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Reducing Uncertainty in Technology Selection for Long Life Cycle Engineering Designs

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Abstract

The best capabilities are usually achieved by having the latest technologies in defense systems. However, including the new, usually immature, technologies in a system design does not always easily result in achieving the capabilities at the right level, at an affordable cost, and in a timely manner. Many programs have suffered from immature technologies as cost overruns, late or no deliveries, and poor performance levels. Another impact of technology selection appears as obsolescence after the deployment of systems, or even before the deployment of the system. As the technologies of a system become obsolete, the cost of maintaining the system increases. Defense systems, which have longer sustainment life cycles, are more vulnerable to obsolescence of technologies. While obsolete technologies increase the cost of maintaining the military systems, they also impact the level of the superiority of the capabilities. In the current literature, several approaches have been proposed by different authors to address either the immature technology risk or the technology obsolescence risk. This study will make an effort to develop an approach which addresses the issue of technology selection for long life cycle defense systems that consider both the feasibility risk of immature technologies and obsolescence risk of technologies.

Keywords
Technology Readiness Level, Technology Obsolescence, Functional Dependency Network Analysis, Genetic Algorithms

1. Introduction
The managers of capability portfolio development programs have to face challenges on the cost, performance, and schedule dimensions [1]. Overcoming these challenges are not easy, especially with ever-constrained resources and the uncertainties of the various factors affecting the programs. Among many factors, one of the most important for the success of a program is the selection of appropriate technologies to include in its design. In this context, a successful program means meeting the user requirements in a timely and cost-effective manner.

2. Description of the Problem
The life cycle of a system is comprised of several phases each with a varying level of “cost-knowledge-freedom” relationship [2]. As the life cycle progresses, the “freedom” of changing the design decreases while the knowledge increases. This decreasing “freedom” to change design results in decisions being made early in the design process rather than later. Therefore, evaluation of particular technology should include risks associated with succeeding phases of the life cycle [3].

The US Department of Defense (DOD) has developed a framework to deal with the complexity of acquiring capabilities to meet the warfighter needs. A snapshot of the DOD acquisition framework and phases of a system life cycle is given in Figure 1.

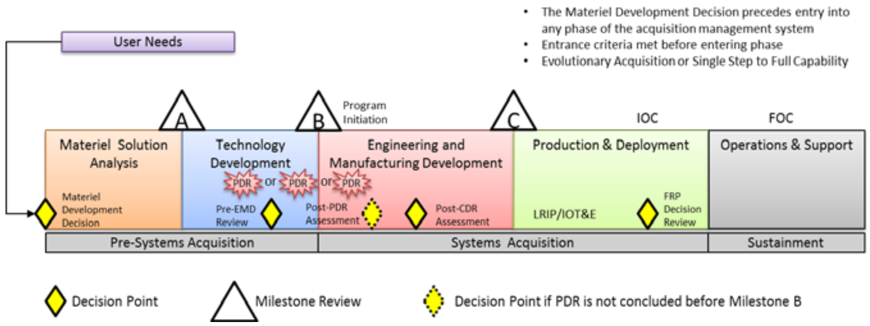

Figure 1: DOD Acquisition Framework [4]

Several decision points, milestones, and phases exist in the DOD acquisition framework to manage several types of risks of new technologies. As an example, Technology Development phase is intended to reduce technology risk of the program. The purpose of this phase is to "**reduce technology risk and to determine the appropriate set of technologies to be integrated into the full system**"[5].

This paper describes the development of a methodology to **reduce technology risk** by reducing the uncertainty of technology evolution and to **determine the appropriate set of technologies** by comparing alternative technologies by considering their impact on cost, schedule and performance dimensions, and obsolescence.

2.1 Risk of Immature Technology

Technology maturity is a term used to define the progress level of an under development technology. Maturity and readiness has been used interchangeably in the relevant literature [6]. An immature technology, which needs further development, has uncertainty in its development cost, development time, and performance level. Depending on the level of the criticality of the technology in a certain program, a probable cost overrun, schedule delay, or poor performance delivery might have severe impact on the overall program. The probability of this risk decreases as the maturity increases and vice versa. In case of inclusion of immature technologies in a system design, with an assumption that the technology will be available (mature) by the production starts, the whole program might encounter severe difficulties depending on the criticality of the immature technologies. The criticality of a technology is proportional to the dependency of the program on it.

