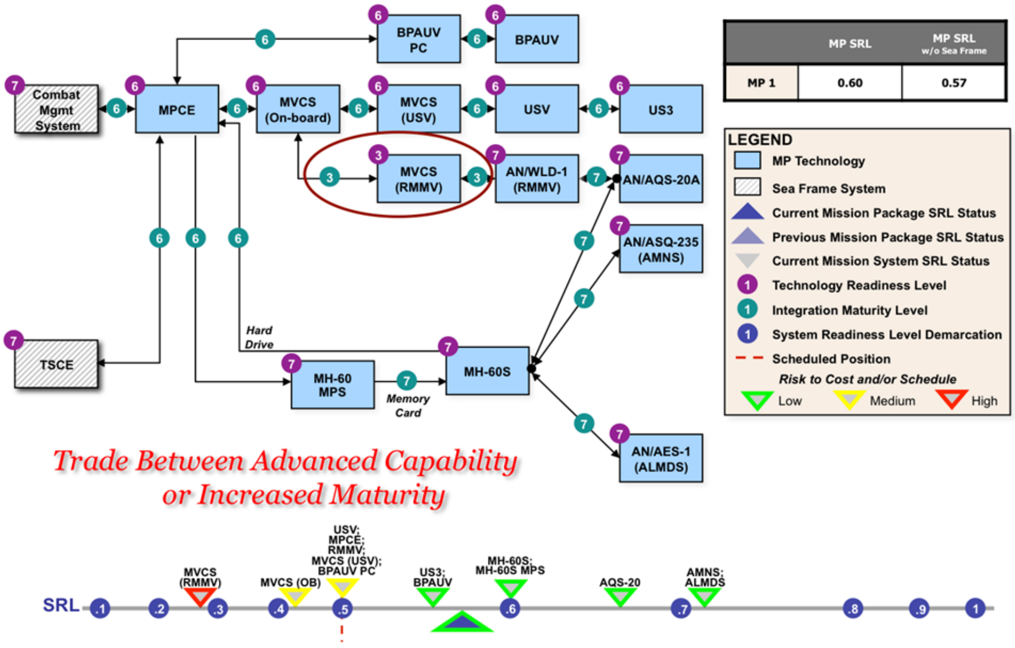


Exhibit 2(a)

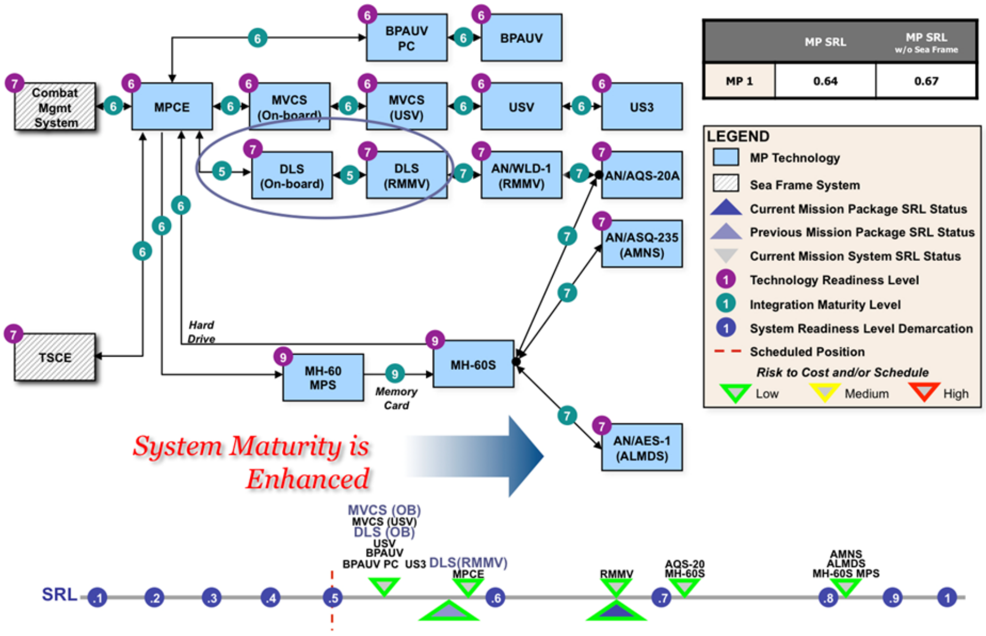


Exhibit 2(b)

Exhibit 2. Technology/Integration Trade-Off Analysis

3. Research Approach

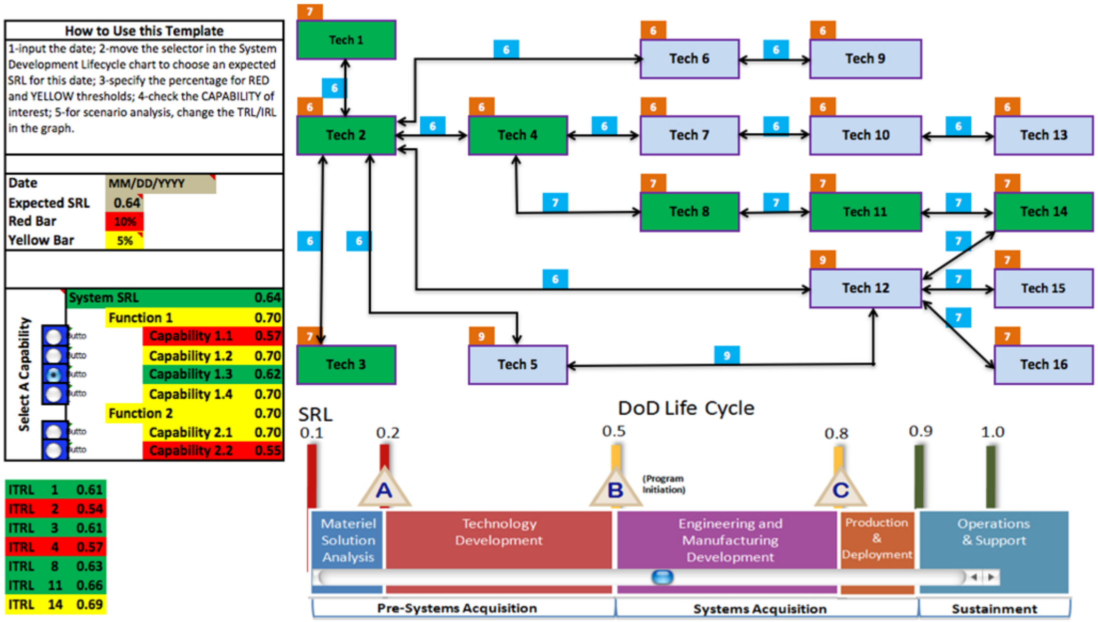
In the acquisition of systems, it is a core objective for a system to be deployed that satisfies stakeholders' needs while staying within acceptable budgetary and schedule constraints. However, achieving this objective has never been easy because of inherent uncertainty, which has been compounded as the complexity of defense systems has increased. This complexity challenges our ability to properly manage system development and acquisition in face of the lack of competent techniques and tools. Therefore, a tension exists between the need for systems development and our actual capability to fulfill this need. Although impossible to eliminate, the tension has attracted significant research in the pursuit of tools and models that can mitigate it to some degree.

