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RMS Reliability, Maintainability and Supportability PARTNERSHIP

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Introduction

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What follows below is an excerpt from the NDIA Weekly Insider's 7 October, 2013 edition:

> The Air Force is considering placing price caps on major procurement programs—that when reached—will force Pentagon buyers to rethink requirements and make tradeoffs in favor of affordability, a senior civilian with the service said Sept. 26.
>
> Richard W. Lombardi, deputy assistant secretary for acquisition integration with the office of the assistant secretary of the Air Force for acquisition, said defense officials are giving more weight to long-term affordability as they lay out a series of spending plans that will be published in coming months.
>
> We have in the past launched off on programs without thinking about long-term affordability," Lombardi told a gathering hosted by the Air Force Association in Arlington, Va. Acquisition officials must consider "what we are willing to pay for something and what we will stop funding in order to pay for it," he added.

Although I am not an acquisition "professional," anytime affordability is mentioned, I can infer RM&S will surely show up on more radar screens.

Additionally, in the Performance of the Defense Acquisition, 2013 report, (found here: *http://breakingdefense.com/wp-content/uploads/sites/3/2013/07/OSD-Acquistion-Report-2013.pdf*) Mr. Frank Kendall, Under Secretary of Defense Acquisition, Technology and Logistics, emphasized, during Performance Assessments and Root Cause Analyses (PARCA) reviews of Nunn-McCurdy breached programs labeled as "critical" (meaning exceeding costs by some significant margin) that:

1. Ten of eighteen (56%) program cost growths were due to poor management performance, relating to:
    - Systems engineering (author emphasis)
    - Contractual incentives
    - Risk management
    - Situational awareness
2. Five of eighteen (28%) program cost growths were due to baseline cost and schedule estimates due to inaccurate framing assumptions.
3. Four of eighteen (22%) were due to change(s) in procurement quantity.

Focusing on that Poor Management Effectiveness category, Mr. Kendall stated this broad category was a root cause in just over half of the cases. Problem areas included:

- **Poor systems engineering to translate user requirements into testable specifications.** This includes the flow down of requirements, interface/environmental management and management of holistic "performance attributes such as reliability or weight. These largely are systems engineering functions.
- **Ineffective use of contractual incentives.** This includes whether the acquisition strategy selected satisfies the conditions necessary for its success, whether it is consistent with corporate environment (including long- and short-term objectives), whether it is aligned with program goals, whether there are perverse effects, and whether it was enforced.
- **Poor risk management.** This includes the identification, quantification, evaluation, and mitigation of risks.
- **Poor situational awareness.** Deficiencies have been identified in program office, contractor, and oversight awareness, and the timeliness and effectiveness of responses, related to the cost, schedule, and technical performance of DoD programs.

So, areas of our Partnership's domain—those pesky "illities"—where attention can be expected to heighten, perhaps, as budget woes and sequestration continue to drive the customer more and more towards "watching the dollars?"

Continuing to focus on reliability, with a slight twist, there is this from the October, 2013 IEEE Spectrum edition—an article titled "Good enough computing." It turns out computer reliability has a direct impact on the computer's energy requirements. If you want reliable calculations/output results from your computer you can expect a continued need for gobs of energy to insure that! In short, more transistors per chip, to handle the voluminous calculations required to ensure accurate and reliable calculations, means hotter running devices. In fact, they've coined a term for that—the "dark silicon" problem; e.g., the chips get so hot they have had to figure out ways to shut a batch of transistors off or go "dark"—thus the "dark silicon" or "rolling blackouts of the silicon world."

However, help is on the way—if you, the consumer, can stand certain less reliable results from your computing device. A research group at the University of Washington, in Seattle, has developed a computer language that allows benign errors to occur, every now and then, while obviating catastrophic ones. The language is called EnerJ and it is boosting energy efficiency through an approach termed "approximate computing."

Without going in to a lot of detail, I can tell you they've seized on the notion that certain computer calculations need to be accurate—for instance, perfection and reliability *is* the goal when determining how much money is in your bank account or analyzing data for a planned NASA flight; those calculations have to be totally accurate and reliable, albeit the calculations eat up computer power 'cuz the chips have to "crank it on." However, for those calculations that don't require as high a degree of accuracy and reliability, e.g., watching a movie on your laptop, game graphics, speech recognition, etc., approximate computing offers one method of reducing energy usage which means less heat generation and, as an intended consequence, more reliable computing chips. For example, the computer could store individual pixel values in unreliable, low refresh-rate Dram but it would use normal, reliable portions of memory to store those values that had to be exact. Or, addition operands that add pixel values for game graphics and the like would be run at lower voltage levels because both operands are tagged as only needing to approximate. In summary, the EnerJ programmer specifies where approximate storage and operations can be used *or* are forbidden.

This article caught my attention because, in my Complex Systems Architecting class, I focus on the notion that the 100% solution may not be attainable OR required—reaching what's called the "satisficed state" may be all that's necessary—the "80% solution," so to speak. This new computing language effort includes elements of that approach while ensuring the reliability of the "system" hasn't been compromised—reliability in the sense the user doesn't notice the slightly degraded performance—while reliability of the system, from the perspective of increasing time to failure due to a cooler running computer, is increased. An aside note: preliminary tests, depending on what kind of computing program it is and how aggressively the simulated hardware seeks to reduce energy, indicate EnerJ can save from 10 to 40 percent—those are some eye popping numbers! So, in the context of "what's good enough," reduced accuracy and reliability can be "ok."

Before introducing our four articles I am adding a "special note" for our readers: Some contributing authors to our professional journal utilize English as their second language and the author(s) may reside in the United States or abroad. It is our policy to edit their written contribution primarily for technical accuracy, e.g., incorporating selective grammatical changes to ensure a sufficient level of readability. We respectfully request you focus on the technical content and insight the author(s) provide, overlooking minor English language text imperfections. We appreciate your understanding.

As usual, we have an eclectic mix of articles for this Journal edition. The article by Dr. Lev Klyatis, *Non-Traditional Solutions for Current Reliability, Maintainability, and Supportability Problems*, kicks off this Winter Journal. Dr. Klyatis introduces a non-traditional approach to testing that is integrated via approaches seen in System of Systems integration methodologies. And, what's not to like about Dr. Klyatis' expectations of stronger requirements, increased safety, more accurate RMS prediction, etc.? When you have finished perusing his article, take a few minutes to read through the About the Author, as you'll see, he is enjoying a full life of education and work experiences, worldwide, across the many facets of the "illities aspects" of engineering.

Next up is an article by Mr. Taylor Hughes and Dr. Andreas Tolk, *Orchestrating Systems Engineering Processes and System Architectures within DoD: A Discussion of the Potentials of DoDAF*. The authors' approach to this article is not for the reader to bring clarity or resolve to questions related to DoD's Architectural Framework (DoDAF) 2.0. They want to bring to light the fact that DoDAF 2.0 isn't at its best as far as articulating the answers. Put another way, questions brought to light in their article are meant to direct the reader to consider why a Systems Architect, at the System of System, or Enterprise, level should be left to guess at the questions and answers. We've watched DoDAF migrate from a product centric to data centric foci—this article seeks more clarity out of DoDAF 2.0, from a taxonomy and ontology perspective, so untrained decision makers can derive a better understanding of the value added of architectures, relative to understanding the requirements.

The third article, *Understanding Risk in Logistics and Supply Chain Systems by Analyzing Costs and Reliability based on Downtime and Safety Stock*, is authored by Dr. Gerard Ibarra. Dr. Ibarra focuses on risk, in terms of cost(s) and delivery reliability related to manufacturing and distribution centers. Gerard's focus is on getting us, as stakeholders across the Enterprise, to understand the myriad influencers—labor, production efficiency, sales, etc.—that can increase the probability of failure, Pf, with regards to manufacturing. Dr. Ibarra was my Professor for a Logistics Reliability graduate course at Southern Methodist University and I was ecstatic when the opportunity to work with him came about to acquire this article for our Journal.

Finally, our fourth author, Milena Krashic, introduces the "Physics of Failure" approach to accelerated reliability growth testing as an affordable solution to the product reliability improvement. Ms. Krashic, like Dr. Klyatis, has a remarkable and varied history of senior "RS style" work assignments. She utilizes that wealth of knowledge and experience to walk us through some of the difficulties and problems with the traditional reliability growth testing as it is performed currently, focusing on the physics, engineering and associated mathematical errors or disconnects between the product life, use profile and tests. Milena and I have communicated for quite some time as she worked towards completing this article. Her work, related heavy travel schedule and personal life kept getting in the way (smiling) and

I am delighted she could finally eke out an hour here and hour(s) there to complete this article in time for our Fall/Winter edition.

So, there you have it: four articles that run through the Enterprise gambit of reliability, risk, and the architecting framework that is supposed to depict a clear picture of the requirements! Enjoy them—it sure was fun, with little "challenges" thrown in along the way, to get them ready for you to peruse.

We hope your Thanksgiving celebration was complete. Here's a toast to offer up as you stand around the table with friends and family throughout this holiday season:

Here's to the blessings of the year. Here's to the friends we hold so dear. To peace on earth, both far and near and the American eagle and the Thanksgiving turkey—may one give us peace in all our states and the other a piece for all our plates.

Most importantly, here's an early Happy Holidays wish to you and your families from the editing staff here at the RMS Partnership.

Jim Rodenkirch, Editor

Non-Traditional Solutions for Current Reliability, Maintainability, and Supportability Problems

Lev Klyatis
Habilitated Dr.-Ing., Sc.D., Ph.D.

Abstract

This article examines the current situation associated with reliability, maintainability, and supportability (RMS) problems. The cause of these problems is the use of traditional test technologies during design, manufacturing, and acceptance. A non-traditional approach is introduced where accelerated reliability and durability testing (ART/ADT) technology is a key factor. This new approach is non-traditional, because its foundation is eight basic principles that are different from traditional approaches. These include accurate simulation, accelerated reliability/durability testing, and accurate prediction processes—which are integrated via a System of Systems (SoS) processes technology. This article considers seven subsequent specific components of accurate RMS prediction. An example of this SoS approach—integration of quality with reliability within the automotive industry—is provided. For producers and consumers of industrial products, this non-traditional approach can lead to the development of stronger requirements, including guidelines and standards, especially for reliability testing, increased safety, more accurate RMS prediction, and accelerated product development and improvement.

The Current Situation

Usually, professionals involved in research, development, and manufacturing, prefer the modernization of traditional ways rather than creating and developing new ways. Similar situations exist in reliability, maintainability, and supportability.

This situation relates specifically to simulation, testing, prediction, and product (technology) improvement for the solution of RMS problems.

This results in more product recalls and complaints, lower safety, higher life cycle cost, and longer maintenance time than was predicted during design and manufacturing. Moreover, these problems are not commonly improved for a long time. For example, in the automotive industry recalls are not decreased from year to year. The Federal Government—NHTSA (National Highway Traffic Safety Administration)—said in 2011 that "Automakers recalled more US vehicles last year than in any of the last six years. Safety recalls affected 20.3 million vehicles, the highest number since 2004" [1]. In the automotive industry the situation can be expressed as "Auto recalls accelerate" [1]. General Motors, Ford, and Toyota each recall more than 1 million vehicles annually. The situation is not better in other industries.

A primary cause is inaccurate prediction. Prediction consists of two basic components:

- Technique (methodology);
- Initial information for using this methodology for providing (calculating) prediction.

There are many techniques for predicting reliability, maintainability, and supportability. But there is a problem in obtaining initial information for calculating the accurate prediction during service life (*or any other time or volume of work*—warranty period, etc.). The source of this initial information is testing results.

Currently, separate types of stress testing are used which simulate only part of real world conditions (Figure 1). They do not offer the possibility to obtain information for accurate prediction. They contradict the real world in which field conditions are interacted. Under real field conditions all input influences (Figure 2), as well as human factors and safety problems, act simultaneously and in combination.

Moreover, in present practice there are separate solutions, during design and manufacturing for these problems:

- Simulation
- Testing
- Reliability
- Maintainability
- Supportability (availability)
- Quality
- Safety problems
- Human problems
- Others

Currently Wiley has published the book Accelerated Reliability and Durability Testing Technology (ART/ADT) [2], with one possible solution to these problems. This book demonstrates that accelerated reliability and durability testing technology are the key factors for product RMS accurate prediction and accelerated development. This publication offers the following non-traditional approach for solving RMS problems:

1. The integration of components from each other from the study of field conditions until RMS accurate prediction and accelerated development (Figure 4). For this goal, System of Systems (SoS) approach (or Interdisciplinary approach)

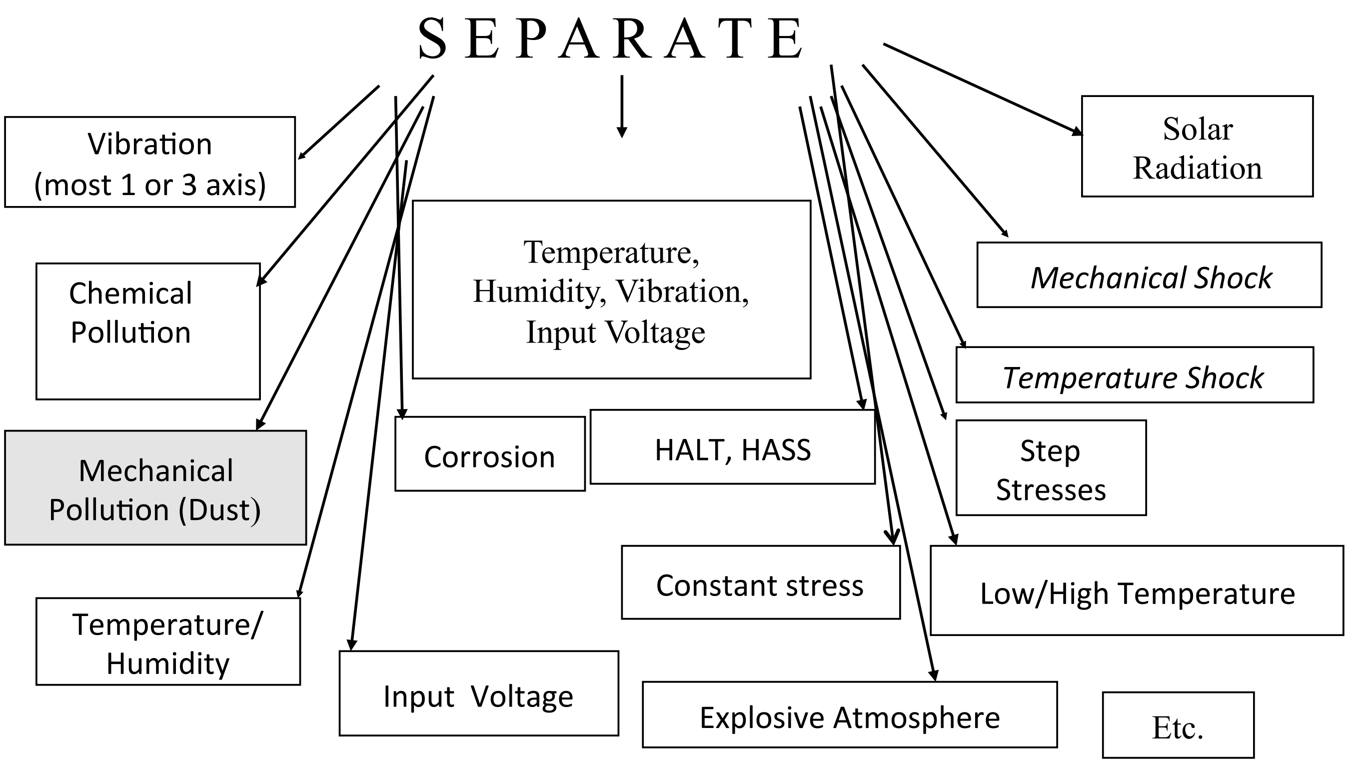

FIGURE 1: EXAMPLES OF SEPARATE TYPES OF ACCELERATED STRESS TESTING USED DURING DESIGN, MANUFACTURING, AND USAGE

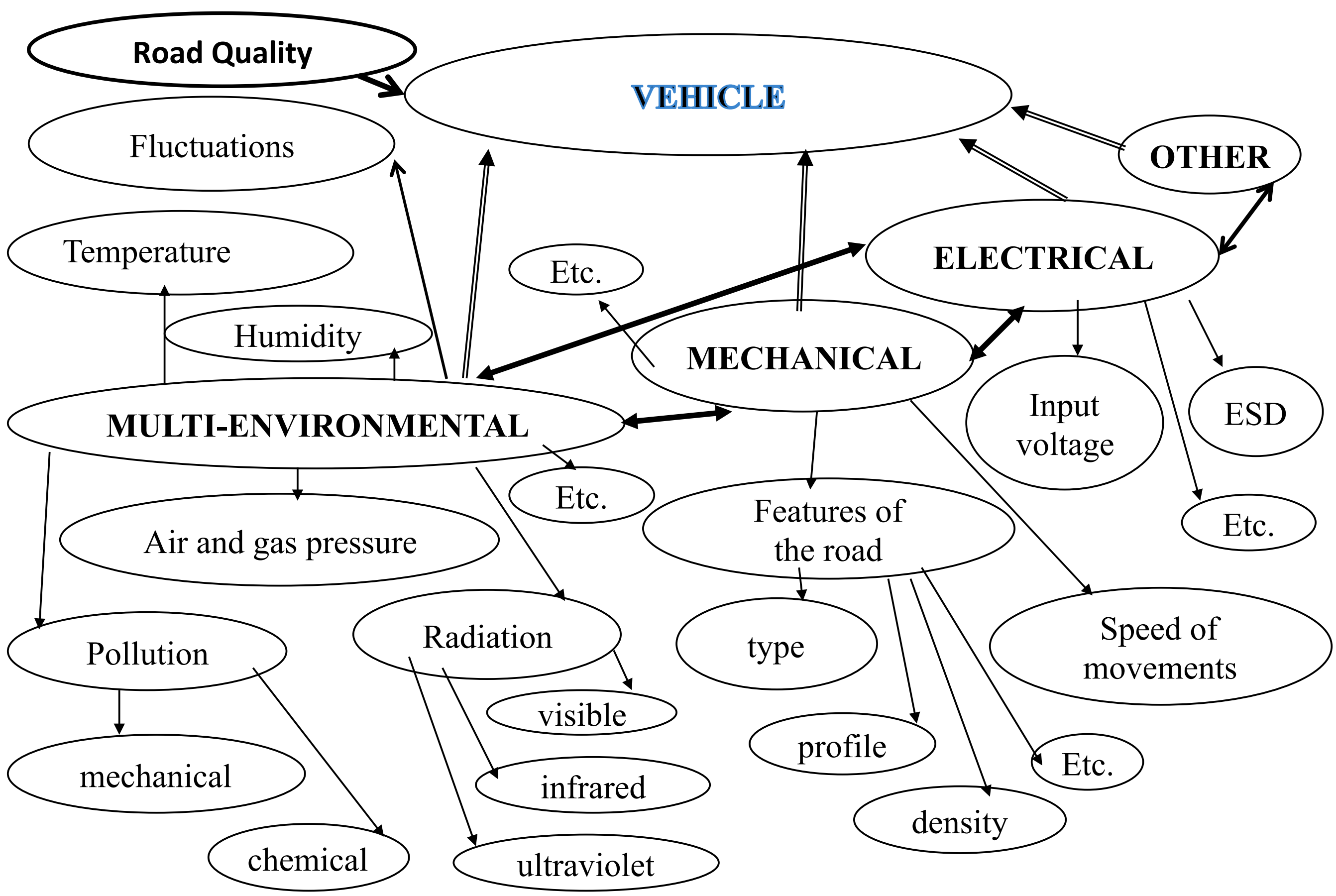

FIGURE 2: EXAMPLE OF REAL WORLD INPUT INFLUENCES (SIMULTANEOUS COMBINATION) ON THE PRODUCT (VEHICLES)

is used.