2.2 Risk of Technology Obsolescence

From a maintenance point of view, obsolescence is "loss or impending loss of original manufacturers of items or suppliers of items or raw materials" [7]. From a performance point of view, obsolescence is defined as "a measure of product's loss in value resulting from a reduction in the utility of the product relative to consumer expectations" [8]. Both definitions point out the impact of the technology on the overall program which is proportional to the level of the criticality of the technology in the program. The effects of obsolescence are seen in the mid and back end of the life cycle as poor performance – to meet the evolved requirements/expectations – which require costly upgrades (if possible and effective) and maintenance issues due to the compatibility and the availability of the technologies/components [9]. The technologies may become obsolete before the deployment of the capability portfolio [10] or even before the start of production in some cases [7, 9, 11-14]. The later one is more critical for longer life cycle products, which is a common characteristic for most defense systems. In addition, longer life cycle systems have significant sustainment costs which are much more than the original procurement cost [7, 15, 16] and make the obsolescence a more severe problem. Darling states that operations, maintenance, and support costs are usually "two or three times as much as the initial development costs" [17].

2.3 Challenges of Technology Selection for Long Life Cycle Defense Systems

Most of the military programs take longer development times to provide the required capabilities when compared to non-military programs. Another aspect of military programs is that these capabilities are intended to be in service for

40 to 90 or more years [9]. Therefore, it is an implicit requirement to design a system which can meet the current needs and the future needs of the warfighter [18]. There is also a competitive nature of military programs where the aim is to outperform adversary capabilities.

In most military programs, engineers need to include immature technologies in their designs to meet the user requirements, although immature technologies pose risk to the program due to the uncertain nature of technology development. Assessing and managing the technology development risk is a major component of overall program risk management [19]. From a program achievement perspective, it makes sense to include readily available (mature) technologies in the capability design, because available technologies deliver the required capabilities in an affordable and timely manner without any significant risk. Although newer technologies allow more satisfaction of requirements [3], they can also take significantly longer time and higher cost to develop [13]. Additionally, these problems may lead to reduction in the quantity of acquired systems with the available budget and the obsolescence of mature technologies while an immature technology is still under development [13]. On the other hand, historical trend of technology evolution rate is getting higher than it was in the past and this higher rate makes the available technologies easily obsolete [9].

3. Solution Approach

The proposed approach handles the technology selection aspect of the problem from an operational perspective. While immature technologies of a system design might result in cost overrun, schedule slip or lower than anticipated performance level, it is considered that these can be categorized as the feasibility risk of the program. The feasibility risk will be addressed in relation to the readiness of the technologies. The Technology Readiness Levels (TRL) approach, which was developed by NASA [20], will be adopted to analyze the feasibility risk of the technologies. A DOD version of TRL is given in Table 1.

Table 1: Technology Readiness Levels [21]

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept.
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
9	Actual system proven through successful mission operations

On the other hand, there is no established or widely accepted approach to handle technology obsolescence from an operational perspective. Most of available literature on the problem of obsolescence addresses the maintainability of a system which assumes that as long as a system can be sustained to operate, it is not obsolete and obsolescence occurs when difficulties are observed in the availability of the parts and components of the system [7, 22-24]. DOD addresses the obsolescence problem with a similar approach called Diminishing Manufacturing Sources and Material Shortages (DMSMS). Few authors addressed the obsolescence issue from an operational perspective [8, 25].

In order to address the problem defined in this paper, a computer model was developed as depicted in Figure 2. As an effort to address the uncertainty in technology selection, a technology evolution environment was simulated to model the advantages and disadvantages of several candidate technologies for a certain system design. By utilizing a modified Functional Dependency Network Analysis (FDNA), the impact of the technologies on the overall capability portfolio, for both feasibility and obsolescence, was evaluated and the candidate technology combinations were compared for their fitness for a set of decision maker preferences. Finally, a Genetic Algorithm was employed to find an optimal set of candidate technology combination for the system design. The time to develop technologies, the cost to develop technologies, and their performance levels were simulated as a part of technology evolution. The compatibility and interoperability of the technologies were not modeled.

