NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ENHANCING SAFETY-BASED DECISION MAKING IN CONCEPT DESIGN: INTRODUCING THE L.E.A.D.S PROCESS

by

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December 2023

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2023	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE ENHANCING SAFETY-BASED DECISION MAKING IN CONCEPT DESIGN: INTRODUCING THE L.E.A.D.S PROCESS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Vikram S. Pandurangan			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

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Legacy systems, still in service or decommissioned, can be a valuable resource for technical risk identification. Applying technical risks and hazard scenarios conceived or experienced by a legacy system to new alternatives via translated safety based performance criteria, can foster better understanding of design boundaries and constraints. This in turn can help designers enhance system form and function early in the life cycle, which may reduce dependency on developing complex operating procedures as technical risk mitigation.

This thesis presents a new framework, titled L.E.A.D.S, to address technical risk identification gaps in the DOD's analysis of alternative process. L.E.A.D.S, which stands for legacy system selection, exploratory study, attribute weighting, derive safety-based performance criteria, and score alternatives, is a new procedure intended to improve safety.

14. SUBJECT TERMS concept design, AoA, active array, systematic, safety, operational effectiveness, alternatives, tradeoff analysis, procedure, traceability			**15. NUMBER OF PAGES** 83
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
CAPE	Office of Cost Assessment and Program Evaluation
CLFA	Compact Low Frequency Active
CONOPS	Concept of Operations
DAU	Defense Acquisition University
DEA	Data Envelope Analysis
DOD	Department of Defense
DoDI	Department of Defense Instruction
DTACS	Deep-Towed Array Geophysical System
FAA	Federal Aviation Association
FHA	Functional Hazard Analysis
FMEA	Failure modes and effects analysis
FTA	Fault Tree Analysis
GAO	Government Accountability Office
INCOSE	International Council on Systems Engineering
L.E.A.D.S	Legacy System Selection, Exploratory Study, Attribute Weighting, Derive Safety Criteria, Score Alternatives
LFA	Low Frequency Active
MCDA	Multi-Criteria Decision Analysis
MOE	Measure of Effectiveness
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVFAC	Naval Facilities Engineering Systems Command
NSC	Naval Safety Center
R&S	Readiness and Sustainment
SME	Subject Matter Expert
SOP	Standard Operating Procedure

SSA	System Safety Assessment
SURTASS	Surveillance Towed Array Sensor System
T-AGOS	Auxiliary Ocean Surveillance
TLTA	Thin Line Towed Array
U.S.	United States
VDS	Variable Depth Sonar
WIN-T	Warfighter Information Network Tactical

EXECUTIVE SUMMARY

As defense systems become increasingly complex, understanding the dynamic interactions between operational context and environment is vital for maintaining system safety. Hazards and safety scenarios, if addressed or even identified early in design, can improve the robustness of systems and significantly reduce program impacts to budget and schedule. The traditional approach to concept design as stated by the Department of Defense's (DOD) acquisition framework guide encourages users to think about safety and invoke the use of industry standards when developing concepts and evaluating tradeoffs; however, there is no explicit requirement or procedure present to analyze alternatives solely on their ability to address safety (The Office of the Director, Operational Test and Evaluation [DOTE] 2013). Furthermore, there is no guidance to addressing system safety emanating from technical risks that are specific to the concept of operations.

The DOD's analysis of alternatives (AoA) approach is a standard procedure used by design groups to evaluate tradeoffs across the various branches of the DOD including the Unites States (U.S.) Army, Navy, and Air Force. The procedure aims to limit bias in alternative selection and directs users to evaluate alternatives against each other based on a multitude of factors including performance, schedule impact, and cost. Although the procedure guides users to consider safety as a criterion, it does not explicitly state how. In addition, inclusion of cost and schedule may leave the door open for bias when strictly creating safety evaluation criteria based on industry safety standards may not fully encompass the distinctive safety risk considerations that arise from specific operational environments. Legacy systems, whether operational or in the early stages of decommissioning, can be a valuable resource for technical risk identification. Conducting an early analysis of hazard scenarios encountered by a former system can significantly increase the chances of early technical risk identification and potentially minimize the necessity for rework due to late or no identification.

This thesis presents a new systematic framework, titled L.E.A.D.S, which stands for legacy system selection, exploratory study, attribute weighting, derive safety-based performance criteria, and score alternatives, to address the existing process gaps in the

DOD’s approach to analyzing alternatives in concept design. L.E.A.D.S is a procedure intended to improve safety awareness in the early stages of defense system design. The process is comprised of five steps:

1. **Legacy System Selection**: Identify and select an existing defense system or similar system within the industry for further evaluation. Factors guiding the selection include program system replacement or upgrade initiatives, timing of last operational use, and applicable industry standards. Leveraging the knowledge and experience gained from these systems establishes a solid foundation based on established safety best practices and mitigates potential technical risks associated with untested approaches.
2. **Exploratory Study**: Conduct in-depth research of existing operational, test, and trade study records for the legacy or similar system to develop a casualty scenario list. This list identifies technical safety risk scenarios that can result in system damage, impact to adjacent systems, or cause human injury and loss of life.
3. **Attribute Weighting**: Sort the casualty scenarios based on consequence and scenario type and assign quantitative weights to prioritize the scenarios with the greatest impact in terms of casualty severity and fault type.
4. **Derive Safety-Based Performance Criteria**: Establish specific benchmarks for evaluating safety performance across alternatives by linking casualty scenarios to measurable attribute measures. Lessons learned from successful systems and key safety attributes are applied, encouraging root-cause analysis to understand failure situations encountered by the previous system. This step enables a comprehensive understanding of the safety implications for each alternative.

5. **Score Alternatives**: Systematically evaluate and compare alternative concepts against the established safety-based performance measure criteria developed in the previous step.

To illustrate implementation, this thesis uses L.E.A.D.S on an example of a current naval system in operation: The Surveillance Towed Array Sensor System (SURTASS) Auxiliary Ocean Surveillance ship designator 25 (T-AGOS 25) Active Array system whose main objective is to produce sonar to locate targets of interest in the water.

The L.E.A.D.S process offers several advantages, including traceability to concept of operations (CONOPS), enhanced safety considerations, informed decision-making, integration of lessons learned, and identification of technical risks for life cycle operational risk management. To ensure the effectiveness and reliability of the L.E.A.D.S process, it is essential to address potential pitfalls through careful implementation, robust data collection, stakeholder collaboration, and continuous improvement. By doing so, the L.E.A.D.S process can support safety-driven decision-making in concept design, promoting safer and more reliable defense systems.

References

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I. INTRODUCTION

A. CONTEXT

As advancements in technology and evolving threats reshape the landscape of defense, ensuring that safety is effectively addressed in early system development becomes an even more critical and non-negotiable objective. Defense systems are complex and include a unique set of casualty scenarios tied to hazards associated with mission objectives. Safety, as seen through the lens of a system's concept of operations, is not cut and dry and can morph beyond what industry standards can dictate. As stated by the International Council on Systems Engineering (INCOSE), "Safety is an emergent property of a system, dependent on how a system behaves when used, and sustained, in a specific way in a specific environment" (INCOSE n.d.).

Furthermore, safety-based vulnerabilities can arise from circumstances that influence the system's interactions with other systems, the operating environment, and human operators The design and development of defense systems requires rigorous attention to safety to ensure the protection of military personnel, assets, and mission success.

The early design stages of system development play a pivotal role in establishing a foundation that guides safety performance over a system's life cycle. Key drivers to determine system functionality and form are reserved for the conceptual design phase. Safety is, more often than not, examined in greater detail in the later stages of the system's development cycle. Safety performance is at risk when mitigations for potential casualty scenarios are addressed in the form of standard operating procedures (SOP) for operators and maintenance staff as opposed to being addressed by a system's inherent design. Operating procedures can also introduce safety risks in the form of human error or faulty component interactions, which can potentially have negative unintentional consequences.

The traditional approach to safety in early system design has primarily focused on meeting established regulations and compliance standards as prescribed by DOD such as the Unified Facility Criteria (UFC), which is prescribed by MIL-STD 3007, and provides

design criteria to be used in the development of designs for new facility construction (Office of the Assistant Secretary of Defense for Sustainment 2023). UFC design criteria are not recommendations, but obligatory requirements that apply to the Military Departments, the Defense Agencies, and the DOD Field Activities. The Code of Federal Regulations (CFR) is another example of a design standard, which provides general and permanent rules published in the Federal Register by the executive departments and agencies of the Federal Government. The CFR goes beyond the UFC to provide rules pertaining to a greater range of project types and is comprised of rules and regulations pulled for various government regulatory bodies such as Occupational Safety and Health Administration (OSHA), which has standards published in Title 29 of the CFR (National Archives and Records Administration 2023, 1910.1). While regulatory bodies like OSHA provide legally binding measures for general safety, defense systems are unique and susceptible to ambiguous safety considerations that derive from the intricate dynamics between environment and evolving threats. These safety considerations in most cases may not be mitigated or even accounted for by design standards such as the CFR.

The degree to which system safety is addressed in the early stages of defense system design is a subjective topic. The alternative analysis process is vulnerable to biases from stakeholders. Oftentimes decision making prioritizes performance and feasibility objectives over addressing safety via form, fit, and function. Schedule and cost drivers play a pivotal role in how much scrutiny is given to safety in the alternative selection stage. Poor system safety performance can also be due to an incomplete understanding of the potential technical risks associated with the system, mission parameters, and operating environment. Technical risk as defined by NASA is "risk associated with the evolution of the design and the production of the system of interest affecting the level of performance necessary to meet the stakeholder expectations and technical requirements" (NASA 2007, 140).

Although defined as a risk, which can impact the system as whole, technical risks are given less priority early on in the design as they have potential to evolve with the life cycle as design matures. A better understanding of potential major technical risks associated with the program objectives can inform alternative development and give another major data point when considering trade-offs during alternative selection. Creating

concepts that assertively claim to prevent casualties to the environment, humans and other systems, without conducting a measurable trade-off analysis that considers less apparent safety situations, can render a system's baseline design more susceptible to vulnerabilities. Safety concerns may emerge later in the development process leading to design flaws, increased costs, delays in schedule, unintended system or human interactions, and potential risks to equipment, personal and other interacting systems.

A more holistic and pro-active process is needed to ultimately foster a safety culture that permeates to all stages of the system development. A process, which injects a safety assessment into the concept design phase, specifically into the analysis of alternatives stage, potentially encourages design teams to build more robust concepts that not only consider high level mission safety objectives, but secondary consequences that either a mission environment or operational scenario can present. System casualty scenarios if addressed in the concept design phase can not only increase fidelity but improve overall performance in regards to mission objectives.