Mathematical optimization is an approach used to maximize or minimize a system figure of merit (FOM; e.g., system reliability, acquisition cost, system maturity) in search of the optimal solution within a feasible resolution space (e.g., not to exceed the dedicated resources or by satisfying other requirements). For optimization to be effective, it is vital to define or choose the appropriate FOM. The metric of Technology Readiness Level (TRL) is a FOM that has been used across many U.S. government agencies serving as a common language for communicating the readiness of a technology before inserting and integrating it to a system (Department of Defense [DoD], 2009). Since its debut in the National Aeronautics and Space Administration (NASA), TRL has gained popularity of application, and ample efforts have been devoted to better articulating its use, tailoring it for the development of other types of technologies, or following its logic to create similar metrics for the use in other domains (Tan, Ramirez-Marquez, & Sauser, 2011).

From a system architecture perspective, any system is composed of a group of individual technologies and the linkages among them, so two types of knowledge would be necessary in order to understand system maturity: component knowledge and integration knowledge (Henderson & Clark, 1990). Therefore, while TRL was introduced to quantify the readiness of technologies representing component knowledge, another nine-level metric known as Integration Readiness Level (IRL) was subsequently proposed to provide integration knowledge that measures the readiness of the linkages among technologies (Gove, 2007; Sauser, Forbes, Long, & McGrory, 2009; Sauser, Gove, Forbes, & Ramirez-Marquez, 2010). These metrics are important since they make it possible for various stakeholders to discuss system development-related issues on a common language, characterized as development maturity that is quantified and expressed as readiness levels. With the two standalone metrics created, the introduction of a comprehensive metric that can combine these two metrics and put them in the context of an overall system development would be beneficial. In the response to filling this gap, the metric of System Readiness Level (SRL) was proposed by the SysDML as a numerical product of the technology TRLs and integration IRLs to provide system-level maturity assessment (Sauser, Ramirez-Marquez, Magnaye, & Tan, 2008; Ramirez-Marquez & Sauser, 2009).

While SRL continues to be verified and validated with systems across private companies and government agencies, there are endeavors being devoted to including this metric in optimization models for systems development planning (e.g., SRL_{max}, $SCOD_{min}$, ESM_SRL_{max}) (Ramirez-Marquez & Sauser, 2009; Magnaye et al., 2010; Sauser, Magnaye, Tan, Ramirez-Marquez, & Sauser, 2010). In general, these models provide system developers and managers support in terms of enhancing their capabilities on decision-making regarding resource allocation during the systems' development and acquisition lifecycle.

These models have advanced the use of SRL to a more dynamic application; however, there are two aspects that have not been taken into account in these models, which limit their application. First, they limit the relevance with the development of complex systems that are designed and deployed to provide multiple functions and capabilities. As addressed by Tan, Sauser, and Ramirez-Marquez (2011b), often systems are designed and developed to provide multiple functions and capabilities with a single solution. In order to track and to manage the development of these MFMC systems, it would be insufficient not to take into consideration the maturity assessment on the capability and function levels. Especially in a situation where some of the capabilities are critical for development because of the urgent demand on the market or in an on-going war theater, the need to measure and advance the maturity of the very functions and capabilities becomes imperative, without which the development could become problematic. To solve this problem, the original SRL definition was enhanced by Tan, Sauser, and Ramirez-Marquez (2011b) to include two layers of maturity assessment (i.e., the function and capability layers) and enable more accurate system maturity assessment. See Exhibit 3 as an example of an SRL assessment on an MFMC system architecture. Compared to the original SRL formulation, this enhanced SRL provides a more holistic picture and better insights into system maturity assessment because the system maturity analysis is more systemic. The focus is not on a myopic view of the system maturity, but on multiple architectural perspectives of the system. However, the aforementioned optimization models were based on the original SRL and therefore fail their relevance to accommodate the development of MFMC systems.



How to Use this Template

1-input the date; 2-move the selector in the System Development Lifecycle chart to choose an expected SRL for this date; 3-specify the percentage for RED and YELLOW thresholds; 4-check the CAPABILITY of interest; 5-for scenario analysis, change the TRL/IRL in the graph.

Date	MM/DD/YYYY
Expected SRL	0.64
Red Bar	10%
Yellow Bar	5%

Select A Capability

	System SRL		0.64
	Function 1		0.70
○		Capability 1.1	0.57
○		Capability 1.2	0.70
●		Capability 1.3	0.62
○		Capability 1.4	0.70
	Function 2		0.70
○		Capability 2.1	0.70
○		Capability 2.2	0.55

ITRL	1	0.61
ITRL	2	0.54
ITRL	3	0.61
ITRL	4	0.57
ITRL	8	0.63
ITRL	11	0.66
ITRL	14	0.69

Exhibit 3. Multi-Function, Multi-Capability Systems Maturity Assessment

Another limitation with these optimization models is that they were developed from a single FOM perspective; that is, they are pursuing the optimization of a single objective subject to a set of constraints. While it is possible to repeatedly run a model in order to get the optimal solutions under different scenarios, it is impossible to observe the interplay between two or more conflicting system attributes, for example, how the maximum SRL changes with an increase in development resources. In an MFMC system development, the maturation of different functions or capabilities will compete for resources, and it is not rare where several critical functions and capabilities share a high priority. An additional challenge encountered in the acquisition of systems is that while there is a necessity to dedicate resources for system development, having a number of options and the respective required resources to advance them can allow for trade-offs between the systems acquisition budget and potential solutions. Therefore, it is beneficial to provide multiple solutions from which acquisitionists can have the flexibility to tailor a maturation strategy so as to ensure stakeholder satisfaction. Therefore, in the development of MFMC systems, the more common desire is to optimize a number of objectives concurrently, where MO optimization models can play an important role.

To address such research gaps, this research employed MO optimization techniques to accommodate the development of MFMC systems. This research created a new model based on the enhanced SRL hierarchy with the objective to maximize capability, function, and system maturity and minimize the consumption of development resources.

Model MO_ SRL
*Max{{SRL_F(**TRL, IRL**)}, {SRL_C(**TRL, IRL**)}, SRL(**TRL, IRL**)}*
Min {R_1*(**TRL, IRL**), …,* R_h*(**TRL, IRL**),…,* R_H*(**TRL, IRL**)}*
s.t.

$$TRL_i \in \{ TRL_i, TRL_i + 1, ..., 9 \}$$

$$\mathrm{IRL}_{\mathrm{ij}} \in \{ IRL_{ij}, IRL_{ij} + 1, ..., 9 \}$$

The matrices *TRL* and *IRL* in the model contain the decision variables. Each of these variables is an integer, bounded by [TRL_i, 9] or [IRL_{ij}, 9], respectively. That is, any TRL or IRL cannot be less than its current level or more than perfect status, which is Level 9 in this case. This model includes the optimization of two types of objectives: (i) maximizing the SRLs which are of interest to managers and (ii) minimizing resource consumption. The first type of optimization as listed in the maximization part is that each SRL (function, capability, or system SRL) is a function of the technology TRLs and integration IRLs of the system. More specifically, the function and capability SRLs are determined by the TRLs and IRLs of the relevant technologies and integration links, which constitute the function or capability in question. The second type of optimization is to minimize the consumption of resources under consideration (for example, dollars, labor hours, machinery, etc.).