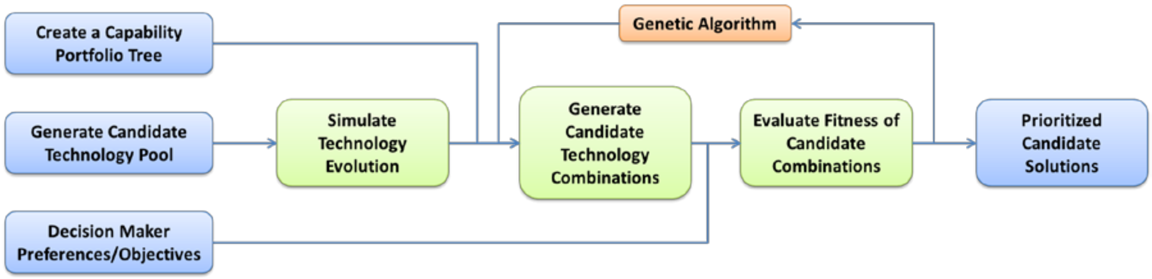

Figure 2. Developed model

3.1 Technology Evolution Model

In contrast to the wide use of TRL approach, there is few data available publicly for researchers [26]. Relying on the other published works, the time to technology and the cost to develop technology was modeled probabilistically. Even though data was limited, it was sufficient for the purpose of modeling a technology evolution environment in order to evaluate their relative properties and compare them as candidate technologies for a certain system design

3.1.1 Time to Develop Technology Model

The *time to develop technologies* model was created based on the initial estimates and probable delays. The model basically distributes the total development time through each TRL transition proportional to a reference time set for each TRL transition. The initial estimates were made in months for fully maturing a technology from an initial TRL value. Then the probable schedule delays for each TRL transition in percentage of the initial values were estimated using Monte Carlo estimation. Finally, by adding the schedule delay to the estimated time to transition values, the probable time for transitioning to the next TRL was calculated for each TRL where the total development time was estimated as the sum of transition times.

3.1.1.1 Reference Time Set for TRL Transitions

The *reference time set* was developed by extrapolating the values given in [27]. Dubos and Saleh provided the average time to transition to the next TRL for TRL 4 through TRL8 for aerospace technologies. It rationalized starting the model from TRL 4, since the DOD usually dealt with new technologies as early as TRL 4 and GAO recommended an initial value of TRL 6. However, some DOD programs include less mature technologies to the design such as Joint Strike Fighter program which had critical technologies at TRL 2 and TRL 3 [28]. Therefore, it was considered that the model should include all TRLs. In order to find approximate values for transition times for TRL1, TRL 2, and TRL 3, a second order polynomial curve was fitted to the given values with an R^2= 0.9999, given in Figure 3. The function for the fitted curve is given in Equation (1) and the full scale mean time to transition values are given in Table 2. The estimated values for TRL 1-3 are acceptable values, since these levels correspond to the initial stages of technology development and most of them are at academic research and concept development level. In addition, most of them are usually not a focused effort in a program, therefore these stages usually take more time to proceed to the next TRL.

$$f(x) = 0.421x^2 - 8.57x + 49.79 \tag{1}$$

Table 2: Mean time to transition to next TRL (months)

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8
41.6	34.3	27.9	22.3	17.5	13.6	10.5	8.2
Estimated			Given				