The integration of this new process should include risk assessment techniques, the incorporation of lessons learned from previous systems, and the adoption of a structured methodology that identifies potential vulnerabilities and provides metrics to measure alternative performance against them. To achieve this, a systematic approach is necessary, one that specifically integrates safety considerations into the Department of Defense (DOD) analysis of alternatives (AoA) process and facilitates informed safety-based decision making.

This thesis presents a new process called L.E.A.D.S, which stands for legacy system selection, exploratory study, attribute weighting, derive safety-based performance criteria, and score alternatives. The L.E.A.D.S process is a comprehensive framework intended to improve safety awareness in the early stages of defense system design, specifically in the alternative analysis of conceptual designs for defense systems. It encompasses a series of steps specifically designed to incorporate technical risk derived from legacy systems.

This thesis will highlight the existing process gap in the DOD's AoA, and aims to introduce and highlight the merits of implementing L.E.A.D.S. It will explore each step of the process and demonstrate its potential to revolutionize the way safety is prioritized and integrated into the early design decision-making processes.

B. STUDY BENEFITS

The traditional conceptual design process for defense systems typically compares alternatives based on a range of factors, including performance, cost, schedule, and technical feasibility. However, the explicit consideration of safety objectives may vary or be limited in the traditional process. The emphasis is often placed on meeting operational requirements and achieving technical specifications, with safety objectives unintentionally treated as a secondary concern.

In contrast, the L.E.A.D.S process aims to explicitly address safety issues that may be tied to a real-world example. This process specifically focuses on incorporating safety objectives into the comparison of design alternatives. This methodology fills an existing gap in conventional methodologies by providing a traceable connection to a new design and a former system's failure modes.

While the L.E.A.D.S process helps bridge this methodology gap, it is essential to continuously evaluate and update the process based on emerging research, advancements in safety engineering, and evolving defense system requirements.

C. GOALS

This thesis provides a detailed breakdown of the L.E.A.D.S process and highlight its merits and potential benefits to the defense system conceptual design phase process. The goals of the process are as follows:

- To enhance system safety performance by aiming to identify and mitigate potential technical risks.
- To systematically evaluate alternatives based on mission-based safety measures.

- To incorporate lessons learned from legacy systems in a traceable manner.
- To facilitate technical risk management through life cycle

Overall, the goals of the L.E.A.D.S process revolve around escalating safety to be a primary objective upon which alternatives are evaluated.

D. ORGANIZATION AND METHODOLOGY

This thesis is organized as such: Part I discusses the significance of this research. Part II uses a literature review to provide information on current methods of addressing safety in concept design including description of process and commentaries on its use. Gaps in methodology are identified as well as a call for the L.E.A.D.S process as filler. Part III presents the L.E.A.D.S process, discusses assumptions and performs a detailed step by step breakdown or each aspect of the process. Part IV presents a case study of a current DOD program U.S. Navy's Surveillance Towed Array Sensor System (SURTASS) Auxiliary Ocean Surveillance Ship (T-AGOS 25) Active Array System as an example of L.E.A.D.S implementation The system's mission uses sonar to locate targets of interest in the water. It is in operation today on multiple vessels or platforms operating in the Pacific Theatre (CRS 2023, 1). The case study will assume a blank design slate for the SURTASS T-AGOS 25 Active Array system, as if it is in the concept design stage. The case study will go through all five steps of L.E.A.D.S. Alternative formation and analysis will not be conducted as part of this example, instead in the final step, placeholders will be used for the alternatives and sample scores given to provide an example of how safety tradeoffs can be assessed. The focus of the case study lies in showing how user inputs are made, organized, and hypothetically processed to portray the rationale behind the building blocks of L.E.A.D.S. Lastly, Part V presents a conclusion with a discussion of the challenges and benefits facing the new process. Discussion will include recommendations for further study and conclude with available applications to validate the L.E.A.D.S process as an effective tool to enhance safety awareness at the concept level.

E. CONTRIBUTION

The main contribution of this thesis is to propose a new sub-process to the existing DOD AoA methodology that emphasizes evaluating alternatives from solely a safety-based perspective. Secondary contributions include explicitly addressing the role legacy system mission and environmental data has in developing pivotal safety-based scoring criteria and building awareness of the importance of fine tuning a system's physical form and function based on safety criteria early in design.

II. LITERATURE REVIEW

To investigate the merits of the L.E.A.D.S process, this thesis delves into current methodologies developed by industry. Aided by a review of design standards, commentaries and literature, research was first conducted on ways safety is currently integrated in the system development process as whole. A deep dive is then taken into how the AoA process is being used across DOD concept design across DOD. This chapter concludes with a brief on gaps and potential opportunities within the current processes.

A. TRADITIONAL METHODS OF ADDRESSING SAFETY IN CONCEPT DESIGN

Safety is assumed to be prioritized in concept design through a combination of inherit design practices, regulations, standards and risk management processes. Ensuring safety of defense systems has been a critical area of research and practice in the field of system engineering. Several traditional methods and approaches have been employed to address safety considerations during this early development stage. Life cycle frameworks such as the V-model incorporate early steps for defining system requirements, conducting trade-off analyses, and verifying system performance against criteria, which may include safety.

The DOD prescribes a method for designers to evaluate tradeoffs between different concepts. The AoA is a structured methodology used to evaluate and compare different alternatives against a range of criteria including cost, schedule, performance, risks and other attributes deemed important by project stakeholders. The DOD further breaks down the definition as such:

> The Analysis of Alternative (AoA) is a documented evaluation of the performance, operational effectiveness, operational suitability, and estimated costs of alternative systems to meet a capability need that has been identified through the Joint Capabilities Integration and Development Systems (JCIDS) process. The AoA assesses the advantages and disadvantages of various materiel alternatives being considered to satisfy the capability need. The AoA also considers the sensitivity of each alternative to possible changes to key assumptions or variables. (Joseph 2021, 7)

AoA is typically conducted during the early stages of acquisition and aims to inform decision-makers about the most effective and efficient ways to fulfill the desired capability. The primary purpose of the AoA process is to assess potential alternatives through the identification of the strengths and weaknesses of each alternative. It is meant to provide decision-makers with a solid foundation for selecting the most suitable solution. The process steps involve defining the objectives, developing alternatives, establishing evaluation criteria, performing an alternative analysis, and down-selecting one solution.

Objectives for AoA may consider cost and schedule, but the DOD also guides users to consider other factors just as critical. There is a growing recognition within industry that safety should not be compromised for other factors; however, there are no explicit rules or processes in place to require the comparison of alternatives against safety criteria. In the AoA, system designers are guided to create multiple alternatives such that a design space can be fully explored. It implied that alternative development considers human based design to protect operators and limit human casualties. Human based design factors may include user interfaces, maintainability, and access point. The process then guides users to establish evaluation criteria to compare alternatives. It notes that users are to comply with relevant safety regulations and standards to ultimately create alternatives that on the surface ensure safety of personnel.

Once evaluation criteria are chosen, a thorough analysis is conducted to evaluate alternative performance. This analysis includes technical assessments, cost estimation, risk analysis, and other relevant studies to evaluate the strengths and weaknesses of each option. Alternatives are ranked and compared based on the evaluation criteria. This ranking identifies the most promising options that align with the desired capability, taking into account the trade-offs between cost, performance, and other factors. This includes a detailed assessment of each alternative, highlighting their advantages, disadvantages, risks, and potential impacts on the defense system's overall effectiveness.

In addition to AoA, there are other traditional processes which may consider system safety and technical risk that are tied to the concept design.

The Concept of Operations (CONOPS) also presents an early opportunity for which safety-based considerations can be defined. The CONOPS is essentially a document which outlines the vision of operations. Sholom Cohen of Carnegie Mellon states the purpose of the CONOPS is

> to represent the *systems user's operational view* for a system under development. This operational view is stated in terms of how a system will operate in its intended environment. … [and] will accomplish much of the same purpose as a CONOPS for a system by describing how the mission or purpose of the product line will be fulfilled, the environment for fielding the product line, and the organizational structure for its fielding. (Cohen 1999, viii)

As the CONOPS identifies system's intended mission, operational scenarios, and the roles and responsibilities of operators and users, it can be an implicitly guide stakeholders to identify potential safety risks and requirements associated with the system's context.

Another practice that warrants consideration for imbuing safety-based thinking into design, but is typically employed later in the design process, is a System Safety Assessment (SSA). A SSA assesses the design against safety standards, regulations, and best practices to identify any potential safety gaps or concerns. Usually requiring mature design refinement, a safety assessment can provide insights into the feasibility of achieving safety objectives with the design to guide further refinement and iteration. SSA is generated as the primary means of compliance to design codes and is used to optimize design with a structured body of objective evidence that the system can be certified as being safe enough to be released into a defined service environment.

The SSA employs several tools to pinpoint failures and assign quantitative basis for the failures in terms of likelihood and cause/effect. These tools include a functional hazard analysis (FHA), failure modes and effects analysis (FMEA), and a fault tree analysis (FTA).

An FHA is a systematic process that aims to identify potential hazards and assess their risks early in the concept design phase. It involves identifying system components, interfaces, and operational scenarios, and analyzing them to identify potential hazards and

their associated risks. FHA helps in understanding the safety implications of design decisions and guides the selection of appropriate risk mitigation strategies.

FMEA is a method for analyzing potential failure modes and their effects on system performance and safety. It involves systematically examining each component, subsystem, and interface to identify failure modes, their causes, and the potential consequences. FMEA helps in understanding the vulnerabilities of the concept design and guides the development of appropriate mitigation strategies. Fault tree analysis (FTA) is a method of analyzing the probability of system failure by breaking down the system into its components and evaluating the likelihood of each component failing.

B. PREVIOUS STUDIES

Research has observed many uses of the AoA method in the defense industry. Work has been done to cross examine the results of AoAs across different defense lines. Among the many benefits found in literature advocating the current methodology, problem areas or areas in need of improvement have also been unearthed. In a survey completed in the years of 2015 to 2021, the DOD found that:

> 43 percent of respondents responsible for conducting AoAs believe they did not fully understand the baseline capability. 71.4 percent of respondents felt that some biasing was a factor when selecting a particular AoA solution. (Joseph 2021, 6)

The DOD's findings presented several perceived deficiencies in the current AoA process. The survey notes that 43% of respondents did not feel as if enough attention was being given to the mission need or that the "Baseline/Do Nothing" capability was not included at all in the program's AoA as an alternative solution. The report ascertains that understanding the baseline is a key component to performing an objective AoA, which may improve team's ability to create pertinent alternatives and evaluate their benefit against the status quo. A legacy system is an example of a status quo baselined alternative. To improve, the report recommends that the DOD "ensure that the baseline capability is understood and introduced prior to conducting an AoA" (Joseph 2021, 6). Under this recommendation, programs would need to bring awareness to the mission environment and operating theatre

in greater detail as well as how the current or past mission systems have been performed in the past.

