Advanced Technologies to Enable Simulation of Life-Cycle Sustainment of Weapon Systems

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Abstract: *The authors have witnessed and been part of the development of the burgeoning complexities of weapons systems. They have focused some of their research on the need to analyze the life-cycle sustainment of these systems. This sustainment analysis has similarly grown in complexity and sophistication. To be optimally useful, the results and insights from these analyses need to be accessible long before the systems are fielded and before sustainment parameters can be established and sustainment data collected from live implementations. This strongly supports the need to employ both constructive and virtual simulations to provide pre-deployment "experience" with systems. These simulations must be programmed to include the various input and output parameters of the system-engineered sustainment model. The size of modern weapons systems and the wide geographical dispersion of such systems calls for significant computational capabilities; this need is exacerbated by the current focus on simulating operations in large urban areas, fully populated by red, blue and civilian populations, all suitably programmed to act in a demographically appropriate way. Because a major factor of sustainment is maintenance and that maintenance is dramatically impacted by environmental factors, the modeling of these factors, along with verifiable functions representing their impact on hardware and personnel, must be modeled as well. There is a long history of using high performance computing to enable and enhance large-scale simulations and some of the authors have been part of that development process since 1995. Further, new advances in computing now offer to create a new computational paradigm for high performance computing, e.g.,*

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the innovations at the University of Southern California, Quantum Computing Center. As Systems Engineering has co-evolved with these computational advances, it has made good use of Markov and martingale analyses, and one of the authors is currently developing a model that relies on this sub-discipline of analysis to better characterize the sustainment of weapons systems. Serendipitously, this line of inquiry is well situated to make excellent use of the quantum annealer at USC, as Markov processes are the foundation of the annealer's operations, This paper will briefly describe the need for and the current state of the art of sustainment analyses, lay out the need for improved and expanded simulation techniques, and discuss the path to facilitating the implementation these across the entire spectrum of the simulation community. Alternative approaches, interoperability challenges, and future developments will be suggested, outlined and documented.

1. Introduction

There is a broadening of the capabilities of simulation for the DOD. Advanced technologies and more sophisticated analytical techniques are expanding the scope of the dual simulation trilogies of modality: Live, Virtual and Constructive and utilization: Training, Evaluation and Analysis. The DOD Acquisition community asserts that "the goal is to ensure sustainment considerations are integrated into all … activities". [1] This paper will focus on the needs and possible contributions of the Systems Engineering community, the impact of the parameterization of life-cycle analyses using Markov, Hidden Markov and martingale analyses, and the contributions of the High Performance Computing discipline, most particularly, the emergence of quantum computing as an emerging technology. The underlying issues to be addressed are : "What can the sustainment professionals contribute to the Simulation community to improve their product?" and "What can the Simulation community contribute to the Sustainment professionals to optimize their analyses." On-going research and early insights will be reported as they are made available.

1.1 Background

Since the earliest days of warfare, leaders have sought to understand and prepare for combat through simulations of various kinds. Early athletics often evolved as competitive test of combat skills in a non-combat arena [2]. Many games such as chess were centered on abstracting and emulating combat [3]. More complex and realistic simulations evolved over the centuries, but they all had in common trying to train people to behave well in combat, trying to see if some new weapon would be effective, or trying to better predict the outcome of an impending operation [4]. Within the professional experience of the authors, simulations have expanded their capabilities along several axes, including: geographical area, resolution of simulated objects, richness of behaviors, duration of simulations, speed of performance (*e.g.*, computer generated constructive simulations can be run at significantly faster than real time), and sophistication of analytic tools to better understand the large amounts of data collected [5]. Many of these advances have been enabled by High Performance Computing (HPC) [6]

1.2 Current Practice

It has been the authors' experience that battlefield simulations rarely take heed of system degradation over time and they can think of no occasion when the Systems Engineering parameters surrounding life-cycle sustainment were incorporated into the functions of the simulation code. This impacts all three of the simulation modalities and all three of the uses of simulation in two ways: it makes the simulations less valid and it deprives the Systems Engineers of valuable insights into life-cycle sustainment issues.

2. New Approach

In 1982 Senator Sam Nunn and Congressman David McCurdy passed legislation that became permanent in 1983 for Department of Defense Weapons Procurement programs. [7] The legislation requires notification to congress if unit cost goes above 25% and program termination if costs rise above 50%. There are provisions where the Secretary of Defense (SECDEF can certified: the program is essential to national security, that no suitable alternative of lesser cost is available; new estimates of total program costs are reasonable; and management structure is (or has been made) adequate to control costs.