2. The accurate simulation of interacted field conditions which is one complex and consists of three interconnected components: full field input influences, safety problems, and human factors.
3. Since field conditions act simultaneously and in combination, accurate simulation of them also means activating all integrated field conditions.
4. For this purpose fully-integrated test equipment needs to be used.
5. ART/ADT (Figure 3) which is based on this simulation, is a key factor for accurate prediction of product quality, reliability, maintainability, and supportability, safety, life cycle cost, profit, and accelerated product development.
6. Accurately moving the field to the laboratory that includes:
   - Simulating full field conditions in the lab in combination with periodical field testing (Fig. 3);
   - Lab apparatus use for study in the stationary conditions cannot physically degrade all conditions the product sees in the field;
   - Technicians have the capability and equipment to analyze the results of integrated testing.
7. As a result, the information (for any time or volume of usage) for maintenance (as well as other parameters) accelerated development and accurate prediction with minimal cost and time is quickly obtained.
8. This test methodology in addition to describing RMS deficiencies also demonstrates how one can solve deficiencies by considering them in interconnection (integration). The diagram below (Figure 3) depicts the requirements for successfully conducting simultaneous and combined laboratory plus field testing, while Figure 4 underscores the components for the accurate predication of reliability, maintainability and supportability and recommended improvements.

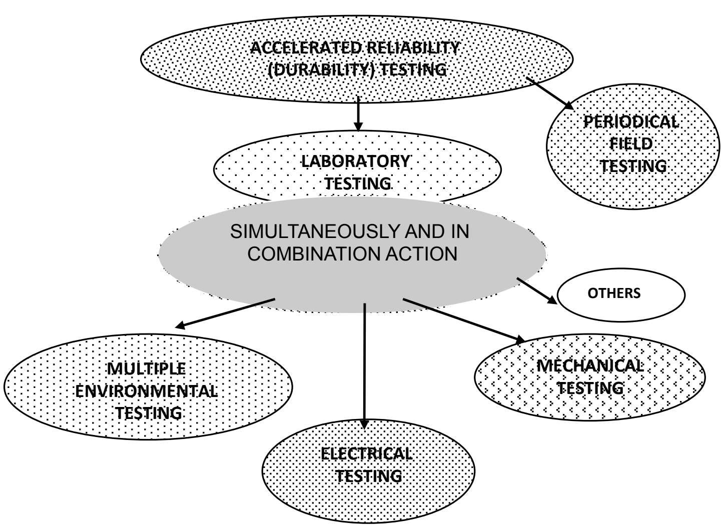

Figure 3: Basic components of accelerated reliability/durability testing (ART/ADT) (key factor for accurate prediction and accelerated development)

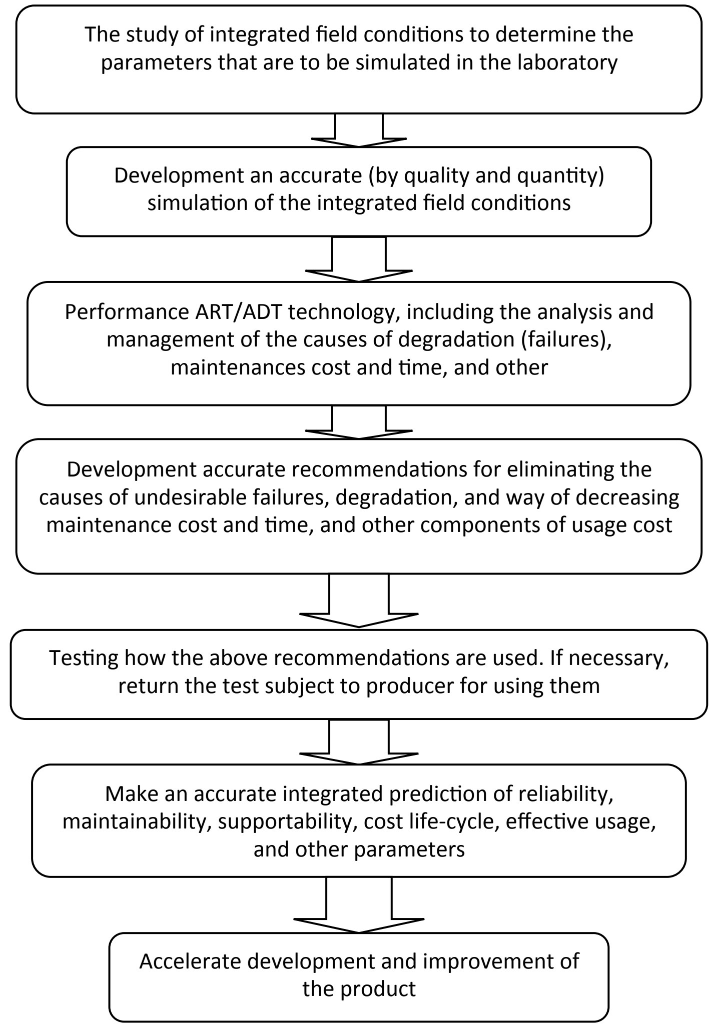

Figure 4: The basic steps of integrated subsequent components of accurate prediction of product reliability, maintainability, and supportability for accelerated development and improvement.

Faulty reliability, maintainability, and supportability predictions are not restricted to one industry. They commonly occur in the automotive, aerospace, aircraft, electronics, electro technical, and other industries. To improve these predications these industries need to use a combination of interconnected actions, beginning with study of the field conditions and ending with successful reliability, maintainability, and supportability prediction and accelerated development.

As shown above, this involves seven interconnected steps.

Accelerated reliability/durability testing (ART/ADT) technology is based on accurate simulation of field conditions; therefore it is a key factor for producing accurate prediction and accelerated development.

Current types of accelerated stress testing, including HALT, HASS, (Figure 1) cannot do it because they are based on the simulation of only several field input influences. Therefore, one cannot hope to develop accurate recommendations for eliminating the causes of undesirable degradations and failures, nor to show the effective way for decreasing maintenance cost and time, as well as solve other problems. As a result, one cannot provide accurate prediction of reliability, maintainability, and supportability (RMS) in the field. In more detail one can see this analysis in the following endnote references [2], [3], [4], [6], [7], and other author's publications.

An Example of Integration Quality with Reliability for the Automotive Industry.

As an example of integration of the above parameters, let us consider the strategy to integrate quality with reliability for the automotive industry.

The Engineering Culture. The engineering culture has an important influence on the product's acceptability by directly influencing its quality and reliability. Consider the role of the engineering culture by comparing that of General Motors Corporation with Toyota. There are three basic elements to engineering culture according to Alfaro [5] as shown in Figure 5: Quality, Rule/Responsibility, and the System.

The comparison of the engineering culture at GM and Toyota shows that Toyota pays the most attention to Quality, less to the System, and least to Rule/Responsibility. In Part A of

Figure 4 GM currently pays the most attention to the System, a little less to Rule/

Responsibility and the least attention to Quality. As a result of analyzing this situation, GM plans to change their priorities and give more attention to the quality elements [5].

How can the engineering culture become more effective?

Many industrial companies have not solved the reliability problems and have not achieved their competitive potential, because they do not integrate quality and reliability. This creates market problems for both the customers and the producers including: recalls, complaints, warranty, repair cost and loss of goodwill. These companies experience many problems with rework that increases the cost of the product and reduces their competitiveness in the market that leads to financial problems.

Neither GM nor Toyota (Figure 5) adequately considers the repercussions. Both need to change their prioritization. Figure 6 shows the approach to an integrated system, where reliability and maintainability are given equal priority with quality, rule/responsibility, and system during the design, manufacturing, and usage phases to achieve better results. Using the system of systems approach that integrates the quality, reliability, maintainability, and

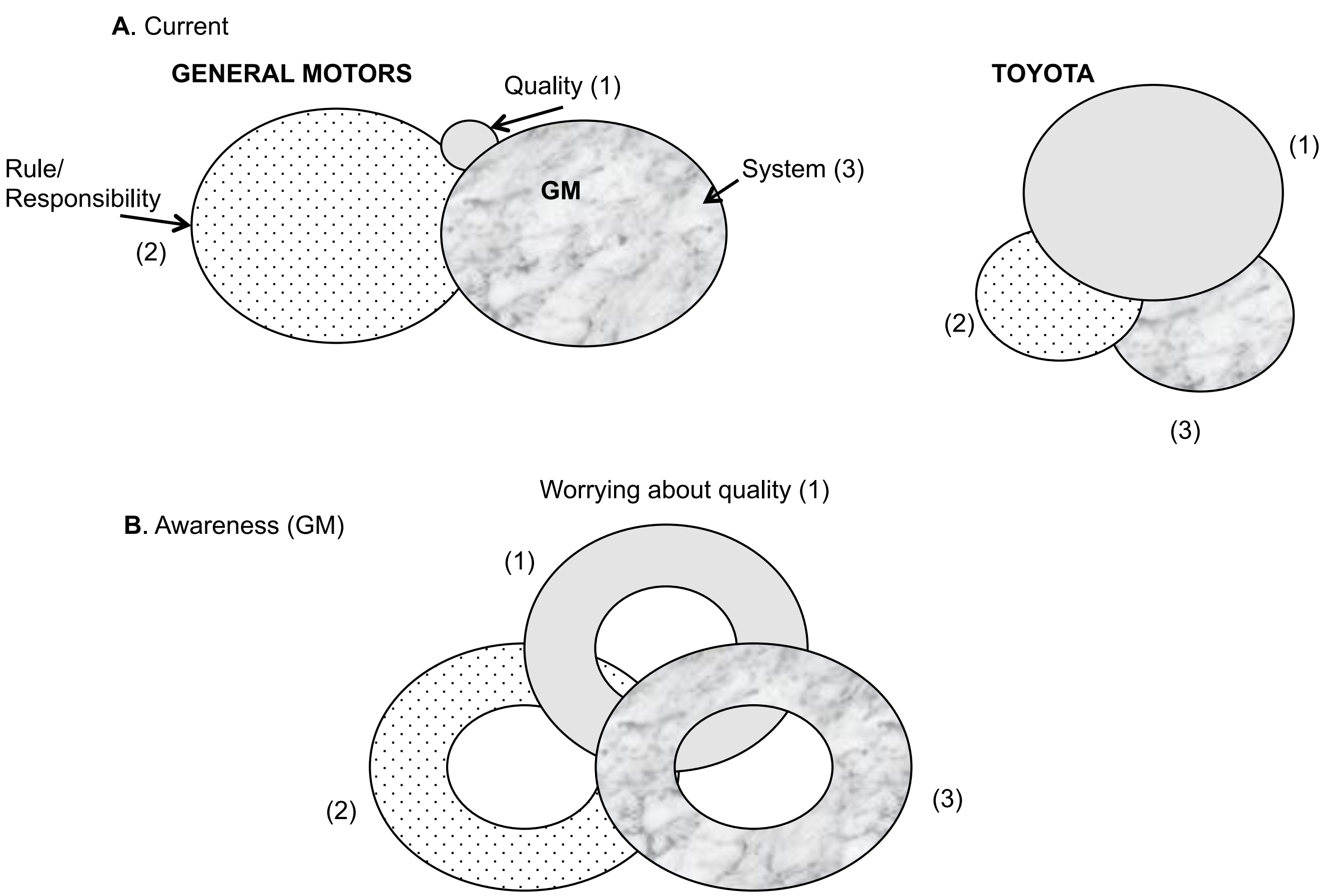

FIGURE 5: DIFFERENCE IN CURRENT ENGINEERING CULTURE BY TOYOTA AND GENERAL MOTORS [5]: (A – CURRENT, B – AWARENESS): (1) IS QUALITY, (2) IS RULE/RESPONSIBILITY, (3) IS SYSTEM.

supportability complex will achieve a more desirable solution.

Industrial companies need this strategy and the appropriate equipment to implement this approach, as well as stronger requirements from the consumers.

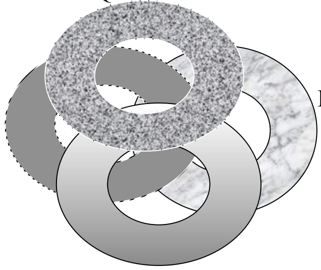

FIGURE 6: PROPOSED STRATEGY OF INTEGRATED QUALITY AND RELIABILITY (DURABILITY/ MAINTAINABILITY) WITH SYSTEM AND RULE/RESPONSIBILITY: (1) IS QUALITY, (2) IS RULE/ RESPONSIBILITY, (3) IS SYSTEM, (4) IS RELIABILITY (MAINTAINABILITY, SUPPORTABILITY).

How can solving RMS predication be done?

The first element is the development of the complex analysis of factors that influence product quality. This includes an analysis in one complex consisting of divergences in the procurement of raw material, of product components, in the procurement of the final product by the customers. It is based on the author's experience in collaboration with Eugene Klyatis and industrial experience as described in [3].

Then one needs to provide analysis during the operation, design, and manufacturing phases.

The author and Eugene Klyatis developed the Quality System that has been successfully used in some companies. For example, this Quality System was implemented by Iskar, Ltd. (Israel). Warren Buffet later purchased Iskar due to its increased sales and profits attributable to higher product quality.

The second element is the development of accelerated reliability/durability testing. The author's and industrial experience in this component are both described in detail in previous publications of the author. To achieve an integrated System of Systems solution for quality/reliability/supportability and maintainability, the industrial company must use this second element. This is a new approach for most industrial companies. It requires significant additional financing, but the payback period is short with a high return on investment as described in [2].

The advantages of a new quality system when compared with the current norm are:

- Online collaboration occurring between customers and all the producer's departments.
- Fewer misunderstandings between the customer and supplier occur during the design and manufacturing phases.
- Timely feedback and good communication between the design department and other technical departments increased customer satisfaction, especially during the early stages of manufacturing and operation.
- A better management process exists to implement any necessary changes in manufacturing technology.
- Maximum customer participation and satisfaction is achieved through feedback during all stages of design and manufacturing.
- All of the design and production departments are responsible for the high quality of the final product.

The specifics of used System of Systems approach, regarding to article topic, are:

- Accurate integrated physical simulation of the simultaneous combination of the field input influences on the product [3], as well as safety and human factors.
- Application of accelerated reliability/ durability testing (ART/ADT) as a key factor for product accurate prediction.
- Integration of ART/ADT with the constant quality improvement [3].

Implementation of this proposed strategy (improved engineering culture through integrated

Reliability and Quality) should improve the culture for industrial, service, and user(s) types of companies. This strategy has been approved by several industrial companies and is described in some publications ([2] and [12]).

The specifics of the proposed strategy follow:

- Develop interconnected reliability, supportability, and maintainability solutions that result in quality (Q) improvement during design and manufacturing.
- Conduct accurate physical simulation of integrated full field influences with safety and human factors, during design and manufacturing.
- Introduce Accelerated Reliability Testing (ART) of the actual product based on the above simulation.
- Incorporate accurate prediction of quality and reliability on the basis of ART results.
- Develop an integrated quality process for the procurement of materials, components, and vehicles throughout the design, manufacturing, and usage phases. One team of professionals from the design, manufacturing, quality assurance, and marketing departments will provide this integration.
- Incorporate the strategic and tactical aspects of quality/reliability into the process.

Experience ([2], [3], [4], [7], and others) shows, that this approach can dramatically improve the quality, reliability, reliability, supportability of a product, reduce recalls, improve the market reputation of the industrial company, as well as consumer's situation.

For consumers of industrial products the above non-traditional approach can lead to the development of stronger requirements, including guidelines and standards, especially for reliability testing, more accurate RMS prediction, increased safety, accelerated product development, and successful solutions of other problems.

Conclusions

1. The benefit to the consumers of industrial products is that the above mentioned non-traditional solutions lead to the development of stronger requirements, including guides, guidelines and standards, especially for reliability/durability testing, safety, accurate RMS (including life cycle cost of maintenance), prediction, accelerated development and improvement and thus lower total ownership cost.

2. For industrial companies the non-traditional testing approach leads to more accurate development of testing methods, equipment, quality, reliability, maintainability, supportability, and durability prediction, as well as, an accelerated process of product development, thereby reducing recalls, and increasing factual profit.

References

1. David Schepp. It's Not Just Toyota: Auto Recalls Accelerate. Daily Finance. 01/19/11
2. Lev M. Klyatis. Book: Accelerated Reliability and Durability Testing Technology. John Wiley and Sons, Inc. 2012.
3. Lev Klyatis and Eugene Klyatis. Book: Accelerated Quality and Reliability Solutions. Elsevier, Oxford, UK, 2006.
4. Lev M. Klyatis. Why Current Types of Accelerated Stress Testing Cannot Help to Accurately Predict Reliability and Durability? SAE 2011 World Congress. Paper 2011-01-0800. Also in book Reliability and Robust Design in Automotive Engineering. Detroit, MI, April 12-14, 2011.
5. Alfaro W. Quality, Reliability, and Durability Strategies. General Motors North America Engineering. Presentation at the SAE G-11 RMSL Division Spring 2005 meeting. Detroit, MI, 2005.
6. Lev M. Klyatis. Why Many Fail to Accurately Predict RMS Parameters? RMS Partnership. A Newsletter for Professionals. Reliability, Maintainability, Supportability. Volume No. 15, Issue No. 1, March 2011.
7. Lev Klyatis. Analysis of the Current Situation in Reliability, Quality, and Durability, and the Reasons for this Situation. SAE 2010 World Congress. Paper 2010-01-0694. Also in book Reliability and Robust Design in Automotive Engineering (Also in the book SP-2272). Detroit, MI, April 12-15, 2010.
8. Lev Klyatis. Accelerated Reliability Testing as a Key Factor for Accelerated Development of Product/Process Reliability. IEEE Workshop Accelerated Stress Testing. Reliability (ASTR 2009). Proceedings on CD. October 7 – 9, 2009. Jersey City.
9. Lev Klyatis. Specifics of Accelerated Reliability Testing. IEEE Workshop Accelerated Stress Testing. Reliability (ASTR 2009). Proceedings on CD. October 7 – 9, 2009. Jersey City.
10. Lev Klyatis & Aysik Vaysman. Accurate Simulation of Human Factors and Reliability, Maintainability, and Supportability Solutions. The Journal of Reliability, Maintainability, Supportability in Systems Engineering. RMS Partnership journal. Winter 2007/2008.
11. Lev Klyatis. A New Approach to Physical Simulation and Accelerated Reliability Testing in Avionics. Development Forum. Aerospace Testing Expo2006 North America. Anaheim, California, November 14-16, 2006.
12. Lev Klyatis. Introduction to Integrated Quality and Reliability Solutions for Industrial Companies. ASQ World Conference on Quality and Improvement Proceedings. May 1-3, 2006, Milwaukee, WI.
13. Lev Klyatis, Lesley Walls. A Methodology for Selecting Representative Input Regions for Accelerated Testing. Quality Engineering. Volume 16, Number 3, 2004, pp. 369-375. ASQ & Marcel Dekker.
14. Klyatis, L. M. Establishment of Accelerated Corrosion Testing Conditions. Reliability and Maintainability Symposium (RAMS) Proceedings. Seattle, WA, January 28-31, 2002, pp. 636-641.
15. Klyatis, L. M. and Klyatis E. Successful Correlation between Accelerated Testing Results and Field Results. ASQ 55th Annual Quality Congress Proceedings. Charlotte, NC, May 7-9, 2001, pp. 88-97.
16. Lev M. Klyatis, Oleg I. Teskin, James W. Fulton. Multi-Variate Weibull Model for Predicting System Reliability, from Testing Results of the Components. The International Symposium of Product Quality and Integrity (RAMS) Proceedings. Los Angeles, CA, January 24-27, 2000, pp. 144-149.
17. Klyatis, L. M. A Better Control System for Vibration Testing of Mobile Product – Part 1. Reliability Review. The R & M Engineering Journal (ASQ), Volume 19, Number 2, June 1999, pp. 22-24.
18. Klyatis, L. M. Principles of Accelerated Reliability Testing. 1998 IEEE Workshop on Accelerated Stress Testing Proceedings. Pasadena, CA, September 22-24, pp. 1-4.
19. W. Grant Ireson, Clyde F. Coombs, Richard Y. Moss. Handbook of Reliability Engineering

20. And Management. 2nd ed. McGraw- Hill. 1998.

21. Wayne B. Nelson. Accelerated Testing: Statistical Models, Test Plans, and Data Analysis.

22. Wiley. 2004.

23. H. Antony Chan. Accelerated Stress Testing Handbook: Guide for Achieving Quality

24. Products. Wiley. 2001.

25. A. Porter. Accelerated Testing and Validation. Elsevier. 2004.

About the Author

Dr. Lev Klyatis is a Sr. Advisor at SoHaR, Inc. and a member of the Board of Directors International Association of Arts & Sciences. His scientific/technical expertise is in accurate efficiency (reliability, durability, maintainability, safety, life cycle cost, profit) prediction. He created a new world technology for accelerated solution of economic/reliability/durability/maintainability/safety problems through innovation in the fields of accurate physical simulation, accelerated reliability/durability testing, and successful problems prevention. He developed a methodology of reducing life cycle cost, complaints and recalls. He has three doctoral degrees: Ph.D. in Engineering Technology, Sc.D. (high level of East European Doctor's degree in Engineering Technology), and Habilitated Dr.-Ing. (high level of West European Doctor's degree in Engineering).