In addition to baselining, more than two-thirds of respondents believed that bias was a frequent contributing factor in alternative selection, placing the DOD at risk of inferior alternative selection. Respondents believe that the selection process is vetting out the most viable alternative, instead alternatives are prone to being chosen based on stakeholder undertones and programmatic pressures. This conflicts with the AoA's objectives as outlined by the Office Aerospace Studies Analysis of Alternatives Guidebook:

> AoA must provide compelling evidence of the capabilities and military worth of the alternatives. The results should enable decision makers to discuss the appropriate cost, schedule, performance, and risk tradeoffs and assess the operational capabilities and affordability of the alternatives assessed in the study. (Bonanno 2017, 2)

In addition, the guidebook the Center of Army Analysis AoA instruction also gives credence to objectively presenting solutions that meet mission requirements,

> Assessment of potential materiel solutions to satisfy the capability need documented in the approved Initial Capabilities Document (ICD). The AoA focuses on identification and assessment of potential materiel solutions, key trades between cost and capability, total life-cycle cost, including sustainment, schedule, concepts of operations, and overall risk. The AoA will inform and be informed by affordability analysis, cost analysis, sustainment considerations, early systems engineering analyses, threat projections, and market research. It identifies the most cost effective solution that has a reasonable likelihood of providing the validated capability requirement(s). (Office of the Secretary of Defense 2021, 6)

To address this problem area, the report recommends that the "Department of Defense implements a process where biasing in the alternative solution is removed from the process as much as possible" (Joseph 2021, 22). In short, a process which selects alternatives with criteria that traces to specific mission needs.

A smaller study was conducted by the Institute for Defense Analysis to review AoA performance (Levine et al. 2020, 1). The study included 41 programs and collected information including questionnaires, interviews of defense leads, and AoA project data

from the U.S. Army, Navy, Air Force and Marine Corps (Levine et al. 2020). The report found that:

- 21 out of 41 analyses included a comparable set of alternatives (Levine et al. 2020, 16)
- 18 out of 41 AoA results or recommendations were supported by analysis. (Levine et al. 2020, 16)

Close to 50% of the analysis reviews were found to lack a good traceable analytical basis in alternative selection extending to both alternative development and trade-off analysis, which puts the quality of the analysis at risk.

Another study was performed by the Government Accountability Office (GAO) on major missile acquisition programs. The study was commissioned after the GAO found that the "2008 portfolio of 96 major defense acquisition programs experienced cost growth of $296 billion, experienced an average delay in delivering initial capabilities of 22 months" (GAO 2009, 1).

In the review, the GAO specifically highlights the AoA's ability or lack thereof to address technical risk, specifying:

> DOD acquisition policy requires that AOAs assess the technical risk of alternatives, but it does not provide criteria and guidance for how and to what extent technical risks should be addressed and it does not specify that other types of risks should be assessed.
>
> Some AOAs we reviewed did not examine risks at all, focusing only on the operational effectiveness and costs of alternatives. (GAO 2009, 12)

Technical risk is noted as a paramount concern by the GAO. It notes that technical risk identification and examination can improve AoA effectiveness:

> Of 12 projects observed to have AoAs with no or limited assessment of risks, 7 programs encountered 25% over baseline estimate cost growth, and greater than a 12-month delay in initial operational capability date. (GAO 2009, 14)

The GAO uses the Army's Warfighter Information Network Tactical (WIN-T) as an example program in which the AoA process did not involve comparing alternatives via

technical risk. The chosen alternative was seen as the best fit operationally and most cost effective. As a result of proceeding with the preferred alternative, the program had a cost breach, citing technical readiness as a key factor. The importance of checking alternatives against extreme non-operational scenarios is highlighted.

In a report titled "Analysis of Alternatives Process Improvement Study," The Center for Army Analysis was initially tasked to devise ways to shorten an AoA duration, however after interviewing the Office of Cost Assessment and Program Evaluation (CAPE) leadership, the focus changed to providing recommendations for improved AoA quality rather than timeline with Army leadership citing that "when they don't get a good rigorous AoA, the performers often end up having to redo it" (Carlucci and Zolner 2016, 4).CAPE concludes that AoA should be "Scenario-based, preferably in a region of key interest" (Carlucci and Zolner 2016, 8).

Several approaches have been made to improve the AoA's effectiveness. Boaz Golany identifies a gap in the AoA, regarding the lack of attention given to risk, specifically how technical, programmatic, and operational risks are tied to mission readiness and sustainment (Golany and Kress 2016, 5). In response to the gap, the author proposes a quantitative method called Data Envelope Analysis (DEA) to evaluate alternatives against readiness and sustainment (R&S). The author develops measures of effectiveness including, but not limited to, mean time between failures, dependency on other systems, repair time, and operators. The DEA helps alleviate levels of bias in AoA by providing an analytical framework to evaluate alternatives against Measures of Effectiveness (MOEs) that consider technical risk; however, MOEs are not explicitly linked to safety performance (Golany and Kress 2016, 24).

Moshe Kress and Brian Morgan present a framework called the Multi-Criteria Decision Analysis (MCDA) to aggregate alternative evaluations into a rating or score, which represents the relative standing of each alternative (Kress and Morgan 2018). The scoring criteria, which separate their process from others, incorporates scenarios in score generation. Scenarios are broken into two categories, operational scenarios and scenarios that have not manifested, but are described by economic, social, political factors that may

impact an alternative. MCDA uses scenarios to weight criteria. It does not, however, derive scenarios or link them to a specific evaluation criterion.

C. CONFIRMATION OF METHODOLOGY GAP

Based on the research discussed in the above sections, the DOD does not provide specific requirements or guidelines within AoA to explicitly require the evaluation of alternatives based on technical safety risk alone. The AoA process focuses primarily on comparing alternatives across multiple factors, including cost and schedule, performance and programmatic risks. In addition to safety technical risk, design mission context is often less well understood, even with the presence of a CONOPS. Mission context is a significant driver in identifying technical safety risks and as it gives less design priority the potential robustness of a concept design is decreased.

Industry, along with the DOD, have established safety policies, regulations and standards that apply to a defense system development throughout its life cycle. However, these considerations are typically integrated into the broader system engineering processes and frameworks such as risk management, which has facets including hazard identification, risk assessment, safety analysis, and risk mitigation. The AoA is an existing framework that is in place for guiding designers and stakeholders alike in addressing safety risks and ensuring measures are in place to limit or even avoid the consequences and likelihood of an event. While the DOD does not prescribe specific requirements for evaluating safety risks and alternative performance against them, it is generally accepted that safety consideration is given due attention and integrated into the decision-making process. At a high level this duty may be given to the program office who dictates program objective and top-level requirements for a new system.

Current risk management framework processes are intended to assess and manage risk across all aspects of a system or project including cost and schedule. It can be seen as a comprehensive tool to track and manage risk. No explicit steps exist for alternatives in the concept design state to utilize the risk management framework as a tool to compare safety performance against. Instead, the risk framework tracks and add new program risks throughout the entire life cycle. To avoid the mitigation of safety-based risk in the later

stages of design, where impacts to form and function are greater, an explicit process is needed to identify significant safety risks and compare alternatives performance against them.

L.E.A.D.S goes a step beyond and puts the onus on the design teams to first identify types of failure emanating from the operating concept prior to forming and evaluating solutions. The type of major safety events that may be incurred as a result of the mission objective. Second, it forces designers to determine ways to evaluate their designs against those situations without a significant level of detail. Finally, designers are required to evaluate trade-offs based solely on safety criteria prior to factoring in cost and schedule.

The L.E.A.D.S process builds on the AoA methodology by placing a strong emphasis on safety-based decision-making. L.E.A.D.S also requires users to analyze the operational history, safety records, and lessons learned from historical systems to identify safety-related issues and inform the design process. This aspect may not be explicitly addressed in the AoA methodology, which focuses more on comparing alternative system concepts.

The research highlights the application of the AoA method in the defense industry, including cross-examination across defense lines. Benefits and shortcomings of the current methodology are evident, as revealed by a DOD survey. The survey identifies deficiencies, such as inadequate attention to mission need and bias in alternative selection. Studies show varying levels of traceable analytical basis in alternative selection, emphasizing technical risk assessment's significance. The L.E.A.D.S process complements AoA by prioritizing safety, leveraging historical systems, and emphasizing risk evaluation. It surpasses AoA in safety evaluation by considering safety records and lessons learned from legacy systems, addressing a gap in the AoA process.

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III. L.E.A.D.S PROCESS

Integrating a structured process to address safety in concept design presents various challenges in practice. While the intention is to prioritize safety from the outset, several factors can hinder the seamless integration of the new process. Concept design is a phase characterized by high levels of complexity and uncertainty. There may be limited information available about the legacy system's requirements, operational context and potential hazards. The solution neutral design space is often molded by various assumptions, approximations, and safety uncertainties primarily in the areas of system interaction and dependencies. Uncertainties can pose challenges in accurately assessing risks and determining appropriate safety considerations. Safety design needs to consider how different physical form and functions interact and the potential cascading effects of failure.

Concept design involves considering multiple design objectives such as performance, cost, schedule, and "ilties" such as maintainability. Integrating a structured safety process requires striking a balance between these objectives. Balancing safety considerations with mission effectiveness can be challenging, as trade-offs may need to be made between the two. Decisions must be made to optimize safety without compromising other critical aspects of design. As programmatic drivers such as cost and schedule may be subject to bias, the L.E.A.D.S process attempts to remove these factors to focus on safety-related criteria exclusively when considering trade-offs.

A. PROCESS OVERVIEW AND ASSUMPTIONS

L.E.A.D.S is a structured process that can be categorized as a decision-making and evaluation methodology. It provides an outline for evaluating and comparing concept alternatives, which are in the early stages of articulating their true form and function. The main focus of L.E.A.D.S lies in enhancing safety-based decision making. It is made up of five steps with each designed to build stakeholder awareness of unique safety threats the system could potentially face. Each step seeks to create a bridge that can tangibly link safety decisions for a new system to casualty scenarios experienced by a legacy one.