In the authors' opinion that Sustainment options fall into the latter part of the Life Cycle Sustainment, see Chart 1.

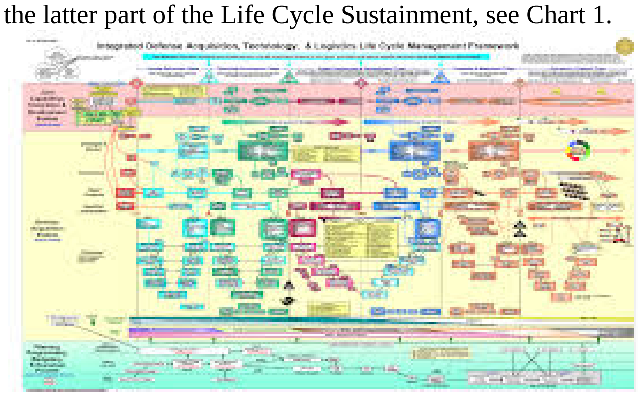

Chart 1
Integrated Defense Acquisition, Technology and Logistics Lifecycle Management System Ver 5.1 12/2004

Sustainment Options remain ripe for budget cutting measures as costs rise in the earlier part of the life cycle. High performance computing capabilities in the form of Quantum Annealers and parameterization analyses would be a new approach for SE's to keep costs on track and below Nunn McCurdy breech thresholds. SE's will then have new trigger point capabilities to alert the PM's that their acquisition program is in heading toward the breech thresholds that are not capable under current modeling and simulation approaches. Quantum Annealers give PM's the ability to not only avoid breech but, by maintaining real cost savings, larger acquisition quantities can be realized.

2.1 SE and Simulation

Modeling and Simulation (M&S) can effectively be employed in support of SE sustainment options. It is extremely costly to design, build and test hardware and then find out after the test program, that the desired system does not meet the requirements or quite possibly does not function as intended. Effective and validated M&S can significantly reduce the cost of the Design-Build-Test Repeat until right scenario. A accurate model, such as a physics based model where ultimately the model is the specification, can be affordably developed and exercised to produce data which then will be analyzed to determine if the system can meet the defined requirements. If not, then modifications can quickly be made to the model and then iterated until the desired outcome is obtained. With that said, a model that is not validated, poses significant risk when employing that model to design a component, system, or experiment. It is always necessary to compare data obtained from M&S with data that is empirically derived even at subscale. If the data resulting from the model reasonably agrees with that obtained empirically, then the only challenge that needs to be addressed is scalability and that is why developing a physics based model is important, as the risk of scalability is mitigated through the use of models based on physics. A key tenant of SE is the identification, reduction and mitigation of risk. Cost is a defined risk factor. The application of validated M&S tools will reduce the risk of cost overrun in the design, development, testing, certifying and employing complex systems.

2.1.1 Requirements

As stated in the previous paragraph, simulations produce data. That data then has to be analyzed and assessed to determine if the system will meet the specified requirements. The SE process will use the results of that analysis and inform decisions (i.e., data driven decisions) that need to be made with respect to any modifications that need to be made to the model to produce the desired result. It is this iterative process, employing the model and results of the model, through 1) Requirements, 2) Functional Analysis, and 3) Synthesis until the desired outcome is obtain. In essence, SE needs validated data resulting from M&S to make informed decisions and thereby reduce and mitigate risk.

2.1.2 Contributions

The SE process can improve simulations through the discipline of iteration of the model until the desired outcome is obtained. The validity of simulations is determined by 1) the accuracy of the assumptions that go into the model or simulation and 2) how closely the model and its formulations accurately represents the real world, and in this case, the physical system that it is representing. The three ingredients of SE include: 1) Requirements, 2) Functional Analysis and 3) Synthesis. The outcome of simulation is manifested in the third ingredient, Synthesis. However, the process by which the model reaches this point is through the first two ingredients, Requirements and Functional Analysis. First and foremost, the requirement needs to be established, and serves as the foundation for the model or simulation. This requirement also serves as a given or assumption for the model. If the requirement is inaccurate, then the model will be right for the requirement, but will be wrong for the system that the model represents. The requirement must be correct initially, and if not the case, the model/simulation needs to be sufficiently flexible or robust to accommodate changing requirements. Additionally, the model and or simulation needs to accurately address the functionality of the system. What is the purpose of the system and following that what are the functions that the system needs to do or what functions it must perform to realize the intended purpose. Therefore, successfully employing and applying the SE process to models/simulation will assist in formulating the model or simulation that assumes the right requirement, or is sufficiently robust to accommodate changing requirements, accurately capture the function that the system is designed to perform, and lastly synthesize the results which should be compared to empirical data, if available, to validate the model such that it can be used to predict the performance of the system and obtain reasonably accurate results.