In order to completely characterize the decision variables in the Model MO_SRL, the following transformations have been introduced:

$$y_i^t = \begin{cases} 1 & \text{If } TRL_i = t \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad x_{ij}^t = \begin{cases} 1 & \text{If } IRL_{ij} = t \\ 0 & \text{otherwise} \end{cases} \quad \text{for } t = 1,\ldots 9$$

Notice that based on these binary variables, each of the possible TRLs and IRLs in the system can be obtained as: $TRL_i = \sum_{t=1}^{9} ty_i^t$ and $IRL_{ij} = \sum_{t=1}^{9} tx_{ij}^t$. Therefore, as defined in the SRL hierarchy, ITRLs, capability, function, and system SRLs can be transformed into expressions that are determined by these binary variables. For example, an ITRL of the Capability C_{fk} may be transformed as follows:

$$\begin{aligned} ITRL\_C_{fk(l)} &= \frac{1}{m_{fk(l)}} \left[\begin{array}{l} \left(\frac{1}{9}\sum_{t=1}^{9} tx^t_{fk(l)(1)}\right)\left(\frac{1}{9}\sum_{t=1}^{9} ty^t_{fk(1)}\right) + \left(\frac{1}{9}\sum_{t=1}^{9} tx^t_{fk(l)(2)}\right)\left(\frac{1}{9}\sum_{t=1}^{9} ty^t_{fk(2)}\right) + \ldots \\ + \left(\frac{1}{9}\sum_{t=1}^{9} tx^t_{fk(l)(j)}\right)\left(\frac{1}{9}\sum_{t=1}^{9} ty^t_{fk(j)}\right) + \ldots + \left(\frac{1}{9}\sum_{t=1}^{9} tx^t_{fk(l)(n_{fk})}\right)\left(\frac{1}{9}\sum_{t=1}^{9} ty^t_{fk(n_{fk})}\right) \end{array} \right] \\ &= \frac{1}{m_{fk(l)}} \sum_{j=1}^{n_{fk}} \left(\frac{1}{9}\sum_{t=1}^{9} tx^t_{fk(l)(j)}\right)\left(\frac{1}{9}\sum_{t=1}^{9} ty^t_{fk(j)}\right) \end{aligned} \quad (5)$$

Thus, based on the computation of the SRL with these decision variables, MO_SRL belongs to the class of integer valued non-linear problems. For a system with *n* technologies containing *m* ($m \leq (n-1)n/2$) distinct integrations, and assuming all technologies and integrations are at their lowest levels, there are 9^{n+m} possible solutions to Model MO_SRL. To solve the model, this research adopted an algorithm that's termed as Multi-Objective Probabilistic Solution Discovery Algorithm (MO-PSDA).

4. Illustrative Example of Implementation of Results[2]

Previously, an MFMC system was examined in Tan, Sauser, and Ramirez-Marquez (2011b) and Sauser, Ramirez-Marquez, Magnaye, et al., (2008). This research used that system to demonstrate the application of the proposed MO_SRL model and compare the results with previous models. Exhibit 4 represents an end-to-end integration of command and control capabilities with a variety of unmanned vehicles and intelligence, surveillance, and reconnaissance sensor packages. These elements are capable of autonomous operations and include both commercial off-the-shelf equipment and cutting edge developments networked seamlessly together to enhance mission effectiveness and efficiency. As configured, there are 20 technologies and 21 integrations in the system, within which there are three functions and nine capabilities to be delivered after the deployment of the system. Each box represents a technology, and the number in the shaded square next to the box is the TRL value of the corresponding technology. The shaded circle contains the IRL value of the corresponding integration. As aforementioned, the potential level for each TRL and IRL is bounded by its current value (as shown in Exhibit 4) and the highest possible value of 9.

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[2] This section is detailed in Tan, W., Sauser, B., Ramirez-Marquez, J., & Magnaye, R. (2012). Multi-objective optimization in multifunction multicapability systems development planning. *IEEE Transactions on Systems, Man, and Cybernetics: Systems.* (available online in IEEEXplore Early View).

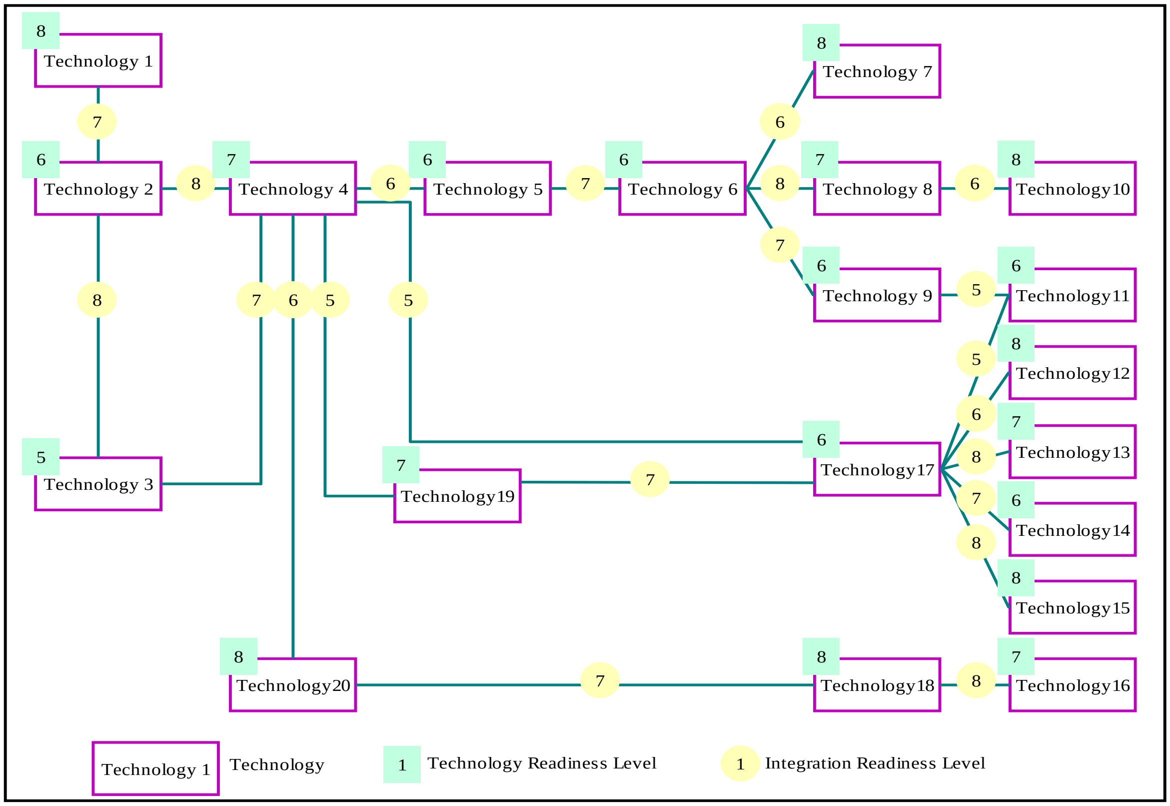

Exhibit 4: System Diagram

The intended notional functions and capabilities of this system are shown in Exhibit 5, where only the required technologies and their corresponding integrations are considered in evaluating the maturity of each of the corresponding capabilities of a function. As a summary, there are basically three different functions under which there are three, five, and one capabilities, respectively. These three functions are Mine-Detection, Mine-Neutralization, and Gun-Combat. Within each function, there are several capability alternatives to ensure the success of the corresponding mission. For example, for the Mine-Detection, one of the capabilities is to pull the sensor by using a submarine which has longer endurance but slower speed, and another capability is by using a helicopter, which is faster, but can only stay out for a limited amount of time. Using the enhanced SRL definition, estimates of the actual SRLs at different levels can be obtained before the system is actually deployed.