Dr. Klyatis was a full professor at Moscow University of Agricultural Engineers, Chairman State Enterprise TESTMASH, chief of governmental programs in testing equipment development and came to the USA in 1993. Lev Klyatis is the author of over 250 publications, technical papers, articles, over 30 patents, and 12 books, including Accelerated Reliability and Durability Testing Technology, published by John Wiley & Sons, Inc. (Wiley), 2012; Accelerated Quality and Reliability Solutions, published by Elsevier, Oxford, UK, 2006; and Successful Accelerated Testing , published by Mir Collection, New York, 2002. Other accomplishments include:

- a seminar Instructor for ASQ seminar Accelerated Testing of Products
- a tutor for Governmental (DoD, DoT) and industry workshop & symposium
- a frequent speaker in accurate simulation, accelerated reliability/durability testing and accurate prediction of quality, reliability, maintainability, durability, and life cycle cost at the RAMS, SAE and ASQ World Congresses, World and US National Conferences, RMS Partnership and IEEE workshops.

Dr. Klyatis has worked in the automotive, farm machinery, aerospace, and other industries and has been a consultant for Ford, DaimlerChrysler, Thermo King, Black & Dekker, NASA Research Centers, Karl Schenk (Germany) and others.

Dr. Klyatis served the U.S. in many capacities: USSR Trade and Economic Council, European Economical Commission of United Nations, US Technical Advisory Group for International Electrotechnical Commission (IEC) in international standardization, ISO/IEC Joint Study Group in Safety Aspects of Risk Assessment. Consultant of ACDI VOCA of US Agency for International Development, a member of World Quality Council, Elmer Sperry Board of Award, SAE G-11 Division Executive and Reliability Committees, Technical Session Chairman and co-organizer, Key Note Speaker for SAE International World Congresses.

Honors and awards include:

- New York State Assembly, Certificate of Merit for Outstanding Service and Leadership. SAE
- International Fellow.
- American Society for Quality (ASQ) Fellow.
- SAE Outstanding Contribution Award (nominated by aerospace council).
- ASQ Allen Chop Award.
- ASQ Special Service Award.
- ASQ Research Grant-Award.

Orchestrating Systems Engineering Processes and System Architectures within DoD: A Discussion of the Potentials of DoDAF

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Introduction

The Department of Defense (DoD) is responsible for the development, procurement, introduction, integration, maintenance, upgrading, and retirement of all defense and related support systems. To facilitate this task, enterprise-level system architectures are used to describe capability, operational capability requirements and lower level system architectures are used to describe the functionality of system solutions which are necessary to satisfy those operational capability requirements. To ensure the attainment of the required capability solution on time and under budget, system-engineering processes are mandated to ensure consistency and rigor across all participating organizations. However, even though architecting is necessary to insure that all understand user requirements in the same way (providing logical rigor, structure, semantic and syntax), the practice of architecture is sometimes set aside as being unimportant, and programs sometimes fail for lack of good requirements. Defense engineering leadership understands this problem, and the DoD now has the challenge to determine how best to harmonize enterprise/systems architecting practices with systems engineering practices. [1]

The International Council on Systems Engineering (INCOSE) defines systems engineering as an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle. It is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, performance, test, manufacturing, cost and schedule, training and support, and disposal. Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user's needs. [2]

It is generally accepted that system architectures are used to add structure, logic, semantics and syntax to stakeholders' need-concepts so that their needs may be captured as formal requirements and understood in the same way by multiple stakeholders and developers for the sake of increasing performance and reducing risks and costs. They provide a common knowledge repository that allow all team members to store and evaluate their special facets of the overall challenge in the context of all other system contributions. Chigani and Balci observe that the process of architecting takes the problem specification and requirements specification as input and produces an architecture specification as an output work product. [3] It seems to be immediately obvious as a good practice that the system engineering process must drive the activities that contribute to the system architecture.

The DoD Systems Engineering (SE) Process is defined in the Defense Acquisition Guidebook Chapter 4. [4] The DoD Architecture Framework (DoDAF) [5] defines how to model system architectures within the DoD. The Deputy Assistant Secretary of Defense for Systems Engineering (DASD-SE) already mandates that architecture products be included in every Systems Engineering Plan (SEP) to include how architecture products will be related to requirements definition. [6] In this paper, the authors evaluate opportunities and the potential for establishing and extending DoDAF as the common architecture framework in support of a coherent systems engineering process to align data and harmonize processes of the different technical team members of all stakeholders and over all phases of the system life cycle embedded into the DoD Enterprise.

Architectures as Knowledge Repositories

The people—processes—tools framework is well known in industry. In order to fix or improve something, the right people are needed. These are the systems engineers supporting DoD with their knowledge and expertise in a multitude of domains. To facilitate their collaboration, common processes are needed. Within the DoD, the DoD SE process fulfills these requirements. Finally, the right tools to support the processes are needed, and DoDAF has been designed to meet this need. It is a good practice to look at the systems engineering process and the system architecture process as mutually-supporting activities that are harmonized for the benefit of the enterprise. In practice, however, the authors have identified several potential reasons for the observed insufficient use and alignment of DoD SE and DoDAF in industry: [7]

1. Engineers are placed in charge of projects who do not have a formal understanding of DoDAF practices and their value for management, governance, and administration.

2. Architecting for requirements is considered as only necessary for developing software but not hardware, and definitely not for hybrid systems.
3. The need to integrate software with hardware in increasingly complex ways has outpaced the willingness or ability of systems engineers to adopt or adapt architecting practices to traditional systems engineering practices.
4. In spite of the legal and regulatory requirement to architect requirements before system solutions move forward through various acquisition phases, engineering leaders sometimes commit to acquisitions without architecture for the sake of saving time and resources or for political reasons.

Most of these challenges can be addressed by education, as they point toward people challenges, not method—i.e., the DoD SE process—or tools—i.e., the DoDAF. However, if we do not apply the system architectures as intended, system architects and systems engineers are in danger of working in a 'vacuum,' side-by-side without really utilizing the mutual benefits of orchestrated collaboration as described in the introduction. To this end, the DoD SE process must guide the processes of collaboration, and the DoDAF artifacts must capture the views and constraints of all participating team members.

In other words, architectures must become the knowledge repository for the team, as proposed in the MIT-based doctoral work of Kim. [8] The enterprise architecture provides the context for the system architectures as well as for any portfolios. However, every phase of the DoD SE process and every view of each team member in each life cycle phase must have its data captured in the form of an individual view, following a common standard, in order to enable such collaboration. For the DoD, the question arises: is this possible with the current state-of-the-art DoDAF artifacts?

The DoD Systems Engineering Process

The introduction course to Systems Engineering (SYS101) at the Defense Acquisition University (DAU) starts with the story of two stone cutters that are working side by side and are asked, "What are you doing?" The first one answers: "I am cutting this stone into blocks." The second one explains: "I am on a team that is building a Monument!" [9]

This story is given as an example to understand the context for all required activities and to communicate a vision for the final product. Only with the big picture in mind can the effects of changes within the actual work being conducted become perceivable for all team members. The DoD SE process has been established to ensure that the right work is done, and that the work is done right! This is done with a set of technical work processes orchestrated by a set of technical management processes.

The technical work processes, sometimes differentiated into technical processes for designing systems and technical processes for realizing system products, are:

- Requirements Development
- Logical Analysis
- Design Solution
- Implementation
- Integration
- Verification
- Validation
- Transition

The supporting and guiding technical management processes are:

- Technical Planning
- Requirements Management
- Interface Management
- Risk Management
- Configuration Management
- Technical Data Management
- Technical Assessment
- Decision Analysis

As discussed by Buede [10] in more detail, understanding the requirements is pivotal, and all activities must be driven by requirements. Requirements specify the users' view on the system, what they want to accomplish, what gaps need to be closed, with whom collaboration is needed to conduct a successful operation and with whom resources will have to be shared, etc. A system is only successful if it meets all requirements and a system architecture enables all team members to contribute to this solution efficiently. The questions that need to be answered now are *"Is DoDAF designed to support all phases of the DoD SE process effectively?"* and *"How well does DoDAF support tracking of requirements?"*

The DoD Architecture Framework

The DoDAF evolved over the last decade into a solid method and tool. The current version is DoDAF 2.02 [11]. Earlier versions were driven by views defining the facets needed by several "privileged" team members. DoDAF originally incorporated a data model able to store all the data needed to support these views, the Core Architecture Data Model (CADM). With the introduction of DoDAF 2.0, the underlying paradigm changed to be data-driven instead of view based. DoDAF 2.0 focuses on an extensible data model that captures all data required by any team member in any life cycle phase in a consistent way. With DoDAF 2.0, the DoDAF Metamodel (DM2) defines conceptual categories for all these data elements needed to describe system architectures. The viewpoints are generated by applying models to the data. i.e., the data model is not generated by the views, as it was the case in the earlier version, but the data can now drive the models to produce views. If new views within viewpoints are needed, they can be generated from the data. If additional data is needed, the data model can be extended within the constraints of the DM2.

Some key conceptual categories of the DM2 are captured in Figure 1.

models generating these viewpoints and eventually by extending the data model as well.

However, although requirements are recognized in the DoD SE process to be pivotal they do not show up in DoDAF, neither as a view in earlier versions nor as a viewpoint or even as a concept within DM2. Does this mean DoDAF does not model requirements? To be fair, let us now review how the various DoDAF viewpoints are expressly intended to affect requirements. [12]

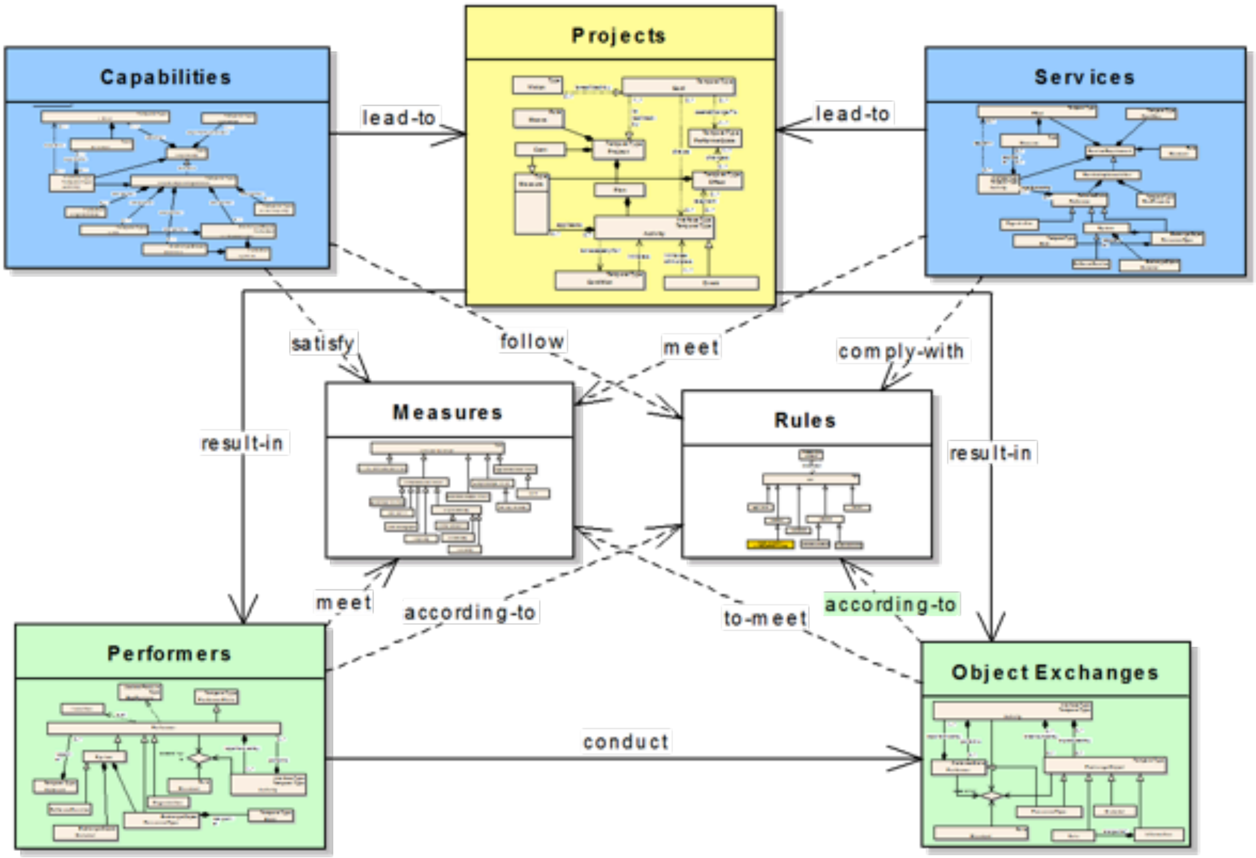

FIGURE 1: HIGH LEVEL CONCEPTUAL CATEGORIES OF THE DM2

Projects hold all activities that belong to a system or a portfolio pursuing the same set of goals and objectives together. They bring in particular required *Capabilities* and available services that provide the functionality needed to expose these capabilities together. To do so, *Performers* exposing the services and resource exchanges needed to orchestrate the participating performers and provide the necessary information are connected under observation of all *Rules*. Finally, measures comprise the *Measures* of merit needed for performance evaluations.

Figure 2 (following page) shows the set of viewpoints provided by DoDAF to support the information needs of team members required in all DoD related projects. These viewpoints are also a courtesy for the users of earlier DoDAF versions to facilitate their work with the new version. It also allows for easier migration of earlier system architectures. As stated before, more views within viewpoints can be generated by each group by introducing new

The Capability Viewpoint

This viewpoint *articulates the capability requirements, the delivery timing, and the deployed capability*. There are seven different "views" or models within this viewpoint, each with a different focus. The following views call out intent to support requirements in some way:

CV-2: Capability Taxonomy. The CV-2 is intended to identify capability requirements, codify required capability elements, and to be a source for the derivation of cohesive sets of user requirements.

CV-6: Capability to Operational Activities Mapping. The CV-6 is intended to be used to trace capability requirements to operational activities.

CV-7: Capability to Services Mapping. The CV-7 is intended to be used in tracing capability requirements to services.

We can therefore conclude that Capability Viewpoint is only

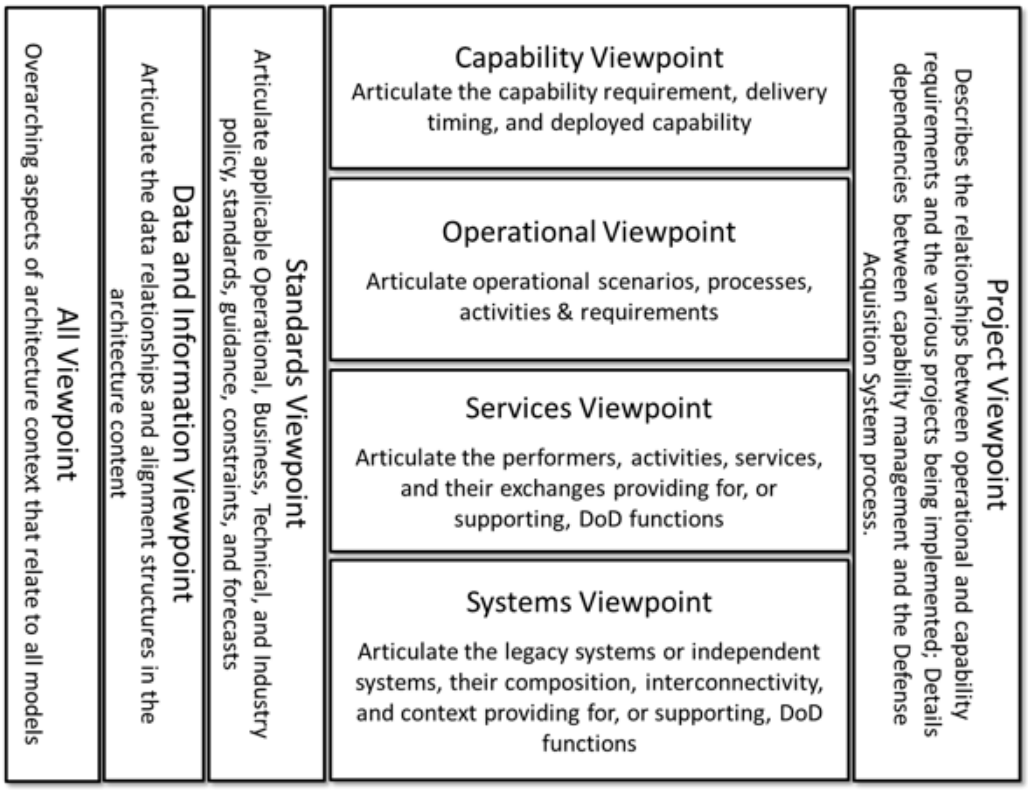

Figure 1: High Level Conceptual Categories of the DM2

expressly used to inform capability requirements. But what is a *capability requirement*? This is not defined in the DoDAF version 2.02. [13]

The Data and Information Viewpoint

This viewpoint *articulates the data relationships and alignment structures in the architecture content for the capability and operational requirements, system engineering processes, and systems and services*. There are three different views (aka, models) within this viewpoint, each with a different perspective. The following views call out intent to support requirements in some way:

DIV-1: Conceptual Data Model. The DIV-1 is intended to include information requirements.