2.1.3 Application

It is the author's opinion that the application of Quantum Annealers forecasting would help control sustainment costs for DOD and be useful programmatic control tool for all government programs. This forecasting is greater than currently available Modeling and Simulation (M&S) tools utilized by the DOD. M&S analysis of traditional Markov and Martingale Life Cycle Sustainment would be appreciable faster when carried out with high performance Quantum Annealers.

2.2 Life-Cycle Sustainment Analyses

Over two-thirds of the life cycle cost of an acquired system is contained in the cost to operate and support a system. Given this fact, one way SEs view sustainment is how to lessen the cost of sustainment of an acquired system. The path that has the greatest impact to reduce the sustainment costs of an acquired system is up front in the acquisition process, during concept exploration or during the preliminary and detailed design phases of an acquisition program. It is here, in early design, where sustainment costs can be most impacted. If a design results in a system that has very low “ilities” driving maintainability costs high and time to maintain high, then the other “ilities” to include availability or Ao and reliability tend to be very poor and costly. A design that keeps in mind how, frequency, who (can the system be sustained at the organizational level or does more costly forms of sustainment such as intermediate or depot level maintenance will be needed.) the system will be maintained/sustained, SE is all about risk identification and mitigation. A system that has a high cost to sustain and or maintain it poses a risk to the viability of endurance of the system. SE’s will seek to design and develop a system that takes into account cost, frequency, level of expertise and disposal considerations during the up front, design phase of an acquisition system.

2.3 Markov Analyses

A classic way to describe the evolution of a system and its life-cycle is to ascribe its behavior to Markov processes, in which each condition or state of system has a set of predictable probabilities for the condition or state to follow. This usually formulated as:

$$P\{X_{n+1}=j|X_n=i, X_{n-1}=i_{n-1},\ldots,X_0=i_0\}=P\{X_{n+1}=j|X_n=i\}$$

Where the probability of the next state (X_{n+1}) is known if the current state (X_n) is known. This gives the simulation team a straightforward process of identifying, amalgamating and implementing a set of stochastic processes in their code to generate a series of predictions about future states. The issue that is not scalable is the issue of how many factors there are in the probabilities under investigation. In systems engineering the life-cycle sustainment of major DOD systems, the number can become incomprehensibly large.

In many large systems there is a significant body of information about what state X_{n+1} will be if we know state $X_{n,}$ e.g., we know the impact of ambient temperature change on the internal temperature of a crew saved weapon. Two issues rather rapidly arise, however: 1) are there some processes that are not Markovian, *i.e.*, are dependent on past states and 2) are the possibilities so numerous, complex, and variable as to make computing any *extrema* virtually impossible using digital computing techniques, even very massive parallel processing clusters or “the cloud.

2.4 Hidden Markov Analyses

Not uncommon in defense work, the Hidden Markov also is amenable to computer simulation. In this case, the states of the process are not directly visible, but the new states produced by the process do become visible in order and the new states can be used to determine previous states. Given field reports of system states or intelligence reports of unobservable systems, the simulation community can assess varying possible processes that may have produced such observed states and thereby do a better job of estimating both past and futures states of friendly and enemy systems. Laying aside the possibility of erroneous or intentionally deceptive information, such and analysis is feasible, *modulo* the impact of too many variables to successfully simulate using current technologies.

One approach that has been successful in these analyses is the Viterbi algorithm that is widely used in communications systems management and voice recognition. [8] There is significant conversation in the community about the use of the Viterbi algorithm to analyze Hidden Markov processes in a general way. [9] This might prove especially useful when modeling “red force” in battlefield simulations It is the opinion of the authors most closely associated with the USC Quantum Computing Center, that the Viterbi algorithm that finds Markov model hidden states is a very efficient algorithm. If an analyst just want to want to find hidden states, then they would not need quantum computers.

2.5 Martingale Analyses

Martingale analyses are also useful in systems engineering and may be employed successfully in simulations of life-cycle sustainment for the analysis of that sustainment or for the better simulation of weapons’ capabilities on the live, virtual or constructive battlefield. Unlike Markov, martingale analyses take very good heed of and are influenced by previous states. The basic formulation for this set of affairs is:

a) $E(x_n) < \mu$,

and

(b) $E(x_{n+1} \mid x_1,\ldots,x_n) = x_n$

In the above, the expected state of X is dependent on the previously states, which must be defined in some detail.