Applying the MFMC SRL Hierarchy to this system, the capability and function SRLs are obtained as shown on the top of each capability thread in Exhibit 5 (refer to Tan, Sauser, & Ramirez-Marquez, 2011b, for details of calculating SRL). The function SRLs are shaded with their capability SRLs. With the given notional numbers for TRLs and IRLs, all of these SRLs fall in a range from 0.58 to 0.68 that corresponds to a system stage in the Engineering & Manufacturing Development phase per the SRL correlation to a typical system development lifecycle (see Exhibit 6). According to Sauser, Ramirez-Marquez, Magnaye, et al. (2008), the main assignments during this phase are to develop system capability, reduce integration and manufacturing risk, ensure operational supportability, reduce logistics footprint, implement human systems integration, design for production, ensure affordability and protection of critical program information, and demonstrate system integration, interoperability, safety, and utility.

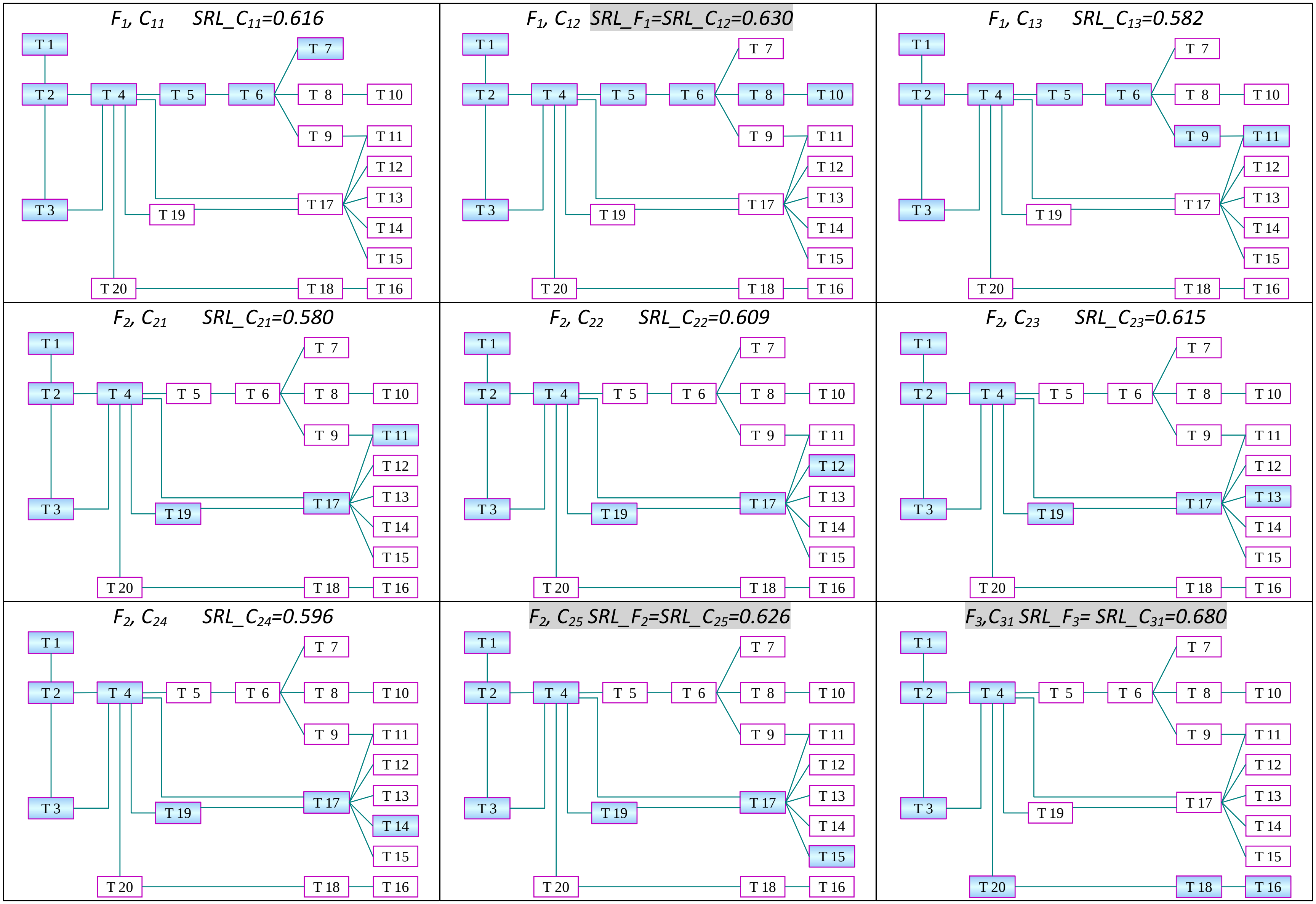

Exhibit 5. Functions, Capabilities Definition and Their SRLs (T stands for Technology)