DIV-2: Logical Data Model. The DIV-2 is not expressed as having a purpose of informing requirements. In that the DIV-2 reflects the theory captured in the DIV-1, there appears to be a gap in expression. It should be expressed as having a value-added purpose of adding logic, syntax and semantics for requirements.

DIV-3, Physical Data Model. Here, one will find for the first time that the DIV-2 is actually intended to help requirements. The DIV-3 is defined as an implementation-oriented model that is used in the Systems Viewpoint and Services Viewpoint to describe how the information requirements represented in DIV-2 Logical Data Model are actually implemented. So, we are led to think here that the DIV-2 contains information requirements and the DIV-3 exists to serve the DIV-2?

We can therefore conclude that Data and Information Viewpoint is only expressly used to inform information requirements. But what is an *information requirement*? This is not defined in the DoDAF version 2.02.

The Operational Viewpoint

This viewpoint *includes the operational scenarios, activities, and requirements that support capabilities*. There are 9 different views (aka, models) within this viewpoint, each with a different perspective. The following views call out intent to support requirements in some way:

OV-2: Operational Resource Flow Description. The OV-2 is intended for the elaboration of capability requirements and for the definition of collaboration needs. Ambiguity enters in here with the need to understand the difference between "capability requirements" and "collaboration needs."

OV-3: Operational Resource Flow Matrix. The OV-3 is intended to be used for the definition of interoperability requirements.

OV-5a/OV-5b: Operational Activity Decomposition Tree/ Operational Activity Model. The OV-5, according to DoDAF 2.02, is intended to be used for requirements capture. What kind of requirements? At what level?

OV-6c: Event Trace Description. The OV-6c is intended to be used for the identification of non-functional user requirements.

We can therefore conclude that Operational Viewpoint is only expressly used to inform capability requirements (elaboration), interoperability requirements, and non-functional user requirements. But these are not defined in the DoDAF version 2.02.

The System Viewpoint

This viewpoint has an ambiguous definition within DoDAF 2.02: *for Legacy support, is the design for solutions articulating the systems, their composition, interconnectivity, and context providing for or supporting operational and capability functions.* Is the Systems View only "for Legacy support?" There are 13 different views (aka, models) within this viewpoint, each with a different perspective. The following views call out intent to support requirements in some way:

SV-1: Systems Interface Description. The SV-1 is intended to be used to capture System Resource Flow requirements. Why not System of System or system interface requirements?

SV-2: Systems Resource Flow Description. The SV-2 is intended to be used as a Resource Flow specification. In general, the term specification implies technical requirements, but that is not clear here. DoDAF does not define specification as it is intended to be understood.

SV-4: Systems Functionality Description. The SV-4 is intended to be used for identification of functional system requirements.

SV-5a: Operational Activity to Systems Function Traceability Matrix. The SV-5a is intended to be used for tracing functional system requirements to user requirements and for tracing solution options to requirements. What is a "user" requirement in this context?

SV-5b: Operational Activity to Systems Traceability Matrix. The SV-5b is intended to be used in tracing system requirements to user requirements and tracing solution options to requirements.

SV-7: Systems Measures Matrix. The SV-7 is intended to be used in the identification of non-functional requirements.

SV-10c: Systems Event-Trace Description. The SV-10c is intended to be used in the identification of non-functional system requirements.

We can therefore conclude that System Viewpoint is only expressly used to inform system resource flow requirements, functional system requirements, system requirements, user requirements, non-functional requirements, and non-functional system requirements. DoDAF version 2.02 does not define these requirements expressions. How does one align these expressions to those needs in the DoD Systems Engineering Process?

The Services Viewpoint

This viewpoint is defined as *the design for solutions articulating the Performers, Activities, Services, and their Exchanges, providing for or supporting operational and capability functions.* There are 13 different views (aka, models) within this viewpoint, each with a different perspective. The views within this viewpoint call out intent to support requirements in a way similar to those within the Systems Viewpoint.

In summary, requirements are captured implicitly and as such already are providing the various team members with guidance, but improvements are possible.

Recommended Improvements

Within the course of the underlying research, the authors searched all uses of the term requirements in the current DoDAF version. This quick review reveals several areas of concern:

- There are over 50 different ways of describing a requirement, with several different expressions referring to the same requirements concept.
- There is neither a DoD requirements taxonomy nor a DoD requirements ontology given.
- There is no obvious alignment of the DoDAF viewpoints to the DoD SE process. Even directly related DoD requirements specification documents and requirements are not mentioned. [14]

Given these observations, and given that enterprise and system architects within DoD are consistently required to utilize DoDAF as their mandated framework for developing architecture artifacts for DoD needs, one can imagine that there can be very serious ambiguity on the part of some architects regarding why they are developing their architectures. In other words: the requirement development phase and requirement management phase of the DoD SE process have to be unambiguously supported by DoDAF artifacts. In order to capture a requirement effectively and make sure it can be validated, one must communicate unambiguously what needs to be observed and measured and what values are within tolerance. In other words, a requirement that cannot be observed and measured at the end of the day is useless for the engineer. This leads to the improvement that requirements shall be traceable to DoDAF artifacts and shall be accompanied by a set of metrics applicable to decide if an implementing system fulfils this requirement within the boundaries of a tolerance interval.

The Systems Modeling Language (SysML) is a graphical modeling language adopted by the Object Management Group (OMG) in 2006. [15] It was developed in response to the huge accomplishments of the Unified Modeling Language (UML) in the software engineering domain with the objective to derive a language supporting system modeling equally successful to that of software modeling. OMG collaborated to this end with the International Council on Systems Engineering (INCOSE) and the European Systems Engineering Group (AP233) to orchestrate a consortium with members from government, industry, and academia. In recognition of the essential importance of requirements, they introduced two diagrams to explicitly capture the ideas described above:

- The *Requirements Diagram* represents visual modeling of requirements for the system, which are pivotal for systems engineering;
- The *Parametrics Diagram* captures the relations between parameters for system components at all levels and provides the metrics to be used for system performance evaluation.

While the requirements diagram supports the description of requirements in the language of the user, the associated parametrics diagram captures in detail which system attributes have to be measured and in which tolerance intervals their value may be under different circumstances. To do this, SysML uses a mathematical description language that can be directly translated into test plans. Another advantage of SysML was pointed out in the doctoral thesis of Shuman. [16] He evaluated several approaches in support of executable architectures and was able to show that architectures specified in SysML are part of the group that supported the idea to execute an architecture based on the produced artifacts best.

As DoDAF is data-driven, there is no reason not to include parametrics under the conceptual category of measures. Requirements fit well under the rule category, if the community doesn't want to give them their own category in upcoming versions.

Conclusion

As pointed out by the authors before, DoDAF Viewpoints should be formally aligned to the DoD SE Process products/requirements and their associated documents which they can directly influence. A clearer guideline on how to accomplish these objectives cannot be left to selected academic organizations, but needs to be integrated in the form of examples into future DoD guidelines. The community of practice must actively participate in discussions to address the concerns formulated in the beginning of this contribution. Harmonizing architecture efforts and DoDAF with the engineering practices captured in the DoD SE processes is pivotal to better support managing the increasing complexity in projects and portfolio efforts of today's engineering challenges.

DoDAF has the technical potential to support all phases captured in the DoD SE process. The flexibility of DM2 and models to drive viewpoints makes it a good tool and method to support the process in the best way. What is now needed is the commitment to educate the people to perform optimally in the triangle of people-process-tools for the DoD: Engineers and other team members following the DoD SE process guiding the collaboration utilizing the DoDAF with respective extensions to support them in all phases of the life cycle. This contribution has the objective to show that this is not a technical challenge, as DoD SE process and DoDAF already provide the foundation for the required capabilities.

References & Notes

1. Assistant Secretary of Defense for Networks and Information Integration (ASD(NII)) DoDAF Team Briefing: DoDAF Maintenance Update, Version 2.03, 5 January 2012.
2. International Council on Systems Engineering (INCOSE): Systems Engineering Handbook Ver. 3.2, October 2011, online: http://www.incose.org/ProductsPubs/products/ sehandbook.aspx
3. A. Chigani, and O. Balci (2012) "The Process of Architecting for Software/System Engineering," International Journal for System of Systems Engineering 3 (1):1-23
4. Defense Acquisition University (DAU), Defense Acquisition Guidebook, Chapter 4.3, "Systems Engineering Processes" online: https://acc.dau.mil/CommunityBrowser.aspx?id=638325
5. DoD Chief Information Officer (CIO), DoD Architecture Framework (DoDAF) Version 2.02, August 2012
6. Systems Engineering Plan (SEP) Outline (DUSD approved), Version 1.0, 20 April 2011
7. T. Hughes, and A. Tolk (2013) "Harmonizing Architecture Efforts With Engineering Practices in DoD: A Brief Discussion," The Newsletter of Reliability, Maintainability, & Supportability 17(3):1-3
8. G.G. Kim (2006) "An analysis of structure and process of corporate alliance development using system architecture frameworks." PhD thesis, Massachusetts Institute of Technology.
9. Learning Material Handout "SYS101: Introduction to Systems Engineering," Module 1, Defense Acquisition University, Washington, DC
10. D.M. Buede (2009) The Engineering Design of Systems: Models and Methods, 2nd Edition, Wiley
11. DoD Chief Information Officer (CIO), DoD Architecture Framework (DoDAF) Version 2.02, August 2012
12. Note that we state nothing about constraints here. While we are aware there are constraints that will influence requirements, diving into a discussion on constraints is beyond the scope of this paper.
13. Capability Requirement is defined in CJCSI 3170.01H, Joint Capabilities Integration Development System (JCIDS).
14. Deputy Assistant Secretary of Defense for Systems Engineering (DASD-SE) mandates that architecture products (i.e., DoDAF) be included in every Systems Engineering Plan (SEP) to include how architecture products will be related to requirements definition. See Section 2, DUSD-approved Systems Engineering Plan (SEP) Outline, Version

1.0, 20 April 2011 for details.

15. The current version of the standard as well as tutorials can be found at http://www.omgsysml.org/

16. Edwin A. Shuman IV (2011), "Understanding the Elements of Executable Architectures through a Multi-Dimensional Analysis Framework," Ph.D. Dissertation, Batten College of Engineering, Old Dominion University, Norfolk, VA

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Understanding Risk in Logistics and Supply Chain Systems by Analyzing Costs and Reliability based on Downtime and Safety Stock

Dr. Gerard Ibarra

Abstract

Risk in logistics and supply chain is an important factor that stakeholders must consider. It plays a major role in businesses that rely on these operational indices for sustainability and growth. The aim of this paper is to provide stakeholders with the ability to understand risk in term of costs and delivery reliability associated with the manufacturer and or distribution centers when the facility goes down for a certain period. Discussed is a mathematical model that considers labor, production efficiency, safety stock, scheduled trailer departure times, sales based on delivery dates, downtime and loss of sales as part of the costs. Also, briefly discussed, is the reliability of the delivery system.

Introduction

Numerous papers have been written that assess and quantify risk in logistics and supply chain (Punniyamoorthy et al. 2013, Son and Orchard 2013, Wagener and Neshat 2012). For instance, supply chain risk management (SCRM) is one area of study that considers risk within the supply chain. SCRM is the process of identifying risks through collaboration with partners within the supply chain and managing the process to reduce supply chain vulnerability (Jüttner et al. 2003). It could be defined further as a process where supply chain partners using risk management tools apply risk mitigation techniques caused by logistic-related activities and manage it (Norrman and Lindroth 2002).

Risk in the supply chain is an important factor to businesses and if not addressed and managed could lead to production losses and disruptions in the supply chain. This type of risk affects the performance of the businesses' supply chain (Wilson 2007 and Wagner and Bode 2008). They are affected negatively by not meeting customer requirements that include product availability, delivery reliability, and all the necessary inventory and capacity in the supply chain to deliver the required performance in a responsive manner (Hausman 2004). The risks also hurt the financials of businesses and lead to lower sales, asset utilization, or profitability (e.g. Hendricks and Singhal 2003, 2005). Supply chains that have a high level of risk are not efficient (Christopher and Lee, 2004) and this ultimately leads to increased costs and poor customer service. The impact of supply chain to the business world is significant. According to the World Economic Forum, it issued a Global Risk Network Report that places supply chains as one of the four emerging issues that affect the global landscape, alongside systemic financial risks, food security, and the role of energy (World Economic Forum 2008).

Another area of study is supply chain agility. It has been identified as one of the most important issues of modern supply chain management (Lee 2004). Agility enables businesses to respond timely and effectively to market volatility and other uncertainties and gives them a competitive edge (Swafford et al., 2006). However supply chain agility is broad, complex and depending on the expertise of the individual, he or she might have different views of agility (Li et al. 2008 and Li 2009). The concept has been defined as wide as total integration of business components (Kidd 1994) or as specific as the ability to rapidly change over from the assembly of one product to the assembly of a different product (Quinn et al., 1997).

Yet another area is supply chain vulnerability. It is the ability to measure the susceptibility of supply chains to supply chain disruptions (Kleindorfer and Saad 2005). This type of study gives stakeholders the ability to understand risk exposure of the supply chains and apply risk management and mitigation techniques where necessary. Yet like supply agility, measuring supply chain vulnerability is hard. It cannot be observed or measured directly. There are numerous variables that drive the supply chain vulnerability such as globalization of the sourcing network, customer or supplier dependence, and supply chain complexity (Wagner and Neshat 2012). In addition supply chain vulnerability is a multidimensional construct that does not have well-developed metrics that could be used to evaluate the drivers on which vulnerability depends (Wagner and Bode 2006, Stecke and Kumar 2009).

Understanding these types of logistics and supply chain risks by assessing and quantifying them is necessary since they are an integral part of businesses and their strategies. It affects their competitive advantage and profits (Gunasekaran et al. 2004, Wilding 2003, Punniyamoorthy et al. 2013, e.g. Hendricks and Singhal 2003, 2005). Part of the risk assessment is to consider the various items that can negatively affect logistics and supply chain risks. Some include natural disasters, plant shutdowns, political and labor unrest, IT system failure, industrial accidents, and global economic recession among others (Snyder and Shen 2006; Tang and Nurmaya Musa 2010). They should also consider their logistics and supply chain strategies as part of their risk. This would consist of just-in-time (JIT), lean operations, safety stock practices and spare parts availability. The risk could be substantial if not identified, evaluated and managed accordingly. They can be costly and could even bring parts of the supply chain to a halt (Handfield et al., 2011). The other part is to provide stakeholders with some type of costs and reliability model to help them with the decision making process. By quantifying the risk with these indices provides them with the ability to make better and more informed decisions. This paper looks at simple supply chain networks where emphasis is on the manufacture and distribution node. It quantifies implications of having the operation down using costs and reliability as the metrics. Trevelen and Schweikhart (1988) discuss supply chain vulnerability risk-reward trade-offs to make decisions. Stakeholders can use this model to match the desired risk-reward trade-offs and make changes to logistics and supply chain policies to reflect the tolerance of the business.

Assumptions

This model is based around the manufacturer. The simulation derived from the mathematical models uses this entity to determine costs and failures based on system downtimes. In addition, there are various assumptions made in development of the mathematical models. To add every item in the system is extremely intricate, requires numerous experts in respective fields and is beyond the scope of this paper. The following assumptions are necessary to create a manageable and feasible model:

1. Just in time (JIT) delivery model
2. Constant demand by the retailer, Monday through Sunday
3. Supplier converts raw material into parts and ships them to the manufacturer
4. Manufacturer assembles parts and ships them as products to the retailers
5. Retailers are the point of sale (POS)
6. Manufacturer hours of operation from 8:00 to 5:00 with 1-hour lunch
7. Manufacturing processing time is steady—no spikes in production
8. Linear production—not one trailer gets loaded faster
9. One SKU by the manufacturer
10. Nonperishable product
11. Any downtime affects the entire manufacturer—that is no products can be produced
12. Manufacturer must complete processing all the products
13. Downtime cannot exceed 8 hours
14. Retailers receive weekly deliveries from one manufacturer
15. All products must be processed by the manufacturer the same day
16. Like and or identical products available at competing retailers
17. Constant failure rate—the manufacturer has been processing the same items for some time
18. Poison distribution—the amount of downtime affects the efficiency of the production
19. Employees guaranteed a minimum of 8 hours
20. Assume empty trailers are parked in outbound bay after the current trailer leaves to its location
21. Each trailer leaves at 50% capacity
22. Assume 2% safety stock
23. Assume that the manufacturer sends out another trailer the next day to complete the missed deliveries
24. Manufacturer cannot go above planned efficiency
25. Management loads trailers with safety stock
26. If safety stocked is used, it must be replenished
27. All safety stock is used before any failures can occur
28. Manufacturer can control flow of products into trailers

Terms and Acronyms

ADT	Actual Downtime: *Actual time production is complete*
DC	Distribution Center: *Assembles and ships products*
D_m	Day: *Mon, Tue, …*
DT	Downtime: *Unplanned time the system is down*
E_r	Employees: *Employees working*
F_p	Failures: *Products not sent to retailer*
H	Hours: *Hours*
MV	Missed Volume: *Amount of products not loaded; failures*
NP	Net Profit: *Net profit per product*
OT	Overtime: *Employee's overtime wages*
PDT	Planned Downtime: *Planned time to complete production*
PFPH	Product Flow Per Hour: *Total products produced by hour*
PLS	Percent Lost Sales: *Percent of lost sales*
PPH	Product Per Hour: *Products produced by hour by employee*
P_q	Products: *Products*
R_n	Retailer: *Retailer1, Retailer2, …*
SC	Supply Chain: *Supply chain of manufacturer*
SS	Safety Stock: *Percentage of safety stock Mfg has on hand*
SSR_n	Safety Stock Retailer: *Percentage of safety stock* R_n *has on hand*
TFC	Total Failure Costs: *Costs of labor and loss of sales*
T_n	Trailer: *Trailer1, Trailer2, …*
TV	Total Volume: *Products needed for the given day*
VD	Volume Distribution: *Distribution of volume by Tn/Rn*
VP	Volume Processed: *Products produced for the given day*
VT	Volume Trailer: *Products loaded into Tn*
WD	Workday: *Eight-hour workday*

Simplified SC Reliability Mathematical Formula

Products delivered successfully are a direct correlation to the reliability of the supply chain. Suppose that in any given day D_m, a manufacturer delivers all ordered products from their *DC* to the designated retailer R_n, at the right date and time, and in the right condition and quantity. Furthermore, suppose all ancillary items considered for the reliability of the delivery (Bolstorff 2012) for D_m are accounted. Then, the reliability of the supply chain on D_m for this scenario is R_{SC} = 1.00. Thus, a simplified mathematical model to determine the reliability of the supply chain for D_m for the network in Figure 1.0 is given by Equation 1:

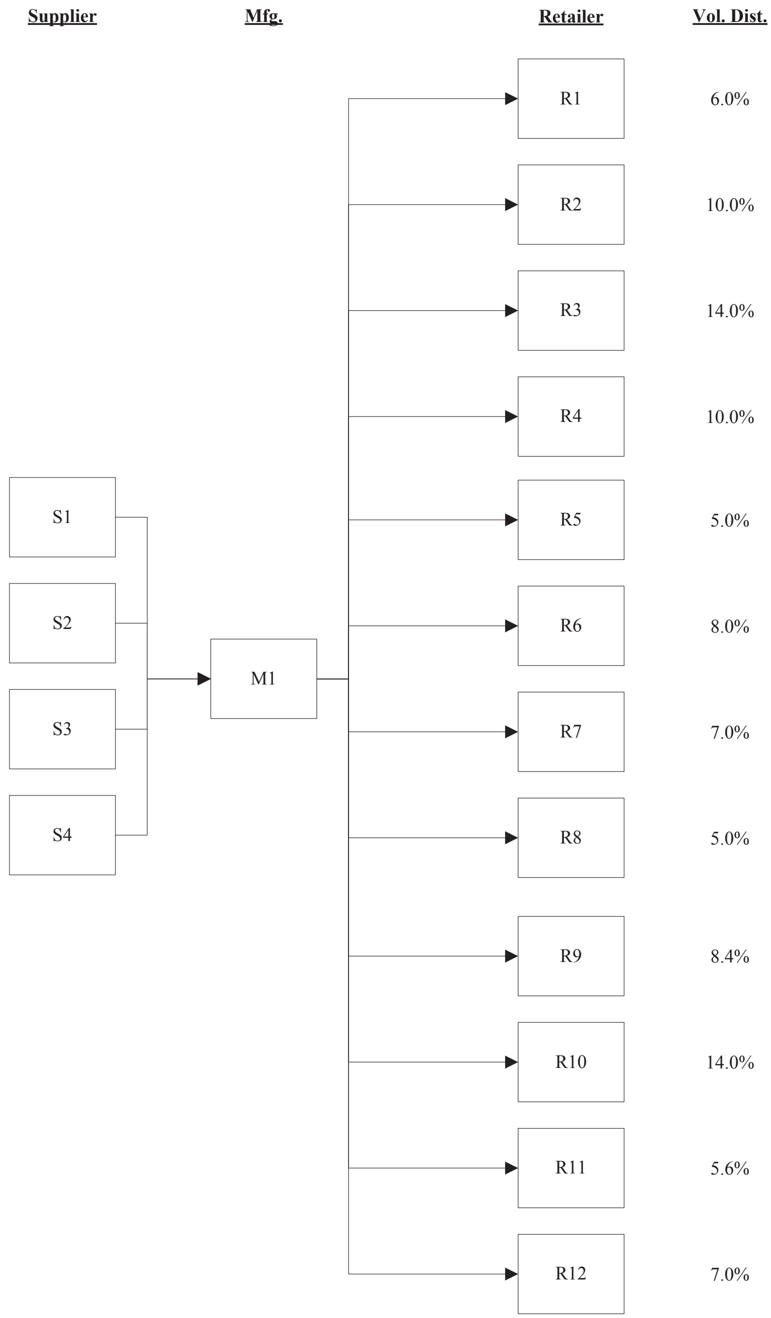

FIGURE 1

$$R_{SC} = 1 \text{ œ} F_{SC}$$

EQUATION 1

where $F_{SC} = \sum_{i=1}^{p} F_p \,/\, \sum_{i=1}^{q} P_q$, and F_p is the number of products (P_q) not loaded into outbound trailer T_n for D_m.

In any given D_m, there are X number of P_q scheduled for delivery. Those P_q not loaded into trailer T_n are considered failures F_p and must be accounted for in the next order replenishment cycle by the supplier of the raw material or parts, the manufacturer/assembler of the raw materials or parts into products, and retailer that sells the products. Hence, the total reliability of the supply chain (*SC*) system for day D_m is one less the total failures over the total products scheduled for delivery.

Simplified Failure Estimation Costs and Reliability Formula

To estimate the total costs incurred by the manufacturer, a simplified model is presented. It considers the labor costs, production efficiency, safety stock, scheduled trailer departure times and delivery dates, downtime and loss of sales.

Suppose the amount of products the manufacturer can assemble, process, and load into trailers Tn is defined by the product flow per hour *PFPH*. The products per hour *PPH* that each employee E_r can do effectively is 2.40. The amount of products required to be processed each D_m is 9,350 and is defined as the total volume *TV*. The total paid work day is eight hours. Thus the *PFPH* required to finish the work in 8 hours is:

PFPH = *TV* ÷ 8.0 Hours = 9,350 Products ÷ 8.0 Hours = 1,168.75 *PFPH*

The number of employees required to reach this rate, discovered through Equation 2, is:

$$\acute{E} = PFPH \div PPH$$

$$\acute{E} = 1{,}169\,\frac{Products}{Hr} \div 2.40\,\frac{Products}{Hr}$$

$$\acute{E} = 486.97 \approx 487.$$

EQUATION 2

This is a 97.4% efficiency rate: 1,169 ÷ 1,200. To keep from working at such a high rate of efficiency, the manufacturer adds incidental time such as employees going to the restroom, taking water breaks or having meetings with management. This is more realistic than each employee working continuously. The manufacture adds an additional 18 employees E_r to cover the incidentals and makes the total employees E_r required to run the operation 505. Thus, the efficiency rate is $\acute{E} \div E$= 96.4%.

Suppose the pull times for trailers T_n are defined by Table 1:

No.	Trailer (*n*)	Plan Pull (*n*)
1	T1	5:15 PM
2	T2	5:15 PM
3	T3	5:30 PM
4	T4	5:45 PM
5	T5	5:30 PM
6	T6	5:15 PM
7	T7	5:45 PM
8	T8	6:00 PM
9	T9	6:00 PM
10	T10	5:30 PM
11	T11	5:15 PM
12	T12	5:15 PM

If P_q is not loaded into T_n by its pull time, then P_q misses going to the retailer R_n and becomes a failure F_p. Table 2 shows the number of ordered products by R_n:

No.	Retailer (*n*)	Products
1	R1	561
2	R2	935
3	R3	1,309
4	R4	935
5	R5	468
6	R6	748
7	R7	655
8	R8	468
9	R9	785
10	R10	1,309
11	R11	524
12	R12	655

Therefore, the total failure costs *TFC* when the operation runs over its planned downtime is the sum of excess wages E_r for going over the planned downtime plus the sum of lost sales for those P_q not reaching R_n. Wages are a direct correlation to the efficiency of production. When the production becomes less efficient, the time required to complete a task takes longer. In that respect, the company loses production due to the 1) ramp up of reaching the targeted *PFPH* after being at zero, 2) employees being tired after an eight-hour shift and 3) having to reschedule or take care of commitments. The loss in production is estimated empirically by the Equation 3.

$$F(DT;\lambda) = \begin{cases} \left(1 - e^{-\lambda DT}\right) \times PPH, & DT \geq 0 \\ 0, & DT < 0 \end{cases}$$

EQUATION 3

where *DT* = downtime and 1 = 0.08.

TFC = *ExcessWages* + *LostSales*, where *ExcessWages* is given by Equation 4:

$$ExcessWages = \left(\sum_{i=1}^{r} E_r \times OT \times DT\right) + \left[\left(\frac{TV - VP}{F(DT;\lambda)}\right) \times OT\right]$$

EQUATION 4

and *LostSales* is given by Equation 5:

$$LostSales = \sum_{i=1}^{n} VD_n \times MV \times PLS_{DT} \times NP$$

where

$$MV = TV - \left(VP + SS + \sum_{i=1}^{n} VT_n\right)$$

EQUATION 5

SS is set at 2% and can be modified based on the criteria and strategy of the business. Brown (1981) and Thomopoulos (2004) provide methods that show how to set the safety stock when the idea is to minimize the lost sales or the backorders.

Lost sales, *LostSales*, was developed empirically since it is difficult to measure the amount of lost sales (Thomopoulos 2004). It is beyond the scope of this paper. Here, *LostSales* assumes when R_n runs out of P_q that most customers will return to R_n at a later date. Those that do not return are because they either 1) purchased P_q at a different store, outside of the network in Figure 1, or 2) changed his/her mind and no longer want to buy P_q. This is because the individual lost the impulse to purchase it. These are a couple of reasons for lost sales. There are many others as to why the customer does not end up purchasing P_q. Some are difficult to almost impossible to obtain and thus makes it hard to quantify and tie back into logistics and supply chain issues. Yet some stores do spend the time and are able to capture with a certain degree of accuracy the amount of lost sales and associate them with reasons as to why. The *LostSales* is given by Equation 6:

$$LostSales = \begin{cases} [MV - (R_n \times SSR_n)] \times NP \times PLS, & MV - (R_n \times SSR_n) > 0 \\ 0, & MV - (R_n \times SSR_n) \leq 0 \end{cases}$$

EQUATION 6

The model uses a uniform distribution over seven days: 100% ÷ 7 days = 14.29% per day. It is easy to make the model more robust by adjusting it to accept the percent of people shopping based on the day of the week, sales and promotions, individuals' pay period and time of year.

Results

Using the *TFC* mathematical model, a simulation program was developed for the network in Figure 1. The simulation also considers the period of the downtime. If the system is down during lunch, there is no effect to the output. On the other hand if the system is down where it overlaps during lunch, then the simulation does not include that as part of the downtime. This provides for a more accurate depiction of the overall system downtime. Table 3 shows the indices used. Following are results of the simulation:

Item	Units	Quantity
Daily Products	Products	9,350
Work Day	Hours	8.00
Product/Hr	Products	2.40
Planned Downtime	XX:XX	17:00
Employees	Employee	505
Hourly Rate Wages	$U.S.	$15.60
Overtime Wages	$U.S.	$23.40
Net Profit Product	$U.S.	$120.00
Safety Stock Mfg	Products	2%
Safety Stock Retailer (n)	Products	2%
Est. Lost Sales*	Products	25%

If the *ADT* = 5:10 PM, then *TFC* = $1,919 and R_{sc} = 1.00000. The reasons for the costs are apparent. *E* are paid during the downtime, there is no activity, and to complete unfinished P_q when the system is back on line. R_{sc} however shows 1.000000. The reason there are no F_q is based on the pull times of T_n as well as the *SS*. The company is able to get everything loaded before T_n leaves the plant. They also use their *SS* during *DT* to mitigate failures. When *DT* > 25 minutes, F_q > 0. Table 4 shows the *TFC* and R_{sc} based on ten minute increments:

ADT	*TFC*	R_{sc}
5:00 PM	$0	1.000000
5:10 PM	$1,919	1.000000
5:20 PM	$3,892	1.000000
5:30 PM	$5,916	0.995876
5:40 PM	$9,277	0.987534
5:50 PM	$13,902	0.972618
6:00 PM	$20,276	0.955145
6:10 PM	$27,525	0.935474
6:20 PM	$35,447	0.913800
6:30 PM	$43,905	0.892127
6:40 PM	$52,430	0.870453
6:50 PM	$61,026	0.848780
7:00 PM	$69,486	0.827386

There is a correlation between the *TFC* and R_{sc}. As the *TFC* increases, the R_{sc} decreases. Plotting the two indices yields Figures 2 and 3 (following page).

Notice *TFC* and R_{sc} increase and decrease for the most part approximately at a 45° linear slope respectively. The *TFC* slope between 5:00 PM to 5:50 PM and R_{sc} straight line between 5:00 PM to 5:20 PM is due to the T_n pull times and R_n safety stock.

By plotting the labor costs and lost sales, it is easy to see that both increase based on system downtime. However, lost sales in-

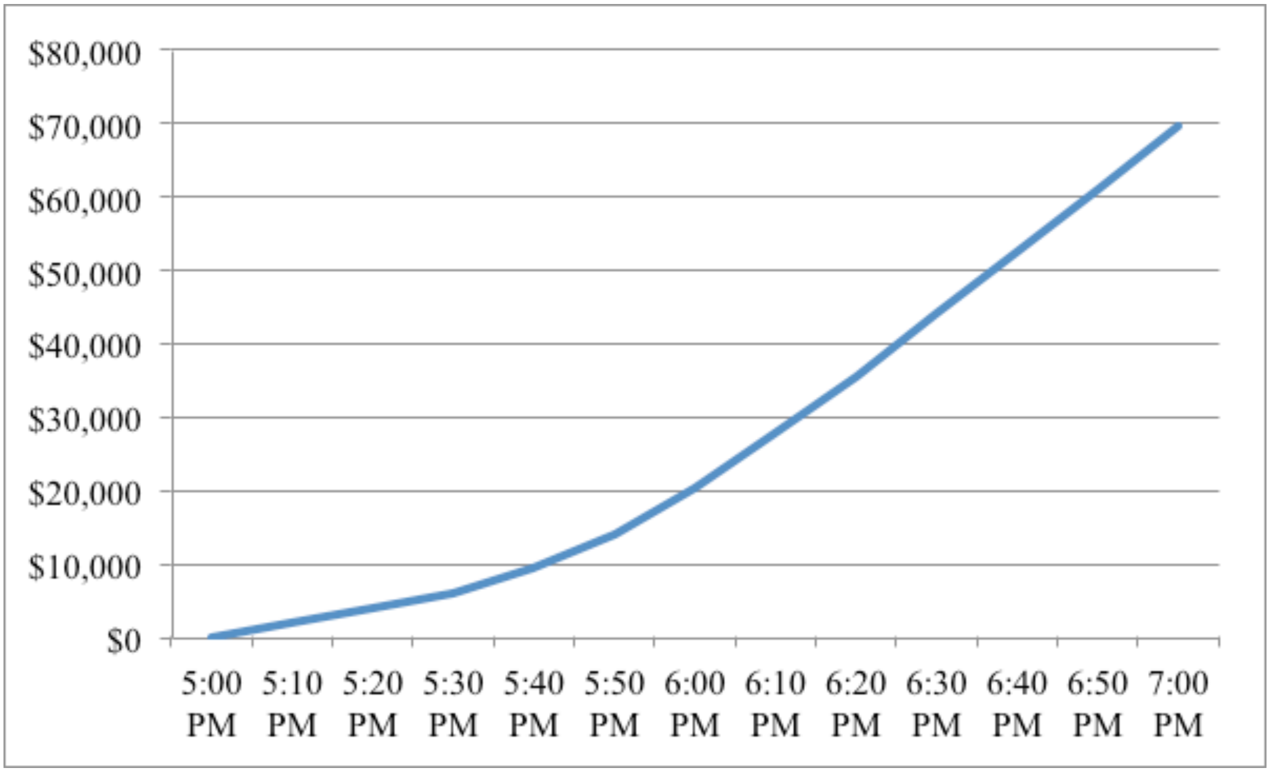

FIGURE 2: TOTAL FAILURE COST (TFC)

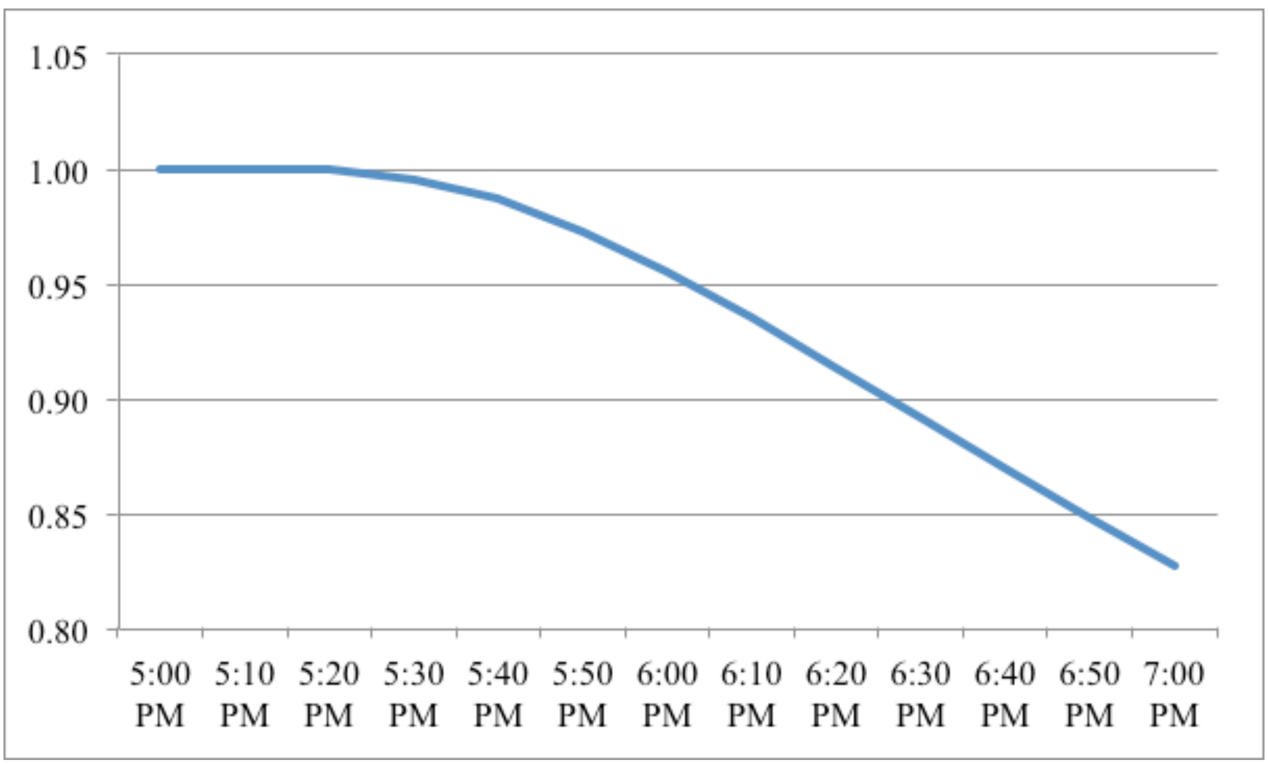

FIGURE 3: RELIABILITY OF THE SUPPLY CHAIN (RSC)

creases at a steeper rate than labor cost. Both could change dramatically depending on the number of *E* receiving *OT* and the *NP* of P_q. It could also change depending on the amount of *SS* or reserves the R_n has on hand. Figures 4 and 5 show the differences between the increases in labor costs versus *LostSales*.