As before, what is a simple simulation problem on its face, soon spirals out of control as the number of parameters that influence the system grow alarmingly. This is a well recognized and often discussed problem in simulation: the implementation of reasonable models without swamping available computer resources.

Clearly the shortcomings of the Markov models with their discounting of the previous trends and impacts of earlier states are addressed by the martingale analyses that acknowledge that which has gone before. Naturally, in doing so, they multiply the parameters that must be identified, quantified and utilized. That process alone may seem daunting, but it is the realm of systems engineers. [10]

3. Early Findings

DOD Program Manager and System Engineers utilizing Quantum Annealers forecasting would be able to model Life Cycle costs and achieve Sustainment cost savings by predicting potential Nunn McCurdy threshold breeches earlier in the acquisition cycle. Traditional Martingale and Markov M&S analyses will benefit from increased high performance computing power of the Quantum Annealers.

3.1 Merging Simulation and Systems engineering

Quantum computing can help the DOD Program Manager navigate through all the required acquisition cycle DODAF system engineering views. The DODAF views aid the DOD Program Managers in managing life cycle costs. High performance computing capabilities of Quantum Annealers would produce the required views. As development progresses, there will be a better understanding of the mapping of life-cycle sustainment and systems engineering to Markov problems. At that time, it should be possible to find the more computationally complex problems that do require quantum computers.

3.2 Use of High Performance Computing

Mandates for DOD research closely follow the vagaries international events. The rapidly changing geopolitical environment imposes a rapidly changing research agenda. [11]. The High Performance Computing (HPC) professionals are in the forefront of these groups being impacted by those changes. They are tasked with projecting the future of US weapons, systems, tactics and strategies. Using HPC for battlefield simulation leads to experiments in which warfighters in uniform are staffing the consoles during interactive, HPC-supported simulations. Experiments to model and simulate the complexities of urban warfare use well-validated entity-level simulations, *e.g.,* Joint Semi-Automated Forces (JSAF) and the Simulation of the Location and Attack of Mobile Enemy Missiles (SLAMEM). These need to be run at a scale and resolution adequate for modeling all the convolutions of urban combat.
There is a long lineage of entity-level synthetic battlefield codes. They consist of representations of terrain that are populated with intelligent-agents representing: friendly forces, enemy forces and civilian groups. Experience has shown that to produce their behaviors in at timely manner, significant compute resources are required [12]. Much of this is true because a major computational load is imposed in the performance of line-of-sight calculations between the entities. The inherently onerous “n-squared” growth-characteristics of an all-see-all program have been identified previously [13]. If several thousand entities need to interact with each other in an urban setting with vegetation and buildings obscuring the lines of sight, inter-node communications chaos and failure are often observed. This situation has been successfully ameliorated, but only partially so, by the use of an innovative interest-managed communication’s architecture [14].

Increasingly, DOD simulators required enhanced Linux clusters of adequate size, power, and configuration to support larger and more sophisticated simulations, especially when there is a requirement for more than 2,000,000 entities within high-resolution insets on a global-scale terrain database. The cluster has been used occasionally to interact with live exercises, but more often has been engaged interactively with users and experimenters while generating only virtual or constructive simulations. [15] It had to be robust to reliably support hundreds of personnel committed to the experiments and it had to be scalable to easily handle small activities as well as larger global-scale experiments with hundreds of live participants, many distributed trans-continentally, as shown in Figure 1 below.

The operators must operate in a distributed fashion over the Defense Research and Engineering Network (DREN), at a scale and level of resolution that allowed dispersed participants to conduct experimentation on issues of concern to combatant commanders, who have participated in the experiments themselves. This provided the requisite simulation federations, software, and networks, joined into one common computer infrastructure that was supporting experiments. Quantitative and qualitative analysis, flexible plug-and-play standards, and the opportunity for diverse organizations to participate in experiments were all mandated by DOD needs.

To order to meet these goals, a team from the Information Sciences of the University of Southern California helped design and develop a scalable simulation code that has been shown capable of modeling more than 1,000,000 entities. This effort is known as the Joint Experimentation on Scalable Parallel Processors (JESPP) project [16]. The dedicated compute power provided additionally allows for the easy identification, collection, and analysis of the voluminous data from these experiments, enabled by the work of Dr. Ke-Thia Yao and his team [17].