The acronym "L.E.A.D.S" is broken down as shown in Figure 1:

Figure 1. L.E.A.D.S Acronym

The first step of the L.E.A.D.S process, "Legacy System Selection," involves finding and picking an existing defense system or similar system within industry to further evaluate. Factors that guide selection include the program system replacement or upgrade initiatives, timing of last operational use, and applicable industry. By leveraging the knowledge and experience gained from old systems, designers could establish a solid foundation that builds upon safety best practices providing a pathway to identifying technical safety risks.

The "Exploratory Study" stage requires users to conduct in-depth research of existing operational, test, and trade study records for the legacy or similar system, to ultimately develop a casualty scenario list. The casualty scenario list is made up of technical safety scenarios, which could have resulted in individual system failure, adjacent system damage, and human injury or loss.

In the "Attribute Weighting" stage, casualty scenarios are sorted by two factors, severity and failure type. These factors are combined to form a quantitative measure of

importance or weights. Weights prioritize casualty scenarios with the greatest perceived safety impact.

The "Derive Safety-based Performance Measure Criteria" step further strengthens the L.E.A.D.S process by establishing specific benchmarks for evaluating safety performance across alternatives. Key safety attributes and lessons learned from successful systems are applied at this stage. The process guides users to create a working link between a casualty scenario and a measurable attribute measure that encompasses a mitigation or lesson learned documented in the same list. This step requires user input to translate scenarios objectively to inform a solution neutral alternative analysis. The underlying goal of this step is to force users to think more deeply and perform a robust root-cause analysis to understand failure scenarios on a deeper level. By deriving both quantitative and qualitative measures, users could gain a more comprehensive understanding of the safety implications of each alternative's make-up.

The final step, "Score Alternatives," involves a systematic evaluation and comparison of alternative concepts against the established safety-based performance measure criteria developed in the previous step. This step leverages off traditional evaluation methodology to organize the alternatives and the measurement criterions in a decision matrix. Ranks are assigned based on criterion performance, which is determined through analysis. Weighting factors are applied to the raw scores, to give priority to more impactful measurement criterion. This step ensures that safety-based decision making is integrated into the alternative analysis process, resulting in the selection of concepts that prioritize safety in defense system design.

The "L.E.A.D.S" process is in theory a concurrent engineering type, or that which occurs when concurrent life-cycles progress in parallel. It requires the system design team in its early stage of development to derive safety-based alternative analysis criteria from a legacy system with similar concept of operations (CONOPS) and operating environment, in its later or post utilization stages of its life cycle. Stakeholders are given the opportunity to think deeply about major technical risk factors that might impact a system independent of funding sources, performance testing, and external schedule pressures.

1. When to Use L.E.A.D.S

L.E.A.D.S is most effective when used on programs involved with upgrading or replacing retired or soon to be retired systems. It is intended to be used during the early stages of acquisition as the most critical tradeoffs occur during this stage in the system life cycle.

During the conceptual design phase, various design alternatives are explored and evaluated to determine the best approach for meeting the desired objectives. By incorporating the L.E.A.D.S process during this phase, designers and decision-makers can systematically consider safety aspects and prioritize them alongside other factors. This ensures that safety considerations are integrated into the design from the early stages, reducing the likelihood of safety issues or challenges arising later in the system life cycle.

Implementing the L.E.A.D.S process in the conceptual design phase allows for proactive risk management and informed decision-making. The process helps identify potential technical safety risks, evaluate trade-offs, and select design solutions that prioritize mission safety objectives. While the L.E.A.D.S process can provide valuable insights in later stages of the system life cycle, such as during system upgrades or modifications, its primary benefit lies in guiding the decision-making in regard to technical risk. This early integration of safety considerations enables designers to make informed choices that align with safety objectives and avoid costly redesign or rework later.

Certain external factors can influence the process's impact. These factors include the availability of existing similar systems to analyze, access to reliable operational data and trade studies, and the presence of lessons learned and best practices. L.E.A.D.S works best when similar systems can be identified with operating environments and mission objectives comparable to the new system under design. Insights regarding potential risks associated with systems in use currently or in the past are valuable and contribute to the translation of evaluating concepts on the merit if they solely mitigate or avoid similar risk as a result of their form and function. Operational data may be hard to gather, inconsistent, or subject to bias. A comprehensive history of events would suit L.E.A.D.S best in terms of enhancing accuracy and reliability of the alternative evaluation process. Guidance from

legacy subject matter experts (SMEs) informs the decision making and risk-management process. External factors if present, can enhance the process's ability to ensure that safety considerations are given proper attention and present in the analysis of design alternatives in a traceable manner.

2. Assumptions

Several assumptions are included to streamline analysis procedure. Assumptions simplify and focus the evaluation scope. It is assumed that the selected legacy system(s) have similar operational environments, mission objectives, or high-level functionalities to the new concept design being evaluated. This assumption allows for meaningful insights and lessons learned from the legacy system to be applied to the new design. Further broken down, it is assumed that specific casualty scenarios identified from the legacy system(s) are relevant and transferable to the new concept design. While there may be differences in performance requirements and scale, it is assumed that similar operational conditions or system components can lead to comparable safety risks and incidents. Casualty scenarios encompass the most at-risk human safety situations.

Another assumption is that derived safety-based performance measure criteria are appropriate and applicable to the new concept design. These measures are assumed to effectively capture the critical safety aspects and provide meaningful insights for evaluating and comparing design alternatives.

It is assumed that the data sources and analysis techniques used to derive safety-related insights are reliable and accurate. The assumptions include the availability of comprehensive historical data, presence of subject matter experts, accuracy in analyzing casualty scenarios, and the use of sound statistical or qualitative analysis methods.

Lastly, although L.E.A.D.S provides a framework for introducing safety criteria as a source of criteria for evaluating alternatives, the process ultimately assumes that safety considerations can be appropriately balanced with other design factors, such as cost, schedule, performance, and operational requirements. The assumption is that safety is not prioritized at the expense of other critical aspects, but rather integrated into a holistic evaluation framework.

It is important to recognize these assumptions and validate their applicability in the specific context of the defense system being analyzed. Assumptions should be regularly reviewed, refined, and updated based on new information, insights, or changes in the system design landscape to ensure the accuracy and effectiveness of the L.E.A.D.S process.

B. STEP 1: LEGACY SYSTEM SELECTION

In the context of defense systems, a legacy system refers to an existing military system that has been in service for a significant period and may be outdated or nearing the end of its operation lifespan. Legacy systems are also those that have an impeding upgrade or replacement initiative identified due to a variety of reasons which may include, technology deficiencies, end of service life, changes in naval needs. These systems are implied to have limitations or shortcomings in terms of mission performance, interoperability, maintenance or support, to continue operational use. They often pose challenges for defense organizations in terms of cost, reliability, availability of spares, and ability to meet current operational requirements. A strong source of data, legacy systems may be more likely to have an active data trail or links to subject matter experts as they require ongoing inspection, maintenance, repair, overhauls, or upgrades. The availability of a legacy system is critical to L.E.A.D.S effectiveness.

Legacy systems possess a wealth of knowledge and experience that can be leveraged to enhance safety in new defense system designs. By carefully selecting and evaluating existing defense systems with accessible safety records, users can build upon established frameworks, architectures, and technologies. This approach helps ensure that the new concept inherits the safety features and lessons learned from successful legacy systems, thus establishing a strong foundation for mission safety.

1. Legacy Systems vs. Similar Systems

A similar system is one that shares similarities or comparable characteristics to the new system in development. It may not be earmarked for replacement nor reaching the end of its service state. It could be a new system with similar functions, capabilities, and an operating environment in a different industry of use. It can serve as a reference point or benchmark. The availability of data primarily in the areas of design basis, operating

manuals, and maintenance reports is critical for the effectiveness of L.E.A.D.S Similar systems within the DOD umbrella should be prioritized in the search, with other systems across industry a fallback option due to lack of available data.

2. Decision Tree

Before diving into concept design, it is crucial to evaluate the existing legacy systems that may be relevant to the project. “Legacy System Selection” is a sub process within L.E.A.D.S that involves identifying pre-existing systems or technologies that serves as a basis for a case study that yields a list of risk events.

A decision tree as shown below in Figure 2 is used to guide the potential decision makers in selecting the most appropriate legacy or similar system for study and analysis.

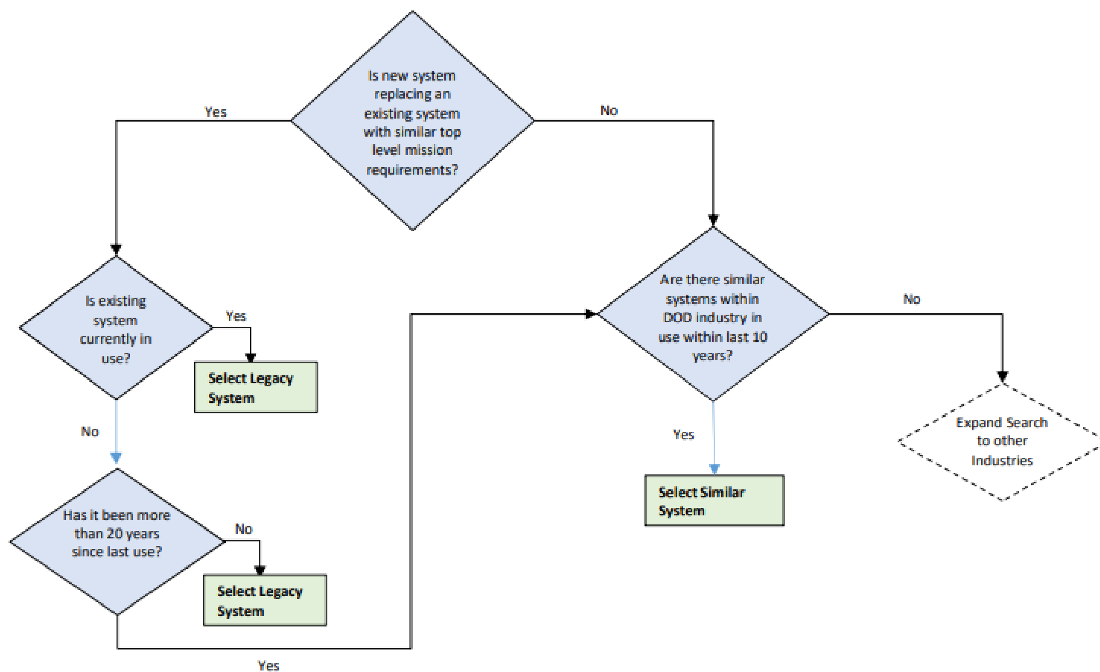

Figure 2. Legacy System Decision Tree

Main decision points lie in the following questions:

Q1: Is the new system replacing an existing system with similar top level mission requirements?