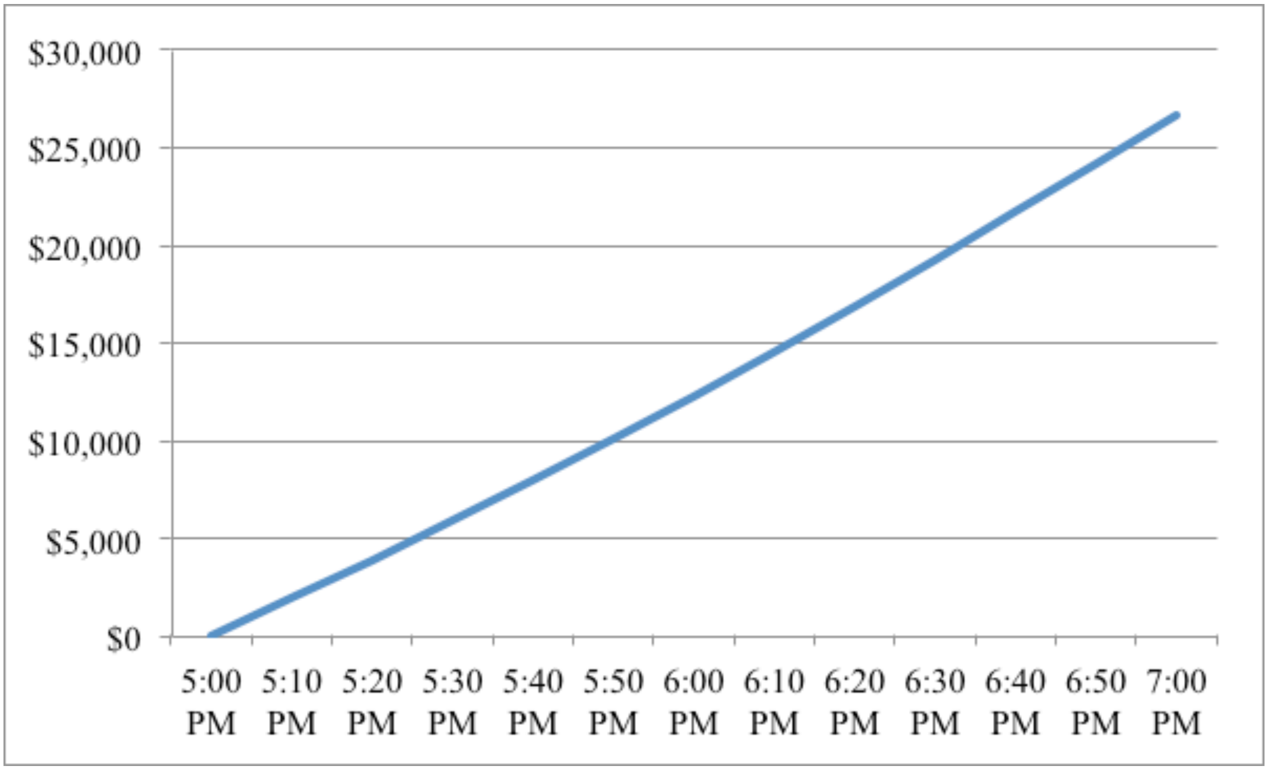

FIGURE 4: LABOR COSTS

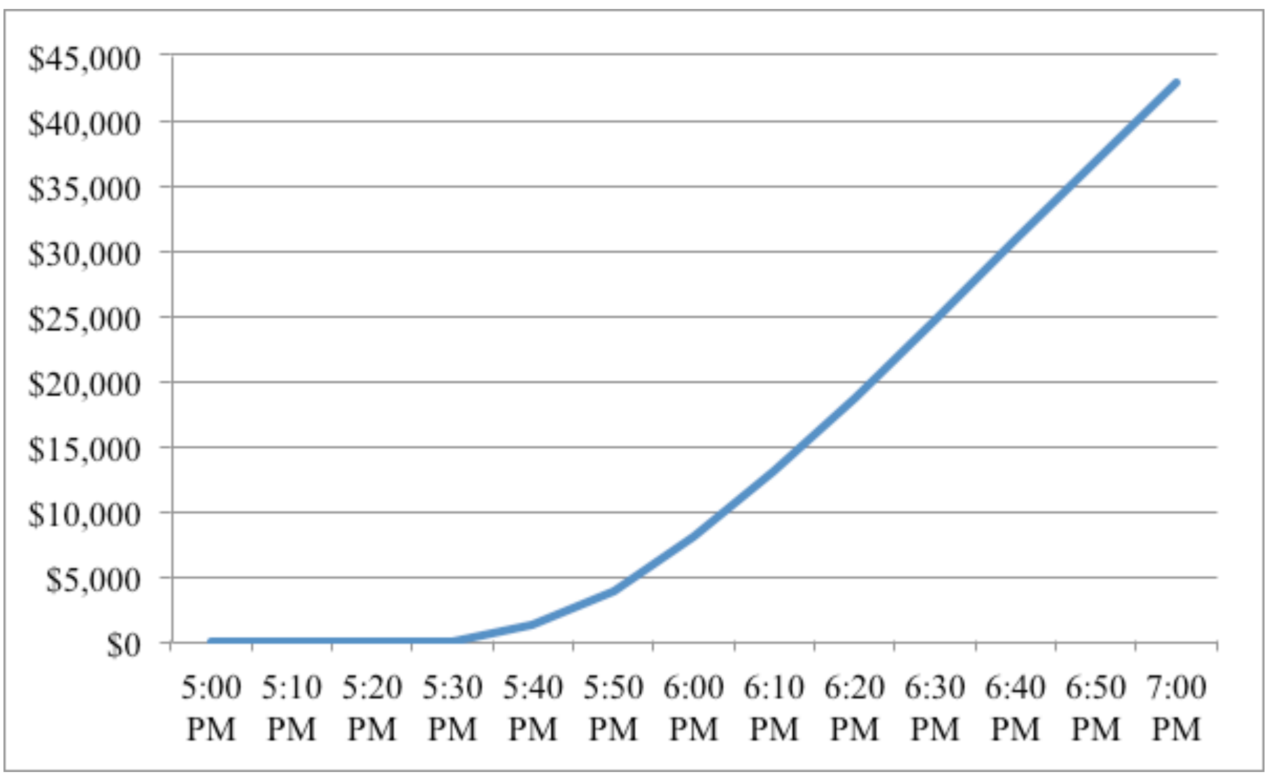

FIGURE 5: LOST SALES

Analysis and Discussion

Stakeholders are able to adjust the parameters in the model to conduct what-if analysis. This allows them to estimate their costs and focus their strategy on the items that would provide the greatest benefit. For example, if the safety stocked of the manufacturer increases from 2% to 10%, and all else remains the same, the *TFC* savings and decreases in F_p are substantial. Table 5 shows the differences for *TFC*, F_p and R_{sc} based on ten minute increments:

	2% Safety Stock			10% Safety Stock			Difference		
ADT	*TFC*	F_P	R_{SC}	*TFC*	F_P	R_{SC}	*TFC*	F_P	R_{SC}
5:00 PM	$0	0	1.0000	$0	0	1.0000	$0	0	0.00%
5:10 PM	$1,919	0	1.0000	$1,919	0	1.0000	$0	0	0.00%
5:20 PM	$3,892	0	1.0000	$3,892	0	1.0000	$0	0	0.00%
5:30 PM	$5,916	39	0.9959	$5,916	0	1.0000	$0	39	0.41%
5:40 PM	$9,277	117	0.9875	$7,993	0	1.0000	$1,284	117	1.25%
5:50 PM	$13,902	256	0.9726	$10,125	0	1.0000	$3,776	256	2.74%
6:00 PM	$20,276	419	0.9551	$12,316	0	1.0000	$7,960	419	4.49%
6:10 PM	$27,525	603	0.9355	$14,566	56	0.9941	$12,959	548	5.89%
6:20 PM	$35,447	806	0.9138	$18,671	154	0.9835	$16,776	652	7.09%
6:30 PM	$43,905	1,009	0.8921	$24,150	295	0.9684	$19,754	713	7.88%
6:40 PM	$52,430	1,211	0.8705	$30,934	470	0.9498	$21,496	742	8.35%
6:50 PM	$61,026	1,414	0.8488	$38,686	666	0.9288	$22,340	748	8.61%
7:00 PM	$69,486	1,614	0.8274	$47,046	866	0.9074	$22,440	748	8.82%

The simulation model has multiple parameters that stakeholders could adjust to conduct further analysis. They can increase the number of employees and keep the efficiency as is and process more P_q per hour. This gives them lead way to have a longer downtime without incurring more F_p. The drawback is the labor costs. However, if the *NP* >> $120, then the costs figures change substantially and labor costs no longer is the main issue. For instance, if the *NP* = $1,000 and all else remains the same, the labor costs for a 2-hour downtime is still $26,678 but the cost of *LostSales* increases from $42,808 to $356,735. And if the percent lost sales (*PLS*) = 50% then the *LostSales* increases to $713,470. This type of analysis empowers stakeholders to make better and more informed decisions about their staffing and safety stock. These are just some examples of changes to the parameters. They can change others to help them understand what their *TFC* and delivery reliability might be so they can develop more effective business strategies. Table 6 shows all the parameters:

Safety Stock
Percent Lost Sales
Net Profit
Sale Distributions
Workday
Planned Downtime
Trailer Pull Times
Staffing Policies
Hourly Wages
Production Rates
Forecasts
Lunch Breaks

If the system was down due to the lack of an effective contingency or spare parts plan, the stakeholders could estimate the downtime and then determine the impact in costs, failures and reliability. Table 5 already shows the differences with 2% and 10% safety stock. Notice by reducing the downtime from 7:00 PM to 6:00 PM based on 2% safety stock, the company saves approximately $49,211. This level of savings warrants having contingency measures in place to minimize the impact to the business.

Conclusion and Further Research

Risk in logistics and supply chain is an important factor that stakeholders must consider. It affects costs and delivery reliability. This paper introduced a mathematical model with multiple parameters to determine costs and reliability: *TFC* and R_{sc}. They ranged from wages and production efficiency, to safety stock, downtimes and lost sales. In addition, a simulation program was developed based on the mathematical model that allows stakeholders to manipulate various parameters to conduct what-if analysis. This gives them the opportunity to adjust and update business strategies based on the changes. These strategies could range from safety stock and staffing policies, to scheduled departure times, creating two five-hour shifts and adjusting the prices of product.

To advance this research paper one should first view the system as a whole. That is to consider the entire supply chain from the supplier and manufacturer, to the distribution centers and retailer. This gives a better understanding and estimation of the *TFC* and overall R_{sc}. This type of endeavor requires numerous experts from operations, transportation, logistics, supply chain, marketing and sales. In addition one should look into obtaining more accurate production efficiencies based on downtime and the number of buyers not returning to the original retailer to purchase the product. The current model defines them empirically. Lastly, one should consider other variables in the model to get a better sense of the costs and reliability. This dovetails to viewing the system as a whole. For instance the decrease in purchasing power or the increases to the transportation rates due to reductions in the order quantity. The model assumes that there are no penalties for either. The purchasing power and transportation rates are a couple of items. Table 7 provides a list of others where more are definitely possible to add based on further research:

Item	Mfg.	Loc.	Description
Delivery Costs*	X		Costs incurred by manufacturer from suppliers due to less raw material and or parts shipped.
Order Quantity	X		Costs incurred by manufacturer from suppliers due to less raw material and or parts ordered.
Location Costs		X	Time spent at location managing disruption in the orders.
Service Level Agrmt.	X		Penalties incurred due to breach in service level agreement.
Order Processing	X		Costs associated with processing orders out of sequence.
Inventory			
Damages	X		Items damaged due to spikes in volume flow, loading at a faster rate to prevent missing pull times, and the like.
Insurance	X		Costs incurred by having excess products on file.
Pilferage/Shrinkage	X		Costs incurred by having stolen or misplaced products.
Holding Costs	X		Costs incurred by having additional inventory in stock.
Management Time			
Operations	X		Time the mfg. operations spends managing the disruption.
Sales Calls	X	X	Time sales spends talking to their customers.
Maintenance	X		Unplanned maintenance time spent working on equipment.
Business Analysis	X	X	Time spent developing accurate forecasts.
Staff Support	X	X	Time staff spent trying to figure out what went wrong.
Discounts			
Goodwill	X		Goodwill discounts given to store locations.
Overstocked	X	X	Costs incurred by selling products at reduced prices due to having more inventory than needed.
Clearance		X	The losses incurred by selling discontinued products.
Marketing		X	Resources spent on marketing discounted/clearance products.
Facility	X		Costs to run facility at full capacity past the scheduled downtime.
Warehouse space	X		Costs incurred by having excess warehouse space for additional products not shipped.
Returns	X	X	Costs incurred by returns: damages, processing, floor space.
Lost Sales		X	Loss in sales due to the shift of customers' buying habits: products are not purchased at regular location. They are purchased at a new location since products were not available at regular location when needed.

*May be built into the price per product/raw material.

References

1. Bolstorff, P., “Measure customer delivery reliability not just perfect order fulfillment,” 2012. Available at: http://www.scelimited.com/measure-customer-delivery-reliability-not-just-perfect-order-fulfillment/ (accessed 17 October 2013).

2. Brown, R.G., “Advanced Service Parts Inventory Control,” Thetford Center, Vt., Materials Management Systems, 1981.

3. Christopher, M. and Lee, H.L., “Mitigating supply chain risk through improved confidence.” International Journal of Physical Distribution & Logistics Management, Vol. 35 No. 4, 2004, pp. 388-396.

4. Gunasekaran,A., Patel, C. andMcGaughey, R.E., “A framework for supply chain performance Measurement,” International Journal of Production Economics, Vol. 87 No. 3, 2004, pp. 333-47.

5. Handfield, R., Blackhurst, J., Craighead, C.W. and Elkins, D., “Introduction: a managerial framework for reducing the impact of disruptions to the supply chain”, 2011. Available at: http://scm.ncsu.edu/scm-articles/article/introduction-a-managerial-framework-for-reducing-theimpact-of-disruptions (accessed 15 October 2013).

6. Hausman, W. H., “The Practice of Supply Chain Management: Where Theory and Application Converge,” International Series in Operations Research & Management Science, Vol. 62, 2004, pp. 61-73.

7. Hendricks, K.B. and Singhal, V.R., “The effect of supply chain glitches on shareholder wealth,” Journal of Operations Management, Vol. 21 No. 5, 2003, pp. 501-522.

8. Hendricks, K.B. and Singhal, V.R., “Association between supply chain glitches and operating performance,” Management Science, Vol. 51 No. 5, 2005, pp. 695-711.

9. Jüttner, U., Peck, H. and Christopher, M., “Supply chain risk management: outlining an agenda for future research,” International Journal of Logistics, Vol. 6 No. 4, 2003, pp. 197-210.

10. Kidd, P.T., “Agile Manufacturing: Forging New Frontiers,” Addison-Wesley Longman, Boston, MA, 1994.

11. Kleindorfer, P.R. and Saad, G., “Managing disruption risks in supply chains,” Production and Operations Management, Vol. 14 No. 1, 2005, pp. 53-68.

12. Lee, H.L., “The triple-A supply chain,” Harvard Business Review, Vol. 82 No. 10, 2004, pp. 102–112.

13. Li, X., Chung, C., Goldsby, T. and Holsapple, C., “A unified model of supply chain agility: the work-design perspective,” International Journal of Logistics Management, Vol. 19 No. 3, 2008, pp. 408-35.

14. Li, X., “Supply chain agility: scale development,”The International Journal of Logistics Management, Vol. 20 No. 3, 2009, pp. 408-424.

15. Nick T. Thomopoulos, “Demands, Backorders, Service Level, Lost Sales and Effective Service Level,” Illinois Institute of Technology, Journal of Business & Economics Research, Vol. 2, No. 11, November 2004, pp. 87-92.

16. Norrman, A. and Lindroth, R., “Supply chain risk management: purchasers’ vs. planners’ view on sharing capacity investment risks in the telecom industry,” Proceedings of the IPSERA 11th International Conference, Enschede, Holland, 25-27 March, pp. 2002, 577-595.

17. Jr, Podgurski, A., Jo, J.-Y., Sterling, L.S. and Kim, Y., “An agile manufacturing workcell design”, IIE Transactions, Vol. 29 No. 10, 1997, pp. 901-909.

18. Punniyamoorthy, M., Thamaraiselvan, N. and Manikandan, L., “Assessment of supply chain risk: scale development and validation,” Benchmarking: An International Journal, Vol. 20 No. 1, 2013, pp. 79-105.

19. Quinn, R.D., Causey, G.C., Merat, F.L., Sargent, D.M., Barendt, N.A., Newman, W.S., Velasco, V.B.

20. Son, J. Y. and Orchard, R. K., “Effectiveness of policies for mitigating supply disruptions,” International Journal of Physical Distribution & Logistics Management, Vol. 43 No. 8, 2013, pp. 684-706.

21. Stecke, K.E. and Kumar, S., “Sources of supply chain disruptions, factors that breed vulnerability, and mitigating strategies,” Journal of Marketing Channels, Vol. 16 No. 3, 2009, pp. 193-226.

22. Snyder, L. and Shen, Z.J.M., “Supply and demand uncertainty in multi-echelon supply chains,” working paper, P.C. Rossin College of Engineering and Applied Sciences, Lehigh University, Bethlehem, PA, 2006.

23. Swafford, P.M., Ghosh, S. and Murthy, N., “The antecedents of supply chain agility of a firm: scale development and model testing,” Journal of Operations Management, Vol. 24 No. 2, pp. 2006, pp. 170-88.

24. Tang, O. and Nurmaya Musa, S., “Identifying risk issues and research advancements in supply chain risk management,” International Journal of Production Economics, Vol. 124 No. 1, 2010, pp. 109-20.

25. Trevelen, M. and Schweikhart, S.B., “A risk/benefit analysis of sourcing strategies: single vs. multiple sourcing,” Journal of Operations Management, Vol. 7 No. 4, 1988, pp. 93-114.

26. Wagner, S.M. and Bode, C., “An empirical investigation into supply chain vulnerability,” Journal of Purchasing & Supply Management, Vol. 12 No. 6, 2006, pp. 301-312.

27. Wagner, S.M. and Bode, C., "An empirical examination of supply chain performance along several dimensions of risk," Journal of Business Logistics, Vol. 29 No. 1, 2008, pp. 307-325.

28. Wagner, S. M. and Neshat, N, "A comparison of supply chain vulnerability indices for different categories of firms," International Journal of Production Research, Vol. 50, No. 11, 1 June 2012, pp. 2877-2891.

29. Wilding, R., "3 Ts of high effective supply chain," Supply Chain Practice, Vol. 5 No. 3, 2003, pp. 30-41.

30. Wilson, M. C., "The impact of transportation disruptions on supply chain performance," Transportation Research Part E: Logistics and Transportation Review, Vol. 43 No. 4, 2007, pp. 295-320.

31. World Economic Forum, "Global risks 2008: a global risk network report," World Economic Forum, 2008. Available at: http://www.weforum.org/pdf/globalrisk/report2008.pdf (accessed 17 October 2013).

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Accelerated Reliability Growth Testing: A Lean Approach to Product Lifetime Reliability

Milena Krasich

Introduction

Improving the reliability of products has been an Industry focus for over two decades. Products were designed with the best of design practices such as selecting parts with higher quality components, adequate stress derating and other design techniques for reliability enhancement. Yet, when the design has been completed and the systems have been produced, it may be possible that some design or manufacturing process unforeseen errors or oversights negatively affect their reliability.

To achieve reliability improvement, reliability improvement/growth tests are performed to allow the appearance of those design related failure modes under expected use stresses and then, by mitigating them, increase product reliability. The documents widely used to learn and apply methodology for reliability growth were and still are MIL-HDBK-189 and 781. For those who are not intimidated by complex equations, assumptions and then confidence limits on assumptions, the first handbook, now in revision C, is dedicated to reliability growth testing and elaborate mathematical estimations of future reliability projections while the latter is a handbook for various reliability testing, including reliability growth with simple explanations of the methodology. Recently, two International Electrotechnical Commission (IEC) standards for reliability growth, have been adopted by American National Standards Institute (ANSI)- IEC/ANSI 61014, Programmes for reliability growth (methodology) and its mathematical supporting standard, IEC/ANSI 61164, Statistical methods for reliability growth. There is a lot of useful guidance provided in both of those International standards and the mathematics is more understandable without offering too many assumptions or projections of distant future reliability. In addition to testing, these two standards emphasize the reliability growth of product(s) while in the design phase; a phase where the introduction of necessary changes are relatively easy and affordable to accomplish. Mathematics for reliability growth and tracking in product design phase is also included in those standards.

This article discusses some difficulties or problems with the traditional reliability growth testing as it is performed currently, the physics, engineering and associated mathematical errors or disconnect between the product life, use profile and the test.

This article then presents the Physics of Failure approach to accelerated reliability growth testing as an affordable solution to the product reliability improvement.