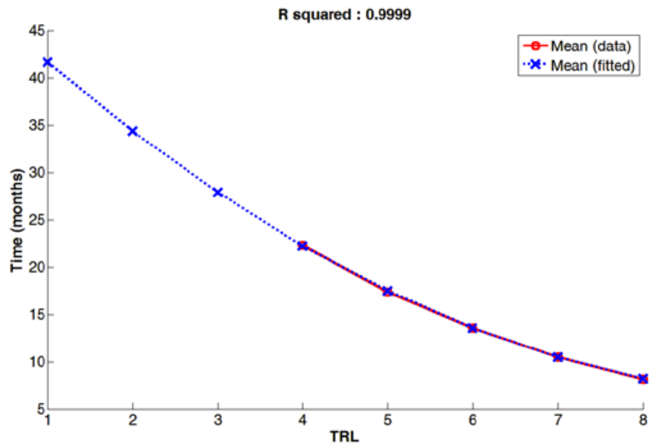

Figure 3: Mean time to transition

3.1.1.2 Schedule Delay Model

Dubos et al. provided a set of normal distribution parameters for schedule delay of technology development at certain TRLs [29]. However, it does not include the values for TRL 1, TRL 2, and TRL 3 schedule delays. In order to obtain normal distribution parameters for TRL 1, TRL 2, and TRL 3, a second order polynomial curve was fitted to the given parameters. The curves for the original parameters and the fitted curves are given in Figure 4 and the fitted functions are given in Equation (2) and Equation (3) for the mean and the standard deviation, respectively. The curves were fitted with an R^2=0.99695 for the mean and with an R^2=0.99684 for the standard deviation which were considered acceptable. Most of the schedule delay stems from the uncertainty in how long it will take to develop a technology. As the development progresses – and the TRL increases, more knowledge about the technology is gained and the uncertainty is reduced. This trend of decreasing uncertainty is reflected with the distance between the mean and standard deviation of the schedule delay as the TRL increases. The given and estimated values for the schedule delay model conforms to this decreasing trend.

Mean $$f(x) = 5.05x^2 - 79.65x + 324.36 \quad (2)$$

Standard Deviation $$f(x) = 3.03x^2 - 47.56x + 192.41 \quad (3)$$

Table 3: Normal distribution parameters for each TRL to estimate the schedule delay

	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8
Mean	41.6	34.3	27.9	22.3	17.5	13.6	10.5	8.2
Standard Deviation	147.9	109.4	77.0	50.6	30.3	16.1	7.9	5.7
	Estimated			Given				

3.1.2 Cost to Develop Technology Model

The *cost to develop technology* model were developed based on the initial cost estimation and the probable cost growth for each TRL. First, the initial cost estimate were distributed to each TRL level based on a reference cost distribution. Then, relative cost growth was estimated using the relative cost growth model and the time to develop technology model. The sum of cost for all TRL transitions were calculated as the total cost to develop the technology.

3.1.2.1 Reference Cost for Each TRL Transition

Hay et al. estimated a cost curve for TRL transitions from TRL 2 to TRL 6 [30], given in Figure 5. They provided the cost values as multiplier of the cost of previous transition, such as the cost of transitioning from TRL 3 to TRL 4 was 3.2 times the cost of transitioning from TRL 2 to TRL 3. In order to estimate the cost multiplier for the other TRL transitions, a second order polynomial function was fitted to the given values with an R^2=0.9999. The curves for given values and estimated function are given in Figure 6. The fitted function is given in Equation 4 and the estimated cost multiplier for each TRL transition (*reference cost distribution*) is given in Table 4.

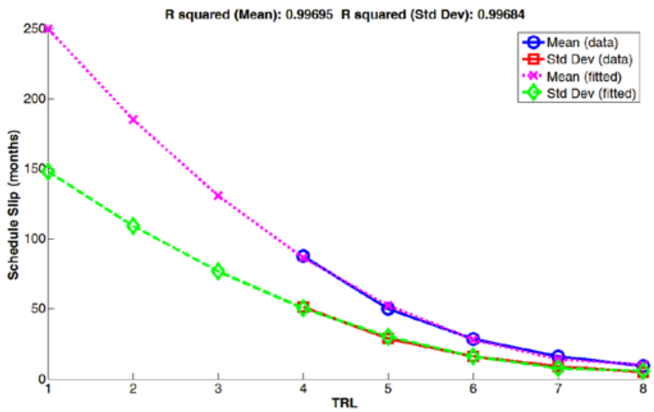

Figure 4: Fitted curve for normal distribution parameters for schedule delay

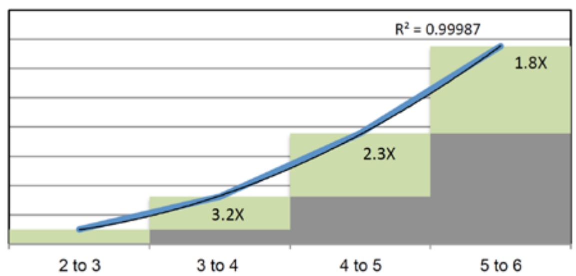

Figure 5: Cost curve for TRL transitions [30]

$$f(x) = 0.42x^2 - 8.57x + 49.79 \quad (4)$$

Table 4: Estimated cost multiplier from each TRL to next TRL

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8
0.6	1	3.2	7.3	13.3	21	30.7	42.1
Estimated	Given				Estimated		