Top-level mission requirements define what functions need to be done to accomplish the mission objectives. If the existing system is tied to the same program of record, stakeholders may be tied to both systems which will supplement the exploration of the former. If the answer is yes, the user can move to question 2, If the answer is no, user should jump down to Q4.

Q2: Is the existing system currently in use?

If the existing system is still in use, then it is a sufficient choice for a trade study, if no, user can proceed to Q3.

Q3: Has it been more than 20 years since last use?

If the existing system has been de-commissioned for 20 years or less, it is still a good candidate for former study. Records may be available and lessons learned via subject matter experts (SME), programmatic direction, and attainable stakeholders. Technology growth may have not completely made the former system inferior. If the answer is no, the user is directed to Q4.

Q4: Are there similar systems within DOD industry in use within the last 10 years?

The similar system must preferably have both similar functional environments and approximate operating environment. Best judgement should be exercised here. If the similar system does not operate in the manner that new program objective state, then it should not be selected. An example is illustrated below:

1. U.S. Navy tasked to develop new system to locate target of interests underwater with requirement that search must be conducted in air.
2. Naval legacy system currently includes shipboard and submersible systems to locate target of interests underwater.
3. Mission environment and top objective may align, but the fundamental difference between how they are to be accomplished eliminate the selection of the existing naval systems as a good source for further study.

Users should pivot their search to systems in different industries who may perform similar functions in the air albeit for different results. If a similar system under the DOD cannot be identified, the user is directed to Q5.

Q5: Expand Search to other industries?

The user should expand search to other industries to track similar systems in an industry performing a similar function derivative. Legacy system selection should expand to a study of multiple systems across industries. Substantial data may be hard to track, however, it is key to continue to collect data on failure modes across different fields.

C. STEP 2: EXPLORATORY STUDY

System development teams should consider and understand why other systems technically fail or how they could potentially technically fail. Beyond simple understanding and awareness, design selection can benefit from an evaluation system that translates the failure modes of a similar system into criteria, which can rank alternatives based on technical safety performance merit. The second step of L.E.A.D.S, "exploratory study," takes on the beginning of this role and requires users to build a list of hazard events that act as the backbone for the development of safety evaluation criterion to be used to assess trade-offs.

Gaining insights into significant incidents that occurred within or were inherent to the operational protocols of legacy systems can assist in comprehending or revealing potential technical risks and hazards that the new system may face. Exploratory study requires the user to gather data on scenario types, impacts, and mitigations used or earmarked by legacy systems or their stakeholders. Data should be gathered from legacy system top level documents, trade studies, production documents, testing reports, incident history and major maintenance activities, operating manuals, and overhauls.

In addition to these methods, it may also be useful to consult with experts in relevant fields such as engineering and specific subjects. These experts can provide insights and perspectives that may not be apparent to those without specialized knowledge or experience. Lessons learned might suggest ways to eliminate the scenario entirely.

The scenarios should focus on system wide failures as opposed to individual components. Although the interaction of parts is essential to how the legacy system operates, understanding system failures plays a deeper role in expand the design space for new system concept design from a safety standpoint. Overarching elements and how their functions interact with the operating environment should be the focus for this process.

The research of potential risk sources, accidents or incidents that could occur during the operational life of the systems, is used to yield a list of casualty scenarios. A casualty scenario list is a compilation of potential incidents or accidents that could occur during operational use of a system. It focuses on identifying and assessment specific hazardous events that may lead to casualties or harm to personnel, equipment, or the mission. The list shall identify potential situations in which there could be significant losses or harm, such as injury or death.

This analysis should consider the various types of threats that the legacy system was designed to defend against, the source of the threat, the target of the threat, the impact of the threat and the likelihood of the threat. The types of assets that the legacy system was protecting, the capabilities and limitations of the legacy system itself, and the potential consequences of legacy system failure or malfunction are all major.

The casualty scenario list, as shown in Table 1, is broken into several different input categories: scenario description, system mode, event sequence, failure category, mitigation device, and if applicable, lesson learned.

Table 1. Casualty Scenario List Template

Scenario Index (C-#)	Scenario Description	System Mode (Operation/Standby/Stowed)	Event Sequence	Mitigation Device	Lesson Learned
C-1	-	-	-	-	-
C-2	-	-	-	-	-
C-3	-	-	-	-	-
C-4	-	-	-	-	-

- **Scenario Index:** A numerical identifier to identify scenarios.

- **Scenario Description**: provide a simple description of the event. Description of the event should include information on the environment in which the event takes place including details such as weather and location if possible. Descriptions should be no more than three sentences long.

- **System Mode**: To capture context, the legacy system mode during the event should be characterized with one of the following designators:

  Operational – Mission operating condition

  Standby – Not in operation, but mission ready

  Stowed – Nonoperational, maintenance operations

- **Event Sequence:** Define the sequence of events that lead to the occurrence of the scenario. Consider interactions between system components, operators, environment, and external factors. This should be seen as a root cause analysis.

- **Mitigation Device:** Describe the existing mitigation measures in place to reduce the likelihood or consequences of the casualty scenario including engineering controls, safety features, specialized resource, i.e., trained operator, procedures, and other measures that can be implemented to minimize risk. This will give design teams awareness of techniques employed on the legacy system and provide a window on the potential opportunities available to mitigate a scenario with changes to alternative form or function as opposed to an operating scenario.

- **Lesson Learned:** list industry best practices that can be incorporated to avoid or mitigation against scenario.

The list gives designers exposure to the potential system vulnerabilities facing legacy systems. A deep understanding of failure can drive design to become more robust or creative in areas of technical risk. By identifying potential casualty scenarios early in

the design process, designers can avoid costly design changes and retrofits later in the project life cycle and minimize the risk of catastrophic failures or accidents.

D. STEP 3: ATTRIBUTE WEIGHTING

In the context of mission safety objectives, attribute weighting plays a crucial role as it imbues importance into the scenarios. This step requires the user to sort scenarios based on the factors of consequence and failure type. Quantitative measures will be applied to these two categories and in addition to ranking, they will be manipulated to create weights to be applied later in the process.

1. Severity

Risk Severity is defined by Stanford University's Office of the Chief Risk Advisor as

"The extent of the damage to the institution, its people, and its goals and objectives resulting from a risk event occurring" (Stanford University 2023).

To account for severity, a new column for severity is added to the casualty scenario index as shown in Table 2:

Table 2. Expanded Casualty Scenario List with Severity and Failure Category

Scenario Index (C-#)	Scenario Description	System Mode (Operation/ Standby/ Stowed)	Event Sequence	Mitigation Device	Lesson Learned	Severity	Failure Category	Weighting Factor
C-1	-	-	-	-	-	-	-	-
C-2	-	-	-	-	-	-	-	-
C-3	-	-	-	-	-	-	-	-
C-4	-	-	-	-	-	-	-	-
C-5	-	-	-	-	-	-	-	-

The L.E.A.D.S process uses an existing categorization scale for severity as proposed by the Federal Aviation Administration (FAA) with some minor modifications. The FAA assesses hazard by four levels of outcome severity: Catastrophic, Critical, Moderate, Negligible (Federal Aviation Administration 2022, 4–1). L.E.A.D.S elaborates on the FAA's definitions and applies a quantitative factor of measurement to each. The greater the severity, the greater the value in the numerical identifier. The categories and associated values are presented in Table 3.

Table 3. Severity Scale Adapted From FAA (Federal Aviation Administration 2022, 4–1).

Title	**Numerical Identifier**	**Description**
Catastrophic	4	Loss of human life, complete system loss, inability to perform mission, collateral damage, system or platform grounded
Critical	3	Damage to system, significant collateral damage, mission performance impacts, overhaul or modification required to continue mission
Marginal	2	Incident to minor damage that impacts mission performance, Repair required to bring back mission performance to status quo
Negligible	1	Minor impact mission performance, system needs routine maintenance to restore mission performance

Although severity impacts could affect programmatic aspects like schedule and cost, the objective is to emphasize technical risk factors influencing system alternative development. When considering severity, users need to assess variables like casualty count, injuries, system interface damage, environmental consequences, and mission impact. Scenarios might share similar severity rankings.

2. Failure Category

The next quantitative measure to be applied to the casualty scenario list is a measure of how the scenario occurred. A step in understanding how and why casualty scenarios

occur is to determine root cause. Root cause can be indicative of internal vulnerabilities or external factors. To categorize each scenario by root case, the process prompts the user to designate each scenario with a failure mode.

L.E.A.D.S leverages off a process to categorize failures proposed by Bryan O' Halloran and Douglas Bossuyt in the paper "How do Systems Fail." The authors characterize failures into seven categories of failures: development failures, induced failures, common cause failures, propagated failures, interaction failures, malicious failures, and management, customer, and misuse failures (Bossuyt and O'Halloran 2020, 3). This thesis leverages off several of these definitions and reduces the total number of categories to four total to simplify categorization. As L.E.A.D.S is a concept design procedure, failures that are induced by misuse, management and common causes are not considered. A description of failure modes and associated values are shown in Table 4.

Table 4. Failure Modes

Title	Numerical Identifier	Description
Malicious Failure	100%	Intended mission threat causes system failure.
Induced Failure	75%	Failures caused by operational environment interaction.
Development Failure	50%	Failures caused by design. Inherent form and function creates vulnerabilities that could expose system elements or humans to harm.
Interaction Failure	25%	Intended interaction of components not working as designed. specific component failure i.e., structurally causes a cascading failure of system
Misuse Failure / Common Cause Failure	0	System used for non-mission objective, human error or maintenance failure that causes subsystems to failure.

The percentage attached to each failure level quantifies the relevance of the failure mode in the context of new system development. If the error is a result of an interaction between internal components, it could possibly be mitigated through an upgrade in technology or a component swap. As internal component identification has the most potential to change as design matures later in the life cycle. It is categorized by lower percentage as it has high potential to be mitigated without major impacts. Induced and developmental failures are a result of both mission concept of operations and inherent form and function. External factors have more weight as technical risks built into the environment and threats are tied to mission objectives. Development failures follow in reduced percentages as these scenarios can be potentially eliminated or reduced to acceptable values from the incorporation of lessons learned from the legacy systems. Misuse and common cause failures are not considered in this exercise as these modes of failure are dependent on mistakes that are may be tied to legacy operating procedures or guidance. These failures are harder to predict and may be eliminated later in the life cycle when designs mature.

3. Weighting

Weighting in the context of L.E.A.D.S is a measure of importance that the casualty scenario may have high impacts on safety performance. Equation 1 yields the weighting factor to be applied to each scenario:

Equation 1: $Cable\ Motion = \text{Severity (S)} \quad \times \text{Failure Mode (FM)}$

Weighting is unit less. Higher values are indicative of higher importance for mission safety objectives, while lower values are indicative to scenarios with less safety impact.

