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Introduction

JAMES RODENKIRCH

The reliability of a System of Systems (SoS) can't be understood and accounted for during its architecting, design or development phases simply by focusing on individual/integrated system(s) MTBF/MTTR/time to failure numbers. The myriad stakeholders, user/operator personnel and their roles, the accompanying operational protocols/policies and the individual materiel system(s) "programmatic(s)" that encompass an SoS are critical components and reliability influencers that require as much reliability consideration or "weight," during the architecting and development phases, as the materiel entities. Thus, we have myriad materiel and "non-materiel" failures lying in wait, internally and externally, to/of an SoS, thanks to a complex and complicated integration of individual systems and software along with non-equipment entities, e.g., the human users and their needed doctrine/protocol(s) and organizations, emergent behavior, facilities, RF interfaces, etc. With all of these new influential system variables, the design for reliability of an SoS rises to the level of, "gosh, engineering reliability for/into an SoS is as complicated and complex as the SoS."

Challenges, for the Materiel Solution

A System of Systems offers an array of system functions that are far more than what is offered by the individual systems and impart challenges to the system architects designing the model and the system engineering team integrating the heterogeneous, independently operable systems. These challenges are derived from the following SoS characteristics, summarized by Mark Maier in his paper, "Architecting Principles for Systems of Systems"; presented at INCOSE's 1996 International Symposium:

1. A set or arrangement of interdependent systems related or connected to provide a given capability. The loss of any part of the system will significantly degrade the performance or capabilities of the whole. The challenge: Developing SoS solutions involves trade space between the systems as well as individual system(s) performance. However, system reliability performance, e.g., time-to-failure, is not an attribute the SoS designer/architect has any control over—that's the territory of the individual system's Program Manager (PM).
2. If disassembled, the systems can and do operate independently. The challenge: Creating an interoperable SoS when one has to resolve interoperability issues amongst systems selected from varied Families of Systems (FoS). Remember, the greatest risk to system(s) engineers is found at the external interfaces, especially amongst a buffet of systems not designed, often, to be interoperable with systems from other FoS(s).
3. The individual systems must be integrated but maintain a continuing operational existence independent of the SoS; i.e., they can be re-used in other situations or SoS(s). Challenges for 2 and 3:
   a. The systems were not

designed and built, necessarily, to function within an SoS; i.e., interoperability issues.

   b. Individual system time to failure(s) may not "help" improve overall SoS' reliability requirements.

4. An SoS does not appear fully formed. Its development is progressive and modified, e.g., individual systems are exchanged, new or previous system functions are exploited, new users join, organizations change, new doctrine/protocols are introduced and new platforms replace old or are added, etc.
5. It performs functions not achievable by or not in residence within components [an aspect of emergent behavior]. The Challenge for 4 and 5: A dynamic, evolutionary environment of change, due to changing or expanding SoS capability requirements or the discovery of unknown functions, the result(s) of emergent behavior, does not materialize because of the SoS' individual systems. It is the result of their relationships to one another coupled with the interaction of the SoS' human users as they operate/use the SoS; i.e., evolutionary change and emergent behavior cannot be predicted by examination of a system's individual parts.
6. It has a large/wide geographic extent, i.e., only information is exchanged, *not* mass or energy! In the world of an SoS' architect, there are myriad platforms—ships, planes, tanks, satellites, shore installations, even the human user, etc.—where the systems that provide functions and the human users who accomplish activities are physically located. The humans and systems are, typically, organized in to operational and system nodes. The resulting increased complexity, in the form of new system-to-system and node-to-node external interfaces strains reliable communication considerations across the SoS' enterprise and will impact interoperability negatively.

The New "Solution Space": DOTMLPF

The activities of the human users/operators, in concert with the Materiel solution—the integrated h/w and s/w components of the SoS—are what make an SoS work. However, human activities produce influencers that were never envisioned during the early days of system(s) integration but, with the advent of systems architecting processes, these activities are now integral pieces of the "total solution set" (DOTMLPF) design and development process for producing a working SoS. These influencers include:

1. The **D**octrine and/or policies that drive(s) how the SoS is used and the protocols the human user follow(s).
2. The affects of the **O**rganizational structure under which the users operate (i.e., collaboration and communication activities outside of their interaction with the actual SoS systems.
3. The required human **T**raining; adding cost, unplanned equipment, potentially, for architecting consideration and the negative effects, potentially, of poorly trained users attempting to integrate with other users and the systems.
4. In an organization, **L**eadership ensuring the right people are on the bus, in the correct seats and the bus is headed in the correct direction—in concert with the crafting of an efficient organization—sets the stage for efficient human interaction throughout the operational and RMS activities of an SoS.
5. The selection of competent **P**ersonnel associated with an SoS, i.e., the users of the SoS and their support personnel ensures technically competent operators/users that understand and follow the doctrine and protocols, can function effectively within the organizational structure and respond to leadership demands.
6. Finally, ensuring the requirements of the needed **F**acilities—e.g., water, power, lighting, support of/for human ergonomics, etc.—are met during the SoS' design.

The total solution set, DOTMLPF, is referenced as a major requirement for DoD systems architects to consider when designing an SoS(s). If DOT and LPF are not treated as important considerations and assigned equal weighting to the Materiel solution, unintended and negative reliability consequences for the SoS architect and system engineering team will result. As an example, new SoS functions can appear and be accepted as the SoS grows and matures; e.g., the users become aware of "what the system can do," through some "Hey, what if we do or try this?" If a reassessment of the architecture isn't undertaken as these SoS characteristics are modulated/altered OR if the SoS isn't designed to adapt its behavior while in an operational scenario (exhibit some resilience—the ability to adjust to unplanned changes) the complex system's reliability will suffer.

Additional reliability influencers can be found within its operational environment; an SoS operates in "the real world." However, its operating environment is non-deterministic, i.e., uncertain. Examples include:

- SoS platforms must operate and be managed, in varying weather conditions, which can be predicted but not with absolute certainty.

- Given an SoS has a wide geographical extent, i.e., only information is exchanged, *not* mass or energy, RF interfaces are a requirement. The RF interface can be Line of Sight (LOS) or Beyond Line of Sight (BLOS). If the interface is LOS, radio wave propagation, affected by sun spots, will impact the probability the interface will be 100% but cannot be predicted with any certainty. If the interface is BLOS, Rayleigh fading and weather, e.g., tropospheric ducting and radio wave absorption, will impact the probability of success but, again, can't be predicted with much certainty.
- The human operator(s) of the equipment/systems make(s) decisions based on information presented by the systems. Factors affecting the probability of success for a human's intervention with other humans and any system include; fatigue, the ability to complete the task 100% of the time (resulting from the degree of absorption and the end competence as a consequence of training) and distracters within the environment they work in, e.g., the mood of other humans they interact with, heat, water, lighting and amount of ergonomic considerations during any Human Systems Integration (HSI) efforts, etc. None of these factors are 100% predictable…simply because the human is involved.

An SoS extends and broadens the need for assessing and the impact of non-deterministic events. In a 2002 paper by William Crossley, (System of Systems: An introduction of Purdue University Schools of Engineering's signature area; [online] URL: *https://esd.mit.edu/symposium/pdfs/papers/crossley.pdf*) the idea of non-deterministic assessment, decision making and design under uncertainty is explored. He points out the "motivation behind the move to a capability-based acquisition strategy requiring system of systems solutions is that the capabilities sought by the customer are driven by the desire to have high performance that is robust with respect to varying operating conditions and scenarios." An example Crossley utilizes to illustrate varying conditions is one mission specified in the Coast Guard's Integrated Deepwater System (IDS) program. Search and rescue is a high-visibility, high-priority mission for the Coast Guard. If one could assume that a distress call from a party in danger always contained exact locations of the party, it would be fairly easy to determine which assets should be used to retrieve the person(s) needing help. However, the distress calls do not always contain precise information (non-deterministic), so the Coast Guard must often search for the person(s) and then retrieve the person(s). If the Coast Guard must cover a large search area, an aircraft asset may prove fastest to locate the missing individual, but would not allow for retrieval of the person. For retrieval, a surface vessel or a helicopter could then be dispatched. Conversely, if the lost person is in a small area, or the sea is at a sea state too high for safe surface vessel operations, a helicopter may best perform both the search and rescue functions. Other variations in weather condition, search area size, location information, etc. could be posed as conditions within which the search and rescue mission is needed. The Coast Guard expects to successfully perform the mission regardless of these variations; hence, the Coast Guard maintains several different types of assets, capable of independent operation, to help perform this mission regardless of the operating conditions [Ed: the majority of operating conditions are uncertain or non-deterministic].

The impact of non-deterministic, uncertain events must be viewed from an external and internal perspective. Internal uncertainties include less than satisfactory design, performance and implementation challenges, program/project execution and the external internal results of emergent behavior. As an example, internally, an SoS does not appear fully formed. Its development is progressive and modified, e.g., individual systems are exchanged, new or previous system functions are exploited by new and established users who, after having operated and gained familiarity with the SoS' functions, simply ask the question, "What if"?

External uncertainty includes changes in the market, the operating environments (discussed above), business processes and threats. Other external influencers include emerging requirements/expectations and changes in priorities (thanks to myriad stakeholders), emerging competitors (including users) and the introduction of new technologies which current users view as "let's improve the SoS by adding new h/w or s/w."

In summary, an SoS is dynamic. It exhibits or engenders an evolutionary environment of/for change. The SoS' known capabilities or the discovery of unknown functions (the result(s) of emergent behavior) doesn't materialize because of the SoS' individual systems. It is the result of their relationships to one another coupled with the interaction of the SoS' human users as they operate/use the SoS and come up with lots of "what ifs" plus factors such as evolutionary change, emergent behavior and the affects of internal and external uncertainty. Thus, SoS' reliability is more than what it was – system, subsystem and/or component MTBF and MTTR numbers. In an article I've been working on, terms that are appearing often that may answer the need for a new "view" of reliability include "robustness" or "resilience"; they don't replace reliability—they embellish it, they add credence to the need to view an SoS' reliability in a dynamic light. Regardless of which one resonates with you, either can be utilized to describe the dynamic part of the SoS' reliability problem that deals with what can "go wrong" across the breadth of the system-of-system (SOS) domain and the time required to "undo the wrong" to return the system to an acceptable—albeit, perhaps, different—level of operation. As an example, multiple internal and/or uncertainties, along with materiel failures may occur, all at once or within short time periods of each other. These combined failures will place the SoS' ability to function correctly over varying times during the SoS' "time in operation" in serious jeopardy and planned/engineered equipment "hot swaps" will, with a 100% chance of certainty, not "fix the problem," completely.

How do we model this new "reliability dynamic(s)"? What new Measures of Effectiveness and Measures of Performance will become KPPs for a SoS architect and system engineering team? These are but a few of the questions surfacing today. We hope the readership and RMS membership will embrace the notion of a new subset of reliability (robust or resilient), begin exploring and offer up articles for our Journal. I, personally, believe instilling the notion of system robustness or resilience into the RMS community will promote and trumpet the innovativeness and forward thinking approaches being fostered by the RMS Partnership. As Dr. Russ Vacante likes to say, "What say you"?

Our four articles for the Spring 2016 Journal continue to offer insight and/or open up new foci across the Enterprise. Our first submittal by Dave Pauling, *"Protecting the Homeland," An Interagency Paradigm for "Protecting the Homeland" through the application of DOTMLPF in Homeland Security's successful reuse of Department of Defense Aerostat Systems,"* was proffered as a study to illustrate how the considerations of/for DOTMLPF can work well and support and promote a successful systems engineering process. Dave is a first-time author for the RMS Journal and we hope he'll consider submitting future articles.

Our second offering, *"Successful Prediction of Product Quality, Reliability, Durability, Maintainability, Supportability, Safety, Life Cycle Cost, Recalls and Other Performance Components,"* was submitted by Dr. Lev Klyatis. We published an article by Dr. Klyatis in the winter, 2013 Journal that focused on his examination of the current situation associated with reliability, maintainability, and supportability (RMS) examines the current situation associated with reliability, maintainability, and supportability (RMS) problems associated with use of traditional test technologies during design, manufacturing, and acceptance. This time around, Dr.Klyatis looks at the predictive side of RMS, focusing on successful strategies employed for more accurate predictions.

Our third article by Michail Bozoudis, a returning author, is "Case Study: A Parametric Model for the Cost per Flight Hour. Mike did such a great job with his Winter, 2015 article, "A Stochastic Model for Availability Projections," that focused on the Hellenic Air Force (HAF) F-16 Weapon System Support Program Office study aimed at optimizing the F-16's Materiel Availability, I asked him to step up with another article. He obliged and we're pleased with his treatment/view of a parametric or "top-down" estimating technique that Mike calls, "a relatively fast and inexpensive estimating tool."

Our fourth offering comes from Mr. John Blyler. John, Dr. Russ Vacante and I have been chatting back and forth the past three months over the concept of resilience as a subset of Reliability. My opening remarks focus on the ideas I've formed during my initial foray into resilience but I wanted a "second view" and treatment so I asked John if he'd provide another viewpoint. John was willing and put forward his thoughts via his submittal, *Design Heuristics for Resilient Embedded Systems: Resiliency May a Richer Metric of Reliability but How Can it be Engineered into Systems?*

So, there you have it—four rich, in depth articles that provide us an eclectic "look" at the world of RMS through the broader lens of systems engineering. With the summer months upon us, the RMS Journal "crew" hopes you have myriad opportunities to enjoy the warm days ahead with friends and families. ●

Protecting the Homeland:
An Interagency Paradigm for "Protecting the Homeland" through the Application of DOTMLPF in Homeland Security's Successful Reuse of Department of Defense Aerostat Systems

DAVID PAULING

Abstract

The focus of testimony by Department of Homeland Security (DHS) and Department of Defense (DoD) executives to the House Committee on Homeland Security, Subcommittee on Border and Maritime Security on November 15, 2011 was "How can DHS reuse retrograded DoD technology to secure the border." This article characterizes, in terms of the total solution set, DOTMLPF (Doctrine, Organizational, Training, Materiel, Leadership, Personnel, and Facilities), the extraordinary interagency cooperation across DHS and DoD, expected and unexpected challenges and quantifiable successes associated with the reuse of a specific DoD technology for homeland border security counter drug, counter terrorism activities.

Highlighted are the positive roles of interagency Cabinet level and Congressional enablers, committed CBP and DoD leadership with a focused vision towards technology innovation, a "front-line" user community seeking contingency-driven "game-changing" capability, the coordination of specialized expertise in operational evaluation and an agile rapid response expeditionary special project team. What attracted community attention was the success of the program in the face of high likelihood and consequence of failure due to related political and legally charged complexities and operationally demanding, compressed schedules for deployment and execution.

Extraordinary challenges and impediments were confronted and successfully addressed to resolve inter and intra agency incongruent doctrine, organization, and training requirements. The materiel involved were tactical aerostat systems, a particular DoD high priority force protection technology deployed in the Southwest Asia theater of operations. These tactical aerostats and re-locatable towers (see Figure 1, following page). were considered unique, expansive technologies for Customs and Border Protection (CBP) border security persistent surveillance, necessitating an extensive evaluation for potential utility in the border environment. It was the positive role of leadership and personnel from the highest levels of the Legislative and Executive Branches of Government down to the tactical project team levels in evaluating, operating and executing timely facility accommodations. It all led to a realization of positive measures of performance, the filling of a technology gap and the ultimate goal—the advancement and improvement of border security and agent safety.

In October 2014, government members of the aerostat team received the DHS Secretary's Award for Excellence for innovation to advance the mission

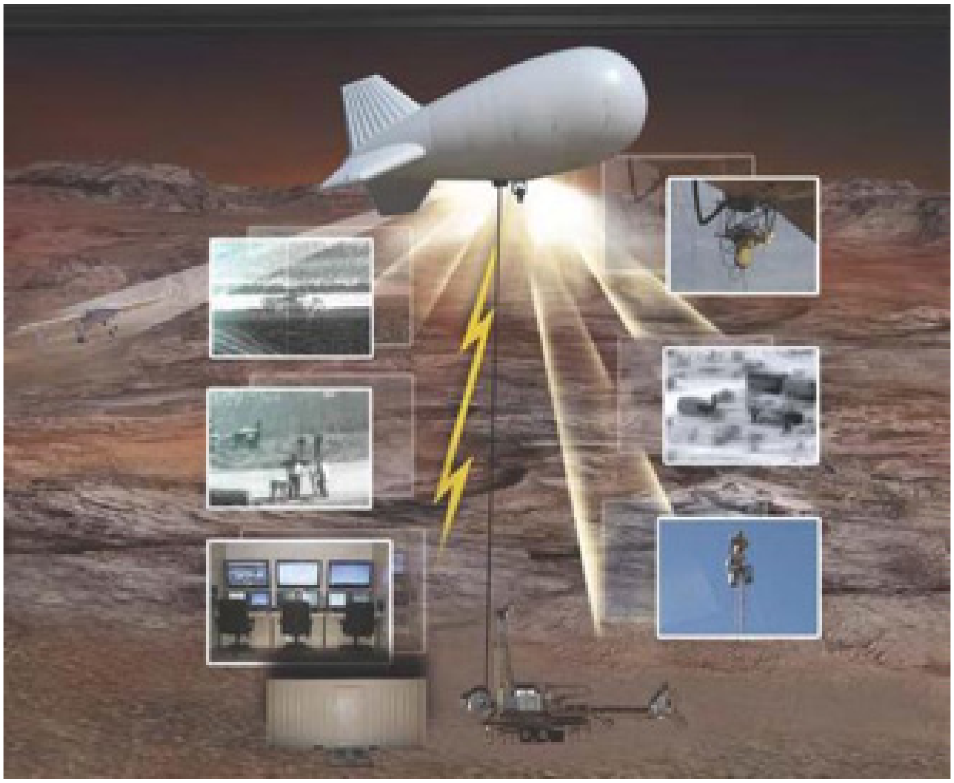

FIGURE I – The Rapid Aerostat Initial Deployment (RAID) OV-1

of DHS. The aerostat team was recognized: "for successfully leading a multi-agency task force to enhance comprehensive border security." Subsequently, in December 2015, the National Defense Authorization Act included statutory language establishing preference of reusing DoD excess equipment for Border Security activities, a direct result of challenges and exceptional results outlined herein.