1.0 Current Methodology and the Associated Problems

1.1 Mathematical Approach for Determination of Test Duration and the Final Test Results

Historically, when a product design was completed and the product was made, multiple analyses had been performed to estimate and/or enhance its reliability. Reliability modeling and predictions provided certain quantitative product reliability estimates; Failure Modes, Effects Analyses, FMEA/FMECA, were also completed and identified while potential design problems were noted and corrected.

To continue product improvement after the design phase or to confirm assessed reliability, reliability growth test is performed to detect and mitigate additional potential design faults which resulted in test failures that could also appear in its field use.

It is expected that three basic failure mode types would be seen during the test:

- Design or process related failure modes, possible to mitigate (B failure modes)
- Design or process related failure modes that cannot be mitigated (A failure modes)
- Random or unknown origin failure modes that are not subject to a reliability growth process.

B-type failure modes are the main focus of the reliability growth program. They are the failure modes that can be mitigated by design measures/changes. The joint failure rate of those failure modes (improvements normally reduce their frequency of occurrence rather than eliminate the failure mode altogether) will decrease in steps. The failure rate is constant until an improvement is done, then it is reduced in a step and continues to be constant till another failure mode is mitigated—improvement made. This process continues throughout the test till its completion. The step line is fitted with a power law curve borrowed from the IEC Power Law Standard [2] the Weibull Intensity Function or the Power Law failure frequency. This later became known as AMSAA/Crow reliability growth model. Those failure modes when mitigated allow reliability improvement/growth.

A-type failure modes are also considered design or process related, however, for technical, economic, or schedule reasons they are not mitigated and remain present in the product. In that manner, their appearance is expected every time the product functions depend on components with those uncorrected failure modes.

Since there are no improvements or changes made, their failure rate remains constant.

Random failure modes are classified under that name because the cause for their appearance is not clearly identified—therefore they are considered as the property, inherent undetermined faults in components and, since they also are not improved, their failure rate also remains constant throughout the test and life.

The failure rates of the three failure mode types are shown in Figure 1.

The Weibull Intensity function for the expected number of observed failures in some time *t* is:

$$n(t) = \lambda \cdot t^{\beta}$$

Where:

$n(t)$ is the number of design related failures as a function of time

λ = scale parameter of the Weibull Intensity Function (not to be confused with the scale parameter of the Weibull distribution)

β = shape parameter of the same function

t = time of observation

The failure rate or failure frequency, the first derivative of the number of failures, is determined by:

$$z(t) = \lambda \cdot \beta \cdot t^{\beta-1}$$

The step function of the failure rate is shown in Figure 1.

This step curve, $z_B(t)$, is attributable to design flaws that were corrected during the test. The part of the system failure rate attributed to the random failure rates, $z_r(t)$, and the part of the total failure rate attributed to the failure modes caused by the design errors, but could not be corrected, $z_A(t)$, are both constant (straight lines) and are added to the power law curve $z_B(t)$

1.1.1 The True and the Reported Test Results

In Figure 1 there are three failure rates attributed to three different failure modes type which all exist in the product and must add up to produce its total failure rate, the line shown as the top curve in this Figure. However, both of the existing Handbooks as well as the standards (the two IEC/ANSI standards currently in revision to correct those deficiencies) show only the reliability growth curve of the B-type failure modes as the failure rate during the test. The final reported failure rate is the final B-type failure

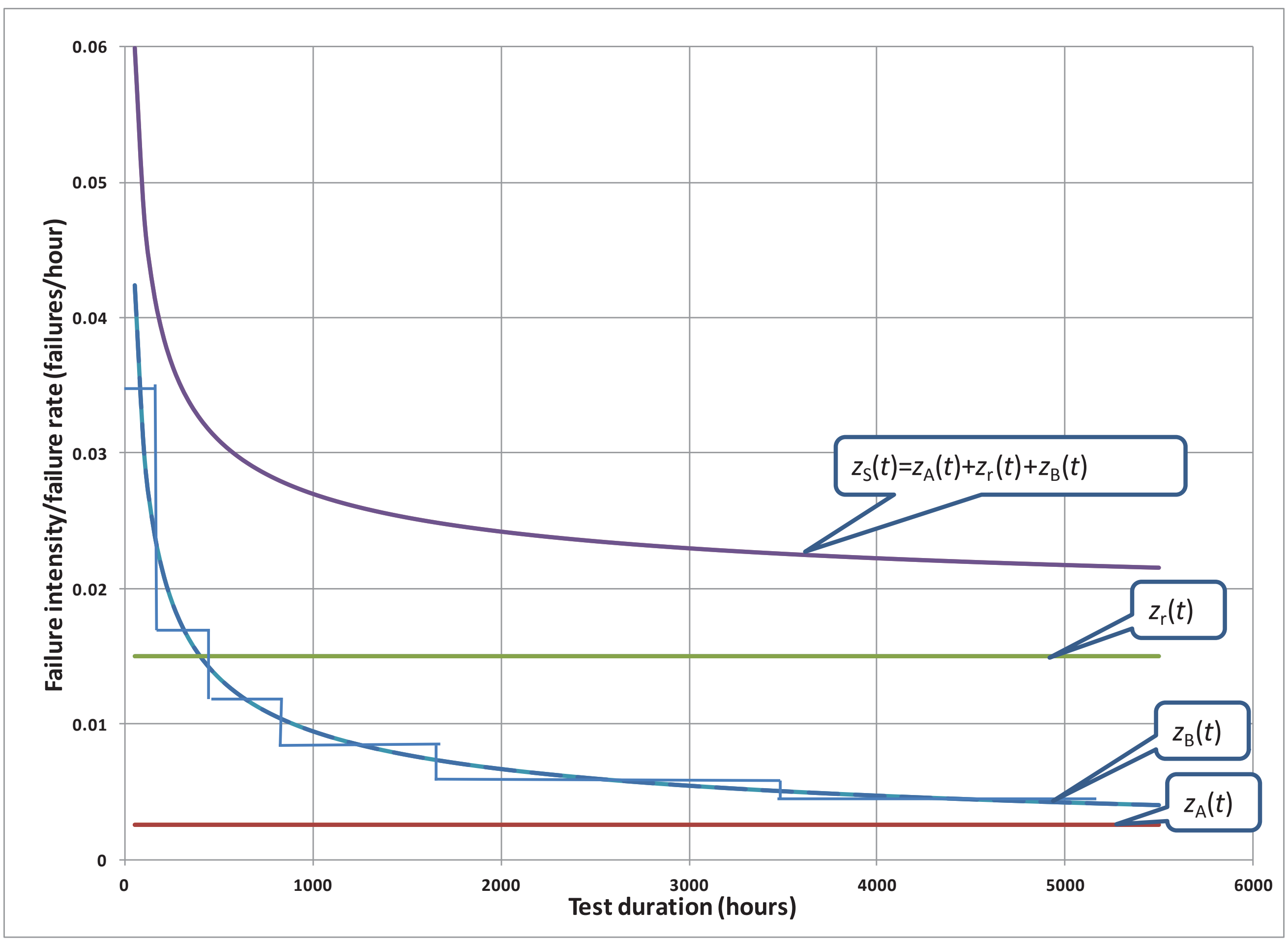

FIGURE 1: FAILURE RATES OF FAILURE MODES ENCOUNTERED DURING A RELIABILITY GROWTH TEST

modes failure rate only.

The random failure rates might be recorded for discussion at the Failure Review Board, but are not included into any failure rate calculations. One of the Handbooks mentions that the A-types failure modes are counted every time they appear and that their time to occurrence is included into the reliability growth calculations. That might be the case even though the examples shown in the Handbooks do not include A failure modes. The inclusion of A failure modes would not be mathematically in accordance with the power law because this law is valid only in the case of the Non-Homogenous Poisson Process (NHPP), the case when the failure rates change in steps. This means that the A failure modes, where there is no change failure rates should be classified as the Homogenous Poisson Process having the constant failure rate. So, if included into power law calculations, the approach is incorrect, if not, then they are omitted from the failure rate calculations and are not presented in the final results. In Figure 1, the real final failure rate is the top curve, and what is reported is the last value on curve second from the bottom.

The reliability growth as reported is then overly optimistically represented. The failure rate starts high, from the product total failure rate (or from low joint MTBF) resultant from all of the failure mode types. Then, the test results are calculated from the reliability growth of B-type failure modes, meaning low failure rate and high MTBF. The final failure rate is naturally very low as, unless the design engineers are very inadequate, there could not really be too many unforeseen design or process related failures and corrections. The reliability growth, as a ratio of failure rates or MTBFs then seems to be impressively high.

The random failures, those which come as inherent property of the components and from design architecture, those failure rates that are the result of reliability predictions are forgotten.

If the random failure rates were to be included into test results, considering the high reliability of present day's products, the test duration would be too short to count all of them and to produce a failure rate with any reasonable confidence level. The reliability growth test should then be a combination of reliability demonstration and growth, and the reliability demonstration tests require a duration of approximately ten MTBF values. But, if the final failure rate is to be the product failure rate, then all of the failure rates must be reported.

Since reliability growth is focused on correction of design related problems, then the final MTBF or failure rates should not be reported as the final achieved product failure rates, they are only final failure rates of the design related failure modes. The reliability growth should be measured only between the failure rates of correctable and the corrected design problems.

1.1.2 The Test Duration

The test duration is mathematically determined based on the assumed "initial" or "current" reliability, the reliability goal, and the "initial test time."

At the beginning of test, at some time t_I, the failure rate is assumed to be $z_I(t_I)$ and the equation would be:

$$z_I(t_I) = \lambda \cdot \beta \cdot t_I^{\beta-1}$$

The final failure rate that is to be achieved is:

$$z_F(t_I) = \lambda \cdot \beta \cdot t_F^{\beta-1}$$

The needed test time (t_F) is then determined from the ratio of the two failure rates:

$$\frac{z_F(t_F)}{z_I(t_I)} = \frac{\cdot\, t_F^{\beta-1}}{\cdot\, t_I^{\beta-1}}$$

$$\ln(t_F) = \frac{\ln[z_F(t_F)] - \ln[z_I(t_I)]}{\beta - 1} + \ln(t_I)$$

$$t_F = t_I . e^{\frac{\ln[z_F(t_F)] - \ln[z_I(t_I)]}{\beta-1}}$$

For the equation above the questions are about the identity of most of the measures:

- Who or what is $z_I(t_I)$?
- What is assumed to be the t_I?
- What does the $z_F(t_F)$ represent?

The handbooks and the reliability growth software state that:

- t_I is the initial test time
- $z_I(t_I)$ is the initial product total failure rate found from the similarity with other products, assumed or determined in some other manner
- $z_F(t_F)$ is the final product failure rate achieved at the end of the reliability growth test program.

The comments to be made here are:

- The initial failure rate, $z_I(t_I)$, since it is shown as the power law, cannot be the total product total failure rate, but the initial failure rate attributed to the correctable design related failure mode
- As discussed in Section 1.1.1, the $z_F(t_F)$ is only one and a small part of the final failure rate attributed to the final failure rate of the design related correctable failure modes.

The initial test time, t_I, is a matter of interpretation, understanding, various assumptions, or just assumptions. There are numerous explanations and papers given on the subject, but simply because of the power law mathematics, it cannot be equal to zero. Some say it is the time to the first failure (a reasonable assumption) others speculate that this is the time by which the "infant mortality" failures are detected and corrected (may not be a practical assumption). Whatever it is claimed to be, it is a large factor in the overall duration of a reliability growth test as shown in Figure 2.

As seen in Figure 2, it seems clear that the test duration may be adjusted if so needed, but adjusting the assumption o the initial test time. The graph was plotted for a rather high initial failure rate (256 failures per million hours) and for a goal failure rate about 60% of the initial failure rate.

If the calculations were done for the B-type failure modes, the initial failure rate would have been approximately 30% of the failure rate used in Figure 2, and the goal failure rate would have been at least 10 times less than assumed for the Figure 2 because those failure modes need to be almost eliminated, then the plot would be as shown in Figure 3 (following page).

Regardless of what was the assumed initial test time, duration of correctly planned reliability growth (for improvements of failure modes that can be mitigated) is cost and schedule prohibitive and more or less not possible to perform. This is because of the lower initial failure rate, where correct goal of mitigating the design related failure modes that can be corrected, is lower than the overall product failure rate, and the goal failure rate is also considerably lower. The correct approach makes the traditional reliability growth testing close to impossible to carry out.

1.1.3 Applied Stresses and the Product Desired Useful Life

With the traditional reliability growth test approach, the test was to be performed under what was assumed to be the product(s) normal use conditions and associated stresses and their magnitude. Those stresses are applied during the test, combined or sequentially, during the duration of the test. Given the mathematically determined test duration which is only a function of assumed initial and goal reliability and the initial test time, the duration of stress applications were unrelated to use profile or the expected product life.

The stresses are applied at the levels they are expected to be in use, the expectation that could in itself have a long and complex debate about where used, how used, who would be using them, what would be OFF or ON conditions. The assumption list is too long to be accommodated by a traditional, rather short reliability growth test.

1.1.4 Additional Conceptual and Mathematical Error

In test failure data analysis, determining the shape parameter of the Weibull Intensity function requires time to design related failures (systematic failures). Both MIL-HDBKs show an example where, when only one of the tested units failed at some time,

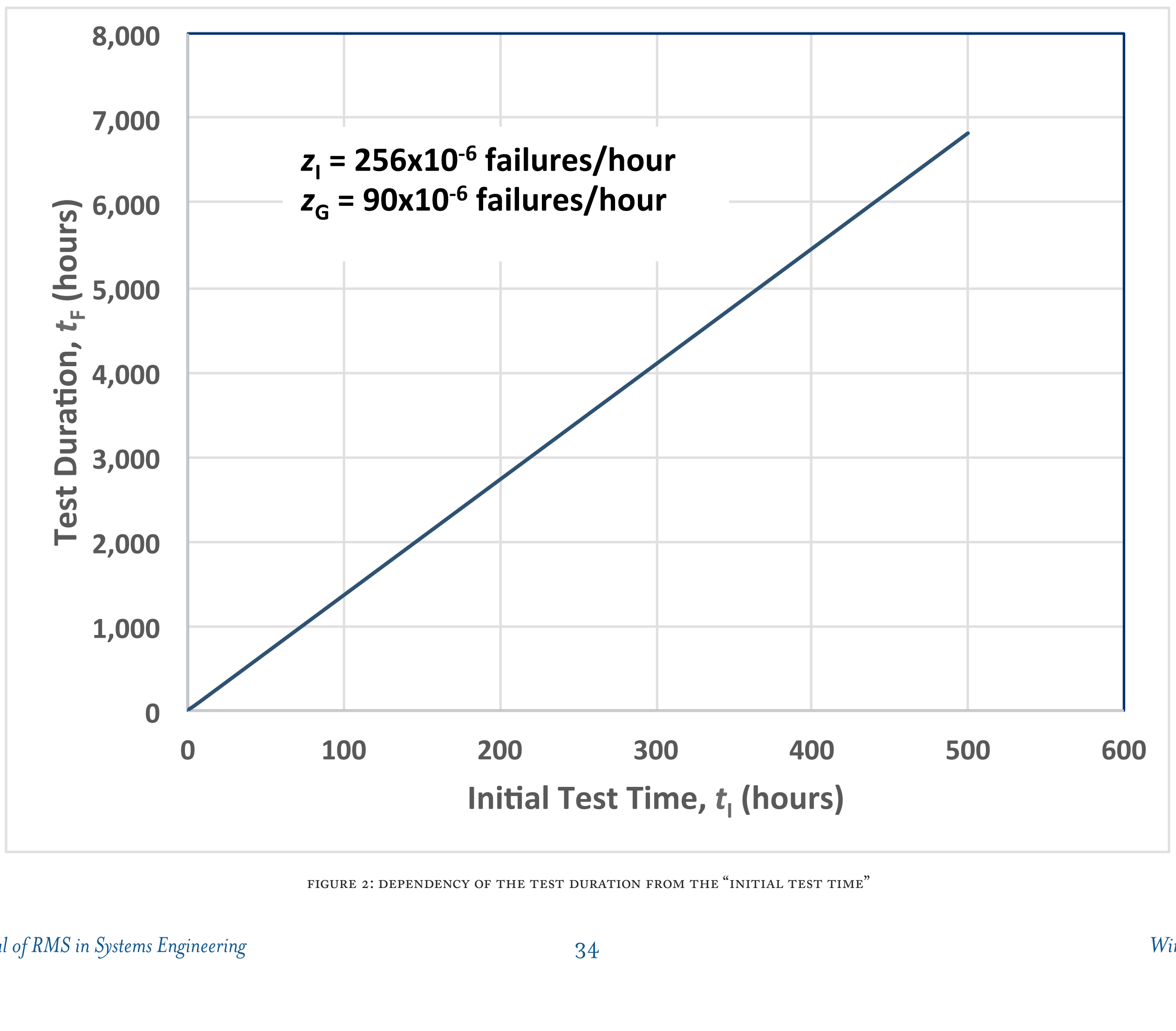

Figure 2: Dependency of the test duration from the "initial test time"

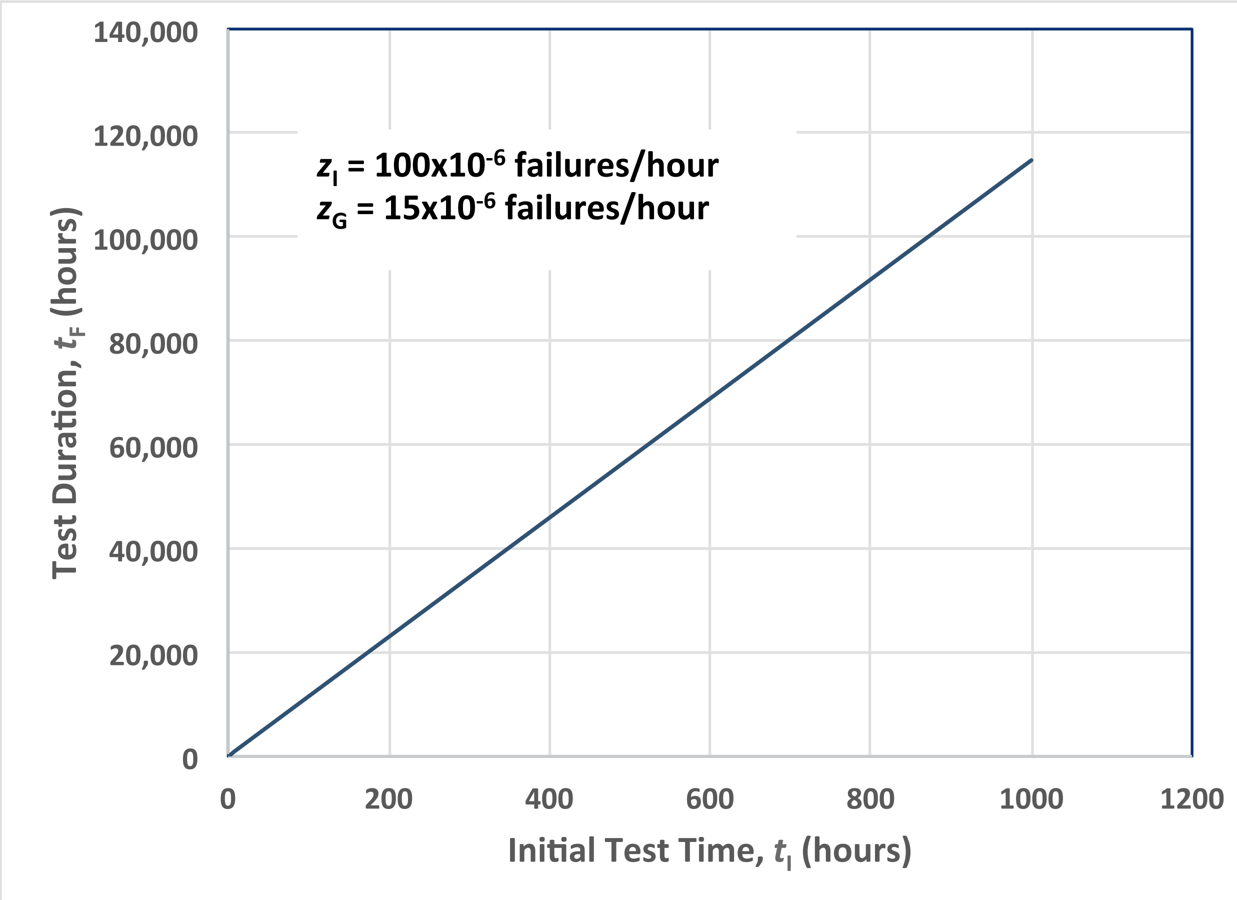

FIGURE 3: RELIABILITY GROWTH PLANNED FOR IMPROVEMENT OF B FAILURE MODES

the amount of accumulated time on the other non-failed units are added to that time. The practice of adding the test times of all units in test even if the failures are random in nature is a dubious approach which physically may not be justifiable. By adding the accumulated test time on all test units, those that did not fail are credited for not failing at the time when one of them fails so that test times become incredibly long. However, even if this approach is proper for the random failures, there is no justification to do so in the case of systematic design failures. If they happen in one unit, they are expected to happen in all of them soon thereafter. The appropriated design fixes will be introduced on the entire product—all of the units so the failure rates of all of them does change. This practice skews the value of the shape parameter and as well the test results. By doing this incorrect accounting, the correct power law equation for the final failure rate is not applied.