Weighting ensures more credence is given to those events that have higher consequence and/or have a high degree of design definition associated with them. In step 5, weights will be applied to derived safety-related measure on criterion to reflect relative importance. This form of weighting is ordinal, indicating that it only represents the rank of the item and does not support numerical analysis like cardinal numbers do.

4. Other Considerations for Weighting

Traditional risk assessment applies a risk level to risks by combining the likelihood and consequence factors. Likelihood refers to the probability or chance of a particular incident occurring. Communicating likelihood to other stakeholders is helpful in establishing a solid basis for the boundaries surrounding the design space. Likelihood is based on available data, historical records, expert judgement or a combination of these factors. Contributing factors or dependencies on other systems that may influence the probability of occurrence. L.E.A.D.S does not consider the likelihood of reducing process complexity. Concept design is a phase characterized by high levels of uncertainty. Likelihood development is a direct function of available legacy system analysis and reporting. As there is a high level of uncertainties that can be associated with this data collection it is not considered.

E. STEP 4: DERIVE SAFETY-BASED PERFORMANCE CRITERIA

The goal of this step is to translate the casualty scenarios into measurable safety performance criterion. Prior to this step, L.E.A.D.S guided users to create a list of legacy system scenarios, perform an analysis on each scenario to inform specific circumstances and potential consequences associated with it. Weights were then assigned in step 3 to factor in severity of outcomes and failure modes. Step 4 capitalizes on the understanding developed in steps 1 through 3 with a focal shift from data gathering to data creation. There is less value in evaluating a scenario against a concept alternative, instead if the scenario is translated to measurable attribute, performance data can be generated to gauge alternative performance.

In this step, safety metrics will be formulated from individual scenarios. Beyond data creation, linking metrics to scenarios is beneficial as it builds an element of traceability. When materializing measure criteria from a casualty scenario,-users first break the scenario down into pieces to ultimately extract the "why" it has occurred and the "what" can be done to eliminate or reduce the risk without breaching the topics of operation and controls. In concept design, components and interactions between parts are marginally understood. The evaluation metrics need to be created bearing that state of knowledge in

mind. Users should avoid metrics that are dependent on the presence of a specific, individual minor part and focus more on the mitigation techniques that can decide how to protect, back up, and/or remove the reliance on the part.

The measures should gauge how an alternative's attributed can prevent recurrence of the same scenario or mitigate its impact. If applying the measure to the new system alternative yields outcomes similar to those of the legacy system, this could be discussed or noted at a program level, indicating that the risk can be addressed through an alternative approach such as a future operational procedure. The focus should remain on metrics that have a substantial impact on human safety, system integrity and mission success. The development of safety-based measurement criterion can be broken up into two parts: the identification of key metrics and the definition of measurable criteria.

1. Identification of Key Metrics

For the context of L.E.A.D.S, an attribute is a property or characteristic, which can dictate system safety performance, form and function. It essentially drives system behavior and once identified can be used to assess safety performance as a key metric. Safety-based attributes relate to the alternative's ability to operate while minimizing risk to users, adjacent systems, and environment. A key metric is essentially a way of quantifying or measuring the attribute.

L.E.A.D.S requires the user to define an applicable attribute that can be directly traced to the mitigation and lessons learn data developed in the casualty scenario table. One should keep in mind that the attribute is one that needs to be compared neutrally across other alternatives including the legacy system. The attribute should be able to be quantified, either qualitatively through expert judgement or observation or quantitatively through analysis. The metric should be objective, relevant, and aligned with the safety concerns of the new system.

Users should define an appropriate measurement approach. Some quantitative metrics may require advanced statistical analysis data collection techniques, which may or may not be easily extracted from concept design alternatives. Feasibility and complexity should be factored in when creating metrics. Attention should be given to qualitative

metrics that involve expert judgment or observational methods to remove the potential of bias.

If casualty scenario is caused by a system exposure to the environment, especially an event that was unaccounted for or environmental events like storms, winds, or waves, it becomes crucial for an alternative to possess a quality that allows it to either avoid such situations altogether or minimize the time spent in vulnerable conditions. This aspect should be reflected in how the alternative approach addresses this issue, highlighting any unusual circumstances in the system design that users should carefully consider, as they may offer significant opportunities for design improvements. This can be materialized in the way the alternative way breaches this topic. Criteria such as this can expose the unusual circumstances of system design, which users must give consideration as they may have most potential for design alterations.

2. Define Measure Criteria

Once a metric is identified, it is paramount that both a measurement method and a baseline or benchmark range for performance be identified. Units and desired safety performance levels or targets for each criterion are determined to facilitate objective evaluation. Adding a form of measure ensures that each criterion is well defined, measurable, and relevant to the safety concerned of the new systems. It also makes the attribute easily understandable such that it can be communicated to stakeholders and decision-makers. Safety performance scales can be based on regulatory requirements, industry standards, best practices, or specific mission objectives. The safety range levels should reflect the acceptable risk tolerances and safety goals for the new system.

It is important to distinguish the scoring criteria from key performance parameters, which originate from program office-defined performance requirements. While these criteria may shape derived requirements or even evolve into key performance parameters, their primary role, in line with L.E.A.D.S objectives, is to assess alternatives. Developers should consider the constraints of their alternative concepts and their ability to generate data, whether through complex analysis or simpler means.

F. STEP 5: SCORE ALTERNATIVES

In the fourth and final step of the L.E.A.D.S process, we systematically evaluate concept alternatives against the criteria developed earlier. To accomplish this, one can utilize a decision matrix, a tool that organizes alternatives based on the criteria and allows for discrete evaluations, including the scenario weighting established earlier. The decision matrix serves the ultimate purpose of providing decision makers with data to assess how the alternatives address, mitigate, and perform against realistic safety measures and a performance baseline derived from a former system.

1. Organization

The decision matrix is a table made up of "n" rows and "m" columns is shown in Table 5. The number of rows is based on the number of alternatives being evaluated. The number of columns is based on the number of safety criteria being evaluated. Under the header column is now reserved for weighting. The criteria weighting should be entered under the corresponding metric.

Table 5. Decision Matrix

		X-AXIS = Safety Performance Measure Criteria						
		Safety Performance Measure Criteria #1	Safety Performance Measure Criteria #2	Safety Performance Measure Criteria #3	Safety Performance Measure Criteria #4	Safety Performance Measure Criteria #5		
	Weights	X.X	X.X	X.X	X.X	X.X	Total Raw Score	Total Weighted Score
Y-AXIS = Alterantives	Baseline - Legacy System							
	Alternative A-1							
	Alterantive A-2		Rank Identifier #					
	Alterantive A-3							
	Alterantive A-4							

2. Preliminary Scores

Although safety-based evaluation metrics may be highly quantitative and depending on system complexity require some order of simulation and analysis, L.E.A.D.S encourages use of approximations as alternative designs may lack maturity. Actual values

of performance are used to inform a whole number ranking scheme based on the total number of alternatives. The legacy system informs the baseline threshold for each measure criteria. It does not, however, inform ranking of the alternatives, instead the legacy system values should also be calculated for comparison only. Each alternative needs to be evaluated against the criterion selected. If a criterion does not apply to an alternative, a max score will be applied per the category. The lowest ranking is given to the best performing alternative and the highest to the worse performing alternative. Scores are tabulated and listed at the intersection between each alternative and its corresponding criteria. Each category of safety metric undergoes the same procedure, until the matrix is populated with ranking values. For those alternatives for which the key metric does not apply, the maximum ranking value should be given. Multiple alternatives can have the same ranking on this basis.

As an example, consider an airport. A major feature of an airport that is indicative of airplane landing and takeoff safety is runway stopping distance. This distance is made up of several factors including available space, average approach angles, presence of vertical features in flight path, and stopping sight distance. Federal Aviation Association (FAA) has standards to determine minimum stopping distance. The minimum stopping distance can be used to baseline the measurement criteria that alternatives' performance can be ranked against. So, in this case, a smaller measure of performance against the baseline would result in higher ranking. The highest ranking score can be given in the event where a measure criterion does not apply for an alternative. In the case of stopping distance, one could envision an alternative that provides a new form or function which eliminates the total need of a traditional runway, indicating a fundamental shift in how the operation is being performed or an avoidance of the scenario occurring. This alternative would receive the highest score in this case.

3. Weighted Scores

To tie the raw scores to the importance weighting developed in step 2, the raw scores are multiplied by the corresponding safety criterion weight. The overall weighted score for each alternative can be calculated by summing up the weighted scored across all

criteria. This will provide a quantitative measure of how well each alternative aligns with the safety-based performance measure criteria. Alternatives can be ranked in ascending order of their total performance. The highest score may not completely tell the story of safety performance but will inform decision makers how that specific alternative measures up against the others in various arenas. The matrix serves as a reference point, but it is still essential for decision makers to factor in new types of safety concerns which may emanate from a change in system interaction or a result of a new mission objective, environment, etc. L.E.A.D.S does not intend to replace the AoA, which may include cost and schedule impacts, but seeks to add more safety-based decision points to it.

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IV. CASE STUDY: SURTASS CLFA

SURTASS is a Naval Maritime Surveillance Systems (PMS 485) program of record system, which provides long-range detection, tracking and classification of targets of interest:

> Surveillance Towed Array Sensor System (SURTASS) is the mobile, tactical, and strategic arm of the Navy's undersea surveillance capability that provides deep ocean and littoral acoustic detection and cueing for tactical weapon platforms against diesel and nuclear submarines as well as surface vessels in any given Area of Operations worldwide. Dedicated Anti-Submarine Warfare. (Navy 2020, 1)

The SURTASS surveillance capability is broken down into two parts, an Active component, which propagates noise in the water to create sonar, and a Passive component equipped with sensors to track reflected signals (DOTE 2012) as shown in Figure 3. The U.S. Navy currently operates SURTASS Active missions on four platforms stationed in the Pacific war theater. The existing platforms are at the end of service life. The T-AGOS 25 Class program was introduced by the U.S. Navy to replace the existing platforms and increase command capability. Predictive performance criteria were developed to outline the need to expand the operational environment to both geographic reach and environmental sea state. The platform program was also given directions to use larger and faster small water plane area twin hull (SWATH) ships (CRS 2023, 1). The T-AGOS 25 Active Array program was developed to accommodate the U.S. Navy's surveillance capability reach and platform interface needs.