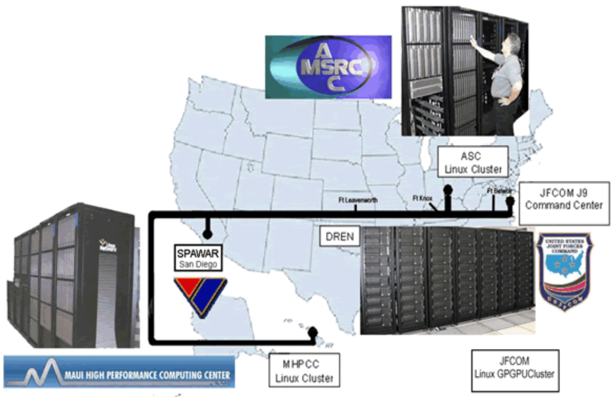

Figure 1
JFCOM's Experimentation network: MHPCC, SPAWAR, ASC-MSRC, TEC/IDA and JFCOM

Even using these powerful computers, the JFCOM experimenters were constrained in a number of dimensions, *e.g.*, number of entities, sophistication of behaviors, realism of various environmental phenomenology, etc. While the scalability of the code would have made the use of larger clusters feasible, a more effective, efficient, economical and elegant solution was sought. One approach is the use of more powerful clusters, especially a GPU-enhanced cluster.

The use of existing DOD simulation codes on advanced Linux clusters operated by JFCOM was the implementation method chosen as being most efficient. This effort supplanted the previous JFCOM J9 DC clusters with a new cluster enhanced with 64-bit CPUs and nVidia 8800 graphics processing units (GPUs). The computer was given the *Joshua*, the Hebrew commander. It proved to be invaluable in achieving the JFCOM mission and set several records over its use by that command.

Figure 2
Joshua

While great strides were made in the number of entities to be simulated, the research implications of this achievement, albeit expected, were a dramatic reaffirmation of the value of HPCs. Most notably, on 14 December 2007, the Joint Forces Command Personnel, under the leadership of Rich Williams simulated a full ten million CultureSAF entities on the Baghdad terrain database. This was accomplished as is visualized in Figure 3 below:

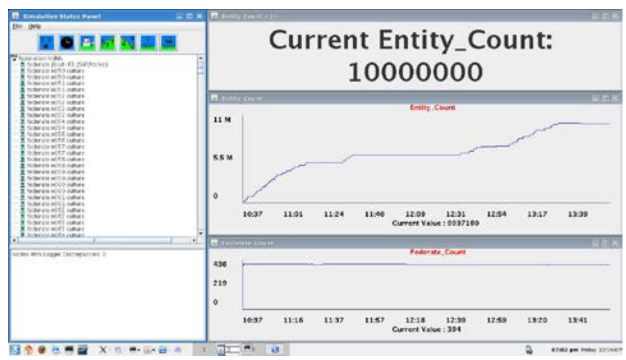

Figure 3
Graph of Entity Count Grow by Time on 14 Dec 07

3.3 Introduction of Quantum Computing

Members of the simulation community are often seeking new capabilities to enhance their computational power. The growth of transistor density, and the related capability of traditional digital computing, postulated by Moore's Law [18] is approaching its limits asymptotically. Hence the need to more seriously reevaluate new computing paradigms. One of the most often discussed paths is quantum computing and its first practical incarnation, adiabatic quantum annealing [19]. This section focuses on issues of concern to the test and evaluation application developers. It presents an overview of quantum computing, a review of some early work on a D-Wave quantum annealer at the University of Southern California and a discussion of the applicability of this technology to simulation. It is not a learned treatise on the theoretical and mathematical intricacies of quantum computing nor does it advocate some specific resolution of the many issues that arise with the introduction of any new technology. Instead, the authors rely on decades of experience in high performance computing and DOD simulations to offer aid to the test and evaluation community in assessing the potential utility of this advance.

According to Gordon Moore himself, the end of Moore's Law is nigh. It is increasingly daunting to continue on the current transistor-based path for increasing the traditional digital computing capability that can be applied to test and evaluation and other national security challenges. The capability growth of individual processors is stagnating and the number of such cores needed is now increasing exponentially in high performance computing systems. Size and power demands now often constrain the computational power that can be brought to bear on defense problems. In this environment, there is a growing interest in alternatives to commercial, off-the-shelf (COTS) technology, which would have seemed inconceivable for most of the last two decades. In many ways, this may be the reemergence of the purpose built systems of earlier decades. New installations include specialized systems such as the Anton at D. E. Shaw Research [20][21] It performs certain biomolecular simulations nearly two orders-of-magnitude faster than the largest general purpose computers. Others are looking beyond CMOS to exploit other physical phenomenon, *e.g.*, quantum computing.