Background: The Challenge

The Army indicated in May 2012 they anticipated their Rapid Aerostat Initial Deployment (RAID) systems and possibly their Persistent Ground Surveillance Systems and Towers (PGSS/T) managed by the Navy to be excessed for transfer to CBP by mid-September 2012. DoD timeline to transfer excess technology (14 days first-come-first-serve) required CBP to complete an Operational Utility Evaluation (OUE) by August 31, 2012, considerably less time than required for a typical OUE that requires the following:

- establish Interagency Agreement to transfer funding to the DoD (120–180 days),
- achieve frequency transmission certifications in the AOR (270–365 days),
- gain DoD approval from Secretary of Army and/or Secretary of Defense (60 days),
- gain environmental approvals/exemptions (45 days),
- achieve rights-of-entry license from the local land owners (45 days),
- gain clearances from the Federal Aviation Agency (45 days),
- employ DoD subject matter experts to operate test systems (30 days),
- deploy border agents to provide OUE team security and law enforcement (30 days),
- transport test systems to remote sites (15 days),
- prep sites to accommodate the aerostats and towers (15 days),
- conduct OUE in an extreme border environment (20 days minimum),
- yield to border agent law enforcement when encountering Individuals of Interest (IOI) activity during the OUE (event driven).

CBP selected the Rio Grande Valley (RGV) as the OUE site due to its challenging border environment for both vegetation and topography. As delineated below in terms of DOTMLPF, CBP was actually able to complete the OUE on time.

Once the CBP Commissioner and executive staff were briefed on the positive results of the August 2012 aerostat OUE, their reaction was to deploy additional aerostat technology to the RGV as soon as possible to counter emerging border security issues. Secretary of DHS (SECDHS) confirmed the urgency; directing an immediate deployment for at least a six-month Force Development Event (FDE). This called for streamlining the internal CBP process for funding and deployment execution. It also unveiled considerable resistance and legal challenges.

The DOTMLPF Paradigm

The standard solution space for both DoD and DHS descripting requirements to fulfill operational capability gaps and strategic direction is Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities (DOTMLPF). Each DOTMLPF element is explored below.

Doctrine

Doctrine is the fundamental DOTMLPF principle that guides an organization and shapes a campaign. Doctrine in DoD and DHS was conflicted specifically for this tactical aerostat initiative and generally for the broader Congressionally endorsed interagency cooperation for reusing available DoD technology for border security purposes. The DoD guidance to transfer available excess DoD technology to Law Enforcement Agencies (LEA) is rooted in

10USC2576a1 whereby the Secretary of Defense (SECDEF) shall give preference for transfer to those applications in the counter-drug or counter-terrorism activities. But Defense Logistics Agency (DLA), delegated the responsibility to carry out the transfer of excess DoD technology, established a first-come-first-serve approach for all LEA's rather than a preference for border security counter-drug, counter-terrorism activities. Also, DLA's procedures did not provide sufficient time (only 14 days versus at least 4 months for aerostat-like technology) to conduct Operational Utility Evaluations (OUE) prior to claiming excess equipment. Compounding the DoD doctrine conflict on interagency cooperation, the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASAALT) issued a memorandum directing Army Program Managers (PM) and Program Executive Officers (PEO) to rescind agreements with non-DoD entities on transferring excess technology.

Respective DHS doctrine was evolving. The DHS virtual standard to validating capability needs and prioritizing joint capabilities was drafted in Joint Requirements Integration and Management System (JRIMS), an estimated 126 day process at best. But the JRIMS process for establishing requirements is incompatible with DLA's process of LEA's claiming excess DoD technology within 14 days of DLA postings, first-come-first-serve. DHS did not have rapid response technology deployment doctrine specifically or to accommodate DoD reuse activity in general.

Notwithstanding these doctrine discrepancies, SECDHS directed immediate aerostat deployment in the Rio Grande Valley to address emergent needs there. The Army PEO and PM responded by loaning aerostat systems to CBP's Office of Technology Innovation and Acquisition (OTIA).

Because of the short timeline, an existing Inter-Agency Agreement (IAA) between OTIA's Logistics and Sustainment (L&S) Directorate and Naval Air Systems Command (NAVAIR) was used for DoD to provide OUE engineering and logistics support for both the RAID systems, via PM Electro-Optic/Infrared Force Protection (EO/IR FP), and PGSS/T via NAVAIR. This IAA enabled the formal statement-of-work and critical funding transfer from DHS to DoD. For the follow-on FDE, this IAA approach was vigorously rejected by a Navy Echelon II lawyer contending it violated DoD doctrine (addressed in the Leadership section below.)

Organization

Organization is the DOTMLPF element through which individuals cooperate systematically to accomplish a mission and directly support joint capabilities. Numerous elements of the DoD organization were involved in the tactical aerostat initiative. These included the US Government cabinet and political sector (SECDEF, Secretary of Navy (SECNAV), Secretary of Army (SECARMY); the DoD Comptroller, Under SECDEF for Acquisition Technology and Logistics; Under SECDEF for Policy, Defense Office of General Counsel, ASAALT), the career uniform and senior executives (Joint Staff, Defense Intelligence, Commander Naval Air Systems Command, Naval Ship Warfare Center, Army Deputy Chief of Staff, Army PEOs, DLA), and tactical managers (Army PMs, Navy PMs, Navy legal counsel, project subject matter experts).

Likewise, DHS political elements (SECDHS and the CBP Commissioner) were involved as well as career senior executives (CBP Assistant Commissioners (AC) for the Operational Components, the United States Border Patrol (USBP) leadership in the Rio Grande Valley Sector, AC OTIA, and tactical managers including legal counsel, the DoD ReUse Integrated Project Team, Operational Evaluators, and Sector Border Patrol Agents).

This aerostat program encountered significant DoD and DHS conflicts within and across both organizations. DoD senior leadership supported the aerostat initiative but Navy legal counsel went to extensive measures to shut down the program. CBP experienced the natural tension between operators needing capability and headquarters addressing resourcing requirements.

Training

Training is the DOTMLPF element that provides a method of providing information, operation, and support necessary to execute Component assigned or anticipated missions. For this aerostat/re-locatable tower project, the training challenge was multi-faceted. Training for aerostat system OUE and FDE operations and maintenance support were offered to the border patrol agents but declined because operations tempo at the border prevented agent availability. Use of the National Guard was also denied due to roles and missions disputes within DoD. Hence, CBP engaged/funded the Army's aerostat project teams which provided aerostat operations and maintenance through Army existing assets. Note: This required special controls on the use of DoD personnel in a law enforcement environment in order to comply with Posse Comitatas Act (18USC1385)[2], DoD personnel shall not engage in law enforcement activity. The strategy was to engage DoD crews for primary operation, maintenance, and perhaps re-deployment for re-locatability evaluation purposes; use typical users, realistic scenarios, logistics support, and threat parameters; activate USBP supervisory agents to direct law enforcement officers during operations that turned live; and provide for some USBP secondary operation for familiarization.

Testing began with "boots-on-the-ground" 10 August and ended 31 August 2012, successfully accomplishing the OUE within the constrained timeline required. As the OUE moved into the testing phase, some amount of "creativity" on the part of the test team was required due to the shortened planning time (weeks rather than months). In assembling a field evaluation team for the aerostat OUE, key personnel were selected from OTIA functional elements. Extensive use of part time, on-call contractors was made to ensure the availability of right talent at minimum cost.

The systems' capabilities to detect, identify, classify, and resolve Individuals of Interest (IOI)s were specifically evaluated by CBP against operational indicators (OI):

1. Does the aerostat system increase situational awareness?
2. Can the aerostat system be deployed over typical operational terrain?
3. Can the aerostat system be operated and maintained in the operational environment?
4. Does the aerostat system provide adequate ground surveillance coverage to provide increased situational awareness in the operational environment?
5. Can the aerostat system be deployed/redeployed in the RGV operational environment?

The OUE team was very active in observing, evaluating, conducting, and reporting their findings. USBP Agents observed the evolution of USBP tactics and techniques in use the aerostats and documented a number of novel applications that are unique to the Border Patrol mission. By the end of the evaluation, it was clear that the participating USBP Agents were committed to the utility of the aerostat and provided a number of observations and insights to the evaluation team. The evaluation took on the aura of a "learning laboratory" for the Border Patrol and the flexibility of the evaluation team enhanced the experience.

Materiel

Materiel is the DOTMLPF element defined as all items necessary to equip, operate, maintain, and support Departmental activities for administrative or operational purposes. The objectives were to identify and exploit excess DoD retrograde technologies from the Southwest Asia operations for re-utilization for border security purposes to: 1) Satisfy critical CBP missions, 2) Save substantial CBP resources, and 3) Leverage new technologies to enhance border security.

As part of CBP's DoD technology reuse program initiative, advanced persistent surveillance technology for deployment along the nation's borders was one critical CBP focus area in support of the USBP mission. Coincidentally, the Army indicated some persistent surveillance technology, tactical aerostats and re-locatable tower systems—specifically their RAID aerostats and re-locatable 107 foot towers—could be available to CBP as DoD excess technology. Army also indicated some PGSS/T and Persistent Threat Detection Systems (PTDS) could be available to CBP on a loan basis after drawdowns from Iraq and Afghanistan. (RAID was managed by the Army PM and operates up to 1000 feet, PGSS/T was managed by Naval Air Systems Command (NAVAIR) in support of the Army Deputy Chief of Staff (G2) Intelligence Futures Directorate and operates up to 3000 feet, and PTDS was managed by the Army Product Director (PD) Aerostats, and operates up to 5000 feet). Estimated savings to the U.S. Government for CBP to reuse versus buy new retrograded aerostats is up to $7.5 million per unit and for re-locatable towers, up to $1.5 million per unit.

Overall, the value of aerostat systems as a force multiplier was palpable. CBP concluded the tactical aerostats provide a major operational advantage, enhance persistent surveillance and mobility, and improve border agent safety. The aerostat was able to eliminate over 39% of detections as not IOI's, thus enhancing the dispatch efficiency of USBP agents. They also demonstrated the lowest cost per square mile of coverage of any comparable technologies deployed in RGV. The view shed effectiveness of one aerostat system equals the coverage of at least 20 alternate technology systems deployed or planned for RGV deployment. Substantial increases in apprehensions of undocumented aliens and seizures of illegal drugs occurred every day the aerostats were deployed. Weather permitting, aerostats provide greater cumulative coverage than towers or other ground-based systems and their cost for the amount of Area of Coverage is lower that the towers or legacy systems. Consideration of the trade space between cost-per-area-of-coverage versus operational availability should be taken into account when making future deployment decision.

Leadership

Leadership is the DOTMLPF element defined as the responsible position or function of leading, providing guidance, and/or direction for group action toward mission accomplishment. As the opportunity to receive excess DoD RAID and PGSS/T systems gained clarity and the increased tempo for law enforcement activity emerged, AC OTIA committed to the aerostat evaluations and fully empowered his Executive Director (XD) with the execution. From the beginning, the AC made it clear the decision chain would be short and directly to him, giving his XD full power of the AC's office with the instruction to delay no critical action pending the AC approval.

SECARMY approval was necessary for DoD involvement in CBP's OUE since the RAID and PGSS aerostat systems were still part of the Army inventory and were being operated by Army personnel. The improbability of gaining timely SECARMY approval, required by 8 August, was a major concern and threat to the timeliness of the OUE. If each system was to be available in time for the proposed evaluation, the corresponding preparation by the fielding teams would have to start long before formal SECARMY approval. Otherwise the OUE would be cancelled and the aerostat technology declined for border security utility. Hence, OIAD accepted a pivotal but significant financial risk of about $40,000 daily to dispatch a robust advance party a week early to the evaluation site to ensure all site access requirements were met and OUE test resources were ready. SECARMY approval was received the afternoon of 8 August and the OUE launched—with two hours to spare.

Based on the OUE results, Chief of Border Patrol, CBP Commissioner, and SECDHS then directed an immediate, follow-on FDE for the RAID, PGSS/T, and PTDS in the RGV to provide for persistence surveillance during emergent, challenging border security operations there. For the FDE, DoD approval to support CBP had to be elevated to SECDEF for the below reasons.

A NAVAIR lawyer contended, after the OUE, that the existing OTIA/NAVAIR IAA used for funding DoD operators and maintainers in the OUE was inappropriate. She indicated two new IAAs were required, one with NAVAIR for the NAVAIR PGSS systems and one directly with the Army for the RAID systems. (This could delay FDE aerostat deployment for up to six months on what the SECDHS considered an emergent border security issue.) The NAVAIR lawyer also questioned the legality of deploying aerostats in RGV. Although Army General Counsel and other Navy lawyers approved the aerostat deployment, the NAVAIR lawyer elevated her objections directly to Office of Secretary of Defense (OSD), which prompted an expedited, broader review by the SECDEF direct reports. The required concurrence by Joint Chiefs of Staff, OSD Comptroller, Under SECDEF for Policy, Under SECDEF for Acquisition Technology and Logistics, Under SECDEF for Intelligence, SECARMY, SECNAV, and OSD General Counsel was quickly achieved and signed by the Deputy SECDEF. The FDE was launched immediately.

Political and Executive Leadership Commitment: At the onset of the OUE, AC OTIA made clear his commitment to assessing aerostat utility in the Border Patrol mission. For the follow-on FDE and upon recommendation by CBP Commissioner and Chief of border Patrol, SECDHS provided cabinet-level "top-cover" directing immediate FDE deployment. These strong executive positions prompted internal cooperation and set the stage for efficient and timely execution by CBP's aerostat team. SECDEF approval to provide DoD assistance was pivotal.

Leadership provided the key leverage to employ agile techniques and streamlined processes, break through barriers and institutional resistance, and achieve game changing success. The success of the OUE in demonstrating the utility and potential of the aerostat systems brought mixed reactions within the USBP. Some in USBP Headquarters expressed concern that aerostats threatened other established USBP programs. But USBP leaders in the RGV Sector argued that tactical aerostats were a "game changer," providing a unique capability they needed for their border security mission. The RGV Sector endorsement was recognized by SECDHS who directed immediate FDE deployment of more aerostats to address emergent issues there.

Rapid FDE deployment of the aerostat systems' technology as a capability gap filler was the initial guidance from SECDHS. The ability to deploy a technology within 60 days to address an emergent border security need was at play. To do so, DHS and DoD Echelons were required to work together in a complementary fashion to meet an emergent DHS need. While these Departments' secretariat-level and program management level leadership stepped forward, the DoD's "in between" Echelon II leadership in the Navy pushed back, citing other higher priorities. This was compounded by the NAVAIR legal resistance elevating objections to the SECDEF. Concurrence by SECDEF and Direct Reports quickly absolved the objections.

Personnel

Personnel "is/are" the DOTMLPF element focused on ensuring qualified personnel exist to support necessary capabilities across the Department. The aerostat evaluation intent was to examine the border security potential of both the RAID and the PGSS/T in an operational environment. No CBP personnel were available or qualified to operate the aerostat systems, so the Army's contracted DoD operators were employed. This required authorization by SECARMY to ensure compliance with the Posse Comitatus Act—no DoD or DoD contractor personnel shall direct or participate in law enforcement activities.

Given the Army's plan to release excess equipment (fiscal constraints) and DLA's short timeline to claim the equipment, CBP's time to complete utility evaluations was shorter than typical. Many participants and observers regarded the OUE and FDE as high risk of failure. The OUE risk was accommodating the short DLA timeline and the FDE risk was resistance by key stakeholder entities. The FDE legal issues raised by NAVAIR seemed most ominous and perhaps insurmountable. But with the ingenuity of the FDE aerostat team and the backing of DHS leadership at the highest levels, timely approval by SECDEF and his direct reports was gained thereby paving the way to deploy and complete the aerostat FDE.

A risk laden plan was devised to meet the deadline. Central to the strategy, was involvement of stakeholders and shared credit for support and eventual success. The Test Director's challenge was to prudently streamline the planning process. Critical objectives were identified, assigned to team members, and pursued in parallel (knowing full well that this entailed high risk). The strategy was to engage DoD crews for primary operation, maintenance, and perhaps re-deployment for re-locatability evaluation purposes; use typical users, realistic scenarios, logistics support, and threat parameters; activate USBP supervisory agents to direct law enforcement officers during operations that turned live; and provide for some USBP secondary operation for familiarization. A core planning team whose chief attributes were long standing government experience and connections to key organizations was established. All team members were very seasoned with extensive executive and/or test and evaluation experience with the embodiment of insight, flexibility, and innovation. Their capability to reach key agency personnel proved to be one of the most important contributions organic to the team.

Each team member brought a sense of ownership and commitment to success. Once aerostats and relocatable towers were fielded, the DOD teams provided exceptional support to CBP in operating and maintaining the aerostat technology, and in fact, were excited to be a part of assessing a capability that had such significant impact on "Protecting the Homeland." Qualitatively, the participating border agents embraced the aerostat technology in a border security environment.

Facilities

Facilities is the DOTMLPF element defined as the real property consisting of buildings, structures, utility systems, roads/pavements, and/or land associated with the designated activity and mission. RGV was the site for the OUE and FDE due to its challenging border environment, both vegetation and topography, and emergent law enforcement activity. Major facility challenges included:

- Achieving frequency transmission certifications in the AOR (typically 270–365 days),
- Gaining environmental approvals/exemptions (typically 45 days),
- Achieving rights-of-entry license from the local land owners (typically 45 days),
- Gaining clearances from the Federal Aviation Agency (typically 45 days).

Radio Frequency Assignment: This was known to be a lengthy process (9–12 months) if standard procedures were followed and radar equipment was not already licensed/certified. OTIA SE subject matter experts with connections to the National Telecommunications and Information Administration (NTIA) immediately coordinated with confederates to identify possible paths for approval that would fall inside the time scope of the aerostat evaluation. Their work identified three factors that could speed approval: first that the specific radar had been approved for use elsewhere, second, the intended areas of use were sparse in population and third, the radiation period would be short in duration. As a consequence of the team working with the NTIA, use was approved in time for the aerostat evaluation.