1.1.5 The Requirements for a Correct Reliability Growth Test

Considering all of the physical and mathematical shortcomings of the traditionally planned and performed reliability growth testing, there is a need for a test that would:

1. Provide test duration so that the following failure mode types can be accounted for:
   - Random and A-type design failure modes to achieve a reasonable statistical confidence in test results, a test duration of about ten times the product's expected MTBF value is required; e.g., if the total failure rate of failure modes is 2,000 hours, the test duration would be on the order of 20,000 hours.
   - Design related failure modes that were corrected for the high technology products of the present times the examples given in MIL-HDBK -189 are not realistic. It takes unbelievably low quality for a product to experience 27 design related failures in only 150 hours of exposure to nothing higher than the stresses of use environment. Not even deliberate destruction could achieve a better result.
2. Provide exposure to all expected stresses during the product's use for its lifetime duration and with the expected cumulative degradation and the use profile (sequence of their application) and a sufficient lifetime duration margin to ensure achieving the reliability goal. The desired test would provide a test of reasonable, affordable duration that would produce a cumulative degradation equivalent to the degradation a product experiences in its lifetime. Such a test is the accelerated reliability growth test.

2.0 Physics of Failure Accelerated Reliability Growth Test

To design an accelerated reliability growth test successfully, it is necessary to know the intended use environment, the magnitude of use stresses, the product's use, storage profile and the product design capabilities. Acceleration of individual stresses uses well-established techniques and the basis for the methodology is the assumption the test demonstrates the product strength regarding all of the stresses and sequences as they are applied in use. During the test, possible failures are investigated and if their cause is determined to be a design or manufacturing process, the improvement(s) is made. Times to failure for B-type failures are recorded for determination of the reliability growth function parameters. Times to failure, for design or process related failures that could not be mitigated, along with the failures scored as "random," are recorded, preferably in separate groups.

2.1 Physics of Failure Reliability

The product must be reliable regarding each of the applied stresses (environmental and operational); its overall reliability is then the product of reliabilities regarding each of those stresses:

$$R_{item}(t_0) = \prod_{i=1}^{N_S} R_i(t_i)$$

Where:

R_i = represents influence of a stress i on reliability of UUT when stresses are independent;

R = represents the reliability of UUT;

N_S = is the total number of independent stresses

t_0 = is the t_i of interest (life, mission, etc)

If equal reliability for simplicity is allocated to each of the stresses, Equation 7 is applicable:

$$R_{Item}(t_0) = \left(R_{Stress_i}(t_i)\right)^{N_S}$$
$$R_{Stress_i}(t_i) = \sqrt[N_S]{R_{Item}(t_0)}$$

The times to failure are usually assumed to conform to the exponential distribution, then the failure rate of that product (Equation 8) is:

$$\lambda_{Item}(Stress) = \sum_{i=1}^{N_S} \lambda_i(Stress_i)$$

The principle of the Physics of Failure is that an item would fail if interference between its strength and the applied stress exists or if the cumulative degradation due to stress application is greater than its designed strength. This principle is shown in Figure 4.

Assuming that the item or a system is tested for each of the

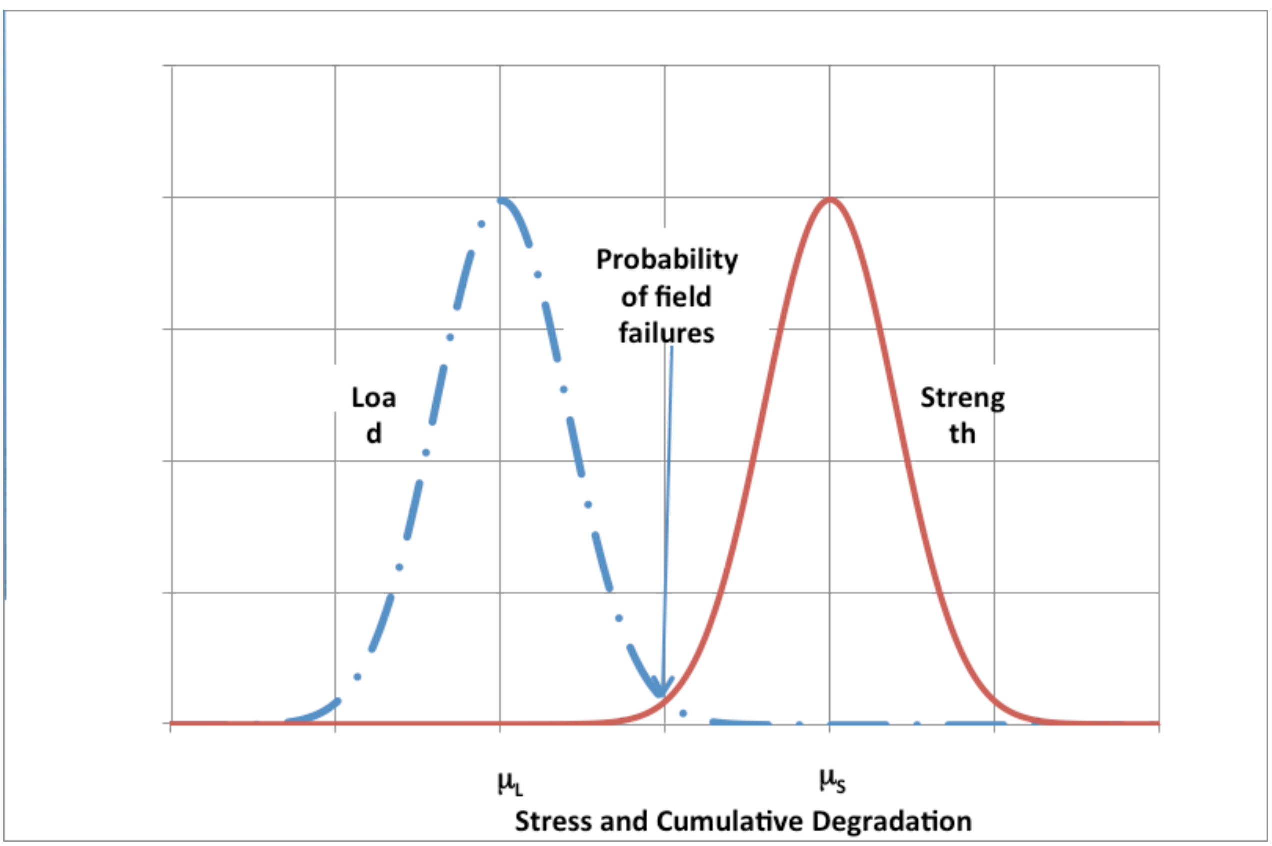

Figure 4: The Relationship of the Probability Density Functions of Stress/Load Degradation vs Strength

expected stresses, operational and environmental, its reliability regarding each of those stresses can be represented (Equation 9) by:

$$R_i(k,\mu_{L\_i}) = \Phi\left[\frac{\mu_{S\_i}-\mu_{L\_i}}{\sqrt{(a\cdot\mu_{L\_i})^2+(b\cdot\mu_{L\_i})^2}}\right]$$

Where:

R_i is the reliability allocated to the item regarding the specific stress during the duration of its application;

k is the multiplier of the actual stress duration, assuming the cumulative damage models;

μ_{L_i} is the mean duration combined with level of that load (stress/load) application in use;

μ_{S_i} is the mean duration combined with level of test required to demonstrate the strength, given that the applied stress in test and the use are equal;

a and b are the multipliers of strength and load mean values that would produce their respective standard deviations;

Φ is the symbol for the cumulative normal distribution

The strength can be represented as a multiple k of the load cumulative damage μ_L, so that the reliability of an individual stress/load is represented (Equation 10) as:

$$R_i(k,\mu_{L\_i}) = \Phi\left[\frac{k\cdot\mu_{L\_i}-\mu_{L\_i}}{\sqrt{(a\cdot k\cdot\mu_{L\_i})^2+(b\cdot\mu_{L\_i})^2}}\right]$$

Simplified, Equation 11 becomes:

$$R_i(k,\mu_{L\_i}) = \Phi\left[\frac{k-1}{\sqrt{(a\cdot k)^2+b^2}}\right]$$

Constants a and b are assumed multipliers of the mean strength and load that estimate their respective standard deviations. The value of the contestant a is considerably smaller than the value of b because the standard deviation in test is expected to be much lower than the standard deviation of the load in use.

Figure 5 shows reliability plotted for different combinations of values of constants a and b.

A "safe" assumption for the values of constants a and b is:

b = 0.2,

a = 0.05.

2.2 Acceleration of Individual Stresses

Test acceleration is performed using methods for quantitative reliability assessment with single or multiple acceleration factors.

2.2.1 Thermal Cycling

Thermal cycling can be a result of different causes, diurnal - nocturnal thermal cycles when an item is not powered (or powered) and thermal - cycling due to turning an electrical item ON and OFF. The cumulative degradation can be for different reasons, e.g., electromigration, crack propagation due to expansion and contraction of materials, etc.

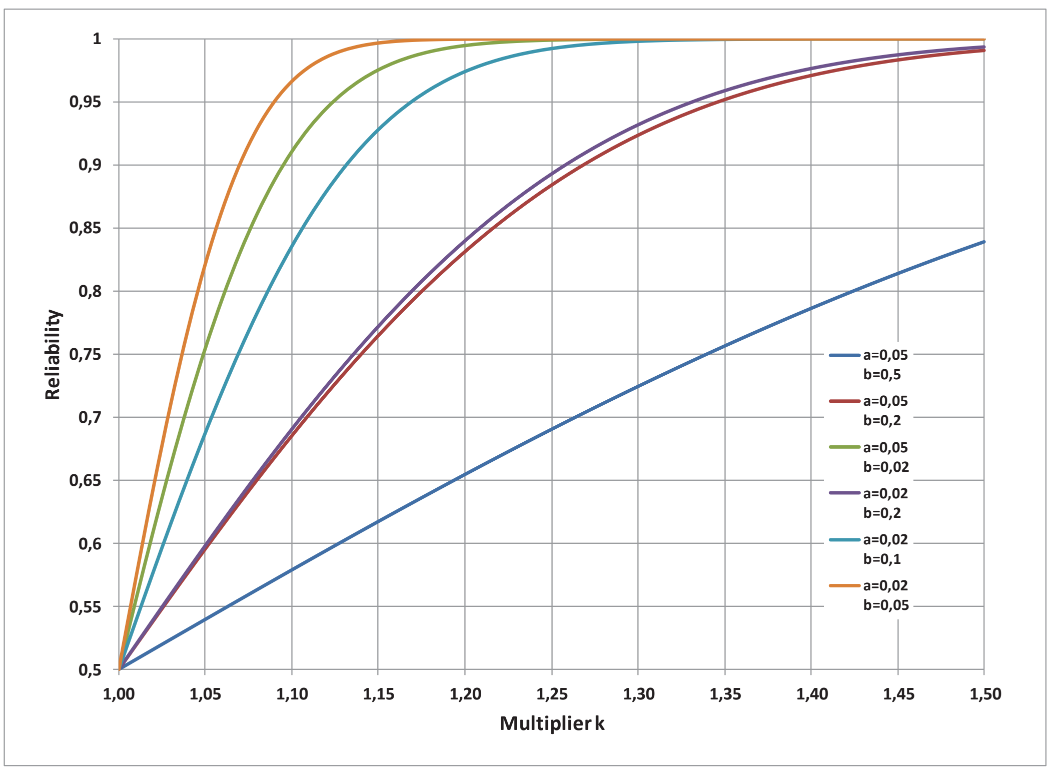

FIGURE 5: DETERMINATION OF THE MULTIPLIER K FOR THE DESIRED DEMONSTRATED RELIABILITY REGARDING AN INDIVIDUAL STRESS

The acceleration (Equation 12) is assumed by the inverse power law (Coffin-Manson):

$$A_{TC} = \left(\frac{\Delta T_{Test}}{\Delta T_{Use}} \right)^{m}$$

Where:

ΔT_{Test} = the temperature range in test

ΔT_{Use}= the temperature range in use (normalized to one value—the highest—using acceleration factors)

m = exponent, determined experimentally from test to failure in thermal cycling or using historical value from a similar product.

2.2.2 Acceleration of Thermal Exposure

The acceleration is assumed to follow the Arrhenius reaction rate relationship (Equation 13):

$$A_{TD} = \exp\left[\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{Use}} - \frac{1}{T_{Test}} \right) \right]$$

Where:

E_a = average activation energy in eV

k_B = Boltzman's constant = 8.62 E-5 eV/K

T_{Use} and T_{Test} are item temperatures in use and test, respectively in degrees Kelvin

Note: multiple exposures in life with different durations should be normalized to one exposure temperature, the highest (and the lowest if applicable); the acceleration is applied for test to that single temperature.

2.2.3 Temperature-Humidity Acceleration

Given that the temperature and humidity affect the same failure modes, the acceleration factors are multiplied. The humidity acceleration is the inverse power law and the temperature in humidity test is accelerated using the Arrhenius equation—thermal acceleration (Equation 14).

$$A_H = \left(\frac{RH_{Test}}{RH_{Use}} \right)^{h} \exp\left[\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{H\_Use}} - \frac{1}{T_{H\_Test}} \right) \right]$$

Where:

RH_{Test} and RH_{Use} are relative humidity in test and use, respectively

h = exponent experimentally developed for the tested item selected from the similar products

2.2.4 Vibration and Shock Acceleration

Vibration and shock accelerations are usually the inverse power law (Equation 15) of the vibration and shock RMS acceleration.

$$A_{Vib} = \left(\frac{W_{Test}}{W_{Use}} \right)^{M}$$

Where:

W_{Test} , W_{Use} = vibration applied in test and in GRMS (For shock it is the area under the shock pulse)

M = empirical constant, usually adopted from literature (black boxes)

2.2.5 Power Cycling Acceleration

Power cycling acceleration is one of the few time-compression accelerations applied in the reliability growth test. It replicates operational cycles—the test item is turned ON and OFF with faster ON/OFF cycles. The thermal cycle due to the ON-OFF cycling should be included into the thermal cycling test with the proper number of cycles and proper dwell temperatures up to temperature extremes.

2.2.6 Test Sequence

When the simultaneous testing is not possible, the life use profiles should be approximated by sequential testing for different environments; these should be partitioned and the sequences should be changed during the test. As an example:

3. Random vibration, 50% of the total duration in three axes
4. Thermal cycling with thermal dwell and operational ON/OFF cycling, 50% of the total duration
5. Humidity test with operational cycling (100%
6. Thermal cycling with thermal dwell and operational cycling (25% of total cycles)
7. Random vibration, the remaining 50% duration
8. Thermal cycling with thermal dwells and operational cycling—the remaining 25%.

2.3 Test Data Analysis

When corresponding times to failure in use are calculated for each of the failures that occurred in the reliability growth/life test, they are then ordered by increasing values and analyzed using one of the reliability growth models. The preferred model would be the analytical Power Law (named the CROW/AMSAA model in US Handbooks). However, in the case of a small number of test failures, where the analytical model may not have enough data points, the Duane graphical model can be applied. This is usually the case with products that had a comprehensive reliability program integrated into the product design/development process. The majority of failure modes addressed during design and development are mitigated, leaving only those failure modes that were not detected, so their number is limited.

Note: a spreadsheet can be developed with the embedded equations for recalculation and conversion of the accelerated exposure to the corresponding exposures in use, times to test are ordered by their increasing values and the parameters of the Weibull Intensity Function for the power law model or MTBF values for Duane model are plotted as is done in the traditional reliability growth test.

3.0 Conclusions

Accelerated reliability growth test allows insight into the entire life of a product to discover when the failures of any kind occur during actual use. A test design methodology does not require any assumptions of initial MTBF, initial test time, or growth rate. The test time is determined based on the goal reliability and stress degradation of the product, if and when it occurs. Testing for each of the stresses represents a life time duration of that stress type.

In addition to a more correct representation of the physical stresses and use, the accelerated reliability growth tests are of shorter duration than the traditional mathematically determined tests (on the average 60% shorter) and, consequently, more cost and schedule effective.

References

1. International Electrotechnical Commission. 2003. IEC 61014, Programmes for reliability growth, Edition 2. Geneva, Switzerland: IEC.
2. International Electrotechnical Commission. 2013. IEC/ANSI 61710, Power Law Model – Goodness-of-Fit Tests and Estimation Methods, 2013
3. Nelson, Wayne. 1990, 2004. Accelerated Testing: Statistical Methods for Reliability Data. New York: John Wiley and Sons, Inc.
4. Krasich, M. 2002. Accelerated Testing for Demonstration of Product Lifetime Reliability. Reliability and Maintainability Symposium.
5. Krasich, M. 2004. Test Design and Acceleration for Product Lifetime Reliability Demonstration. SAE World Congress, March.
6. Pecht, M., A. Dasgupta, and D. Barker. 1990. The Reliability Physics Approach to Failure Prediction Modeling. Quality and Reliability Engineering International 276-73.
7. Hu, J. M., D. Barker, A. Dasgupta, and A. Arora. 1993. The Role of Failure Mechanism Identification in Accelerated Testing. Journal of the Institute of Environmental Sciences July 39-45.
8. International Electrotechnical Commission. 2004. IEC 61164, Reliability growth – statistical test and estimation methods, Edition 2. Geneva, Switzerland: IEC.
9. Krasich, M. 2007 Accelerated Reliability Growth Testing and Data Analysis Method, Journal of the IEST, V.50, No. 2, 2007
10. Krasich, M, Accelerated reliability Growth Testing and Data Analysis, Reliability and Maintainability Symposium, Tutorial Proceedings, 2008

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