There has sprung up a considerable body of proffesional interest in Quantum Computing beginning with a ground-breaking paper from the Nobel Laureate Richard Feynman in 1982 [22], in which he said "… with a suitable class of quantum machines you could imitate any quantum system, including the physical world.". The authors are unaware of any such "general purpose" quantum computer that is even nearing operation. However, a more manageable adiabatic quantum annealing device has been conceived, designed, produced, and delivered to the University of Southern California. Figure 4 shows the D-Wave Two, as installed in the USC – Lockheed Martin Quantum Computing Center (QCC) at the Information Sciences Institute (ISI) in Marina del Rey (ISI, 2015)

Figure 4
USC QCC D-Wave 2

In recent years, other authors have touted quantum computing's ability to produce more power, using terms like "magic" to stir the imagination and whet the appetites of the user community. [23] They point out that the capability of quantum computers arises from the different way they encode information. Digital computers represent information with transistor-based switches having a state of 0 or 1, labeled a bit. In contrast, the basic unit of quantum computer operation, the quantum bit or qubit, can exist simultaneously as 0 and 1, with the probability of each being given by a numerical coefficient, a condition physicists call "superposition". The quantum computer can act on all these possible states simultaneously.

The authors have witnessed and participated in the development of high performance computing for several decades and have developed a significant body of experience with newly introduced technologies. They were engaged in the very early introduction of parallel computing and aware of its rivalry with sequential computing and with vector computing. They heard the detractors of parallel computing argue the limits of parallelism [24] and the proponents [25] who argued that it could be used more universally. While acknowledging there are many problems that have remained outside of the easily parallelized arena, it is evident that the majority of all large-scale computational problems are now run in parallel. This is due to the application of new techniques to decompose both data and computation in effective ways [26]. Such technology has proven very useful to the simulation community [27] [28] and which may very well have a revolutionary impact as its abilities to resolved currently intractable problems.

The D-Wave Quantum Annealers have demonstrated acceptable evidence that they are operating as a quantum device, but the high levels of performance gains are yet to be achieved were anticipated. This may indicate just the issues that always have arrived with any new technology [29], or it may reflect some fatal flaw in the approach. Current work at USC and at Ames seems likely to resolve this issue in the upcoming months. Nevertheless, it should be remembered that this will not be the general purpose quantum computer envisioned by Feynman, but a quantum annealer, capable of many analytic and optimization analyses of interest to the simulation community.

3.4 Quantum Computing and Markov/Martingale Analyses

Given the virtually boundless number of inputs into any analysis of life-cycle sustainment, the simulation of those processes becomes an overwhelming task in short order. N squared growth in computing requirements quickly mandates some drastic action. Heretofore a common solution was to substitute a "look-up" table for actual simulation of the physical or behavioral characteristics of the simulated entity. In some cases this was rational and easily implemented. In others, a serious problem arose with the questions as to the validity of such a table and the number of factors that would impact on that solution.

As many of these issues involve an optimization function, not a specific physical simulation, simulated annealing becomes a viable alternative. If annealing is feasible, then Adiabatic Quantum Annealing may hold promise of a truly valid and rapid solution. The authors assert that all of the analyses proposed here should be amenable to the computational power of the Quantum Annealer. Should the need arise for pursuing this route, the current D-Wave Annealers are capable of accepting a set of test codes to ascertain if the process can be implemented on the existing hardware. As these machines become larger and more capable, they should be able to provide the kinds of power to make system engineering life-cycle sustainment simulations possible and enable similar simulation efforts.

Markov analyses have been conducted for some period of time using digital simulated annealing, and these approaches should be implemented on the D-Wave Quantum Annealer without significant alteration. [30]
An interesting conclusion of the authors in the cited article is the ability of the Quantum Annealer to achieve results that digital simulated annealing could not.

The authors' assertion that martingale analyses are more illustrative of real-life systems engineering, in both operational and simulated implementations, raises the question as to the applicability of quantum annealing. Simulated annealing has been studied as a technique for martingale analyses [30]. While the authors are unaware of any attempts to program the D-Wave for martingale optimizations, they see no reason that this could not be easily accomplished by both the simulation and the SE communities.

The need here is to identify the most important factors to be optimized. The D-Wave company has developed both tutorials and "front end" software systems to make this process easier, but the authors' experience is that, not unlike their earlier experiences in parallel competing, the decomposition of the data is the critical function and is most amenable to those who are deeply aware of the interrelations of the parameters. Once these parameters are identified and appropriate weights are assigned, programming becomes much more prosaic.