Environmental Assessment (EA): Two senior members from the OTIA Systems Engineering (SE) Directorate were assigned to coordinate the EA prior to site identification. The intent was to obtain approval in principle pending final site location. The strategy proved well-conceived. The EA representatives fully understood the intent of the aerostat evaluation and were convinced of its value. As a consequence they issued a Category Exclusion (CAT EX) once the sites were finalized. Normal clearance procedures, typically take up to 12 months, would have breached the timeline. The CAT EX was provided within the month.

Rights of Entry (ROE): This responsibility was accepted by the Border Patrol Sector Chiefs. The team coordinated with the chiefs who in turn identified cooperative land owners and began the negotiations for establishing aerostat sites. The Border Patrol identified one land owner in particular who had an active interest in the enterprise and his cooperation accelerated the ROE process. He actually cleared the sites himself.

Federal Aviation Agency clearances: DoD's relationship(s) with local FAA representatives was the key to accomplishing expedited clearances for the aerostat system OUE and FDE. While some alterations of the test plans and test sites were required to accommodate FAA needs, clearances were achieved in sufficient time to initiate evaluations on time.

Summary

The on time completion with sufficiently comprehensive results that enabled CBP leadership to decide to deploy aerostat systems immediately is a tribute to the tenacity, professionalism, and innovative attributes of key individuals. Executive "top cover," empowered authority and responsibility, and exceptional risk assessment and management skills were the "game changers" that produced a quality product for CBP. The essential attributes that drove success are executive leadership commitment, clear communication of expected outcomes, aerostat project execution and outcome alignment, leadership enabled short decision chain, selection of a skilled and experienced core for the evaluation team, and operational involvement early and throughout the project. Thanks to a focused effort on the total solution set, the Aerostat(s) and Re-locatable Towers are, now, a CBP Program of Record. ●

References

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Successful Prediction of Product Quality, Reliability, Durability, Maintainability, Supportability, Safety, Life Cycle Cost, Recalls and Other Performance Components

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Introduction

The topic of the article below relates to Systems of Systems approach. The term prediction has historically been used to denote the process of applying mathematical models and data for purpose of estimating field-performance of a system before empirical data are available for the system. Scientific-technical and technological prediction of performance are not developed enough. Especially if it relates to successful prediction, during service life, of industrial product/technological performance as interacted complex of performance components (quality, reliability, durability, maintainability, functional characteristics, life cycle cost, profit, recalls, and others).

There are many publications in reliability prediction. Published reviews in this area considered that for more than 30 years the reliability engineering community's appropriate use of empirical and physics-based reliability models, and their associated benefits, limitations and risks. Finally, in David Nicholls' *An Objective Look at Predictions*[1], it was concluded: "How can one ensure that prediction results will not be misinterpreted or misapplied, even though all assumptions and rationale have been meticulously documented and clearly stated?" The answer was: "We can't. Empirical and physics-based prediction will always need to be justified as to why the predicted reliability does not reflect the measured reliability in the field."

This situation relates not to reliability only, but to other components of performance also. This is one of the basic engineering problems with impact to the producer and user economic situation, as well as safety, reliability, supportability and other components of performance. Many industrial companies, including automotive, aircraft, aerospace, electronics, and other industries, experienced an increase in global recalls and complaints. For example, Toyota, Honda, General Motors, and other large automakers have each recalled millions of vehicles annually during the last years, lost $ billions and cannot stop this process.

In February J.D. Power announced the results of its 2014 U.S. Vehicle Dependability Study, and the news wasn't good. For the first time in more than 15 years, owners of three-year-old vehicles reported more problems than did owners of three-year-old vehicles the previous year."[2]

On September 19-20, 2012, RMS Partnership organized in Springfield, VA, a Department of Defence, Department of Transportation, and Industry workshop and symposium "A Road Map to Readiness at Best

Cost for Improving the Reliability and Safety of Ground Vehicles."[29] During this workshop, many presenters and attendees voiced a concern that reliability, durability, and safety are exibiting decreasing trends.[29] One possible explanation for such observations is that there are not enough strong requirements to industry in these areas, especially through standards.

There are many recent publications concerning automotive and other product recalls and related technical and economic problems. Mostly, these publications concentrate on safety issues that are related to a product's quality, reliability, and durability that in turn affect economic problems and people's lives.

In fact, the above information is not a cause for recalls, but merely the result. The cause of these recalls is actually the inefficient or inadequate prediction of product safety-reliability and other performance components during the design and manufacturing processes.

Therefore, safety issues and other problems are the result. This is one of the basic reasons for the issues outlined above. Unsuccessful prediction for service life (often for warranty period) of the product performance is one basic reason of many recalls and complaints, as well as higher cost and time for maintenance, higher life cycle cost than was planned during consumer's requirements, design and manufacturing. This problem is connected with the engineering culture.

Usually, advances in technology, especially in design, lead to economic development through more complicated products. Such advances require more attention to successful prediction of product performance and its components (safety, reliability, durability, quality, maintainability, supportability, life cycle cost, profit, recalls, and others). Mistakes in prediction lead to decreasing economic situation, safety, and others.

The recalls rate is the best component for analysis of the performance prediction level during service life, because, first, the recall rate accumulates the safety, reliability, durability, quality, profit, and total economic situation. Second, there is open official and objective information about recalls from the U.S. Government (National Highway Traffic Safety Administration and others), as well as companies-producers. Therefore, for analyzing the situation with the product performance, including its prediction, it makes sense to analyze the situation with recalls.

Current Situation with Recalls and Related Problems

Recalls relate to different products. For example, "Sony recalled 26,000 Vaio Fit 11A laptop/tablet hybrid computers in April 2014 amid reports of overheating batteries causing burns. A few weeks prior to this, Lenovo was forced to recall 34,500 batteries sold in the US and 2,900 batteries sold in Canada due to similar overheating and fire hazards."[3]

"Laptop batteries that catch fire. Pet foods that make animals sick. Children's toys covered in lead paint. It's hard to pick up a newspaper, watch TV or browse the headlines online without stumbling onto a report of a recall. In the past few years, there have been recalls for beef, chicken, candy bars, spinach, peanut butter, medicines, power tools and baby cribs."[4]

More examples: "As electronics have become more prevalent in everything from biomedicine to transportation, the need for advanced assessment of electronics reliability has become a necessity. Cochlear Inc. was forced to recall its cochlear implants due to moisture-induced failure in the electronics, resulting in major surgeries, explants, and losses of more than $150 million. Similarly, Medtronic Inc. recalled its pacemakers due to electrical 'opens' of interconnection electronics.

Since 2011, GM has recalled over 19 million vehicles and Toyota has recalled over 25 million vehicles due to electrical problems. The Boeing 787 Dreamliner fleet, certified to achieve a battery failure of no more than 1 per every 10,000,000 flight hours, was taken out of operation for more than 14 weeks due to two Li-ion battery fires in a two-week span (2 failures in less than 52,000 flight hours), and then allowed to resume flying without identification of the root cause of failure. Unfortunately, many of these electronics systems failures are in some sense inevitable, because the current methods to assess such systems have fundamental flaws due to unique application environments, complex degradation mechanisms, and interactions between performance parameters."[5]

"An automotive recall is a way for a manufacturer to tell you that there could be something about your car or truck that presents a risk of injury or property damage. And if you want to drill down to the very core of the issue, automotive recalls are intended to fix known problems with vehicles in an effort to keep roadways safer. Traffic crashes are the number-one killer of Americans under the age of 34, and a staggering 42,000 deaths are recorded each year on U.S. highways. Some of those lives could be saved by repairing unsafe vehicles or removing them from the roads. But who has the authority to do something like that?"[5]

If one will analyze the situation with recalls, the first conclusion from the above is: this problem is connected directly with safety-quality-reliability-durability.The second conclusion is: one recognizes these problems years after beginning manufacturing. That means: no designers, no researchers, no testers,

Year	Company	Vehicles Recalled (M)
2012	Toyota	5.3
	Honda	3.6
	General Motors	1.5
2013	Toyota	5.3
	Chrysler	4.7
	Honda	2.8
	Hyundai	2.2
2014	General Motors	26.8
	Honda	9.0
	Fiat-Chrysler	8.8
	Toyota	5.9

Table I – Top auto manufacturers that issued recalls in 2012–2014.[7, 8, 9, 10]

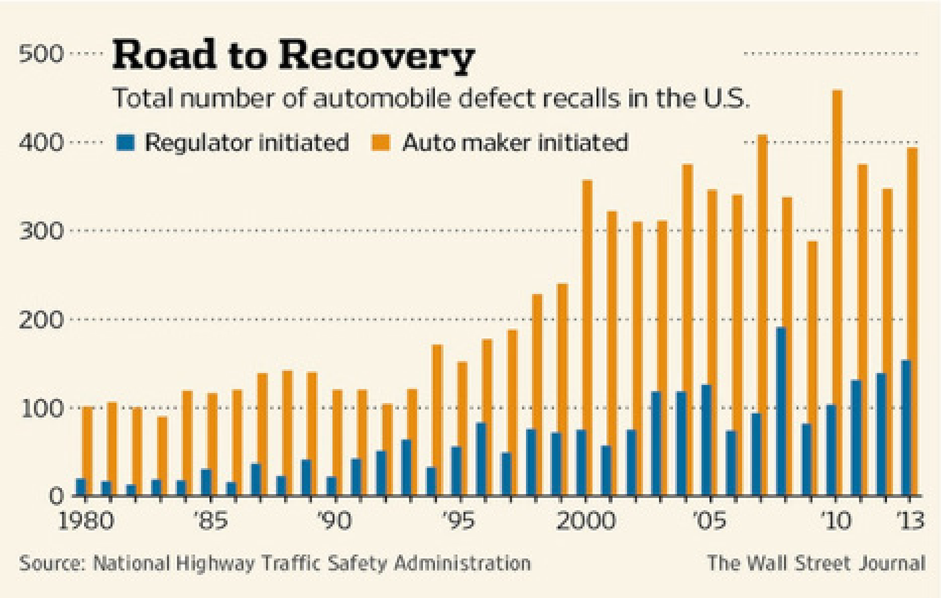
no manufacturers, no other group of professionals could predict and successfully prevent these problems during research, design and manufacturing - before the product came to the consumers. The third conclusion is: the companies in the automotive and other industries do not have reliable strategies and methods to successfully predict and prevent recalls during the service life of the product and even during warranty period.

The recall problem is also connected with problems of maintainability, availability, life cycle cost, and many others that influence the economic situation. Economic situation, during the development of technology, often leads to decreasing instead of increasing, as was planned during research, design, and manufacturing. If we consider the situation with recalls over a long period of time, we will see:

- Trends demonstrate that the safety-quality-reliability-durability are going down.
- The total number of automobile recalls in the USA during last more than thirty years has been increasing (Figure 1)

"Recalls by auto makers have been steadily increasing over time and the pace is accelerating in the past three years. A study by financial advisers Stout Risius Ross Inc. showed recalls ramping up between 2010 and 2013, attributing at least some of the increase to stronger enforcement by National Highway Traffic Safety Administration and the highly public nature of Toyota recalls in 2009 and 2010."[11]

The continuation of the above problems one can see on example General Motors situation in 1st and 2nd Quarters 2014. "This quarter, it has forecast taking a $1.3 billion loss for costs related to recalling 7 million vehicles, including those with faulty ignition switches. It has also said it will take a $400 million retax charge for changes in Venezuela's currency. That will come on top of any losses in Europe, which have totaled more than $18 billion since 1999."[30] The New York Times wrote June 30, 2014[31]:" But even as G.M. addresses its safety shortcomings with a beefed-up roster of product investigators, the spiraling number of new recalls—G.M. has surpassed 29 million worldwide this year—is threatening to undermine the company's reputation for quality"[31]. And, this year, federal prosecutors fined Toyota $1.2 billion, the largest criminal penalty for an automaker in the United States, after Toyota admitted to concealing information and misleading the public about the safety issues behind recalls of 10 million cars."[32]


Road to Recovery

Total number of automobile defect recalls in the U.S.

Source: National Highway Traffic Safety Administration

The Wall Street Journal

Figure 1 — Total number of automobile recalls in the USA.[13]

The problem is not only in economic situation, but with people's life. In Ben Klayman's article, it was written: "At least 29 people have died and 27 people have been seriously injured in crashes involving General Motors cars with defective ignition switches. Attorney Kennet Feinberg, who was hired by GM to compensate victims, updated the totals Monday (Arizona State)."[33] Feinberg says he has received 184 death claims since August. Of those, 29 have been deemed eligible for compensation, up two from last week. Twenty-seven of the 1,333 injury claimants have also received compensation offers. GM knew about faulty ignition switches in Chevrolet Cobalts and other small cars for more than a decade but didn't recall them until February. The switches can slip out of the "on" position, which causes the cars to stall, knocks out power steering and turns off the air bags. Feinberg will accept claims until December 31."[33]

This leads to lost money over recalls. For example, The Attorney General of Arizona said on Wednesday that the state had fielded a lawsuit against General Motors, claiming that the automaker had defrauded the state's consumers of an estimated $3 billion.[34] He added, "We're proceeding with our own suit because it's the best way to protect the citizens of Arizona.

Attorney General Thomas C. Horne, a Republican, said in an interview, "General Motors represented that it was taking care of the safety of its cars and in fact there were serious defects that it did not disclose to the public for years. Despite 4,800 consumer complaints and more than 30,000 warranty repairs, G.M. waited until 2014 to disclose this defect," the complaint says.[34] About 300,000 of the G.M. vehicles recalled this year were registered in Arizona. The Arizona consumer penalty statute stipulates $10,000 per violation, potentially amounting to $3 billion."[34]

The similar situation with recalls also exists in other markets (UK[35], Australia[36], and others). As was demonstrated earlier, the problem is not only in economic situation, but with people's life.

The Basic Strategy of Successful Prediction Technology

There are many recent publications concerning automotive and other product recalls and related technical and economic problems. Mostly, these publications concentrate on safety issues that are related to a product's quality, reliability, and durability that in turn affect economic problems and people's lives.

In fact, the above information is not a cause for recalls, but merely the result. As was mentioned earlier, the cause of these recalls is actually the inefficient or inadequate prediction of product safety-reliability and other performance components during the design and manufacturing processes. Therefore, safety issues and other problems are the result.

The real cause is unsuccessful prediction. People need prediction capabilities in different areas of their personal life, as well as in their professional activity. Such capabilities relate also to professionals who are involved in research, design, manufacturing, usage, marketing, finance, management, teaching, and other areas, because they need to know how to access the results of their current work in the real world for an extended period of time.

Prediction is an inalienable component of technology development. It is known that prediction is useful when it is successful. It was not published in books until 2016 the successful prediction of industrial product performance; there are mostly publications in reliability prediction, where reliability is considered as a separate component, without interaction with other performance components. But industrial engineers and managers, as well as users, teachers, students, consultants, and other professionals need publications, here, as in the real world, reliability interacts with other performance technical and economic components.

This article considers the strategy of successful prediction of industrial product performance, which is based on a consideration in one complex integration methodology and source for successful implementation of this methodology. Therefore, the focus of this article is to show the basis of technology of successful practical prediction of product performance. As a result, there will be an improved understanding in regards to recalls, leading to a solution of many reliability, durability, maintainability, supportability, and cost problems.

This technology is based on a new approach to prediction, which consists of two basic components:

1. Methodology of prediction, which reflects common principles of changing parameters of the product's performance components during the service life in the real world;
2. Obtaining accurate initial information of how to change the above parameters for specific models of the product during its service life (or warranty period) with using accelerated reliability and durability testing (ART/ADT).

Figure 2 demonstrates strategic scheme of successful prediction technology.

One can find the basic contents of this prediction in the author's book "Successful Prediction of Product Performance..." (SAE International, 2016). The basic approach of this article as an abstract of the above book applies to successful prediction technology for a large number of products and processes beginning with automotive, aerospace, military, commercial, and continuing, for example, in the consumer goods, medical, pharmaceutical, and teaching, fields. Therefore, the article has global character. As demonstrated the above scheme, strategic scheme of the above technology consists of two basic components.

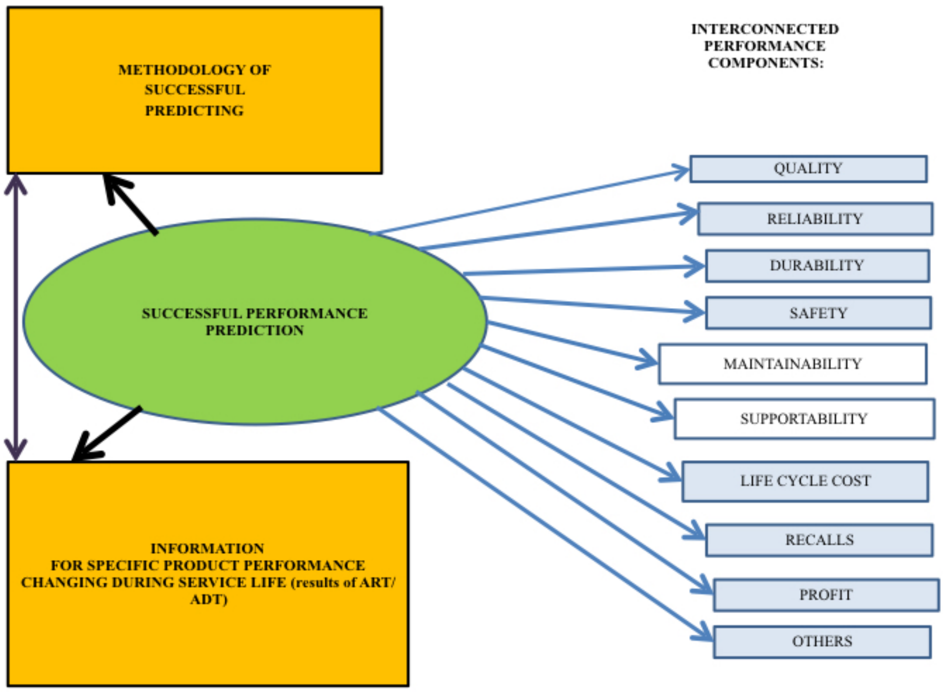

METHODOLOGY OF SUCCESSFUL PREDICTING
INTERCONNECTED PERFORMANCE COMPONENTS:
SUCCESSFUL PERFORMANCE PREDICTION
INFORMATION FOR SPECIFIC PRODUCT PERFORMANCE CHANGING DURING SERVICE LIFE (results of ART/ ADT)
QUALITY
RELIABILITY
DURABILITY
SAFETY
MAINTAINABILITY
SUPPORTABILITY
LIFE CYCLE COST
RECALLS
PROFIT
OTHERS

Figure 2 — Strategic scheme of successful prediction technology.