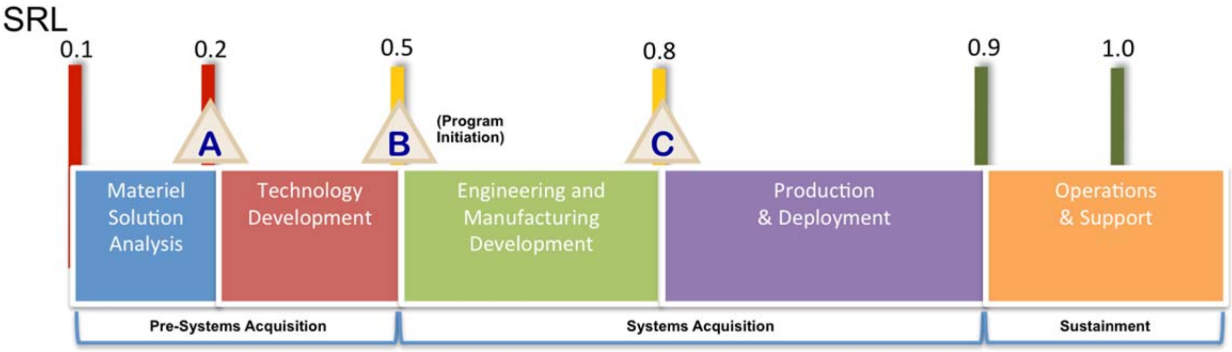

Exhibit 6. Correlation of SRL to a System Development Lifecycle

Cost (in thousand dollars)											
	TRL	Level 6	Level 7	Level 8	Level 9		IRL	Level 6	Level 7	Level 8	Level 9
Technology	1	0	0	0	446	Integration	1,2	0	0	820	407
	2	0	275	481	623		2,3	0	0	0	867
	3	163	181	279	872		2,4	0	0	0	213
	4	0	0	227	100		3,4	0	0	613	881
	5	0	944	992	310		4,5	0	648	743	465
	6	0	305	820	446		4,19	952	743	832	424
	7	0	0	0	844		5,6	0	0	828	401
	8	0	0	665	726		6,7	0	900	859	661
	9	0	169	348	669		6,8	0	0	0	179
	10	0	0	0	114		6,9	0	0	172	556
	11	0	173	442	470		8,10	0	988	434	861
	12	0	0	0	128		9,11	714	311	935	732
	13	0	0	376	585		16,18	0	0	0	942
	14	0	630	602	694		17,11	543	511	165	933
	15	0	0	0	604		17,12	0	800	771	504
	16	0	0	282	171		17,13	0	0	0	634
	17	0	224	541	668		17,14	0	0	510	506
	18	0	0	0	221		17,15	0	0	0	937
	19	0	0	406	822		17,4	370	351	558	919
	20	0	0	0	160		18,20	0	0	651	507
							19,17	0	0	681	563
							20,4	0	280	321	859

Exhibit 7. Cost for TRL and IRL Upgrade

As mentioned previously, the second type of optimization is to minimize the resource consumption, and the resource can be anything that is consumed to advance the maturity of a system (e.g., dollars, labor hours, machinery, etc.). For illustration purposes, this research considers dollars as resource consumption for upgrading TRLs and IRLs as shown in Exhibit 7. For example, it requires $446,000 to move Technology 1 from its current level of 8 to the next level of 9. This research focuses on the incremental development efforts needed to advance the system from its current reference point. It does not consider the budget invested in the past for bringing the TRL or IRL to its current level. As stated in Ramirez-Marquez and Sauser (2009), it is the obligation of the program manager to obtain these estimates of resource consumption as accurately as possible. It must be noted, however, that there is ongoing research in the development of a System Maturity Model to enhance cost modeling capabilities for better understanding of the true lifecycle cost (Volkert, Jackson, & Whitfield, 2010). Nonetheless, the notional estimated cost equals to $51,153,000 to completely mature the whole system.

Since MO_SRL emphasizes the maturity assessment at the function and capability levels, in order to demonstrate the proposed MO_SRL model, two scenarios are assumed and examined–one for function and another for capability SRLs of interest. These are described separately in the following section.

4.1. Function SRL Maximization and Cost Minimization

In this scenario, the objectives are to maximize the SRL of Functions 1 and 2 and to simultaneously minimize the cost of upgrading the SRLs. Therefore, the MO_SRL model can be specified as follows:

Model MO_SRL_Function

*Max {SRL_F1 (**TRL, IRL**), SRL_F2 (**TRL, IRL**)}*

*Min {cost (**TRL, IRL**)}*

For this scenario, the MO-PSDA algorithm was applied 10 times with different initial appearance probabilities for $p_{i,t}$ and $p_{ij,t}$, and within each setting of initial appearance probabilities, 10 cycles of 1000 solutions were generated and analyzed. Therefore, approximately 10^5 solutions were compared in order to search for the Pareto optimal solutions. Compared with the possible total 9^{20+22} feasible outcomes in the solution space of this system, the portion that was searched counts less than 0.1% in an affordable time period. Out of these 10^5 solutions, this experiment was able to locate 644 Pareto optimal solutions, which collectively consist of the Pareto optimal front as depicted in Exhibit 8. Each dot in the figure represents a Pareto optimal solution that corresponds to a development strategy for the further advancement of Functions 1 and 2 with the minimal budget. These solutions range from resource consumption of $0—that is, investing no money—to the amount of $41,789,000, which can improve the SRLs of Functions 1 and 2 to a fully mature level of 1.

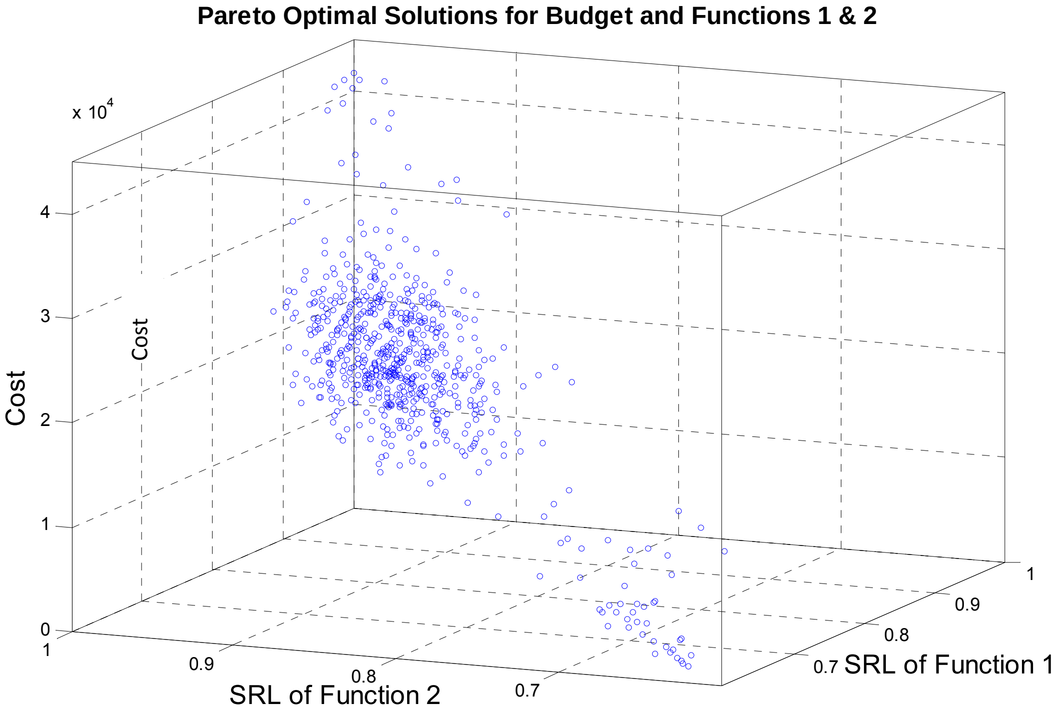

Exhibit 8. Pareto Front for Budget and Functions 1 & 2

Since SRL can be used to determine the development status of a system (e.g., determining the development phase the system is currently in), this experiment is further interested in discovering strategies that can improve either Function 1 or Function 2 or both functions to more mature development phases with minimum cost. Thus, with the consideration of the correlation of SRL to system development lifecycle, as shown in Exhibit 6, this experiment was able to locate seven Pareto optimal strategies that will advance Function 1, Function 2, or both to pass development milestones with minimum cost. These seven strategies are depicted in Exhibit 9, and the cost for executing each development strategy is also attached to each solution. For example, in order to mature both Function 1 and Function 2 to pass the milestone from the Engineering and Manufacturing Development phase (SRL between 0.5 and 0.8, see Exhibit 6) to the Production and Deployment phase (SRL between 0.8 and 0.9, see Exhibit 6), the minimum cost will be $10,410,000.