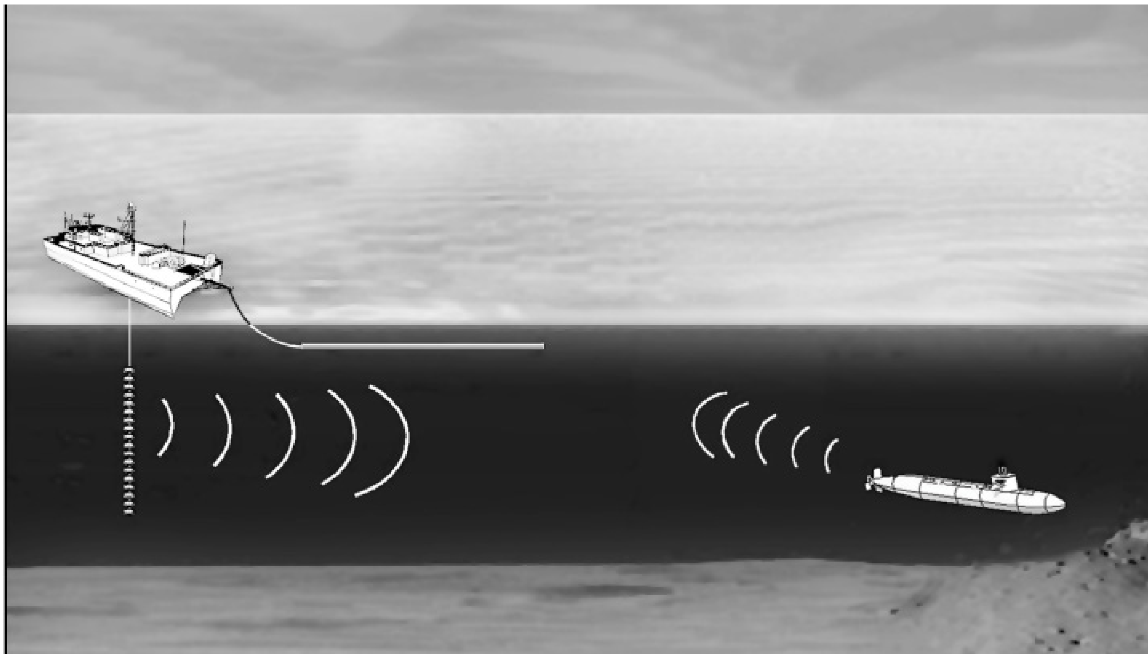

Figure 3. Diagram of SURTASS LFA System, Source: Wiggins (2002, 4)

The long-range tracking of undersea targets using shipboard Naval active array systems have a high level of operational safety risk, which can lead to loss of human life and the ship. The crux of mission safety success lies primarily with the handling of the active array mission system (Ruffa 2002, 2). Two functional requirements prevalent in active sonar arrays are the ability to deploy and retrieve the sonar in and out of the water. These involve a level of interaction with the oceanic environment with system exposure to wave forces, wind, and chemical corrosion. Interactions are often a less well understood arena in design, even though they can ultimately impact the system the most. Due to the high-risk nature of active array handling, optimizing the tradeoffs between active array handling operation potency and operational safety is paramount to SURTASS mission success.

This case study will apply the L.E.A.D.S process on the T-AGOS 25 Active Array system to showcase how the process is used and to highlight how identifying lessons learned from legacy systems can create a pathway to bettering safety perform for future development of shipboard active sonar systems. Alternative development will not be performed as part of this study, as the focus lies in demonstrating the process.

A. STEP 1: LEGACY SYSTEM SELECTION

The first sub-process of L.E.A.D.S lies in identifying an existing system as an applicable source for further study to identify the technical risks facing the new system. Using the decision tree presented in Figure 4, the search starts with a scan of existing or recently decommissioned towed sonar systems in use by the U.S. Navy. The goal is to identify a system that shares similar objectives and concepts of operation as the T-AGOS 25 Active Array. The most ideal source to start is the program of record itself.

The T-AGOS 25 Active Array is a direct predecessor to another SURTASS program titled Compact Low Frequency Active (CLFA). Based on the CLFA description of operations, the capability need behind system development is the need to perform target of interest search in littoral ocean regions (DOTE 2012, 1).

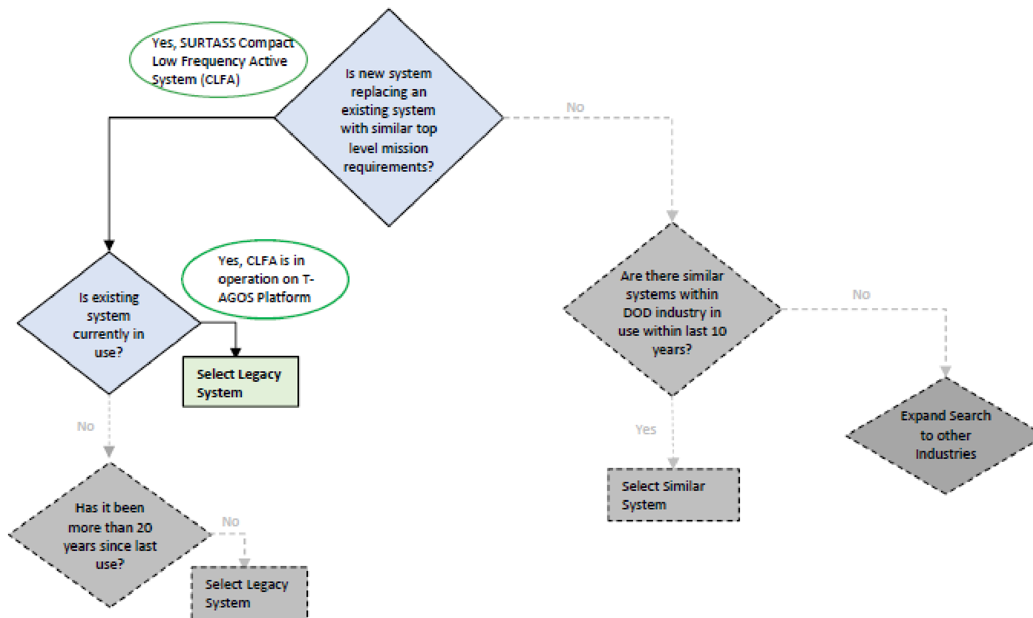

Figure 4. T-AGOS 25 Active Array System – Legacy System Decision Tree

CLFA meets the requirements for decision point 1, as both the T-AGOS 25 Active Array and CLFA share similar stakeholders, CONOPS, and mission objectives. Advancing down the decision tree, using the path opened by answering “yes,” the next decision point

requires information on CLFA operation. As noted by the U.S. Navy master plan and budgetary documents, CLFA was first commissioned on the T-AGOS platform titled "Able" in 2011 and operates across (3) separate T-AGOS platforms still in use (Taddiken and Krock 2021). CLFA complies with decision point 2 as it falls within the min the 20-year threshold of operation required. Based on the "yes" input, CLFA is a valid legacy system and can be used to inform the next set of steps in the L.E.A.D.S process. In the case that CLFA did not have a direct predecessor, similar systems within DOD and outside of DOD which could qualify as potential candidates for selection were identified. These systems are:

- Low Frequency Active (LFA) on T-AGOS Vessel Impeccable: LFA was installed on the T-AGOS vessel in 2001 and is still in operation. It works in a similar operational environment as CLFA less shallow waters (Taddiken and Krock 2021).

- LFA on Research Vessel Cory Chouest: LFA prior to being integrated into the T-AGOS vessels which are small-water plane-area twin hull (SWATH) type was installed on the Cory Chouest which was a monohull system. The handling and operational limits differed from the T-AGOS Impeccable, but mission objectives were similar making this a sufficient choice for a similar system alternative (Taddiken and Krock 2021).

- Variable Depth Sonar (VDS) systems: "operate in challenging shallow-water environments to detect and track submarines with low target strengths" (L3Harris n.d.).

- Deep-Towed Array Geophysical System (DTACS): The system is "towed near the bottom in the deep ocean and provides the capability to determine detailed geophysical character of the sea floor and upper sub bottom structure" (Fagot and Spychalski 1984).

- Thin Line Towed Array (TLTA): enables "smaller vessels such as Offshore and Inshore Patrol Vessels (OPV/IPV) and Unmanned Vessels to

host and deploy an anti-submarine warfare Towed Array capability" (Slater and Naval Undersea Warfare Center 2021).

B. STEP 2: EXPLORATORY STUDY

In the previous step, CLFA was chosen as the legacy system. Research was conducted on testing reports, manuals, and trade studies to formulate a list of casualty scenarios as shown in Figure 5.

	Scenario Description	System Mode (Operational/Standby/ Stowed)	Event Sequence	Mitigation Device	Lesson Learned
C-1	Ship Platform detected by external threat	Operational	Array towing in water causes water vibrations that are detected by enemy sonar	Reduce deployment and recovery time can allow platform to perform evasive maneuvers	Limit Array flow disturbance when not producing sonar
C-2	Resonance from sound pressure causes injury to wildlife	Operational	Array operation occurs when wildlife is present	Check for mammals within operating range prior to operations	Resonance from sound pressure can cause injury when over a certain decibel
C-3	Maneuverability of platform impaired	Operational	Towed array drag influences ship steering	Array operations limited to few combinations of ship headings	Reduce drag of array for better tow performance
C-4	Array rakes ocean bottom	Operational	Array deployed in shall waters and fouls landmass on sea bottom	Array limited to certain deployment depths based on bottom surface	Condensing suspended Array Package can reduce risk, refraction patterns can interfere as long as its minor
C-5	Loss of towed Array in event of tension surge	Standby	Waves in transition zone refract from ship hulls and surge into handling space	Limit moon pool operations to NATO sea states	Increase breaking strength of the cable; Code of Federal Regulations requires handling system to consider this strength
C-6	Submarine fouls tow cable at depth	Operational	Hostile subsurface vessel grapple active array	Jettison Array from Handling System	Include various "breaking" points in Array to reduce risk of failure propagating
C-7	Active Array projectors pitch violently	Deployment/Retrieval	Wave forces in transition zone cause damage to array	Reduce potential for slack in Active Array in Air-Water Interface zone Resultant Vector Distance between C/M and Front Contact Plane	Increase stability in tow bodies
C-8	Array suspension is vibrating violently under tow	Operational	Flow of water across tensioned, round cable could cause a vibration due to vortex shedding.	Operating procedure to install exterior fairing device on suspension cables	Hydrofoil shapes, that expand trailing surface area, can lessen vibration.
C-9	Man-overboard during handling	Operational	Moon-pool in middle of ship opened during operations, Ops occurring in area	Main operations under specific environmental limits	Provide clearance between tow point and moon pool and handling equipment from open environmental spaces
C-10	Snap-loading of suspended array	Operational	Vessel drops off swell faster than array can fall; slack in cable causes instantaneous	Measure tension values and stop operations if tension limit met	Consider heave compensation to reduce loading

Figure 5. CLFA Casualty Scenario List

As an example, let us focus on a casualty scenario to add context to the data needed to educate the next steps, specifically Casualty Scenario Index C-8.

