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DESIGN FOR SUPPORTABILITY AS A MEANS OF REDUCING TECHNOLOGY TRANSITION RISK

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ABSTRACT

In order to assess a design from a supportability perspective early in a technology's prototyping phase, TARDEC's Systems Engineering Directorate has established a Design for Supportability (DfS) competency. This competency, under the SE umbrella, encompasses the relationship between Design for Reliability (DfR), Design for Maintainability (DfM), and Design for Logistics (DfL). The combination of DfR, DfM and DfL form a trifecta of knowledge that determines whether a developing technology will: 1) perform its intended function for the complete duration of the mission it's designed for; 2) be designed in a way to be fixable in a reasonable amount of time using standard tools; 3) be designed to have replaceable parts as accessible as possible; 4) not increase the logistics burden for our men and women in uniform.

INTRODUCTION

One of the key areas of focus in the scope of Systems Engineering (SE), as outlined in the Defense Acquisition Guidebook (DAG), is transforming needed operational capabilities into an integrated system design through concurrent consideration of all life cycle needs. The more analysis that can be done upfront in the design and development phases, the more the cost of production and maintenance significantly decrease. When supportability considerations are taken into account early in the design and development phases, key performance parameters (KPPs) such as reliability and operational availability can be optimally met. When these parameters are considered early and upfront, there are less programmatic risks, thus increasing the probability of a successful transition into a program of record, and ultimately, into the hands of the warfighter. This paper will explain what analysis is needed for reliability, maintainability and logistics during the design phase, the relationships between the three areas of the trifecta, the timeline of analysis, and the payoff for making DfS a key focus of SE.

THE IMPORTANCE OF MILITARY VEHICLE RELIABILITY

Reliability is the ability of a product or system to perform its intended function for a certain period of time under specific operating conditions. Before purchasing a vehicle, most people check the reliability score of that vehicle. A consumer wants to know that after investing their hardearned money into a specific car that, if properly maintained, will get them safely to and from their destination without disruption caused by failed components or features. However, an average American driving to and from work every day, or driving to and from school to drop their children off, is usually within an hour or so drive of an automotive maintenance shop. With the availability of warning lights within the vehicle, roadside assistance services, tow trucks, Onstar©, cell phones and the like, even the failure of a common car component can be serviced in a relatively short amount of time while the passengers remain in a safe environment. Obviously, there are exceptions to this general rule, such as those living in remote areas with long country roads where cell phone service may not reach all areas, or those engine and transmission failures which occur without any notice while travelling at high speeds on the highway. However, in terms of what is at stake when a failure occurs on a normal passenger vehicle made for average city commutes is vastly different than what is at stake on a military vehicle operating in remote environments across the world.

Imagine for a moment that you are an armor company commander in charge of three platoons of Abrams tanks. The lives of the men and women in your company are dependent on your leadership – some soldiers are straight out of high school, some are married, some have children, etc. Your division has been deployed on a combat mission to Southwest Asia, and your company is responsible for patrolling and guarding a 10 square mile area of operations from the enemy. Division intelligence reports that an enemy armored battalion will be attacking your sector in less than 20 hours. You decide to emplace a deliberate defense as it is critical to the division's mission that the enemy not advance past your area of operations. Division is helping you by giving you priority of artillery fires and will be giving you a combat engineer platoon for 15 hours in order to dig two-tier fighting positions, emplace turning and fixing obstacles to canalize the enemy into kill sacks, and dig anti-tank ditches. In a deliberate defense, the defending force is supposed to defend an offensive force three times its size. It is critical to dig in as many tanks as possible. An engineer dig team can emplace a full two tier fighting position in 3 hours. An Armored Combat Earthmover (M9 ACE) platoon has 4 ACEs that are assigned to your company. One ACE can dig 5 full fighting positions in the 15 hours. As you arrive in the center of your defense, you send for the four vehicles to help prepare the landscape for battle. With a strategy already in mind, you have high confidence of protection after the dig. However, once the four construction vehicles arrive, due to reliability problems, only one is fully mission capable, one is currently available to push, only one can dig, and the other one can only be used for raking. The preparation that was supposed to take 15 hours will now take 45 hours, which is more time than is available. The operational capability which was planned to be around 95% of a success is now somewhere around 40-50%. The lives of your soldiers could be at stake, and the success of the mission is less promising without major help from higher headquarters.

Often, it is easy to "wait and see" with many logistics, reliability and maintainability issues until the Operational Test and Evaluation. However, at that time, millions of dollars in RDT&E money has already been spent, the design of certain components have been frozen, LRIP is starting and transition partners are awaiting delivery of a product which fulfills the requirements they communicated early in the program. As time passes in development and more and more decisions are made, it requires more money, time and effort to make even the smallest changes on a vehicle/component design.