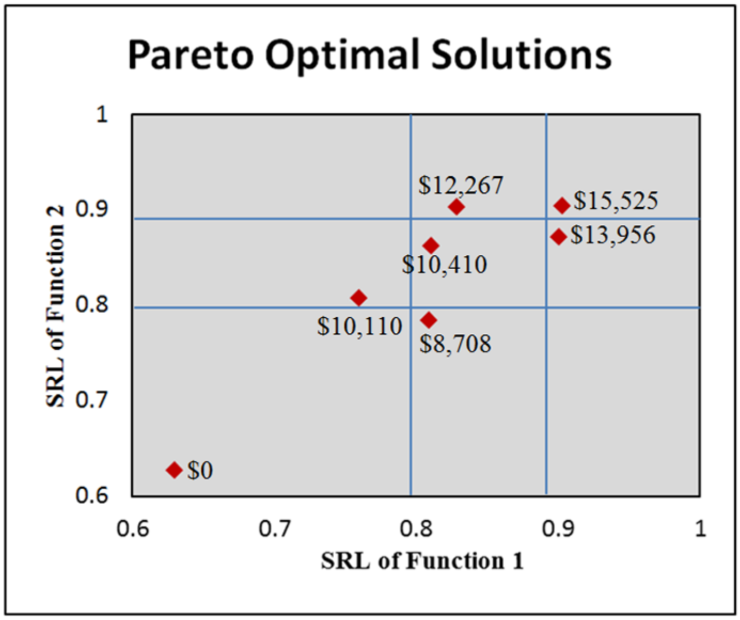

Exhibit 9. Pareto Optimal Solutions with Development Milestones (Cost is in 1000s)

Since no solution dominates another with respect to all the objectives of the model, any solution is not necessarily better than another one, so managers have flexibility in selecting the solution that best meets their goal in terms of advancing system maturity. For example, the manager may start with a preconceived rough budget, look through the solutions with the needed money that falls within his or her range, and then balance among the objectives to select a satisfactory development strategy to mature the system.

To explain the result, we take one solution, which is the upper right solution as shown in Exhibit 9, as an example to drill down the development strategy to the levels of technologies and integrations. This strategy will bring Function 1 and Function 2 from their current phase (i.e., Engineering and Manufacturing Development) to the Operations and Support phase with a minimum resource consumption of $15,525,000.

As illustrated in Exhibit 10, the grayed cells show that the corresponding technologies and integrations need to be advanced from their current status to an expected readiness level as specified in the table. For example, Technology 1 should be advanced from TRL 8 to 9 under this development strategy. The clear area of Exhibit 10 indicates that these technologies and integrations will stay on their current status, that is, no further budget should be allocated on them. Exhibit 11 shows the capability and function SRLs under this strategy as well as the cost to achieve them. The grayed cells are the objectives of this scenario, which are the cost and SRLs for Functions 1 and 2. This table shows that if this strategy is adopted, with a budget of $15,525,000, SRLs for Functions 1 and 2 will be upgraded to above 0.9. Exhibit 11 also shows the resulting SRLs for other capabilities and functions.

Technology	**Technology**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
	Upgrade to TRL	9	9	9	9	9	9	8	7	6	9	
	Current TRL	8	6	5	7	6	6	8	7	6	8	
	Technology	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	
	Upgrade to TRL	6	8	7	6	9	8	9	8	8	8	
	Current TRL	6	8	7	6	8	7	6	8	7	8	
Integration	**Integration**	**1,2**	**2,3**	**2,4**	**3,4**	**4,5**	**4,19**	**5,6**	**6,7**	**6,8**	**6,9**	**8,10**
	Upgrade to IRL	9	9	9	8	6	5	7	7	9	8	6
	Current IRL	7	8	8	7	6	5	7	6	8	7	6
	Integration	**9,11**	**16,18**	**17,11**	**17,12**	**17,13**	**17,14**	**17,15**	**17,4**	**18,20**	**19,17**	**20,4**
	Upgrade to IRL	5	8	5	6	8	7	8	6	7	8	6
	Current IRL	5	8	5	6	8	7	8	5	7	7	6

Exhibit 10. Development Strategy of One Example Solution

System SRL	0.8								
Function SRL	F1			F2					F3
	0.9			0.9					0.8
Capability SRL	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1
	0.9	0.8	0.8	0.8	0.9	0.9	0.8	0.9	0.8
Cost	$15,525,000								

Exhibit 11. SRLs and Cost

4.2. Capability SRL Maximization and Cost Minimization

In this scenario, the objectives are to maximize the SRLs of Capability 1.1 and Capability 1.2, and to minimize the cost of upgrading SRLs. Thus, the MO_SRL_Capability model can be written as follows:

Model MO_SRL_Capability

*Max {SRL_C1.1 (**TRL, IRL**), SRL_C1.2 (**TRL, IRL**)}*

*Min {cost (**TRL, IRL**)}*

Running the same experiment scheme as the above scenario, this experiment located 337 solutions in the final Pareto optimal set. These solutions consist of the Pareto front that is visualized in Exhibit 12, with resource consumption ranging from $0—that is, requiring no improvement action—to $23,402,000, which advances the SRLs of Capabilities 1.1 and 1.2 to a complete mature level of 1. Each solution informs a Pareto optimal strategy for advancing the system's maturity.

With the consideration of the correlation of SRL to system development lifecycle, this example was able to locate five Pareto optimal strategies that will advance Capability 1.1, Capability 1.2, or both to pass development milestones with minimum cost. These five strategies are depicted in Exhibit 13, and the cost for executing each development strategy is also attached to each solution. For example, in order to mature both Capability 1.1 and Capability 1.2 to pass the milestone to the Operations and Support phase (SRL between 0.9 and 1.0, see Exhibit 6), the minimum cost will be $11,590,000.