The first component considered in this article is methodology of successful prediction, which consists of the following basic sub components:

- Strategic scheme of product's performance successful prediction during service life (Fig.2);
- Common scheme of methodology for product's performance successful prediction;
- Modification of Kolmogorov's and Smirnov's criteria as common criteria of successful performance prediction;
- Methodology for selecting representative input regions for accurate simulation of real world conditions;
- Methodological aspects of successful prediction of product's performance with taking into account coefficients of recalculation, which depends on the manufacturing technology factors and usage conditions;
- Building specific type of influence function for reliability and maintainability prediction;
- Basic methodological aspects of quality prediction;
- System reliability prediction from testing results of the components;
- Methodology of durability prediction with consideration of expenses and losses;
- Methodology of the product's spare parts prediction;
- Successful prediction of financial components of performance (life cycle cost, profit, recall and others).

The entire methodology is too large for one article. The readers who are interested in detailed description of this methodology, can read many of its sub-components not only in mentioned author's book, but also in the books.[16,17,18]

One can see below some basic aspects of this methodology. Figure 3 is demonstrating the common scheme of successful performance prediction methodology and its basic components that one needs to use for different products.For this scheme implementation, one needs the criteria for successful prediction of product performance components. The problem is formulated as follows: there is the system [results of use of the product in the real world] and its model [results of ART/ADT for the same product specimens during design or manufacturing]. The performance component of the system can be estimated by the random value ϕ with the known or unknown law of distribution $F_S(x)$. Estimated performance component of the model use the random value φ with the unknown law of distribution being F_M.

The model of the system will be successful if the measure of divergence between F_S and F_M less than a given limit Δ_g.

The model results yield the realization of random variables φ_1: $\varphi_1^{(1)}, \ldots \varphi_1^{(n)}$. If one knows $F_S(x)$, using $\varphi_1^{(1)}, \ldots, \varphi_1^{(n)}$, then one needs to check the null hypothesis H_0. The null hypothesis

H_0, the measure of divergence between $F_S(x)$ and $F_M(x)$, is less than Δ_g. If $F_S(x)$ is unknown, it is necessary also to provide testing of the system. As results of this testing one obtains realizations of random variables φ_1: $\varphi^{(1)}, \ldots, \varphi^{(m)}$. For the above two samplings it is necessary to check the null hypothesis H_0 that the measure of divergence between $F_S(x)$ and $F_M(x)$ is less than the given Δ_g.

If the null hypothesis H_0 is rejected, the model needs updating, i.e., to look for updating the simulation of the basic mechanism of real world conditions for performing accelerated reliability/durability testing.

Estimates of the measure of divergence between $F_S(x)$ and $F_M(x)$ is done using a multifunctional

distribution and depends on a competitive (alternate) hypothesis. The practical use of this criterion depends on the type and forms of this functional distribution. To obtain an exact distribution of the statistics to test the correctness of hypothesis H_0 is a complicated and unsolvable problem in the theory of probability. Therefore, here the upper limits are shown for studied statistics and their distributions are found, so the level of values will be increased, i.e., explicit discrepancies can be detected.

Let us consider the situation when $F_S(x)$ is known. First, we will take as the measure of divergence between the functions of distribution $F_S(x)$ and $F_M(x)$ the maximum of modulus difference:

$$\Delta[F_M(x), F_S(x)] = \max\limits_{(x)<\infty} / [F_M(x) - F_S(x)] /$$

We understand that H_0 is the hypothesis that the modulus of difference between $F_N(x)$ and

$F_S(x)$ is no more than the acceptable level Δ_g, i.e.,

$$H_0\text{: } \max\limits_{x<0} [F_N(x) - F_S(x)] \leq \Delta_g$$

where $F_N(x)$ is the empirical function of distribution.

Against H_0, one checks the competitive hypothesis:

$$H_1\text{: } \max / F_N(x) - F_S(x) / > \Delta_g$$

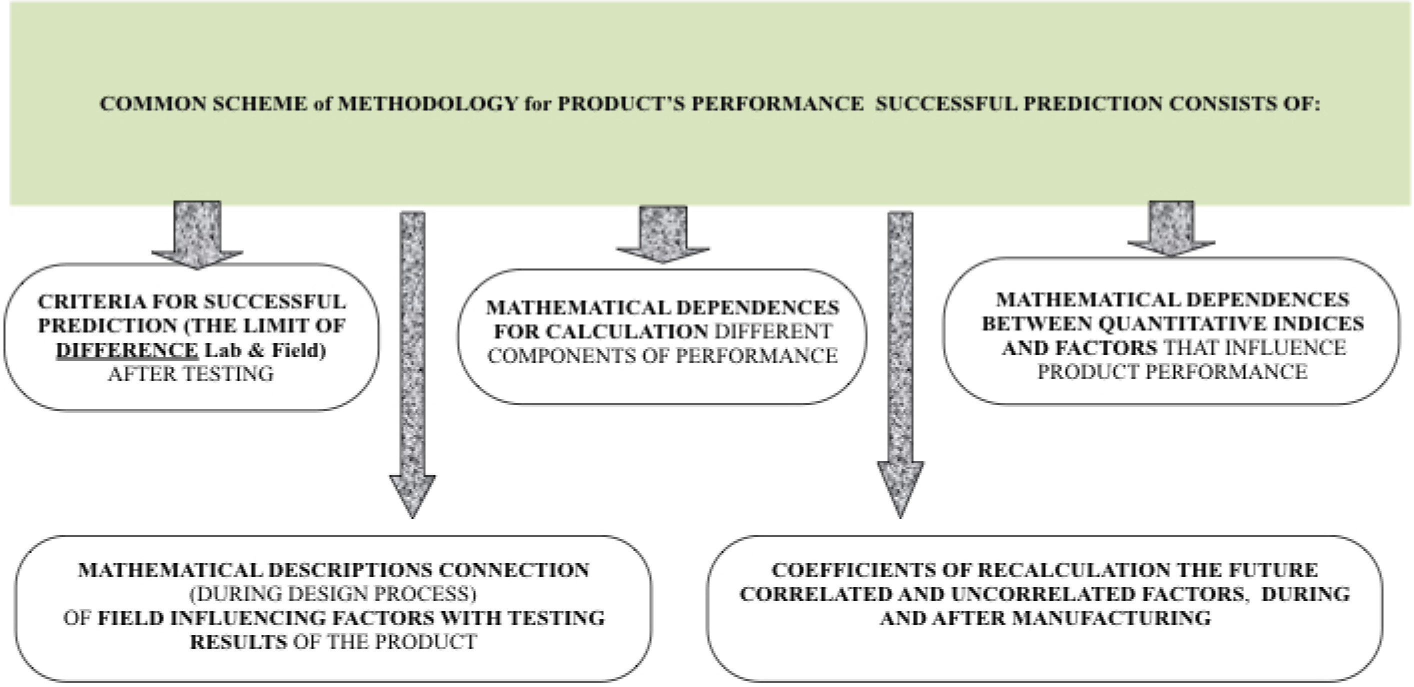

COMMON SCHEME of METHODOLOGY for PRODUCT'S PERFORMANCE SUCCESSFUL PREDICTION CONSISTS OF:
CRITERIA FOR SUCCESSFUL PREDICTION (THE LIMIT OF DIFFERENCE Lab & Field) AFTER TESTING
MATHEMATICAL DEPENDENCES FOR CALCULATION DIFFERENT COMPONENTS OF PERFORMANCE
MATHEMATICAL DEPENDENCES BETWEEN QUANTITATIVE INDICES AND FACTORS THAT INFLUENCE PRODUCT PERFORMANCE
MATHEMATICAL DESCRIPTIONS CONNECTION (DURING DESIGN PROCESS) OF FIELD INFLUENCING FACTORS WITH TESTING RESULTS OF THE PRODUCT
COEFFICIENTS OF RECALCULATION THE FUTURE CORRELATED AND UNCORRELATED FACTORS, DURING AND AFTER MANUFACTURING

Figure 3 — Common scheme of methodology for product's performance successful prediction.

The statistic of the criterion can be given by the formula:

$$\begin{array}{c} D_n = \max / F_N(x) - F_S(x) / \\ (x) < \infty \end{array}$$

Practically it can be calculated by the following formula:

$$\begin{array}{c} D_n = \max \{\max [\text{——} - F(\eta_m)], \max [F(\eta_m) - \text{——})\} \\ 1 \le m \le n \end{array}$$

It is very complicated to find the distribution of this statistic directly.[27] The $D_n \rightarrow \Delta_g$ as $n \rightarrow \infty$.

Therefore, it is necessary to look for the distribution of random value $\sqrt{n}(D_n - \Delta_g)$.

The statistics of the criterion can be expressed by the formula:

$$\begin{array}{c} F_n(x) - F_S(x) \\ R_n\ (a, 1) = \max \rule{3cm}{0.4pt} \\ F_S(x) \ge a\, F_S(x) \end{array}$$

The upper value for this statistic was found to be:

$$\begin{array}{c} / F_n(x) - F_S(x) / \quad F_n(x) - F_M(x) \quad F_M(x) \\ R_n\ (a, 1) = \max \rule{4cm}{0.4pt} \le \max \rule{3.5cm}{0.4pt} \cdot \max \\ \rule{2cm}{0.4pt} + F_S(x) \ge a \quad F_S(x) \quad F_M(x) \quad F_M(x) \quad F_S(x) \ge a\ F_S(x) \\ + \Delta_g \le R_n\ (a, 1)\ 1/a + \Delta_g \end{array}$$

Hypotheses H_0 and H_1 then become:

$$\begin{array}{c} / F_n(x) - F_S(x) / \\ H_0\text{: } \max \rule{4cm}{0.4pt} \le \Delta_g \\ F_S(x) \ge a \quad F_S(x) \end{array}$$

$$\begin{array}{c} F_n(x) - F_S(x) \\ H_1\text{: } \max \rule{5cm}{0.4pt} > \Delta_g \\ F_M(x) > a \quad F_S(x) \end{array}$$

Conclusion:

1. The engineering version of the obtained solution is that the upper estimation of the statistic criteria of correspondence, for some measures between the functions of the distribution of studied characteristics of reliability, maintainability, etc., were created in the laboratory conditions and in the field conditions. This can be useful for reliability, maintainability, and other components prediction as well as for solving other engineering problems, including accelerated development and improvement of various performance components, and others;
2. The mathematical version of the solution obtained follows: Approximate criteria, as modifications of the Smirnov and Kolmogorov criteria[8], by divergence ($A_g < 0$), were obtained for the comparison of two empirical functions of the distribution by the measurement of the Smirnov divergence:

$$\begin{array}{c} \Delta[F_M(x), F_S(x)] = \max [F_M(x)) - F_S(x)] \\ (x) < \infty \end{array}$$

And the Kolmogorov's divergence,

$$\begin{array}{c} \Delta[F_S(x), F_M(x)] = \max / F_S(x) - F_M(x) \\ (x) < \infty \end{array}$$

In Smirnov's criterion by the null hypothesis:

$$\begin{array}{c} \max [F_M(x) - F_m(x)] < \Delta_g \\ (x) < \infty \end{array}$$

By the alternative hypothesis:

$$\begin{array}{c} \max [F_M(x) - F_m(x)] > \Delta_g \\ (x) < \infty \end{array}$$

If $\Delta_g = 0$, we have Smirnov's criterion. An analogous situation applies for Kolmogorov's criterion. One can find in more detail the mathematical part of the above solutions in.[16] The difference between both versions is that in the measure using Smirnov's criterion one takes into account only the regions (the oscillograms of loadings, etc.) where $F_S(x) > F_M(x)$ and one looks for maximum of the differences only for those values. In measuring with Kolmogorov's criterion one takes into account the maximum of differences on all regions by modulus. The consideration of both criteria makes sense, because Smirnov's criterion is easier to calculate, but does not give the full picture of divergences between $F_S(x)$ and $F_M(x)$; Kolmogorov's criterion gives a full picture of the above divergence, but is more complicated in calculation.

One can choose the better criterion for a specific situation if the dependence on specific conditions of the problem is solved. Let us show the obtained solution by a practical example. In the real world were obtained 102 failures ($m = 102$) of details of car trailer transmissions. As a result of ART/ADT 95 failures were obtained [($n = 95$), Δ_g is 0.02]. For the real world situation, one builds the empirical function of distribution of the time to failures $F_m(x)$ by the intervals between failures. For the ART/ADT conditions, one builds by intervals between failures of the empirical function of distribution time to failures $F_M(x)$.

This is last variant to be considered.

If we align the graph $F_M(x)$ and the graph $F_m(x)$, then we will find the maximum difference between $F_M(x)$ and $F_m(x)$.If we draw the graph $F_m(x)$ and also overlay it, then the maximum difference $D^{+}_{m,\,n} = 0.1$. We obtain $\lambda_0 = 0.99$ for tested transmission using the results of ART/ADT.

$$\text{The } k = \frac{m}{n} \approx 1,$$

therefore:

$$F_x(x) = 1 - e^{-2x2} [1 + x\sqrt{2}\pi \cdot \Phi(x)]$$

For the above situation, we obtain F_x (0.99) = 0.55. And 1 – F_x(0.99) = 0.4. Therefore, 1 – F_x(0.99) is not small and the hypothesis H_0 can be accepted. For the above situation, we obtain F_x (0.99) = 0.55. And 1 – F_x(0.99) = 0.4. Therefore, 1 – F_x(0.99) is not small and the hypothesis H0 can be accepted. Therefore, the divergence between actual functions of distribution of time to failures of the above transmission details for the tested car trailer in real world conditions and in ART/ADT conditions (with taking into account the accelerated coefficient) by Smirnov's measure is within the given limit $\Delta_g = 0.02$. Meeting this statistical criterion shows that successful performance prediction of reliability, as well as other performance components prediction, can be achieved using the above approach.

The second basic component of successful prediction is accelerated reliability/durability testing (ART/ADT). ART/ADT is a key factor for successful prediction of product and technology performance, reducing recalls, increasing quality, safety, reliability, profit, maintainability, and decreasing life cycle cost. One can find detailed description of ART/ADT technology in.[17]

Companies in automotive, aerospace, commercial, as well as other industries, use different types of testing, where corrosion, vibration, solar radiation, and others, are simulated separately. One sometimes uses only testing with combination 3–4 parameters (temperature + humidity + pollution, or temperature + humidity + vibration, etc.), mostly for testing electronic products. These separate testing ignore interaction between different types of real world conditions, therefore simulating them inaccurately that contradicted the real world conditions. This is a quantitative negative aspect of current types of testing.

Moreover, companies ignore interaction between units and details during their work in whole vehicles, as it is in the real world. Currently, during the design, research, manufacturing, and usage of the product/process, one considers separately solutions for problems of reliability (durability, maintainability, serviceability, etc.) from other factors, such as quality, human factors, and safety problems. However, in the real world these processes act simultaneously and as one complex: they are interacted, interconnected, interdependent, and influence each other. Therefore, when one uses separate consideration of the above problems, one artificially ignores the real world situation. As a result, the reliability, durability, safety, maintainability, planned profit, and life cycle cost during research, design, and manufacturing are different than in the real world. The final result is unpredicted recalls and other economic losses. One can see from Figure 4 how poor product's performance influences profit through returns.[28]

There is incorrect qualitative testing, which is an obstacle for obtaining information for successful prediction. For example, one provides corrosion testing in chambers with simulation only chemical pollution. But in the real world vehicles corrode as a result of the interaction of chemical pollution, mechanical pollution, temperature, moisture, vibration, deformation, friction, and other components of real world conditions. One has to be careful with using physics-of-failure approach as a basic criterion of similarity real world results with current types of accelerated testing results. The quality of using this criterion needs more attention. The users have to ask themselves: if this criterion is so good, why do companies begin to recall many cars and other products several years after beginning manufacturing?

The Basic Concepts of the Strategy for Development of Accurate Physical Simulation of Real World Conditions and Accelerated Reliability and Durability Testing (ART/ADT)

For description of basic concepts, let us consider the real world situation and common types of simulation this situation for research and testing of the product/process, for obtaining information for successful prediction of specific product/process. For example, for automobiles, the real world interacting input influences consist of several groups: mechanical, electrical, multi-environmental, and others.