The implications for the simulation community are evident in the ability to render complex problems into resolvable optimizations programs. The systems engineering approach brings a new and useful discipline in these analyses and offers to contribute readily adaptable algorithms, if not directly applicable code segments and functions.

3.5 Potential for further Collaboration

Given that there is similarity in planning, processing, procuring and delivering systems, there exists the potential for further collaboration between government agencies and between government and industry. Best practices and lessons learned for adopting SE principals should be made available to prevent "reinventing the wheel" every time an acquisition program adopts and applies SE principals to a program. Much can be learned from other industry/agency programs in terms of what worked well, what did not, different mechanisms to perform risk identification and mitigation. All of these are calling for more collaboration amongst the SE community both in industry and government.

4. Analysis

System Engineers understand the programmatic drawbacks of the System Engineering "V." DOD Program Managers and System Engineers would benefit from increased Investment and Research (I&R) for D-Wave Quantum Annealers in the future. These benefits would assist DOD PM's in maintaining life cycle costs and bringing US Government weapons and acquisitions programs on time and budget. Quantum Annealers high performance computing capabilities can map out future courses while reacting to changing requirements and prevent Nunn McCurdy breeches from occurring.

4.1 Understanding the Problems

SEs strive to understand the problems or pitfalls in the design, development and fielding of acquisition systems. To reduce the risk of pitfalls and mitigate risks in the acquisition of new systems, SEs can draw upon past experiences or lessons learned from previous similar acquisition programs. What were the lessons learned? What were their impacts? How can these lessons learned be applied to the acquisition of future systems so that the same pitfalls will not be repeated? These lessons learned then become risks and a risk matrix plotting likelihood of the risk occurring versus significance of impact on the system should the risk occur. SEs weigh this information to help drive decisions where resources will be made available to mitigate these risks.

4.2 Reacting to new Requirements

Previously stated, the robustness of a model/simulation is measured by its flexibility in reacting to new requirements. One phenomena, if not checked and addressed throughout the acquisition life cycle process is what is known as "Requirements Creep" While it is understood that new requirements will emerge during the acquisition process of a system as information about the objective and functionality of the system gets further defined resulting from more knowledge about the objective or goal of the system, it is important to keep to a minimum this phenomena of Requirements Creep as it will have, as an examination of previous acquisition programs subject to Requirements Creep, a detrimental and sometimes unrecoverable consequence to a program. The Navy's DDG-1000 program ended up with 10 new technologies resulting from the identified requirements that the ship had to meet. Earlier in its design period, there were significantly more technologies identified as requirement creep raised it ugly head. But, through judicious examination of the core requirements and functions to address the requirements, the growing list was reduced to the 10 needed new technologies. This action helped to reduce acquisition cost and keep the ship acquisition and budget close to being on par with available resources to build and deliver the ship.

4.3 Coding Challenges

Conceptually, the D-Wave Quantum Annealer should provide a much needed capability to resolving the otherwise incalculable interactions of the wide range of parameters identified in the discussions above. After nearly a century of digital computing, it is hard to remember how hard-fought the successes in our computing standard were. But quantum computing is in its infancy; the D-Wave is the first practicably programmable device showing quantum behavior. Getting it to reliably perform useful analyses is the first challenge that must be met before even considering how to use it to enable these analyses.

The experience so far has indicated that with a few weeks of study, journeyman computational scientist can program the D-Wave and realizable results can be achieved. Much of the work done at the University of Southern California Quantum Computing Center has been focused on benchmarking and theoretical programming. A significant effort would be required to decompose the issues identified above, indentify those with the greatest amenability to QA, and run a series of tests to assess the validity of the results.

It has been found that the generalizations of Hidden Markov Models (HMM) are Dynamic Bayesian Networks. Similar(DBN) to HMMs, DBNs are directed graphs. Markov networks (and D-Wave networks) are undirected. There is away to transform directed DBNs to Markov networks by adding edges. Finding hidden states in general DBNs is much more difficult problem. Here, potentially, quantum computing would provide an otherwise unavailable capability. Similar situations are thought to be prevalent in the simulation community as well.

Experience at USC would suggest that current hardware limitations, *i.e.,* the usable Cubit population of the D-Wave, coupled with the current six-way connectivity architecture, will present challenges to the programmer. While daunting, these challenges are, in the opinion of the authors, not insurmountable. Future increases in Cubit count and in connectivity architecture will provide the power needed to really enable this approach. The authors base this analysis on their decades of experience in the evolution of the high performance computing discipline, but issue the caution that the quantum computing developments may follow a different path or may hit a hitherto unforeseen and immutable obstacle. These advances, improvements, and capability increases would putatively make this capability extensible to the simulation community as it faces similar challenges in large scale simulations with a wide range of parameters. Increases in Cubit count and connectivity paths will be critical and only time will answer if they are forthcoming at a cost that can be justified by the benefits that are so alluring.