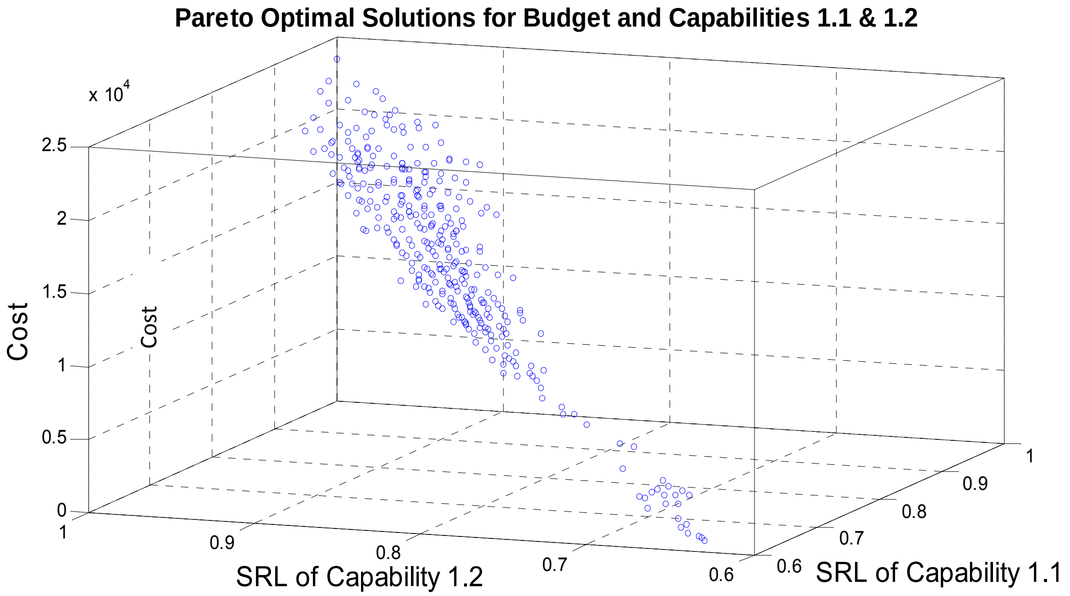

Exhibit 12. Pareto Optimal Solutions for Cost and Capabilities 1.1 & 1.2

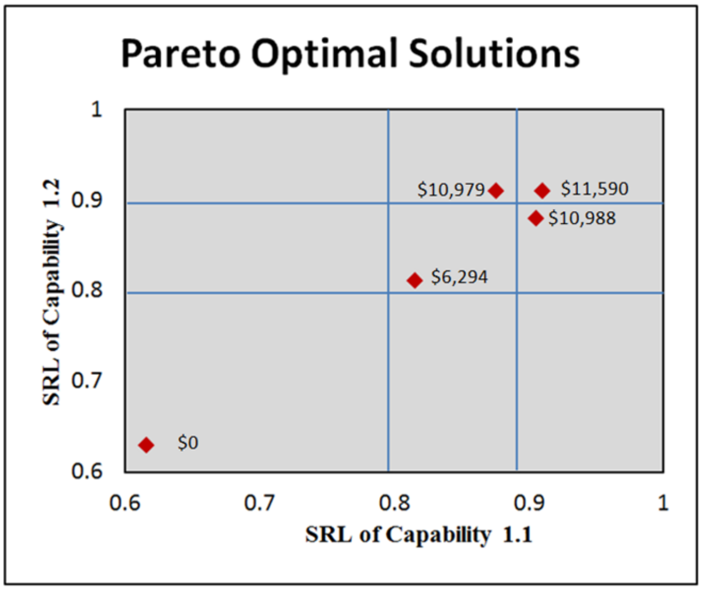

Exhibit 13. Pareto Optimal Solutions with Development Milestones

One solution corresponds to the development strategy of advancing both capabilities from the Engineering and Manufacturing Development phase to the Production and Deployment phase is drilled down as shown in Exhibit 14, in that the grayed cells indicate the corresponding technologies and integrations needed to be advanced from their current readiness levels to an expected readiness level as specified in the table. Meanwhile, the other technologies and integrations will stay on their current status. Capability and function SRLs under this strategy, as well as the cost to achieve them, are listed in

Exhibit 15, where the grayed cells are the objectives of this scenario–the cost and SRLs for Capabilities 1.1 and 1.2. Exhibit 15 indicates that if this strategy is adopted, with a budget of $6,294,000, SRLs for both Capabilities 1.1 and 1.2 will be upgraded to above 0.8.

Technology	**Technology**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
	Upgrade to TRL	8	9	8	9	6	9	8	7	6	8	
	Current TRL	8	6	5	7	6	6	8	7	6	8	
	Technology	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	
	Upgrade to TRL	6	8	7	6	8	7	6	8	7	9	
	Current TRL	6	8	7	6	8	7	6	8	7	8	
Integration	**Integration**	**1,2**	**2,3**	**2,4**	**3,4**	**4,5**	**4,19**	**5,6**	**6,7**	**6,8**	**6,9**	**8,10**
	Upgrade to IRL	9	8	9	8	6	5	9	6	9	7	6
	Current IRL	7	8	8	7	6	5	7	6	8	7	6
	Integration	**9,11**	**16,18**	**17,11**	**17,12**	**17,13**	**17,14**	**17,15**	**17,4**	**18,20**	**19,17**	**20,4**
	Upgrade to IRL	5	8	5	6	8	7	8	5	7	7	6
	Current IRL	5	8	5	6	8	7	8	5	7	7	6

Exhibit 14. Development Strategy of One Example Solution

System SRL	0.83								
Function SRL	F1			F2					F3
	0.91			0.81					0.88
Capability SRL	C1.1	C1.2	C1.3	C2.1	C2.2	C2.3	C2.4	C2.5	C3.1
	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.8
Cost	$6,294,000								

Exhibit 15. SRLs and Cost

5. Managerial Implications and Future Research

This research extends the research on how best to allocate scarce resources during the development of complex systems. Currently available optimization models as proposed rely on the use of the System Readiness Level (SRL) scale as a measure of the readiness of a whole system. This SRL scale has been mapped notionally to existing system development lifecycles such as the ones being used for space and defense systems. Preliminary results appear to be encouraging. However, the SRL scale was conceptualized to be applicable to the whole systems, which do not take into account system functions and capabilities in the development of MFMC systems. With this in mind, an enhanced SRL concept called the multi-function multi-capability SRL (MFMC SRL) has also been proposed. It measures the maturity of the system including the maturity of the functions and capabilities themselves (Tan, Sauser, & Ramirez-Marquez, 2011b). Since these systems are designed to perform multiple functions and capabilities, the development process will have to contend with competing desires to advance the maturity of several functions or capabilities, if not all of them, at once. This is what the research addresses.

Using the enhanced MFMC SRL Hierarchy, this research proposes a multi-objective optimization model, which can be used to allocate development resources such that the objectives of the development strategy are met. The model, referred to as MO_SRL, is used to evaluate the development of a notional sample case, which is a system intended to perform three functions and nine capabilities relying on 20 technology elements with 21 integration links among them. Two scenarios, both with three objectives, were assumed and analyzed to tailor the model for function and capability SRL maximization, respectively. With the use of the Multi-objective Probabilistic Solution Discovery Algorithm (MO-PSDA), an evolutionary algorithm, this research was able to find a number of Pareto optimal solutions for each scenario. These indicate to which level of readiness each system component (technology element or integration link) must be advanced to achieve the development objectives (readiness of functions and capabilities) and how much they will cost.

One aspect to be emphasized is that the proposed model only applies to coherent systems in which every technology has to be integrated with the rest of the system, no matter if there are multiple interfaces or just one link. As a first step to address multi-objective optimization in system maturity assessment and advancement, model MO_SRL comes with some limitations. Future work will further the current research by addressing the following issues.

First, it should be pointed out that while the case example in this report did not consider the situation in which multiple technologies with the same functionality, but different readiness levels, are competing for their adoption by the system, the proposed model has the potential to be expanded for decision-making in such a situation. That is, engineering managers can evaluate the impact of trading off one technology for another on system readiness. The results presented in this report will serve as a basis for exploring a more complicated situation of decision-making on system development.