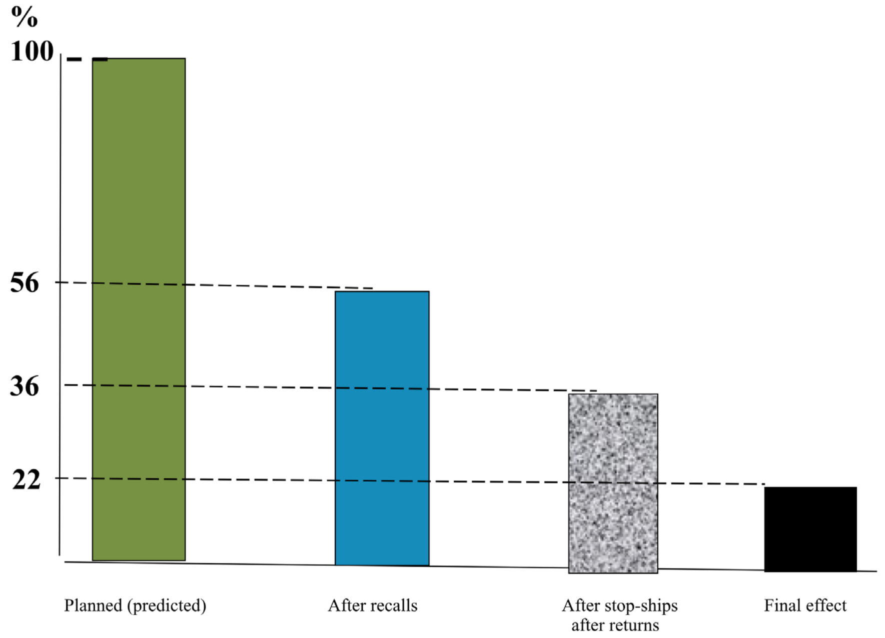


Figure 4 — Effect of poor quality, reliability, durability, and safety influence profit through returns, including recalls.[28]

Each group consists of various input influences. The multi-environmental group of influences consists of the interaction of temperature, humidity, pollution (chemical and mechanical), solar radiation (visible, ultraviolet, and infrared components), rain, snow, air fluctuations, air and gas pressure, speed and direction of wind, etc. The mechanical group consists of features of the road (concrete, asphalt, sand, cobblestone, profile, density, etc), and others. The electrical group consists of input voltage, ESD, electromigration, etc.

One can see a description of these processes below, and in more detail in [16], [17], [24], and other author's publications. Let us consider the influence path from real world input influences to the product reliability and durability (Figure 5). This influence path relates to the product quality, safety, life cycle cost, profit,and probability of recalls.

One can simulate physically and study under artificial conditions the physical essence of the above actual processes. For better understanding of the basic concepts for accurate physical simulation of field input influences, one needs to know what kind of field influences have to be simulated in the laboratory. Different types of input influences are active on the "in the field" subject while it is working as well as during its storage (Figure 5). These are interacted temperature, humidity, pollution, radiation, road features, input voltage, and many others ($X_1 \ldots X_N$). The results of their action are output variables (vibration, loading, tension, output voltage, and many others ($Y_1 ... Y_M$). The output parameters lead to the degradation (deformation, cracking, corrosion, etc.) and, finally, failures of the product.

One needs to simulate the input influences ($X_1 \ldots X_N$) in the laboratory for accelerated reliability and durability testing (ART/ADT) of the product. This article considers physical simulation of the above influences on the actual product, e.g., those which preserve the physical essence of the actual product processes (direct physical contact with the product).

The author demonstrated the above situation in detail in published books [16], [17], and [18]. In the above books one can also read many real examples from automotive, aerospace, commercial vehicles, electronics, and other areas. These books also analyze current literature in reliability and durability, and demonstrate how often some literature does not offer industrial companies and users a better understanding where money is lost, and where saving is possible. For example, one compares the cost of different types of testing without considering the cost of subsequent processes.

But many industrial companies and users use testing with the simulation of separate input influences that contradict the real world. Moreover, there are no standards with accurate definitions of the basic terms, such as reliability testing, durability testing, accelerated reliability testing, and others. Therefore practical engineers and managers, for example, often provide proving ground testing or vibration testing, but call them durability testing. Accelerated reliability/durability testing technology (ART/ADT) can be used for obtaining initial information for successful performance prediction. One can see the common structure of ART/ADT in Figure 6.

As we can see from Figure 6, ART/ADT consists of two basic components:

1. Accelerated testing in the laboratory;
2. Periodical field testing.

Figure 7 (following page) shows that accelerated testing in the laboratory includes simultaneous combination of:

- multiple environmental testing;
- electrical (electronics) testing;
- mechanical testing;
- human factors;
- safety problems;
- other necessary groups of testing.

Accelerated testing in the laboratory (Figure 7) is based on accurate simulation

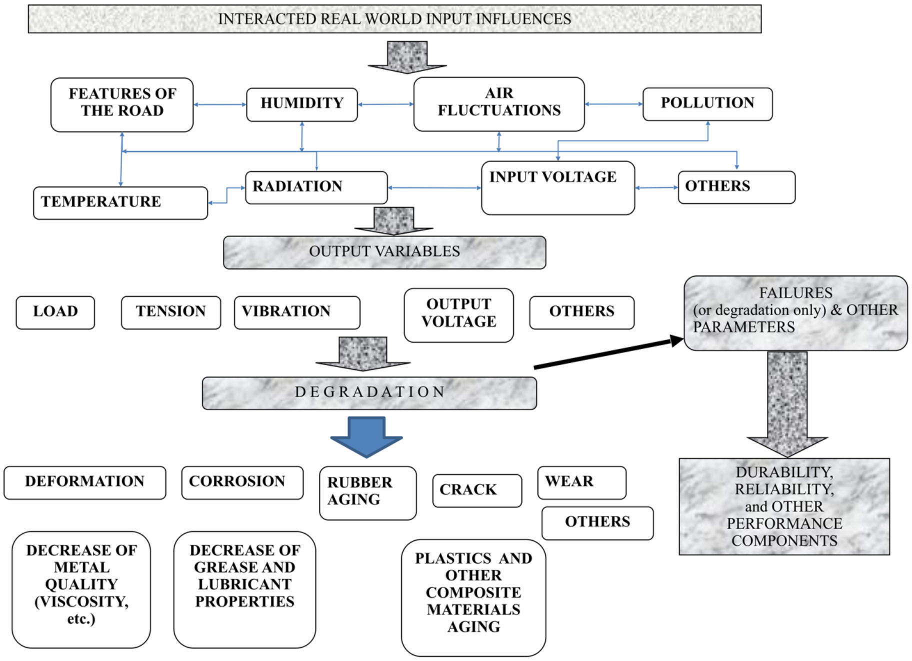

INTERACTED REAL WORLD INPUT INFLUENCES
FEATURES OF THE ROAD
HUMIDITY
AIR FLUCTUATIONS
POLLUTION
TEMPERATURE
RADIATION
INPUT VOLTAGE
OTHERS
OUTPUT VARIABLES
LOAD
TENSION
VIBRATION
OUTPUT VOLTAGE
OTHERS
FAILURES (or degradation only) & OTHER PARAMETERS
DEGRADATION
DEFORMATION
CORROSION
RUBBER AGING
CRACK
WEAR
OTHERS
DURABILITY, RELIABILITY, and OTHER PERFORMANCE COMPONENTS
DECREASE OF METAL QUALITY (VISCOSITY, etc.)
DECREASE OF GREASE AND LUBRICANT PROPERTIES
PLASTICS AND OTHER COMPOSITE MATERIALS AGING

Figure 5

The path from real world input influences to the product reliability, durability, and other performance (for mobile vehicles and their components).

of real world conditions. One also has to take into account the influence of design level and quality to the product performance. Accelerated testing in the laboratory consists of the interaction of different groups of testing: multi-environmental, mechanical, electrical, and others that act simultaneously and in combination.

One needs to simulate in the laboratory human factors (psychological aspects, individual difference, group factors, anatomical aspects, and others). Simulation of safety problems consists of risk problems and hazard analysis and can be provided during laboratory testing, as well as periodical field testing.

It is necessary to provide periodical field testing (Figure 8, following page) (for example, after each 500 hours of laboratory testing). During both types of testing that are equivalent to service life (or warranty period, or other period of work) the product's degradation process influences the functional, safety, cost, quality, and other factors. For sufficient prediction, one has to take into account the product's performance components.

One can see in Figure 9 how to study the important portions of human factors—management and operational factors—on the product reliability, durability, and safety. It cannot be studied separately from real world input influences and safety, because that will bring minimum benefits.

Summary

This article considers new concepts and strategy of undeveloped earlier problem how one can successfully predict the product performance during service life of this product. As a result, dramatically increasing of product reliability, durability, maintainability, supportability, profit, decreasing life cycle cost, complaints and recalls, and saving people's life, as well as improving other aspects of economic situation by producer and user. ●

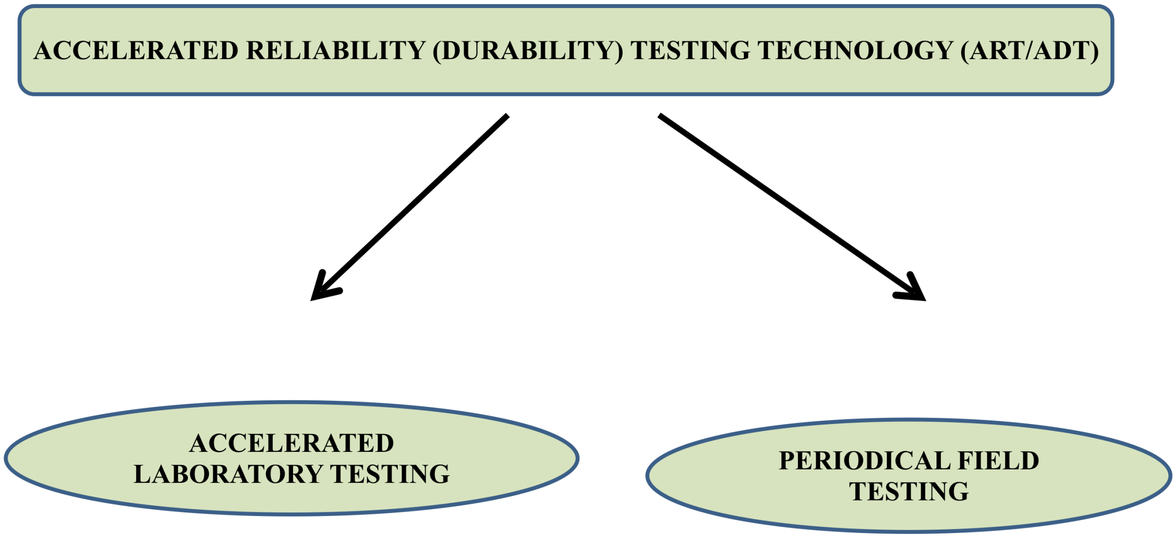

ACCELERATED RELIABILITY (DURABILITY) TESTING TECHNOLOGY (ART/ADT)
ACCELERATED LABORATORY TESTING
PERIODICAL FIELD TESTING

Figure 6

Scheme of obtaining information for successful performance prediction.

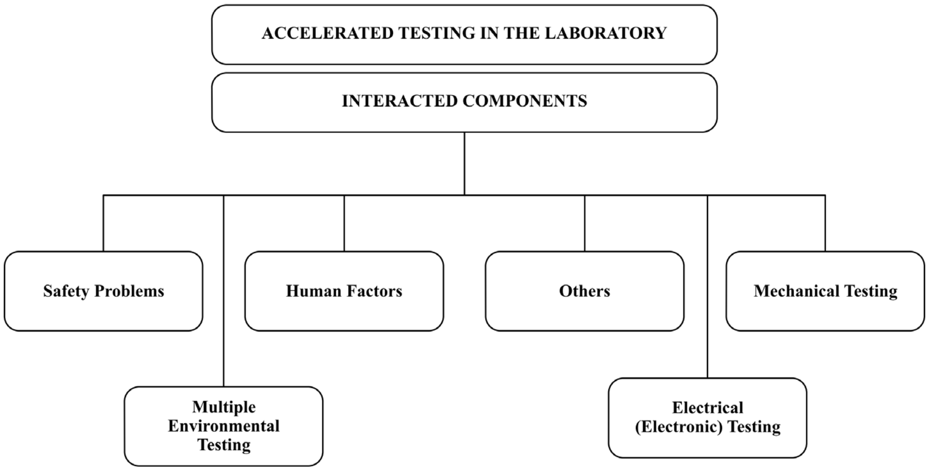

ACCELERATED TESTING IN THE LABORATORY
INTERACTED COMPONENTS
Safety Problems
Human Factors
Others
Mechanical Testing
Multiple Environmental Testing
Electrical (Electronic) Testing

FIGURE 7 — SCHEME OF ACCELERATED TESTING IN THE LABORATORY.

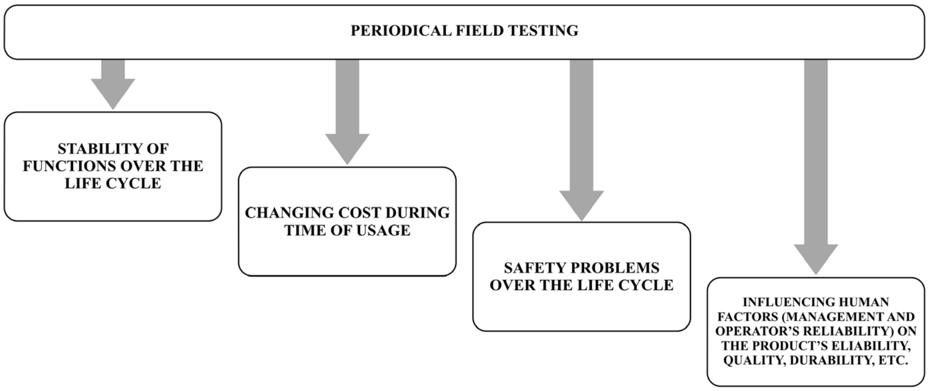

PERIODICAL FIELD TESTING
STABILITY OF FUNCTIONS OVER THE LIFE CYCLE
CHANGING COST DURING TIME OF USAGE
SAFETY PROBLEMS OVER THE LIFE CYCLE
INFLUENCING HUMAN FACTORS (MANAGEMENT AND OPERATOR'S RELIABILITY) ON THE PRODUCT'S ELIABILITY, QUALITY, DURABILITY, ETC.

FIGURE 8 — PERIODICAL FIELD TESTING.

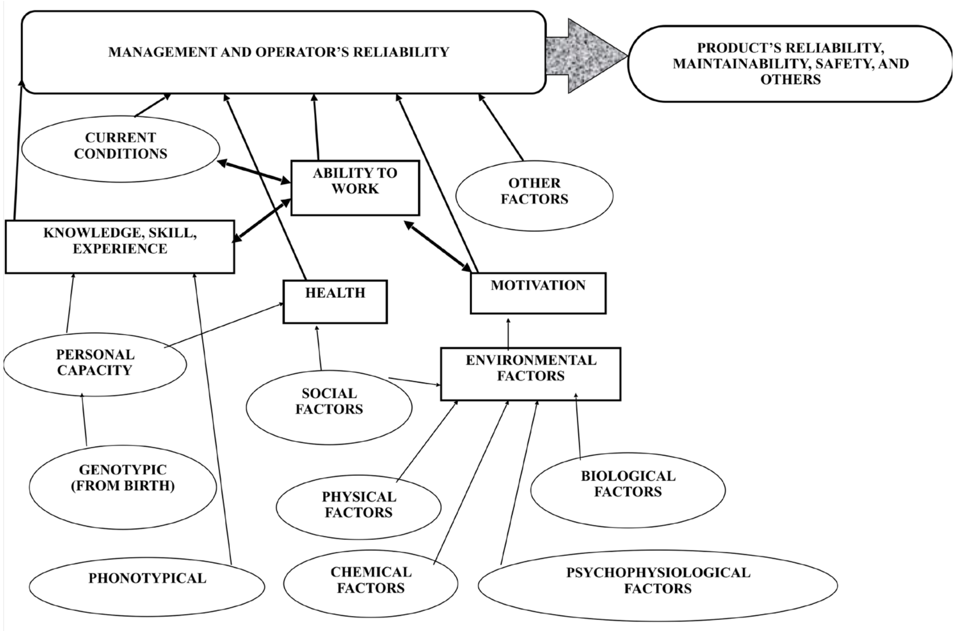


FIGURE 9
INTERACTING COMPONENTS OF HUMAN FACTORS (OPERATOR'S AND MANAGEMENT RELIABILITY) AND THEIR INFLUENCE ON THE PRODUCT'S RELIABILITY, DURABILITY, SAFETY AND OTHERS.

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Case Study: A Parametric Model for the Cost per Flight Hour

MICHAIL BOZOUDIS

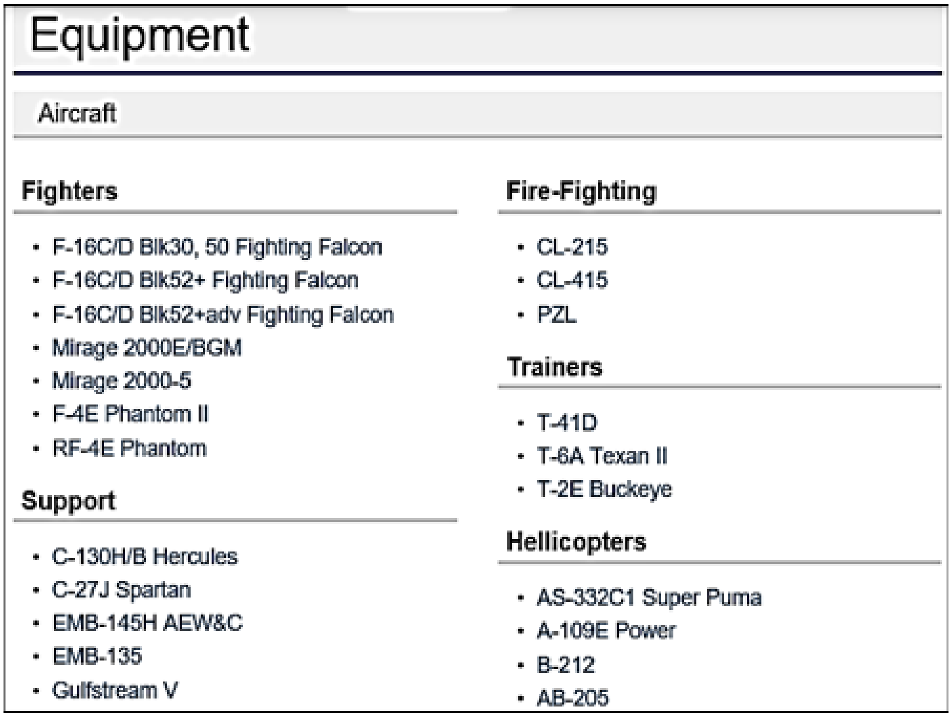
Acronyms

AAP	Allied Administrative Publication
AFMC	Air Force Materiel Command (US Air Force)
AIC	Akaike Information Criterion
ALCCP	Allied Life Cycle Cost Publication
CALS	Continuous Acquisition and Lifecycle Support
CAPE	Cost Assessment and Program Evaluation (US)
CER	Cost Estimating Relationship
CI	Confidence Interval
COTS	Commercial-Off-The-Shelf
CTOL	Conventional Takeoff and Landing
CPFH	Cost per Flight Hour
CRUA	Cost Risk and Uncertainty Analysis
DAU	Defense Acquisition University (US)
DoD	Department of Defense (US)
DoDCAS	DoD Cost Analysis Symposium
FAA	Federal Aviation Administration
HAF	Hellenic Air Force
ISPA	International Society of Parametric Analysts
JSF	Joint Strike Fighter
LCC	Life Cycle Cost
LCM	Life Cycle Management
MEDEVAC	Medical Evacuation
MTOW	Maximum Takeoff Weight
MUPE	Minimum Unbiased Percentage Error
NASA	National Aeronautics and Space Administration (US)
NATO	North Atlantic Treaty Organization
OLS	Ordinary Least Squares
O&S	Operating and Support
OSD	Office of the Secretary of Defense (US)
PI	Prediction Interval
RDT&E	Research, Development, Test, and Evaluation
RMS	Reliability-Maintainability-Supportability
ROM	Rough Order of Magnitude
SAR	Search and Rescue
SCEA	Society of Cost Estimating and Analysis
SFC	Specific Fuel Consumption
VAMOSC	Visibility and Management of Operating and Support Costs (US Navy)
ZMPE	Zero Bias Minimum Percent Error

Introduction

The Hellenic Air Force (HAF)'s mission[1] is to organize, staff, mobilize, and train its personnel, in order to develop an air power capable of dissuasion, intensive and prolonged air operations, obtaining and retaining air superiority, securing the air defense of the country, and providing air protection and support to ground and maritime operations. During peacetime, HAF also conducts public service operations supporting many aspects of public interest, such as fire-fighting, search and rescue (SAR), air transports and medical evacuations (MEDEVAC).