SPECIALTY ENGINEERING COMPETENCY

The role of the Tank, Automotive Research Development and Engineering Center (TARDEC) is largely RDT&E efforts. Engineering technology teams work to design new systems and subsystems which push the envelope on performance, mobility, survivability, and fire power. Researchers strive to meet the end user's requirements with the latest technology, which is often still under development. While this stage of development can be lengthy and costly, the majority of the cost of a program rests in the Operations & Sustainment of a vehicle, as shown in Figure 1 below.

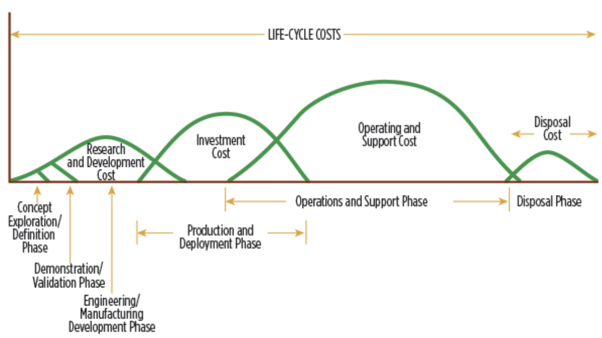

Figure 1: Adapted from Operating and Support Cost-Estimating Guide, published by the Office of the Secretary of Defense, Cost Analysis Improvement Group, 1992. [1]

Figure 1 demonstrates the forethought needed while still in the research and development phase of a project. Every decision that is made during the R&D phase will affect not only the cost of the Operations and Support Phase, but also the efficiency with which the warfighter will be able to operate the system. Again, this can be a matter of combat success and safety versus combat failure.

In order to assess a design from a supportability perspective early in a technology's prototyping phase, TARDEC's Systems Engineering Directorate has established a Design for Supportability (DfS) competency. This competency, under the SE umbrella, encompasses the relationship between Design for Reliability (DfR), Design for Maintainability (DfM), and Design for Logistics (DfL). The following sections will outline and explain the analyses and artifacts which are the focus of each Design Area, and how each of those deliverables aids in the prevention of an undue logistics burden after the product's transition.

DESIGN FOR RELIABILITY (DfR)

The DfR analyses, assessments, models and progress are all summarized in the Reliability Case Report. Depending on the maturity of the technology and stage of development, the level of detail of the Case Report will vary. For a technology entering a Preliminary Design Review (PDR), the Reliability Case Report should include a Reliability Block Diagram, Reliability Predictions, and a Failure Mode Effects and Criticality Analysis (FMECA). The Reliability Block Diagram is a functional diagram which shows the logical connections of the components in a system to complete a specific function. One block diagram pertains to one specific function, i.e., a separate block diagram is needed for each function. Components in a block diagram are modeled as either series or parallel structures. A series structure is a system that is functioning only if all of its n components are functioning. A parallel structure is a system that is functioning if at least one of its n components is functioning.

There are multiple methods and approaches to generate reliability predictions. While the descriptions and ratings of those various methods are outside of the scope of this paper, the objective of the reliability predictions is to show the confidence, at this early stage of development, of reaching the reliability requirements for Mean Time between System Abort (MTBSA) and Mean Time between Essential Function Failure (MTBEFF). The predictions may be based on preliminary test data, historical test and/or field data, or various statistical methods. Failure rate information on a component level is needed to generate accurate system-level predictions.

The Failure Mode Effects and Criticality Analysis (FMECA) is a method used to identify potential failure modes of each of the functional components of a system. The downstream effects on other functions of the system are also identified, so that the domino effect of each failure throughout the system is known. There are various methods for generating a FMECA. However, the important elements of the analysis include: the component/subsystem, its function, its operational mode, the failure mode, the failure cause or mechanism, detection of failure, and the next level effects and end effects on the system of that failure. Each failure mode is also given a criticality score for the Difficulty of Detection, Probability of Occurrence, and Severity. The product of these three criticality scores is the Risk Priority Number, or RPN. The failure modes are ranked according to RPN magnitude, and those with the highest scores are marked as critical failure modes.

The Specialty Engineering Team has opted to use a model-based approach to generating a FMECA. This process begins with creating a functional model which identify material, energy and signal flows into and out of the system and subsystems. Each component also has a failure mode, mechanism, and cause associated with it. Through the use of the functional model, a FMECA report can automatically be generated which accounts for all of the upstream and downstream effects of a particular failure. A model-based approach has the advantage of providing efficient updates during design changes and improvements, as well as trackable version control between updates.

The deliverables for a technology at a level of maturation ready for CDR are much the same as for PDR. All that is required are updates to the Reliability Block Diagram and FMECA based on changes to the design, and a gap analysis to show differences in the reliability predictions and requirements.