Second, the model in the report appears as an open model without constraints. This is, however, not a necessary format, and the model can also be applied for MO problems with partial constraints. Our future research will address similar problems with MO but partial constraints.

The MO-PSDA has been adopted to solve the MO_SRL model because of its capability to efficiently find converged optimal solutions for MO optimization problems. However, the initialization of the appearance probability influences the direction in the search for optimal solutions. Although this research employed a means to combine the results from several initial appearance probabilities, further research is needed to investigate and explore a sound approach for selecting the probability.

The MO_SRL model is based on the assumption that there are available data on resource consumption for upgrading each TRL/IRL level. As the premise for running the proposed model, reliable resource estimation plays a vital role in the viability of the solutions generated by the MO_SRL model. Although in practice, it mainly depends on the system managers and developers to provide these data, effective models developed in academia can help these individuals to achieve reliable estimation. Therefore, future research can devote efforts to this area (e.g., developing cost estimation models).

As previously mentioned, the SRL methodology has gained acceptance in study and practice; however, it needs to establish statistical effectiveness through rigorous testing with systems. In general, the effectiveness of the SRL methodology as a risk management tool for system development can be greatly enhanced by a thorough verification and validation with a wide cross-section of technologies and systems across relevant domains (e.g., strategic national defense, aerospace, software, energy, transport, environment, and economic systems). Future work is needed for both cross-sectional and longitudinal research with case studies for this purpose.

6. Knowledge Transfer to Industry/Government

The SysDML is currently developing a Java-based tool that will work with three commercially available systems architecting tools (i.e., Enterprise Architect, Systems Architect, and Rhapsody). This effort is funded by the University-Affiliated Research Center in Systems Engineering (SERC). The objective of this development is to translate into practice academic research results from the SysDML via a practitioner tool. A first version of an SRL Calculator has been completed that works with Enterprise Architect on Windows XP, Vista, and 7. This tool is being tested with Northrop Grumman and the U.S. Army ARDEC. A prototype of an SRL Calculator that will work with Rhapsody was completed in August 2011. Also, the SysDML has established a partnership with ViTech Corporation, developers of the systems engineering architectural tool(i.e., CORE) to integrate SysDML research results into their commercial offering of CORE. Our industry and government partners have agreed to work with the SysDML and ViTech in testing any prototypes developed by ViTech.

The success of our previous research and of this proposed research is contingent on our strong active stakeholder relationships. These relationships are designed to accumulate research data and help us keep an application focus to the practitioner needs and alignment with acquisition activities. In addition, all of the reductions to practice of our research have been through pilot programs within the representative organizations. We have always encouraged this, as each organization needs to become comfortable with the methods as well as assure they are viable and reliable for use with existing programs. Exhibit 16 is an example of some of our active stakeholders and the value of the relationship.

Active Stakeholder	Research Value
Lockheed Martin	The implementation into practice of the SysDML methods has allowed the refinement of current industry methods to incorporate research-derived insights, provide expanded functionality, and demonstrate the utility of the method in the context of a multiple pilot projects. Lockheed Martin has developed their own version of an SRL Calculator that will work with Rhapsody and has been able to actively utilize the tool.
Northrop Grumman	A long-term relationship with NGC has resulted in significant reduction to practice and the recent release of Littoral Combat Ship Mission Module Program System Maturity Assessment Guide, which details the application of research from the SysDML. They have also incorporated work from this research into their program management tools.
NAVSEA/PMS 420	Working closely with PMS 420 has allowed for the leveraging of the SRL body of knowledge to explore the effects of technology and integration maturity on systems engineering effort and cost; ability to expand the scope and applicability of the SRL to address System of Systems methods, processes, and tools; and the enhancement of current SRL methods and tools to incorporate research-derived insights, provide expanded functionality, and demonstrate the utility of the tools in the context of a pilot project.
U.S. Army Armament Research Development and Engineering Center (ARDEC)	ARDEC has been a longstanding collaborator with the SysDML and are currently developing internal procedures to implement the SRL and other research results into practice.
ViTech Corporation	The SysDML and ViTech Corporation have entered into a partnership that will transition research results into future releases of ViTech's systems engineering architecture tool, i.e. CORE. We are also advising ViTech on how the results should be interpreted and presented within a systems architecting tool.

Exhibit 16. Active Stakeholders and Research Value

7. Project Accomplishments

7.1. Publications

7.1.1. Journal

Tan, W., Sauser, B., Ramirez-Marquez, J., & Magnaye, R. (2012). Multi-objective optimization in multifunction multicapability systems development planning. *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems.* (accepted)

7.1.2. Conference Proceedings

Sarfaraz, M., & Sauser, B. (2012, March). Improving system maturity assessment using system engineering architectures. Paper presented at the Conference on Systems Engineering Research, St. Louis, MO

7.1.3. Working Papers

Magnaye, R., Sauser, B., & Pantanakul, P. (2011). *Earned readiness management for scheduling, monitoring and evaluating the development of systems*. (working paper)

Sauser, B. J., Magnaye, R., Tan, W., Ramirez-Marquez, J., & Sauser, B. W. (2012). Optimization of system maturity and equivalent system mass for space systems engineering management. *International Journal of Space Science and Engineering.* (under review)

7.2. Presentations

Sauser, B., & Ramirez-Marquez, J. (2012, May 16–17). *Multi-objective optimization of system capability satisficing in defense acquisition*. Paper presented at the Ninth Annual Acquisition Research Symposium, Monterey, CA.

8. Other Related Activities

8.1. 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 sustained our website (http://www.SysDML.com) for the distribution of our research results. At this website, you will find a research overview, a list of publications and research projects, tools, and a "Who We Are" section.

8.2. Student Research Supported/Supervised

Our funding from the Naval Postgraduate School has afforded us the privilege to support one PhD student to assist in the execution of this research. It has also allowed us the ability to attract graduate students to pursue related and supportive research. These students are as follows:

Ivonne Donate. *PhD Student*. (supported by Department of Defense) "Evolutionary Lifecycle Assessment for Disruptive Technology Integration"

Ryan Gove. *PhD Student.* (supported by Lockheed Martin) "Model Based Systems Engineering for Effective System Maturity Assessment"

Samuel Russell. *PhD Student.* (supported by NASA) "The Thermodynamics of System Development: A Mechanistic Approach to System Maturity Assessment"

Matin Sarfaraz. *PhD Student.* (supported by the *Innovation and Entrepreneurship Graduate Fellowship*) "Systems Engineering Artifact Correlation to Systems Maturity Assessment"

Joseph Uzdzinski. (supported by Lockheed Martin) "System Maturity Assessment for Dynamic Interoperability in Complex Systems"

Graduates

Weiping Tan. *PhD Student*. (supported by NPS) "Methodologies for Component Importance Analysis in Multi-Function, Multi-Capability System Developmental Maturity Assessment"

8.3. Student Awards

School of Systems and Enterprises Best Student Paper Award, Weiping Tan, 2011

For a graduate student who has distinguished themselves in the development of scholarly work through the publication of a peer-reviewed conference or journal paper:, "Analyzing Component

Importance in System Maturity Assessment," *IEEE Transactions on Engineering Management, 58*(2), 275–294.

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