The diversity in HAF's mission profiles is portrayed in the different aircraft types. In order to fulfil a particular mission, an aircraft should meet analogous technical and performance specifications. Do the aircraft physical and performance characteristics affect its *Operating and Support* (O&S)[3] cost? If yes, how? During the procurement process there is an emphasis in affordability and cost management issues, therefore the answers to the aforementioned questions are critical



Equipment

Aircraft

Fighters

- F-16C/D Blk30, 50 Fighting Falcon
- F-16C/D Blk52+ Fighting Falcon
- F-16C/D Blk52+adv Fighting Falcon
- Mirage 2000E/BGM
- Mirage 2000-5
- F-4E Phantom II
- RF-4E Phantom

Support

- C-130H/B Hercules
- C-27J Spartan
- EMB-145H AEW&C
- EMB-135
- Gulfstream V

Fire-Fighting

- CL-215
- CL-415
- PZL

Trainers

- T-41D
- T-6A Texan II
- T-2E Buckeye

Helicopters

- AS-332C1 Super Puma
- A-109E Power
- B-212
- AB-205

Table I – The Hellenic Air Force (HAF) fleet[2]

for the comparison and evaluation of new ("unknown") systems.

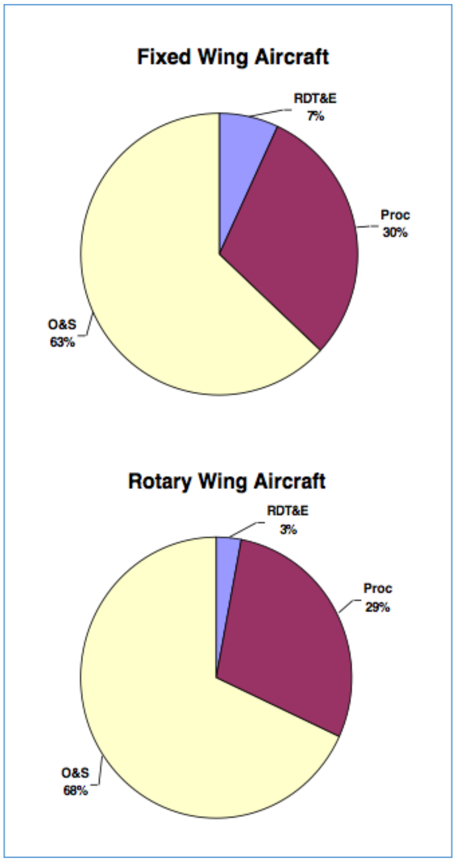


Figure I – Typical allocation of aircraft life cycle cost[6]

Despite the lack of actual data from the *Utilization and Support life cycle stages*[4] where the largest portion of the *Life Cycle Cost* (LCC)[5] is incurred, an analyst must carry out a timely and reliable O&S cost estimate. At this critical time point, the capability of conducting a parametric estimate is an asset.

The Parametric Estimating Technique

The parametric or "top-down" technique is a relatively fast and inexpensive estimating tool. Properly applied, it may provide reliable predictions and, most important, timely estimates. According to ISPA/SCEA Parametric Handbook[7]:

"Parametric estimating is a technique that develops cost estimates based upon the examination and validation of the relationships which exist between a project's technical, programmatic, and cost characteristics as well as the resources consumed during its development, manufacture, maintenance, and/or modification. Parametric models can be classified as simple or complex. Simple models are cost estimating relationships (CERs) consisting of one cost driver. Complex models, on the other hand, are models consisting of multiple CERs, or algorithms, to derive cost estimates."

The parametric technique is applicable during the early stages of a system's the life cycle, amidst analogy and engineering estimating techniques (see Figure 2, following page).

The parametric technique uses regression analysis, a statistical process for estimating the relationships among variables. Regression analysis helps an analyst to understand how the typical value of the dependent variable (response or criterion variable) changes when any one of the independent variables (predictors or explanatory variables) is varied, while the other independent variables are held fixed (see Figure 3, following page).

Pros & Cons of theParametric Technique

The implementation of the parametric technique is a blended process and the interpretation of the results has to be

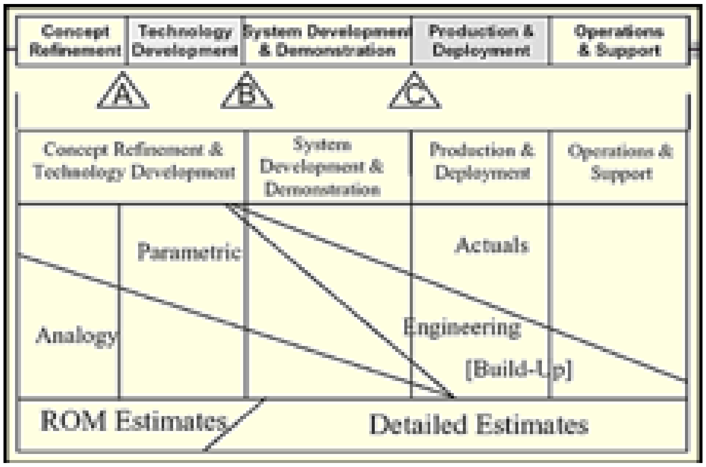


Figure II – Typical application of estimating techniques through a system's life cycle stages[8]

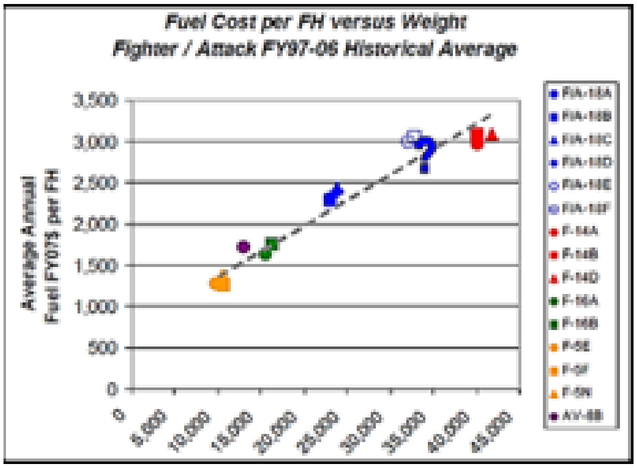


Figure III – The development of a simple parametric model: Application of regression analysis to identify a CER between the fuel CPFH and the weight of fighter aircraft[9]

done with extreme caution. An analyst should always consider the following pros and cons about the parametric technique:

Pros

1. It does not require actual and detailed cost information about a new system. Compared to the engineering or "bottom-up" cost estimating technique it requires less data, duration, and resources.
2. It may reveal strong CERs between cost and Reliability-Maintainability-Supportability (RMS) metrics[10], helping to optimize maintenance and logistic procedures.
3. A parametric model can be easily adjusted when the main cost drivers change. The CERs may be easily updated and sensitivity analysis may be applied.
4. It is a sound statistical process and can be objectively validated.
5. The uncertainty of the estimate can be quantified, allowing cost risk analysis.
6. There are many available commercial-off-the-shelf (COTS) parametric tools. Additionally, general-purpose statistical packages support the parametric technique.

Cons

1. It is a rigorous statistical technique (uses regression analysis).
2. CERs are often considered "black boxes," especially if they derive from COTS tools with unknown data libraries, and/or if the CER mathematical expression can't be logically explained.
3. Appropriate data adjustments might be required before the analysis, depending on the selected regression method (OLS, OLS-Log space, MUPE, ZMPE). Also, standard error adjustments for sample size and relevance might be required.[11]
4. CERs must be frequently updated to ensure validity.
5. The validity of the prediction interval (PI) heavily depends on the residuals diagnostics.
6. The decision makers may feel "itchy" to base their final decision on a parametric estimate (probably won't be statisticians).
7. Wide-ranging prediction intervals may render the estimate useless. Why not use the rule of thumb instead?

Building a Parametric Model for the Hellenic Air Force

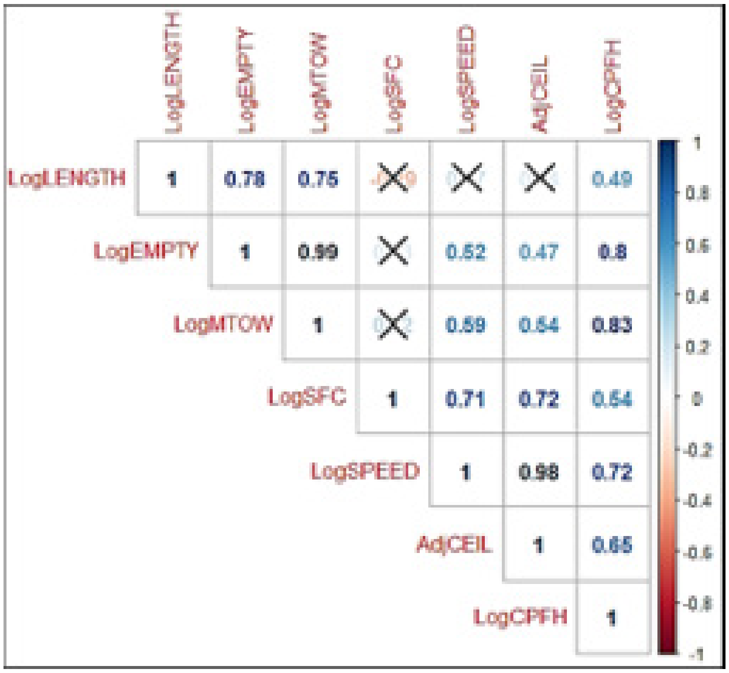
This case study investigates the relationship between historical CPFH[12] data and specific aircraft characteristics. The objective is to identify a strong CER that will be used to estimate the hypothetical CPFH for "unknown" aircraft.

Constraints & Requirements	Results
Use the sample of 22 aircraft operated by the Hellenic Air Force.	OK. The sample is taken from Table 1.
Use the appropriate cost information.	OK. Current CPFH data used, excluding the *indirect support* cost category.
Use cost drivers (independent variables) that are easily accessible and quantifiable.	OK. The cost drivers are physical and performance characteristics.
The model must be as less complex as possible and include no more than two cost drivers.	OK. The selected model includes two independent variables.
The model should be statistically significant at the 5% level.	OK. p-value = $3 \cdot 10^{-8}$ (Table 4)
The model should capture at least 75% of the CPFH variance.	OK. R^2_{adj} = 0.82 (Table 4)
The model's prediction intervals must be valid.	OK. The residuals pass all tests (Table 5). There are many outliers though (Figure 6).
The model's mathematical expression should make sense.	OK. The model suggests that the aircraft weight and the engine specific fuel consumption correlate positively with the CPFH.

Table II – A generic view of the constraints / requirements and the parametric model performance.

Variable	Simple CER's Regression Line	Variable Adjustment
dependent: CPFH		log-transformation
independent: Length	hyperbolic	log-transformation
independent: Empty weight	hyperbolic	log-transformation
independent: MTOW	hyperbolic	log-transformation
independent: SFC (max)	hyperbolic	log-transformation
independent: Speed (max)	hyperbolic	log-transformation
independent: Ceiling	exponential	$\times 10^{-4}$

Table III – The variables used for the analysis.
The log-transformations support the implementation of linear CERs.



	LogLENGTH	LogEMPTY	LogMTOW	LogSFC	LogSPEED	AdjCEIL	LogCPFH
LogLENGTH	1	0.78	0.75	✕	✕	✕	0.49
LogEMPTY		1	0.99	✕	0.52	0.47	0.8
LogMTOW			1	✕	0.59	0.54	0.83
LogSFC				1	0.71	0.72	0.54
LogSPEED					1	0.98	0.72
AdjCEIL						1	0.65
LogCPFH							1

1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

Figure IV – The variables correlation matrix. The symbol "X" indicates the insignificant correlations at the 5% sig. level. Multicollinearity is evident among several independent variables.

The examination of the independent variables may reveal multicollinearity issues. Two or more independent variables may be highly correlated, for example Log(empty weight) and Log(MTOW), meaning that one can be linearly estimated from the others with a substantial degree of accuracy. A parametric model should not include strongly correlated independent variables, because its predictive ability degrades. The variables correlation matrix offers an overview of the existing correlations.

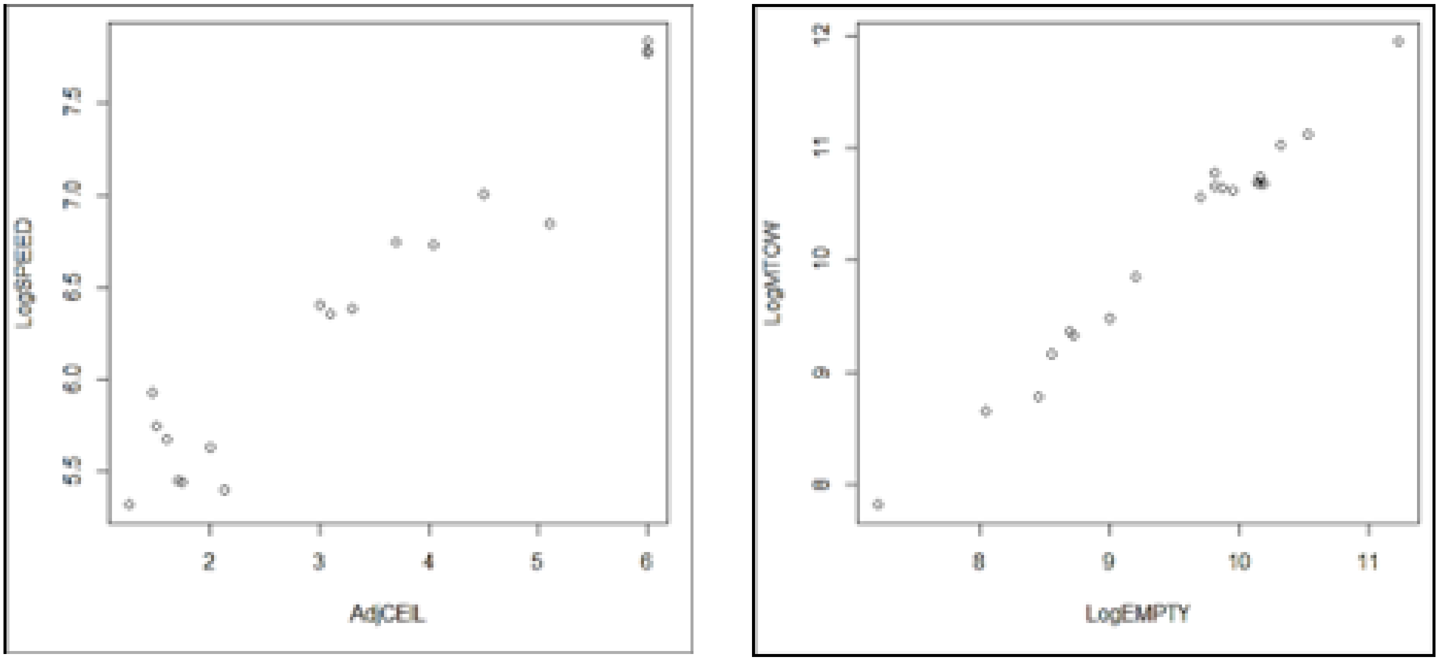


Figure V – Examples of multicollinearity.

Selection of the Optimal CER

The highest correlation coefficient between Log(CPFH) and the independent variables is $r = 0.83$. Therefore, Log(MTOW) would be the best choice for building a simple linear CER. Unluckily, this model doesn't comply at least with one of the requirements in Table 2, which is: $R^2_{adj} \geq 0.75$ (indeed, $r^2 = 0.83^2 = 0.69 < 0.75$).

The next step is to investigate all CERs of the form:

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_1X_2.$$

The implementation of stepwise regression along with the Akaike Information Criterion (AIC), as the measure of the CERs relative quality, derives the following model:

$$\text{Log(CPFH)} = \beta_0 + \beta_1\text{Log(empty weight)} + \beta_2\text{Log(SFC)},$$

where $\beta_0, \beta_1, \beta_2$ are known coefficients.