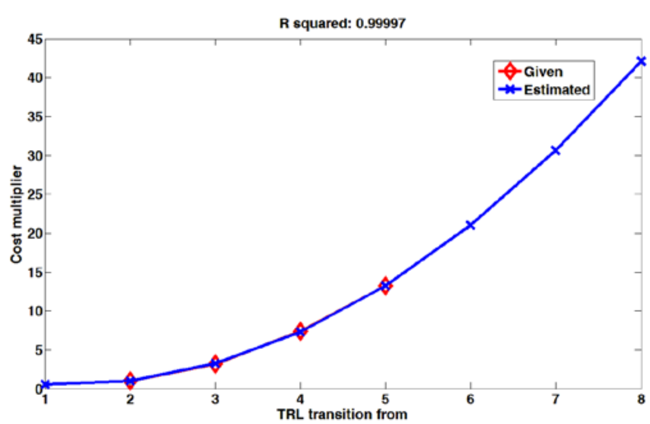

Figure 6: Cost multiplier values for each TRL transition and the fitted curve

3.1.2.2 Relative Cost Growth Model

The *relative cost growth* model was developed based on the data given in Table 3 of a study by Lee and Thomas [31]. They provided the annual relative cost growth values for the time spent at TRL 3 through TRL 8. Using Matlab

Statistics Toolbox, the most appropriate probability distribution functions (PDF) for the cost growth for TRL 3 through TRL 8 were estimated. The PDFs and respective parameters are given in Table 5. For TRL 1 and TRL 2, cost growths were calculated based on the schedule delay for the respective level. In other words, the cost for TRL 1 and TRL 2 increased proportional to the schedule delay for each level.

Table 5: Distribution parameters for cost growth rates for TRL 3 to TRL 8

TRL	Distribution	Parameters		
3	Logistic	$\mu = 0.0950$	$\sigma = 0.0951$	
4	Generalized extreme value	$k = 0.1750$	$\sigma = 0.0959$	$\mu = 0.0268$
5	Extreme value	$\mu = 0.1953$	$\sigma = 0.2313$	
6	Generalized extreme value	$k = 0.4419$	$\sigma = 0.1359$	$\mu = 0.0320$
7	Generalized pareto	$k = 0.1073$	$\sigma = 0.1288$	$\theta = -0.0740$
8	Generalized pareto	$k = 0.6580$	$\sigma = 0.1821$	$\theta = -0.1440$

3.2 Modified FDNA Approach

Complex systems and system-of-systems feature interactions and interdependencies between their entities. It is critical to address the dependencies – developmental and functional relationships – between entities in order to estimate the behavior of a complex system [32]. When various systems within a higher system architecture is dependent on each other, any problem of development or functionality of a particular system will affect the overall system development or performance [33]. A modified FDNA was utilized to address the functional dependencies within the overall system.

Reader is referred to [1] for the details of original FDNA approach.

In Figure 7; A, B, C, and D are capability nodes, where A is a receiver node and B, C, and D are feeder nodes. B and C are enabling nodes and strength of their relationships with A (illustrated with red solid lines) are represented by m_{BA} and m_{CA}. D is an enhancing node and strength of its relationship with A (illustrated with blue dashed line) is represented by n_{DA}. Enabling relationship is depicted by red (solid) lines and enhancing relationship is depicted by blue (dashed) line. P_A, P_B, P_C, and P_D are the operability levels of A, B, C, and D, respectively. Hence;

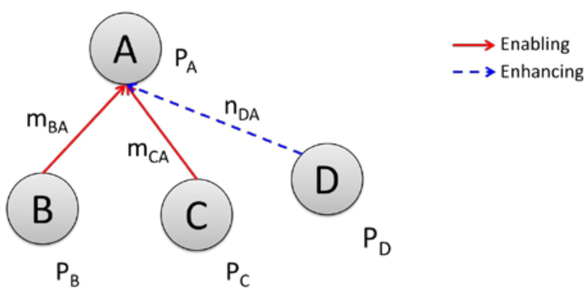

Figure 7. Graphical representation of the modified FDNA

$$0 \le P_B, P_C, P_D \le 1 \tag{5}$$

$$m_{BA} + m_{CA} = 1 \tag{6}$$

$$0 < n_{DA} \le 1 \tag{7}$$

$$P_A = (P_B m_{BA} + P_C\, m_{CA}) + (P_B m_{BA} + P_C\, m_{CA}) * P_D n_{DA} \tag{8}$$

The modified FDNA approach was used to evaluate the fitness of candidate technology combinations. A sample capability portfolio is given in Figure 8. Several technologies, which are either mature or under development, are proposed to fulfill the functionality of the respective systems. Capabilities deliver functionality by the supplier systems based on their dependency values and respective performance outputs. The level of capability is calculated using Equation (8) by dependency levels of supplier systems (candidate technologies) and their performance levels.