5. Conclusions

Quantum Annealers can aid System Engineers and Program Managers in maintaining life cycle costs and keep their respective programs from over runs and Nun McCurdy breech thresholds. Further investment is needed to bring the high performance computing capabilities of Quantum Annealers to their full potential. Increased research funding for Quantum Annealers would yield greater opportunity to explore and document stochastic models and variables in DOD acquisition programs. Future developments would benefit from past explorations of acquisition programs that were delivered on time and under budget as well as those that suffered Nunn McCurdy breeches.

5.1 Uses of SE

SE is extensively employed in the commercial sector as well as the defense industry. As stated previously, a key role of SE is to reduce the risk of designing, developing, testing, certifying and employing systems. Major Program Managers in the Acquisition Community of the defense industry, resulting from what was previously known as a Missions Need Statement (MNS) conduct Analysis of Alternatives (AoA's) to a address a specific military need (e.g., requirement) and determine the solution space ranging from the employment of existing equipment, software, policy to developing a new system. The key tenants of SE which are 1) Requirements, 2) Functional Analysis, and 3) Synthesis are all employed in the acquisition process to identify, reduce and mitigate risks involved with the acquisition of a solution set to address specific military needs and requirements from the beginning of the process, i.e., concept definition through fielding and even disposal of the system; a "cradle to grave" process.

5.2 Benefits of Parameterization

One benefit of these sorts of analyses is the impact of having to seriously reconsider which parameters are most important and which are merely distractions. Especially in their early work with parallel computers at Caltech, the authors noted that having to do a disciplined reassessment of the parameters and functions on the topic being simulated was often very illuminating, both in terms of the computational approach, but also in terms of the insights of the user into what was really critical in their systems.

In the instant case, the multitude of parameters involved in Markov, Hidden Markov and martingale analyses will likely have a salutary impact on the simulation community and on its user clients.

5.3 Investment Required

Applying SE principals to major programs does not come for free. There is an investment required to implement SE principals to acquisition programs or in the M&S environment. The Rand Corporation, in their report entitled, "New Techniques Help to Estimate Systems Engineering and Program Management Costs for Military Aircraft and Guided Weapons" [31] commented that "Systems engineering and program management (SE/PM) is one of the more costly below-the-line items for military aircraft and guided weapon systems." The report also stated that Rand Project Air Force (PAF) studied the factors that drive SE/PM costs, surveyed government and industry personnel regarding current techniques for estimating these costs, collected historical data from several aircraft and missile development and production programs, and investigated the effects of new acquisition approaches on SE/PM costs. Their reports revealed major findings, to include the following:
"

- **SE/PM** costs are a large portion of acquisition costs and appear to be rising for aircraft development programs. For aircraft development programs, SE/PM represents about 12 percent of the total contractor costs. For guided weapons development programs, SE/PM represents about 28 percent of total contractor costs. SE/PM production data for aircraft showed a large amount of variation, while similar data for weapons seemed to follow a traditional learning curve.
- **Three categories of independent variables are related to SE/PM costs.** *Program scope variables* capture the size of the effort apart from SE/PM costs. *Programmatic variables* capture the duration of the effort (in the case of development) and the quantity of items produced (in the case of production). *Physical descriptor variables* are generally based on the weight and diameter of the weapon.
- **New acquisition approaches have mixed effects on SE/PM costs.** Recent innovations include minimizing military specifications to invite more commercial contractors into the military acquisition process, using integrated product teams to optimize management, and using evolutionary acquisition of new technologies to field systems more quickly. PAF found that minimizing military specifications did not have a significant effect on SE/PM costs as compared with the overall sample of programs. SE/PM costs were either similar or slightly higher for programs that used integrated product and process teams. Finally, evolutionary acquisition resulted in above-average SE/PM costs." [32]

Based on these findings, PAF developed a set of cost-estimating relationships (CERs) that can be used to estimate the specific SE/PM cost element for development and production of both aircraft and weapons programs. These CERs are most useful in the early stages of a program's life cycle, when little is known about the program. When more detailed information is available, other techniques (such as drawing analogies from historical programs) could be used to develop more-accurate SE/PM estimates, and concomitantly develop more accurate simulations. This may entail the formulation of new simulations standards or the modification of existing ones.

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