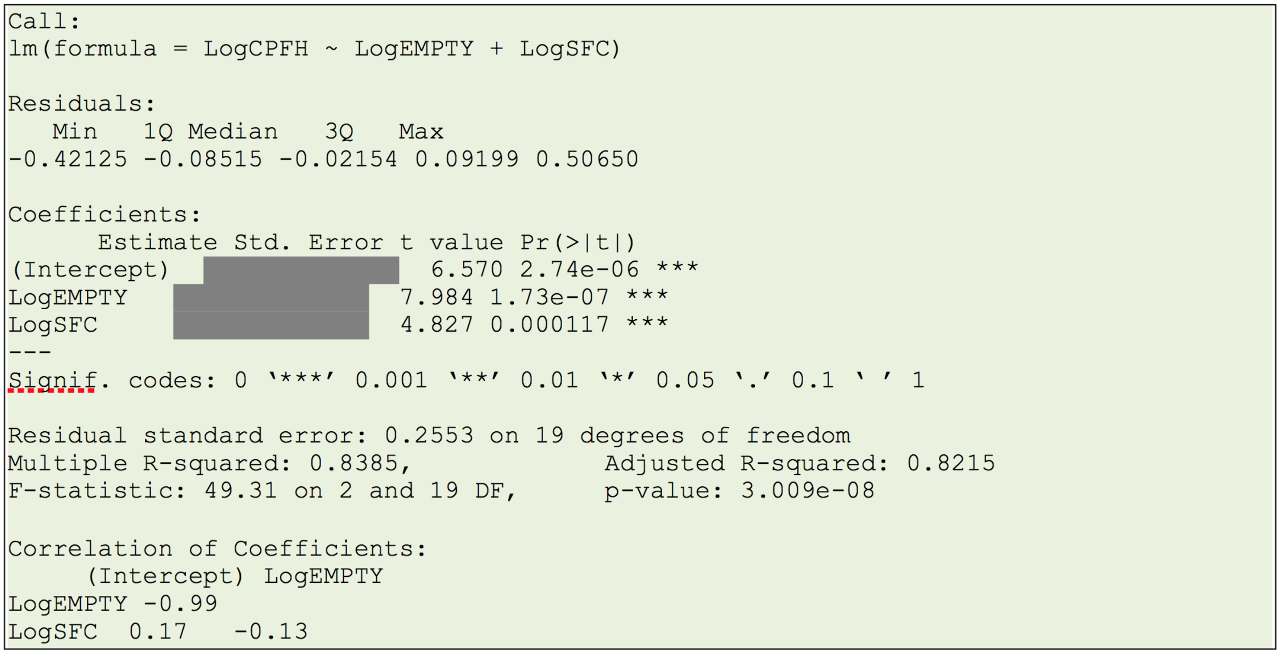
Notably, the two selected independent variables do not correlate significantly (Figure 4), so there is no multicollinearity in the selected model. Also, the interaction of the two independent variables is not significant hence the term X_1X_2 is omitted from the right hand of the equation. Although the model explains a remarkable 82.15% of the Log(CPFH) variance, it does not demonstrate analogous predictive ability on the training set.[13] Indeed, 7 of the 22 actual costs fall outside the 95% prediction interval (notice the existence of outliers in Figure 6, following page).

Residuals diagnostics

The construction of valid prediction or confidence intervals relies on the assumptions that the residuals are normal, have constant variance and no autocorrelations. Remarkably, the residuals of the selected model pass all tests:

Test	Null Hypothesis	*p*-value	Reject the null hypothesis at the 5% sig. level?
Shapiro-Wilk normality test	normality	0.161	NO
Breusch-Pagan test for heteroscedasticity	constant variance	0.332	NO
Durbin-Watson test for autocorrelation	no autocorrelations	0.342	NO

Table V – The residuals diagnostics.



```
Call:
lm(formula = LogCPFH ~ LogEMPTY + LogSFC)

Residuals:
   Min    1Q Median    3Q    Max
-0.42125 -0.08515 -0.02154 0.09199 0.50650

Coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept)  [redacted]  6.570 2.74e-06 ***
LogEMPTY   [redacted]  7.984 1.73e-07 ***
LogSFC     [redacted]  4.827 0.000117 ***
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2553 on 19 degrees of freedom
Multiple R-squared: 0.8385,         Adjusted R-squared: 0.8215
F-statistic: 49.31 on 2 and 19 DF,      p-value: 3.009e-08

Correlation of Coefficients:
     (Intercept) LogEMPTY
LogEMPTY -0.99
LogSFC  0.17   -0.13
```

Table IV – The optimal model's properties.

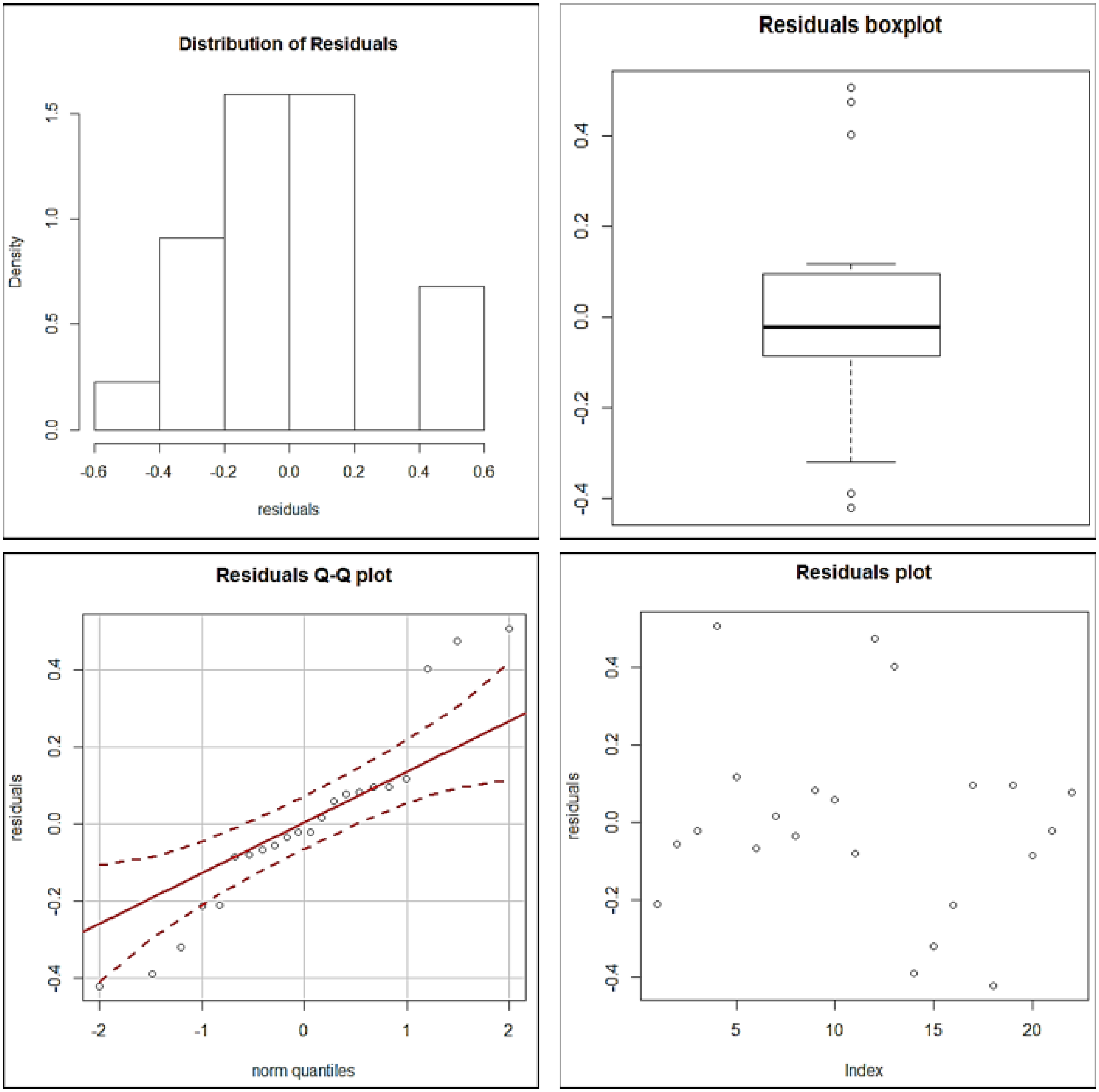


Figure VI – Typical residuals graphs. Although the residuals pass the tests, the existence of many outliers should keep the analyst alerted on the validity of the model's prediction intervals.

Joint Strike Fighter
F-35 Lightning II Propulsion
F135 Conventional Take-Off Landing
Approved for Public Release

FIGURE VII – THE LOCKHEED MARTIN F-35A CTOL VARIANT[14] AND ITS POWER PLANT PRATT & WHITNEY F135-PW-100 AFTERBURNING TURBOFAN ENGINE.[15]

Making Predictions for an "Unknown" System

The Lockheed Martin F-35 Lightning II is a family of fifth generation, single-seat, single engine, stealth multirole fighters undergoing final development and testing by the US. The F-35 program, also known as the Joint Strike Fighter (JSF), is the most expensive weapon system in history with a projected service life up to 2070. The JSF is designed and built by an aerospace industry team lead by Lockheed Martin. Besides the US, many NATO members & close US allies participate in the funding of the JSF development. Several additional countries have ordered, or are considering ordering, the F-35.

Supposing that the Hellenic Air Force considers the procurement of a new fighter aircraft, a rough O&S cost estimate of the alternatives, including the JSF, will be required. According to the parametric model, the F-35A empty weight (= 29,098 lb) and the F135-PW-100 specific fuel consumption (≈ 1.95 lb/lbf·h) must feed the right hand side of the model, in order to get an estimate for the cost per flight hour:

$$\text{Log(CPFH)} = \beta_0 + \beta_1 \text{Log}(29{,}098) + \beta_2 \text{Log}(1.95)$$

The CPFH distribution properties are estimated through two different approaches:

1) Theoretical Approach

The mean (μ = 8.9434) and standard deviation (σ = 0.1066) of the dependent variable are estimated explicitly, according to the regression analysis theory. Log(CPFH) is assumed to be normally distributed; therefore, CPFH follows a lognormal distribution with parameters μ and σ. Any CPFH percentile or prediction interval is then estimated according to the identified lognormal distribution.

2) Monte-Carlo Simulation

According to the coefficient correlation matrix (Table 4), an algorithm generates pseudorandom values for 3 student-t distributed variables (with 19 degrees of freedom) that correspond to the model's coefficients β_0, β_1, and β_2. These 3 random values feed the right hand side of the above equation to compute a value for the CPFH. After this process has been repeated a million times, the mean (μ = 8.9435) and standard deviation

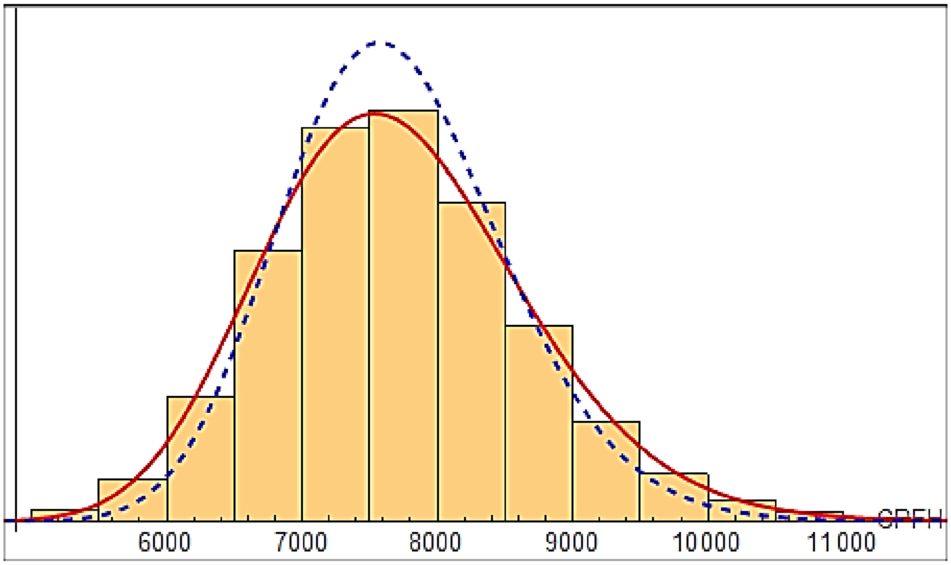


FIGURE VIII
A LOGNORMAL DISTRIBUTION WITH μ = 8.9434 AND σ = 0.1066 (BLUE DASHED LINE) DENOTES THE THEORETICAL CPFH ESTIMATE. A LOGNORMAL DISTRIBUTION WITH μ = 8.9435 AND σ = 0.1254 (RED LINE) FITS THE SIMULATION-GENERATED CPFH (HISTOGRAM).

Property	Theoretical Output	Simulation Output
Log(CPFH) mean	8.9434	8.9435
Log(CPFH) standard deviation	0.1066	0.1254
CPFH mean	7,701 €	7,719 €
CPFH median	7,658 €	7,658 €
CPFH mode	7,571 €	7,539 €
CPFH standard deviation	823 €	973 €
CPFH 80th percentile	8,376 €	8,481 €
CPFH 95% prediction interval	6,214 to 9,436 €	5,975 to 9,822 €
Prob(CPFH > 10,000 €)	0.61%	1.83%
Cost risk (80th percentile - mode)	805 €	942 €

Table VI
The parametric model's predictions on the F-35A cost per flight hour (excluding indirect support cost), assuming it had been operated by HAF. The theoretical regression model underestimates the uncertainty of the estimate.[16]

(σ = 0.1254) of the Log(CPFH) are estimated using Monte-Carlo simulation. Finally, the CPFH is fitted by a lognormal distribution with parameters μ and σ. Any CPFH percentile or prediction interval may be estimated according to either the fitted lognormal distribution properties, or the simulation output.

Epilogue

The parametric estimating technique may provide timely cost estimates for "unknown" systems, through the utilization of cost estimating relationships deriving from historical datasets. The reliability of parametric estimates depends on many factors which an analyst must be aware of. This case study offers an overview on the development of a parametric model that estimates the cost per flight hour for "unknown" aircraft. The cost derives as a function of the aircraft empty weight and the engine's specific fuel consumption. As an example, the F-35A cost per flight hour is estimated under the hypothetical scenario that it is operated by the Hellenic Air Force. ●

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12. The CPFH includes the following 6 main cost categories, according to the O&S cost element structure: *Unit-level manpower, unit operations, maintenance, sustaining support, continuing system improvements,* and *indirect support*. Since the purpose of the parametric model is the comparison of alternatives, the indirect support cost category is excluded from the analysis.

13. The dataset that generated the model.
14. Image source: https://en.wikipedia.org/wiki/Lockheed_Martin_F-35_Lightning_II#/media/File:F-35A_three-view.PNG
15. Image source: http://www.pw.utc.com/Content/F135_Engine/img/b-2-4_f135-ctol-cutaway-high.jpg
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Design Heuristics for Resilient Embedded Systems:
Resiliency May be a Richer Metric of Reliability, but How Can It Be Engineered into Systems?

JOHN BLYLER

Resiliency has been proposed as yet another needed capability for today's ever complex "smart" systems. Understandably, system architects and design engineers may be reluctant to add yet another "ilities-like" requirement to an already long list that includes reliability, availability, maintainability, safety, and more.

What is resiliency, especially when applied to the engineering of complex hardware-software embedded systems? What is the difference between resiliency and reliability, availability and maintainability? How can engineers incorporate resilience that would measurably restore partial or full functionality over a specified period of time and in a specified environment? This paper will attempt to answer these questions.

Definitions

To help avoid semantic entanglements, let's define a few terms. In general, a resilient system is one that can recover from a significant failure. INCOSE defines resilience as the capability of a system with specific characteristics before, during and after a disruption to absorb the disruption that allows it to recover to an acceptable level of performance and sustain that level for an acceptable period of time. Further, it lists the main attributes of resilience as *capacity*, *flexibility*, *tolerance* and *cohesion*.[1]

The IEEE adds a security element to resilience by defining it as a combination of trustworthiness and tolerance.[2] Wikipedia describes resilient control systems as those that maintain a state of awareness and an accepted level of operational normalcy in response to disturbances, including threats of an unexpected and malicious nature.[3]

It's noteworthy that resilience is not defined in the usual reliability terms of subsystem or component MTBF and MTTR numbers. As Jim Rodenkirch notes[4], resiliency is the extended part of the reliability problem that deals with what can "go wrong" across the breadth of the system-of-system (SoS) domain and the time required to "undo the wrong" to return the system to an acceptable—albeit different, perhaps—level of operation.

There is disagreement in today's literature about the difference between resilience and similar terms like robustness. Sarah Sheard, Researcher and Consultant for the Software Engineering Institute (SEI), notes that some practitioners say the former is a subset of the latter, while others say the opposite. She goes on to explain "the exact relationship between survivability and resilience, for example, depends on the environment, although what it has to survive and what it has to be resilient to (event) are probably the same. Similarly, maintainability might involve both preparation/avoidance and short term and long term recovery."

Resilience seems to be differentiated by the way system risks are assessed. This reasoning follows from the definition of availability as the capability of a system to operate within its design parameters and responds to internal failures, technical or human. Availability is affected by both reliability and maintainability, explains Dan Wilson, Asset Data Manager at Electricity North West.[5] "Resilience on the other hand is the capability to respond to external shocks which are outside the 'normal' range and are unexpected (i.e., weather events, terrorist attacks, economic shocks)." According to Wilson, the difference is in the source and how the risks are assessed but the design considerations are similar.

A slightly different viewpoint is offered by Paul Swart, Systems Engineer at SKA South Africa. Swart agrees that [inherent] availability is a function of both reliability and maintainability. "I think resilience enables maintainability (e.g., mean time to repair), and therefore desired resilience can be specified in terms of availability (inherent, achieved or operational)."

Finally, Kenneth Lloyd, CEO of Systems Science at Watt Systems Technologies, notes that resilience relates to continued functional integrity (at some level) despite component failures (and other perturbations) through a range of operating conditions. Reliability relates component failures to MTTR and MTBF independent of functional integrity.