Finally, the capability portfolio performance level is calculated using Equation (8) and supplier capability dependency levels and their performance levels.

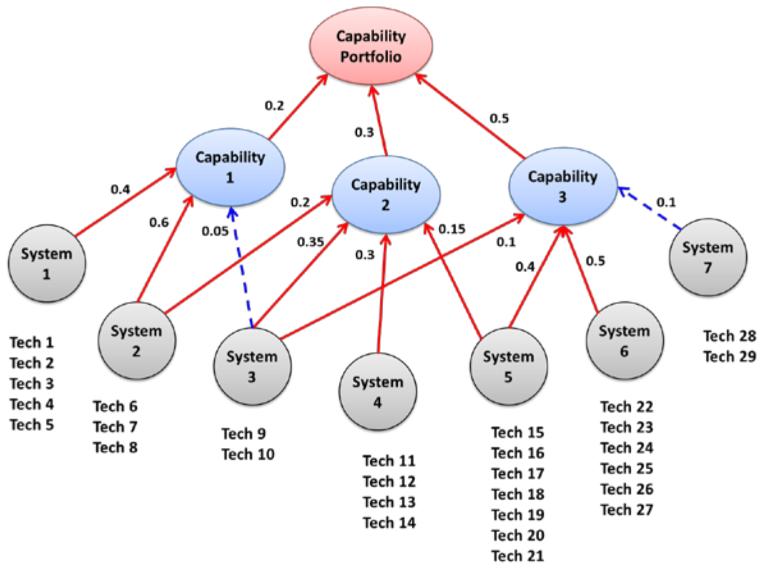

Figure 8: A sample capability portfolio tree

3.3 An Example Portfolio Application

The sample capability portfolio, given in Figure 8, was analyzed in order to observe the capabilities of the developed model. The simulation was run for 500 months. The objective of the portfolio was identified as to deliver the capabilities in around 180 months with the lowest development cost and the highest performance level.

In the first phase; a total of 230 hypothetical technologies from different technology areas, which were candidate for a specific system in the capability portfolio, was simulated to estimate their development cost, development time, and relative performance levels over the life cycle. The technologies were simulated with various values of initial TRL, time to start development, estimated time to develop, estimated cost to develop, and estimated performance level. By utilizing the probabilistic model described above and employing a Monte Carlo simulation, for each technology, the development time, the development cost, and the performance level for the whole life cycle were estimated.

In the second phase, a genetic algorithm was developed to determine an optimal set of candidate technologies to realize the capability portfolio. In order to determine how good each technology combination performs, the modified FDNA approach was utilized by using the dependency coefficients given in Figure 8. In addition, each candidate technology combination was compared for their development cost, delivery time, and performance level. While the model is still under development, it was able to provide some valuable results.

Evaluation of a sample candidate technology combination is given in Figure 9. In the figure, the bottom plot shows how TRL of technologies of the candidate combination evolves over time. The blue solid lines are for technologies and the magenta dashed line shows the overall technology readiness of the portfolio. The red dotted line is the time of delivery for the portfolio. In the top plot, the blue solid lines show the relative performance level of the portfolio technologies. The magenta dashed line shows the portfolio capability level which is calculated using the modified FDNA approach. The red dotted line is the time of delivery for the portfolio. The performance level of the technologies are calculated as relative performance levels where the reference is the best performing technology to provide the same functionalities at the time of evaluation. Therefore, once a new technology with a superior performance level is available, all technologies with similar functionalities become obsolete proportional to their performance level. This trend is shown with the decreasing performance level of technologies and the portfolio over the life cycle. This represents the technology obsolescence perspective of this study.