All of the assessments included in the Reliability Case Report are expected to be continuously updated throughout the testing phases of the system. Any critical failures that surface during testing, and any design changes which are made to improve the design against the failures, are documented in relation to the FMECA and the reliability predictions. This not only shows credibility in the final design and a higher confidence of success to a transition partner, but also documents important design decisions as reference for future iterations/updates to the design. These decisions can be taken into consideration during future design changes, and will hopefully save time and money in not repeating the same trials/possibilities.

DESIGN FOR LOGISTICS (DfL)

DfL exists to ensure that proper Logistics related considerations are being taken early on during technology development phases. This is done in two main ways; design assessment and design influence. Design assessment is captured and documented in what is called the Logistics Engineering Assessment Report (LEAR). The LEAR provides an assessment of all relevant Integrated Product Support (IPS) Elements that have an impact or are impacted by the technologies being developed. The LEAR includes a scaled-down product support analysis completed at the appropriate level for Research and Development (R&D) and Science and Technology (S&T) initiatives along with a maintainability assessment using 3D CAD models to assist in determining any accessibility, maintainability, safety or human factors design or integration risks. The LEAR is a document that is to be used as a transition product to the transition partner's Product Support Manager (PSM) who can use the data within the LEAR to assist in developing the Life Cycle Sustainment Plan (LCSP) for their system.

The Logistics Engineer analyzes and documents in the LEAR the project's current assessment with respect to each one of the twelve IPS Elements. The twelve IPS Elements and a brief explanation of how these elements are addressed in the R&D and S&T community at TARDEC are as follows:

- Product Support Management - includes identification of the sustainment metrics and the Logistics Policy Implementation.
- Design Interface – includes Environmental Management and Corrosion Protection.

- Sustaining Engineering – includes obsolescence, risk, safety and human factors analysis.
- Supply Support - includes identifying Long-Lead and Key Supply Chain elements and identifying Sustainment Cost Drivers.
- Maintenance Planning and Management - includes ensuring Diagnostics and Prognostics are incorporated into the System Performance Specifications as well as establishing the project's Maintenance Concept and ensuring the DFMEA is completed.
- Packaging, Handling, Storage and Transportation (PHS&T) – includes analysis on design against PHS&T requirements
- Technical Data – includes supporting the Data Rights Management plan for the project.
- Support Equipment Analysis - includes any support equipment required for the technologies being developed
- Training and Training Support - ensure the identification of any training systems and training plans.
- Manpower and Personnel - includes supporting Mission Engineering (ME) team with operator and maintainer skill level requirements.
- Facilities and Infrastructure - analysis identifies the need for any special facilities to support the technologies being developed.
- Computer Resources Support - identifies the software support requirements. [7]

The above analysis against the twelve IPS Elements is done concurrently with the design process. Having a Logistics Engineer embedded as part of the technology project team in the R&D and S&T community enables continuous feedback to the development team that is critical during the technology development process to ensure that constant design influence is occurring that leads to better informed decisions. The earlier supportability related issues are identified and corrected the better chances of a achieving a supportable technology solution.

DESIGN FOR MAINTAINABILITY (DfM)

In addition to Logistics Engineers being embedded into technology project teams, there has been determined that a need for Maintainability Engineers exists within the R&D and S&T community at TARDEC. Maintainability Engineers develop a Maintenance Task Analysis (MTA) like document that analyzes the remove and replace tasks for every LRU candidate on the system. The inputs for the MTA are the 3D CAD model, product structure, all-inclusive failure rates, scheduled maintenance frequency, tools available, system specifications, and system level requirements. The Maintainability Engineer analyzes each step of the remove and replace task and assigns a time for each subtask. The remove and replace task is broken down to the subtasks; Diagnose, Access, Remove, Replace, Reassemble, and Verify.

In order to ensure that standard task times are being used during the analysis, the Maintainability Engineer utilizes a TARDEC developed Maintenance Analysis Tool that offers standard fastener times and subtask times and integrates all identified tasks together and rolls them up to the higher system levels. This tool provides outputs that include MTTR, Unscheduled Maintenance Ratio, Preventative Maintenance Time, Scheduled Maintenance Ratio, tools used, special tools used, crew percentage, and potential maintenance induced failures. The Maintainability Engineer receives this data output and analyzes it against the supportability related requirements. The results of this analysis provides quantitative and qualitative data for technology teams to use to assist in prioritizing the integration of critical maintenance items into their design in order to reduce both the maintenance burden and logistics impact to the transition partner.

Design for Supportability Trifecta

The Design for Reliability, Design for Maintainability, and Design for Logistics engineers all rely on each other to maximize the Design for Supportability goals of each project. Results are best when all three are actively pursued by the individual project teams. Figure 3 below illustrates the relationships between the three supportability areas.