To summarize, resilience is the extended part of the reliability problem that deals with what can "go wrong" (see Figure 1). Some people prefer the words robustness and survivability to resilience, although the exact differences in these words seem to relate to the environment in which the system must operate. For example, network designers use the word resilience where combat military engineers prefer survivability.

Resilience is differentiated by the way system risk is assessed. For example, availability deals with internal and typically expected failures, whereas resilience must handle external and unexpected threats. The actual design to implement availability or resilience may be the same—at least at a component or subsystem level.

Perhaps the biggest differentiator of resilience is the consideration of multi-discipline and multi-domain solutions and implementation to the potential threat or attack.

Differentiators of Resilience:

1. Extended part of the reliability that deals with what can "go wrong" beyond the component level.
2. Depends upon the way that system risk is assessed – internally or externally.
3. Solutions involve multi-discipline and multi-domain implementations.

Figure I
Summary of how resilience is different from other terms.

Over-Arching Conditions

Resiliency has been described as a richer metric than reliability, as resilient systems have the capacity to survive, adapt and grow in the face of change and uncertainty.[6] In today's world of complex embedded systems, resiliency might be equated with "smart recovery" systems, those that contained the capacity to evaluate and act on situational inputs via microprocessor hardware, software and connectivity to other systems like the Internet.

Unlike reliability, maintainability and systems safety, resilience is less of a specific topic and more of an over-arching set of considerations and design principles that help a system recover from a disruption. For the purposes of this paper, we are considering designed-in resilience, as opposed to intrinsic resilience, where the latter is the focus of material science, psychology and ecology.

A good analogy that ties resiliency, reliability and maintainability together is provided by Ivan Mactaggart, Principal Systems Engineer at Dstl, and President-Elect INCOSE UK: "My car is reliable in that it starts every time and has never broken down. The vehicle is reliable in part due to scheduled maintenance by a trained mechanic, which helps it perform the primary transportation function. However it is not resilient to a head-on impact with another vehicle, in which case it may no longer perform its primary function. It is not resilient to that shock. I might be able to return the car to a normal (acceptable) level of performance with repair. Or the damage may be too severe to repair."

Resiliency might be added to the design of the car by selecting a hybrid architecture—gas and electric - though the severity of the accident might damage both systems, as well. If one considers the system to extend beyond the car, resiliency can be added with public transportation—until the car is repaired or replaced. Public transportation is a more limited option in terms of where it can travel compared to a car, but it might be acceptable. At least, it returns some level of transportation function to the overall system.

What does this tell us about resilience in the context of the systems engineering "ilities" disciplines such as reliability, maintainability, and safety? Our previous automotive discussion showed that resiliency has strong connections to reliability and safety. This is one reason why many argue that resiliency is not a separate and distinct discipline from the other 'ilities.' Rather, resiliency depends upon the other "ilities," in the same way that safety depends upon reliability, etc.

Creating Resilience

How does one design resilient systems? This question assumes that resiliency is

Design Principles for Resiliency

- Design in some level of anticipated changes in the environment [Weitekamp and Edson, 2007]
  - Include diversity [=degeneracy]
  - Design in unused capacity
  - Have less internal connectedness (makes it stiff)
  - Create an ability to sense changes in the environment
  - If applicable, incorporate prior experience with same disturbance
- Create loose coupling, which allows a balance between stability and flexibility [Grote, 2006]
- Design a control structure that will enforce necessary constraints on development and operations. [Leveson et al., 2006]
- Design tradeoff: Systems live on edge of chaos; they create order but need residual disorder (i.e. flexibility) to survive. [Paries, 2006]”

Figure II – These principles apply to system design, and if followed lead to systems that are inherently more resilient than systems not designed with resilience in mind.

a measureable quantity. There is some debate on this point. Like many system concepts, incorporating resilience requires both analytic and holistic processes and architecting/modeling of the entire system will be aided by the use of associated heuristics.

The over-arching nature of resiliency may be one reason why designing and measuring resilience is difficult, e.g., multiple threats, multiple failure modes and multiple recovery modes over different critical intervals of time. These issues make it hard to predict the resilience of a system.

Creating resilience has become a contemporary discussion point for many experts across a wide-range of disciplines and systems. Sarah Sheard from SEI has compiled these discussions into a set of prescriptive principals to improve the resilience of a system, organization and ecosystem.[7] For this paper, we are only considering resilience as viewed by the designer of a hardware-software intensive technology system (see Figure 2).

Before demonstrating how these design heuristics might actually be implemented, let’s examine each one from a systems engineering perspective.

To anticipate changes to the normal operating environment, system architects and designers should incorporate as much diversity into the system as possible. This diversity should take the form of engineered degeneracy, where different components, subsystems, and associated software can perform similar functions in certain situations (i.e., are effectively interchangeable). Some technologies are well suited for this dynamically changing functionality, e.g., reconfigurable semiconductor chips like FPGAs. Another example might be that of a strain gauge that can measure both the mechanical strain on a load and—under certain conditions—also act as an electrical patch antenna. Regardless of the implementation, engineering degeneracy takes careful architecting and testing to be successful.

Designing a system with such diversity is inherently difficult as most domain experts implement solutions from their specific expertise. For example, a software engineer is unlikely to include a mechanical or chemical solution to a problem.[8] Including multidiscipline and multi-domain diversity requires a system perspective.

The second element in designing for change is incorporation of unused capacity. As defined within the Systems Engineering Body of Knowledge (SEBoK), capacity is one of the four main attributes that a system must possess to be resilient. The other three are flexibility, tolerance, and cohesion. “The Capacity Attribute allows the system to withstand a threat. Resilience allows for the capacity of a system to be exceeded, forcing the system to rely on the remaining attributes to achieve recovery.”[9]

In practice, unused capacity is often associated with redundancy. If you need a system to have high availability, then adding redundant systems is the typical approach though it may come at a high price as will shortly be explained. Regardless, unused capacity should be added where appropriate to the system, perhaps as extra memory to allow a safe haven for uncompromised software during a hacking attack or to quickly cache critical data before one part of the system goes down.

Next on the list is to design with “less internal connectedness (make it stiff).” In software development, this is part of the twin design goals of high cohesion and low coupling. In highly cohesive systems, similar things are put together. Highly cohesive materials bond together tightly, i.e., they are stiff. Software systems strive for highly cohesive modules that all contribute to the execution of a well-defined task.

Coupling relates to the flow of information or parameters passed between subsystems or software modules. Optimal (low) coupling reduces the interfaces of modules and thus the resulting complexity of the systems.[10] Low coupling often correlates with high cohesion and vice versa.

Creating the capability to sense changes in the environment enables a resilient system to anticipate attacks. Sensing when a component is likely to fail or an attack is eminent provides the system with increased reaction time. Depending upon the time cycle, a redundant system can be brought on line or another solution can be achieved before failure. With the rise of the sensor-rich Internet of Things (IoT), data from a world of sensors is slowly becoming more available on the cloud. But this requires the system of interest to have the capacity of wired or wireless connectivity—again, at an additional system cost.

Incorporating prior experience with the same disturbance gives designers a heads-up to deal with familiar problems. The challenge here is that prior experience may not be well communicated from senior to junior engineers or across the organization as a whole. If the disturbance relates to well-understood and commonly occurring environmental conditions, e.g., cold, heat, humidity, etc., then resilient systems will have the capability to react.

As mentioned previously, creating loose coupling should be balanced with high-cohesion to provide a system that, while connected, is reasonably capable of acting autonomously.

Another key heuristic for resilience is to design a control structure that will enforce necessary constraints on development and operations. In many cases, the control structure is embodied in the life-cycle risk management process. The reasoning is that risk management is the control function within the development process in the same way that system components may play the control role within a product system. One way to implement this approach is to calculate a weighting for each system component's role to the SoS' resilience and then characterizing each system's impact on the SoS' reliability through resilience patterns. (More on resilience patterns later on.)

In this case, the aim of risk management is to watch for a drift into failure before break-downs occur. Typically, this requires an evaluation as to what extent safety has been compromised by recent decisions. One warning sign would be an undesirable drop in system capacity. Whatever the measure, a concern for risk must pervade the entire system development process, especially on high consequence/low likelihood events.

It should be apparent that all of these heuristics will impact the total system cost. Balancing the required level of resilience with other technical parameters, cost and scheduling requires design tradeoffs. As noted by Paries, "Systems live on the edge of chaos; they create order but need residual disorder (i.e., flexibility) to survive.[11]

Sheard explains that resilience costs money to implement and may also require tradeoffs in system functionality. A system or organization needs to avoid danger consistently over time to be resilient. Building resilient systems is a matter of setting priorities and performing tradeoffs. Some tradeoffs mentioned in the literature include:

- Negotiate the tension between stability and change over time.
- (System) Performance improvement often comes at the cost of static resilience against targeted attacks.

How can these design principals or heuristics be used by the designer? Let's consider a few examples and rate them according to our heuristics above.

Communication Capacity Example

According to Rodenkirch, the capacity attribute allows the system to withstand a threat. "Resilience allows for the capacity of a system to be exceeded, forcing the system to rely on the remaining attributes to achieve recovery."

If engineers can quantify the capacity of a system to withstand failures, that quantity can serve as a measure of resilience. In the case of an SoS, resilience can be defined as the level of performance achieved relative to different levels of failure. Capacity is required to withstand these various levels of failure.

In a related study, researchers at Purdue University[12] considered the challenge in measuring resilience. To perform this measurement, they first defined two types of SoS resilience: conditional and total. Conditional resilience is the ratio of the percentage of SoS performance in response to a failure in a particular system or combination of systems (see Figure 3). This can be thought of as a particular performance measure that indicates how much performance is maintained for failure in a given set of systems.

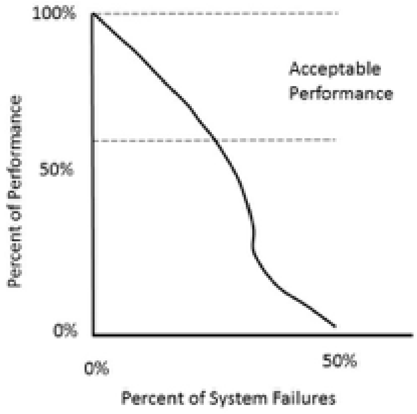

Figure III – Representative diagram of failure vs. performance. to systems that are inherently more resilient than systems not designed with resilience in mind.

Total resilience shows how performance is degraded as the total level of component system failures increase. According to the researchers, resilience patterns for the system are influenced by two factors: architecture type and system-level risk of the SoS. The architecture determines the general shape of the resilience pattern. The goal is to architect a system design that recovers to the highest level of performance possible after the failure.

In contrast to the resilience pattern, the system-level risk determines the scale or magnitude of the pattern, that is, how the system performance degrades as systems fail.

In the Purdue paper, researchers determine the two most critical systems of a multi-component threat detection SoS using the conditional resilience metric. They demonstrated that adding a communications link between these two systems (combat surface ships) increased the resilience, resulting in higher expected performance and slower expected performance degradation as a result of system failure (see Figure 4). The goal now is to develop resilience patterns for more complex interactions.

The Purdue study showed that some attributes of a resilient system can be measured. Treating resilience as an evolving, richer metric of reliability might help facilitate further interest and study of this system design consideration. Finally, there is a need to place a greater emphasis on recoverable instead of just optimal states in the engineering of systems, which is another reason to consider augmenting reliability with resilient design.

Redundancy Example

Recently, there have been a plethora of articles dealing with network resilience in the IT space. Even the semiconductor space has picked up on the trend with at least one network-on-chip vendor writing about the need for resilience in the end-to-end error protection for on-chip interconnects. In this case, the implementation was more focused on reliability and error correction rather than resilience.

Another example is from the semiconductor defense space, focused primarily on cyber security.[13] The community wants to decrease the likelihood of unintended behavior or access, increasing resistance and resilience to tampering and counterfeiting, and improving the ability to provide authentication in the field. This effort is part of research activity by NSF and SRC, which seeks to support research on Secured, Assured and Resilient Semiconductors and Systems (STARSS), with a focus on Design for Assurance. The latter requires new strategies for architecture, specification and verification, especially at the stages of design in which formal methods are currently weak or absent.

Most applications of resilience in the networking IT world involve redundant implementations to achieve high availability systems. This effort is being driven by the trend to move internal corporate datacenters to the cloud, i.e., an external set of network servers. In keeping with cloud-based nomenclature, this trend is sometimes known as Infrastructure-as-a-Service (IAAS). One concern is that the high availability (HA) of cloud solutions will be less than currently experienced from enterprise datacenters. This warrants comparison of the two in terms of resiliency.[14]

Availability is typically defined as the ratio of unplanned down time divided by total time per year. A component or element with an availability of 99% means that, on average, the element will run 99 days out of 100 days. For a "5 nines" availability (or 99.999%), the availability of unplanned downtime would be 86.4 seconds per 100 days of operation. This level of high availability does not come cheaply, which is why high availability and total cost of ownership (TCO) are often considered in trade-off decisions.

Moving data centers to the cloud may improve the actual downtime but the impact of the any downtime can become more critical. Downtime for internal corporate data centers tends to be caused

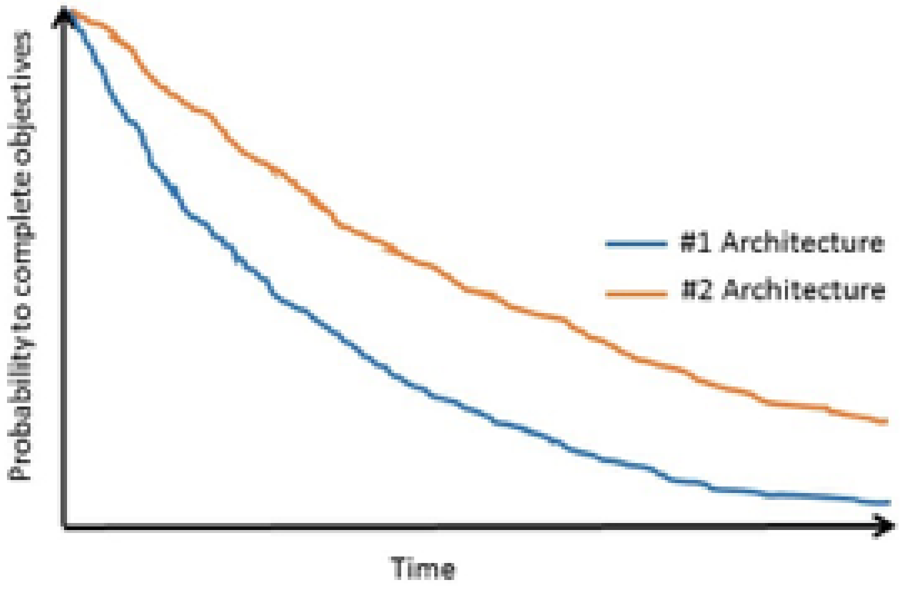

Figure IV – Evolution of the LCS SoS performances of both architectures

by a single set of components. However, downtime on the cloud tends to affect all corporate users—not just one.

The traditional way to achieve high availability in the data center is to provide a redundant system (see Figure 5). This assumes that the inter-connections between components A and B are designed so that every failure of component A or B can be bypassed without the loss of functionality. Understandably, the doubling of everything also doubles the TCO.

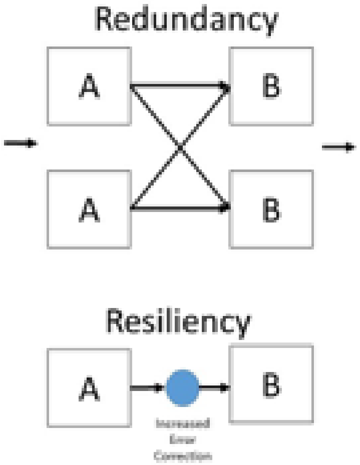

Figure V – High Availability can be achieved with redundancy or resilience, but each has its cost.

This is where resiliency can help. Resiliency can avoid doubling TCO by carefully incorporating a built-in error recovery mechanism. In this case, resiliency is defined as the capability of the systems to recover from temporary failures through error handling and error correction—without redundancy. The cost for added error recovery mechanisms is typically greater processing speed and power. Additional memory buffers may also be needed. Finally, resiliency works best when systems are loosely coupled, which might require more time to be spent architecting the system.

In this example, the total cost of development (TCD) vs. the total cost of ownership (TCO) must be examined in a trade-off study to decide whether a redundant, resilient or hybrid solution is better. In general, loose coupling tends to be a design criteria on the application development side. If one can afford the higher development costs then resiliency might be the better answer. If hardware and operational costs are less expensive, then a redundant approach might be better to achieve high availability.

A simple, subjective weighting scheme serves in a general way to gauge the importance of each heuristic in these different examples (see Table 1). In the communication capacity example, only a few criteria played a key role in the resilient design—namely, capacity, sensing change and prior experience. The redundancy example shows that the resilient (non-redundant) solution meets more of the criteria for resilience.

These examples show how a set of design heuristics can help guide the creation of resilient systems. The overarching nature of resiliency makes it difficult to follow a specific, formula driven approach to resilience. Additionally, the multi-discipline and multi-domain of resilient design makes it the responsibility of the project and program systems engineer.

Instead, the system architecture must incorporate resilience as a design objective that spans the entire system. At the very least, this approach will result in a far more robustly reliable system. But at the very best, the system will be capable of recovering from a significant failure while maintaining some acceptable level of performance. ●

	Example - Capacity	**Example - Redundancy**	
		Redundant	**Non-Redundant**
1. Anticipate change			
Diversity	Low	Low	High
Unused Capacity	Medium	High	Low
Less Internal Connectedness	Low	Low	High
Sense Changes	Medium	Low	High
Prior Experience	High	High	High
2. Loose Coupling	Low	Low	High
3. RM – Resilience Characterization	High	Equivalent	Equivalent
4. Trade-off Studies	Low	Low (Duplication)	High

Table 1 – Simple, subjective scheme to weigh the importance of each design heuristic in different implementations.

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