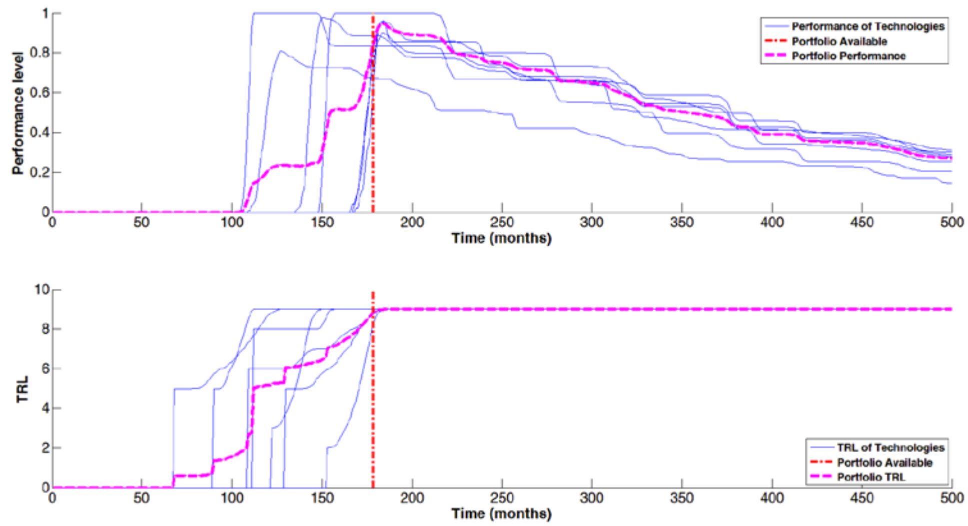

Figure 9. Evaluation of a sample candidate technology combination

4. Conclusion

Initial results of the study reveal that the developed model is able to simulate a technology evolution environment. The model can simulate the development time, the development cost, and the performance levels of various technologies over a given time frame. A novel obsolescence approach was also briefly proposed in this study which addresses the obsolescence problem from an operational perspective. The proposed obsolescence approach evaluates the performance level of a specific technology with respect to other technologies with similar functionalities.

The simulated technology environment, the utilization of the modified FDNA approach and the proposed obsolescence approach helps decision makers understand the advantages and disadvantages of various technologies over time which are to be selected for a specific capability portfolio. Thus, it is considered that the approach proposed in this study is able to reduce the uncertainty in technology selection for long life cycle engineering projects by addressing both the feasibility risk and the obsolescence risk.

References

1. Pinto, C.A. and P.R. Garvey, *Advanced risk analysis in engineering enterprise systems*. 2012, Boca Raton: CRC Press.
2. Kirby, M.R. and D.N. Mavris. *A method for technology selection based on benefit, available schedule and budget resources*. in *5th World Aviation Congress and Exposition, San Diego, CA*. 2000.
3. Mathias, D.L., A.M. Goodsell, and S. Go. *Technology development risk assessment for space transportation systems*. in *Proceedings of 8th Probabalistic Safety Assessment and Management Conference, New Orleans, Louisiana*. 2006.
4. DOD. *Acquisition Framework*. Defense Acquisition Guidebook [cited 2014 29 July]; Available from: https://dag.dau.mil/Pages/acqframework.aspx.
5. DOD. *System Acquisition Framework*. 2014 [cited 2014 July 23]; Available from: https://dap.dau.mil/aphome/das/Pages/Default.aspx.
6. Azizian, N., S. Sarkani, and T. Mazzuchi. *A comprehensive review and analysis of maturity assessment approaches for improved decision support to achieve efficient defense acquisition*. in *World Congress on Engineering and Computer Science*. 2009.
7. Sandborn, P. *Designing for technology obsolescence management*. in *Proceedings of the 2007 Industrial Engineering Research Conference*. 2007.
8. Rai, R. and J. Terpenny, *Principles for Managing Technological Product Obsolescence.* Components and Packaging Technologies, IEEE Transactions on, 2008. **31**(4): p. 880-889.
9. Josias, C., J.P. Terpenny, and K.J. McLean. *Component obsolescence risk assessment*. in *Proceedings of the 2004 Industrial Engineering Research Conference (IERC)*. 2004.