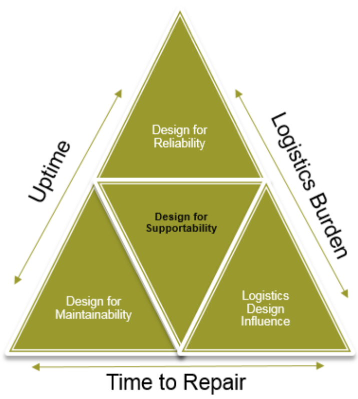

Figure 2: Relationship between Design for Reliability, Design for Maintainability and Design for Logistics

One of the main metrics needed for reliability calculations is the failure rate of individual components, subsystems and of the overall system under analysis. The failure rate, λ, is defined in Eq. 1 below.

$$\lambda = \frac{\text{No. of Failures}}{\text{Total Time, T}} = \frac{1}{\text{MTBF}} \qquad (1)$$

MTBF is the Mean Time between Failures, and is the average time between failures, or the total functioning life of a population of an item divided by the total number of failures in that population in a specific period of time [2]. For a product with a failure rate which is assumed to be constant, the Reliability can be calculated using the exponential failure rate as [3]:

$$R(t) = 1\text{-}e^{-\lambda t} \qquad (2)$$

One of the main metrics used in maintainability is the Mean Time to Repair (MTTR). It is defined as the total clock hours for corrective maintenance divided by the total number of corrective maintenance actions for a given period of time [4]:

$$\text{MTTR} = \frac{\text{Total Maintenance Time}}{\text{Number of Repairs}} \qquad (3)$$

The MTTR is related to the failure rate, in that it governs the total number of repairs. Any change made which affects reliability will either lessen or increase the maintenance burden, and either take soldier manpower away from other tasks or free them for other important tasks within the command.

A change in the design of a component which will require either routine or emergency maintenance must take into consideration the lifting equipment needed to remove any heavy components in order to expose the component to be repaired, the availability of that equipment, the manpower needed to operate that equipment, the necessity of special tools to perform the maintenance, and the environment in which the maintenance can be performed. For example, will a vehicle need to be towed back to base to repair the engine, or can it be repaired in the field? Will the presence of possible contaminants in the field affect its future operation? However, will the safety of the soldiers be at stake if they are mid-operation on an important mission and are experiencing a system abort? All of these questions and considerations affect the logistics burden. Each seemingly small design change has an effect on the maintenance and logistics burden which will become a part of the warfighter's daily life.

Military Sustainability Failures

Although there have been several notable systems that have not been designed to be sustainable throughout its lifecycle, one significant project to note was the Expeditionary Fighting Vehicle (EFV). The EFV (once also known as the Advanced Amphibious Assault Vehicle) was developed by General Dynamics for use as an amphibious assault vehicle by the Marine Corps. The agility and mobility was designed to surpass the M1 Abrams [5].

In 2009, the USMC had reduced the number of EFV's to purchase from 1,013 to 573 by 2015 because of a drastic increase in per unit cost. In 2011, the program had already cost $3 billion, and the entire program was projected to cost only $15 billion. The remaining funds would not be sufficient to cover operation and sustainment. The EFV program was criticized for its wasteful spending through a join report by the U.S. Public Interest Research Group and the National Taxpayers Union. The cancellation of the program was supported by the co-chairs of the National Commission on Fiscal Responsibility and Reform. Finally, in January 2011, the Secretary of Defense, Gates, called for the cancellation of the EFV program [5].

Before cancellation of the program, there were several major schedule delays due to significant failures during operational testing. There were major problems with the Hull Electronics Unit which controlled the EFV's mobility, power, and auxiliary computer software. There were also significant issues with the new bow flaps during testing. For each issue, testing was delayed several months while a root cause analysis was performed and design updates were made [6].

The intention of the Design for Supportability competency is to catch design issues which may become major reliability or logistical issues early on in the design process so that they do not cause major surprises or delays later in a program. Early detection of failures, root cause analysis, and re-design while there is still flexibility to change the design is important in saving time and money, and in meeting the requirements and needs of the end user.

Conclusion

The DfS competency within the Systems Engineering Directorate at TARDEC is a new establishment, initiated in late 2017. It has grown out of the Logistics Engineering team, which was started in 2016 with the realization that there was a need to take logistics issues into consideration earlier in the design process. While there may be parallel efforts in other parts of the DoD, this is a new in-house competency for TARDEC. The process described in this paper is currently how the S&T community is encouraged to incorporate reliability, maintainability and logistics considerations into the early design of new technologies. However, we recognize that there is room for improvement and room to learn from industry and other established organizations. As the competency grows, we hope to continue to mature the processes and guidance to be more accessible to technology development teams and which will yield products that are low risk items during transition.

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