10. Dubos, G.F., *Stochastic modeling of responsiveness, schedule risk and obsolescence of space systems, and implications for design choices*. 2011, Georgia Institute of Technology.
11. Hitt, E.F. and J. Schmidt. *Technology obsolescence (TO) impact on future costs*. in *Digital Avionics Systems Conference, 1998. Proceedings., 17th DASC. The AIAA/IEEE/SAE*. 1998.
12. Livingston, H. *GEB1: Diminishing manufacturing sources and material shortages (DMSMS) management practices*. in *Proceedings of the DMSMS Conference*. 2000.
13. Dacus, C.L., *Improving Acquisition Outcomes Through Simple System Technology Readiness Metrics.* Defense Acquisition Research Journal: A Publication of the Defense Acquisition University, 2012. **19**(4): p. 444-461.
14. Concho, A.L., J.E. Ramirez-Marquez, and T.E. Herald. *Functionally Equivalent COTS for Optimal Component Substitution within System Evolution Planning*. in *7th Annual Conference on Systems Engineering Research*. 2009. Loughborough University.
15. Jenab, K., et al., *A dynamic model for hardware/software obsolescence.* International Journal of Quality & Reliability Management, 2014. **31**(5): p. 588-600.
16. Nolte, W.L., *Did I ever tell you about the whale?, or, Measuring technology maturity*. 2008, Charlotte, NC: Information Age Pub.
17. Darling, D.R., *Parts Obsolescence Management Technology Transition (POMTT) Final Report*. 2004, Lockheed Martin Missiles and Fire Control: Orlando, FL.
18. Herald, T.E. and J.E. Ramirez-Marquez, *System Element Obsolescence Replacement Optimization via Life Cycle Cost Forecasting.* Components, Packaging and Manufacturing Technology, IEEE Transactions on, 2012. **2**(8): p. 1394-1401.
19. Wilhite, A. and R. Lord, *Estimating the Risk of Technology Development.* Engineering Management Journal, 2006. **18**(3): p. 3-10.
20. Mankins, J.C., *Technology readiness levels.* White Paper, April, 1995. **6**.
21. DOD, *Technology Readiness Assessment (TRA) Guidance*, D.o. Defense, Editor. 2011.
22. Bartels, B., et al., *Strategies to the Prediction, Mitigation and Management of Product Obsolescence*. 2012, Wiley: Hoboken.
23. Herald, T.E., et al., *An obsolescence management framework for system baseline evolution—Perspectives through the system life cycle.* Systems Engineering, 2009. **12**(1): p. 1-20.
24. Romero Rojo, F.J., R. Roy, and E. Shehab, *Obsolescence management for long-life contracts: state of the art and future trends.* International Journal of Advanced Manufacturing Technology, 2010. **49**(9-12): p. 1235-1250.
25. Mellal, M.A., et al., *Optimal Policy for the Replacement of Industrial Systems Subject to Technological Obsolescence - Using Genetic Algorithm.* Acta Polytechnica Hungarica, 2013. **10**(1): p. 197-208.
26. Dubos, G.F., J.H. Saleh, and R. Braun, *Technology Readiness Level, Schedule Risk and Slippage in Spacecraft Design: Data Analysis and Modeling*, in *AIAA SPACE 2007 Conference & Exposition*. 2007, American Institute of Aeronautics and Astronautics.
27. Dubos, G.F. and J. Saleh, *The Risk of On-Orbit Obsolescence: Justifiable Concern or Extenuating Circumstance for DOD's Space Acquisition Practices?*, in *AIAA SPACE 2008 Conference & Exposition*. 2008, American Institute of Aeronautics and Astronautics.
28. General Accounting Office, *Joint Strike Fighter Acquisition: Mature Critical Technologies Needed to Reduce Risks*. 2001, Washington, D.C.: U.S. Govt. Accountability Office.
29. Dubos, G.F., J.H. Saleh, and R. Braun, *Technology Readiness Level, Schedule Risk, and Slippage in Spacecraft Design.* Journal of Spacecraft and Rockets, 2008. **45**(4): p. 836-842.
30. Hay, J., et al., *Evidence for Predictive Trends in TRL Transition Metrics*, in *AIAA SPACE 2013 Conference and Exposition*. 2013, American Institute of Aeronautics and Astronautics.
31. Lee, T.-S. and L.D. Thomas, *Cost Growth Models for NASA's Programs, Final Report*. 2000, Marshall Space Flight Center: Huntsville, AL.
32. Guariniello, C. and D. DeLaurentis, *Integrated Analysis of Functional and Developmental Interdependencies to Quantify and Trade-off Ilities for System-of-Systems Design, Architecture, and Evolution.* Procedia Computer Science, 2014. **28**(0): p. 728-735.
33. Reeves, J.D., L. Evan, and K. Kamal, *Schedule Risks Due to Delays in Advanced Technology Development*, in *AIAA SPACE 2008 Conference & Exposition*. 2008, American Institute of Aeronautics and Astronautics.