Casualty Scenario Description

As noted in former Training manuals, CLFA is vulnerable to a hydrodynamic phenomenon of cable strumming (Naval Facilities Engineering Systems Command 2016, 7). As described by O.M. Griffin et al.

> In the case of cable these relatively high frequency oscillations, which are predominately in the direction normal to the incident flow are called strumming. Reduced fatigue life, large hydrodynamic forces (particularly drag) and induced stresses, and high acoustic noise level often accompany vortex-excited oscillations. (Griffin et al. 1982, 2)

Strumming has the potential to induce vibrations to not only the active array system itself, but also to the platform. Damage to the platform is a severe consequence and could result in loss of human life.

While system engineering concept design guidance advocates for a solution-neutral design space in alternative development, it remains crucial to observe industry trends as a preliminary step toward shaping the physical form of the system. In the context of handling systems in use today and throughout history, cables are predominant feature used to suspend the sonar array, making this scenario prevalent to safety evaluation. There is a high potential for alternatives to employ similar techniques to meet functional requirements.

System Mode

Strumming occurs when cables are moving through the water column or when the system is in operation.

Event Sequence

Report created by the David W. Taylor Naval Ship Research and Development Center elaborates on the root cause: "Vortices shed coherently from a tow cable generate transverse oscillations of the tow cable at the vortex shedding frequency and longitudinal oscillations at twice the vortex shedding frequency. These waves travel along the tow

cable" (Rispin and Webster n.d.). The flow of water across tensioned, round cable could cause a vibration due to vortex shedding.

Mitigation Device

CLFA uses fairings to reduce vortex shedding. When the device is placed on the cable, cable motion as measured in amplitudes is reduced.

Lessons Learned

Hydrofoil shapes that expand trailing surface area can lessen vibration.

C. STEP 3: ATTRIBUTE WEIGHTING

Differentiating scenarios by level of importance enhances an alternative analysis. To develop weights, the scenarios identified in the prior step need to be characterized based by failure type and their potential impact on human safety, system safety performance, and mission success. Two columns are added to the table as shown in Figure 6 and populated with category descriptors and quantitative identifiers.

	Scenario Description	Severity		Failure Category	
		Descriptor	Rating	Descriptor	Rating
C-1	Ship Platform detected by external threat	Catastrophic	4	Malicious Failure	100%
C-2	Resonance from sound pressure causes injury to wildlife	Marginal	2	Induced Failure	75%
C-3	Maneuverability of platform impaired	Marginal	2	Development Failure	50%
C-4	Array rakes ocean bottom	Catastrophic	4	Development Failure	50%
C-5	Loss of towed Array in event of tension surge	Critical	3	Induced Failure	75%
C-6	Submarine fouls tow cable at depth	Catastrophic	4	Malicious Failure	100%
C-7	Active Array projectors pitch violently	Critical	3	Induced Failure	75%
C-8	Array suspension is vibrating violently under tow	Catastrophic	4	Induced Failure	75%
C-9	Man-overboard during handling	Catastrophic	4	Interaction Failure	25%
C-10	Snap-loading of suspended array	Critical	3	Interaction Failure	25%

Figure 6. Severity and Failure Mode Factors

Continuing with the same casualty scenario C-8 as an example, the severity and failure categories are determined as follows:

Severity

Strum from towing can propagate up the system and affect the platform. Vibrations can increase to the point where fatigue is prevalent in the load path, which can induce damage to both system and vessel. Vibrations can cause movement of loose equipment in

human occupied operating spaces which may lead to human injury. This description, when compared to the scale shown in Table 3, meets the requirement for the catastrophic designator.

Failure Category

Strum results from a system interaction with the environment, in specific terms it occurs when a suspended array interacts with the water column under motion. This falls under the "induced failure" definition indicated in Table 4.

This failure mode is a prime example of how L.E.A.D.S can benefit users. It is a technical risk that is not related to a performance driver, instead it is a consequence derived from a basic function requirement.

Weighting

Using Equation 1, the casualty scenario carries a weight factor of 3. List of weighting factors are shown in Figure 7.

	Scenario Description	Severity		Failure Category		Weighting
		Descriptor	Rating	Descriptor	Rating	
C-1	Ship Platform detected by external threat	Catastrophic	4	Malicious Failure	100%	**4**
C-2	Resonance from sound pressure causes injury to wildlife	Marginal	2	Induced Failure	75%	**1.5**
C-3	Maneuverability of platform impaired	Marginal	2	Development Failure	50%	**1**
C-4	Array rakes ocean bottom	Catastrophic	4	Development Failure	50%	**2**
C-5	Loss of towed Array in event of tension surge	Critical	3	Induced Failure	75%	**2.25**
C-6	Submarine fouls tow cable at depth	Catastrophic	4	Malicious Failure	100%	**4**
C-7	Active Array projectors pitch violently	Critical	3	Induced Failure	75%	**2.25**
C-8	Array suspension is vibrating violently under tow	Catastrophic	4	Induced Failure	75%	**3**
C-9	Man-overboard during handling	Catastrophic	4	Interaction Failure	25%	**1**
C-10	Snap-loading of suspended array	Critical	3	Interaction Failure	25%	**0.75**

Figure 7. Weighting

D. STEP 4: DERIVE SAFETY-BASED PERFORMANCE CRITERIA

The scenarios are now ready to be translated into measurable criteria on which alternatives can be analyzed for. A list of derived safety measure criteria is shown in Figure 8.

	Scenario Description	Derived Safety Measure Criteria	
		Metric	**unit**
C-1	Ship Platform detected by external threat	Time Required to Recover Array at maximum depth	Minutes
C-2	Resonance from sound pressure causes injury to wildlife	Minimum decibels required for sonar operations	Decibels
C-3	Maneuverability of platform impaired	Average Array drag across operational profile	Foot-Pounds
C-4	Array rakes ocean bottom	Suspended Array length	Feet
C-5	Loss of towed Array in event of tension surge	Maximum breaking strength of suspension device	Pounds
C-6	Submarine fouls tow cable at depth	Number of breaking points below tow point under operation	Each
C-7	Active Array projectors pitch violently	Resultant distance from front plane to center of mass	Inches
C-8	Array suspension is vibrating violently under tow	Cable motion under tow; Amplitude over Diameter	Unit less
C-9	Man-overboard during handling	Distance between control station to moon pool	Feet
C-10	Snap-loading of suspended array	Average tension during maximum sea state events	Pounds per Foot

Figure 8. CLFA Derived Safety-Based Performance Criteria

Continuing with the C-8 example, one can use the casualty scenario data developed in the prior steps to derive a measurement of safety performance. To start, the scenario should be broken into two parts to answer both why the scenario has occurred and what can be done to lessen risk. According to the scenario root cause, cable motions are induced by flow (Horton and Ferrer 1987). Digging deeper and using research, round cable shapes

cause pockets of low pressure around trailing edges for the cable to move in the presence of flow. The measure of cable motion as used on CLFA is a function of measured Amplitude (A), or the length of a wave oscillation, and a round cable's diameter (db.). The ratio is shown in equation 2 (NAVFAC ESC 2005).

Equation 2: $Cable\ Motion = \frac{A}{db}$

The ratio is unit-less. Data collection for approximate amplitude involves advanced computational modeling but is attainable in the realm of concept design.

A threshold for acceptable performance of the unit less value 0.5 can also be pulled from past CLFA reports for the ratio is 0.5 (NAVFAC ESC 2005). This value will act as the baseline legacy system value for performance comparison against the new alternatives. If an alternative is found to have a smaller ratio, it indicates less motion than CLFA or a better solution in terms of mitigating strum.

E. STEP 5: SCORE ALTERNATIVES

A decision matrix, as shown in Figure 9, is used to link the legacy system data to the new system development. Three sample alternatives were developed for this example. The alternatives are listed on the left-hand column along with a placeholder for CLFA. The safety criteria developed in the step prior is listed along the top row with corresponding weights in Figure 9.

	Derived Safety Measure Criteria # C-1	Derived Safety Measure Criteria # C-2	Derived Safety Measure Criteria # C-3	Derived Safety Measure Criteria # C-4	Derived Safety Measure Criteria # C-5	Derived Safety Measure Criteria # C-6	Derived Safety Measure Criteria # C-7	Derived Safety Measure Criteria # C-8	Derived Safety Measure Criteria # C-9	Derived Safety Measure Criteria # C-10
Weights	*4*	*1.5*	*1*	*2*	*2.25*	*4*	*2.25*	*3*	*1*	*0.75*
Baseline - Legacy System	2	2	2	1	1	2	2	2	1	1
Alternative A-1 (Double Cable)	4	4	3	3	3	4	3	1	4	3
Alternative A-2 (rigidStructure)	1	1	1	4	4	1	4	4	3	4
Alternative A-3 (Single Cable)	3	3	4	2	2	3	4	3	2	2

Figure 9. T-AGOS 25 Active Array – L.E.A.D.S Decision Matrix

Alternative development is not part of this study and raw ranking scores are placeholders. The quantitative measures are notional and are only being used to communicate how the table is populated and scored.

Ranking raw scores in practice is determined by ranking individual alternative performance against safety criteria. The criteria values are used to inform ranking. These values represent the raw scoring. Looking specifically at criteria number "C-8," performance data documenting cable motion is collected and compared. Sample performance along with corresponding ranking is listed in Figure 10:

Alternative	Amplitude / Diameter (A/D)	Differential from Baseline	Ranking
Alternative A-1 (Double Cable)	0.65	0.14	1
Alternative A-2 (Rigid Structure)	N/A	N/A	4
Alternative A-3 (Single Cable)	0.48	-0.03	3
Baseline - Legacy System	0.51	-	-

Figure 10. Derived Safety Measure Criteria "C-8" Alternative Performance

Data in this case would be determined using computation analysis to determine the unitless value for cable measure. Alterative A-2 uses a non-standard approach to performing the functional requirements of deployment and retrieval. It does not employ a cable to suspend the array, instead opting for a rigid structure. This criterion does not apply to this alternative and is given the high raw ranking of 4. The next best performing Alternative A-1 has a smaller ratio denoting the less cable motion than the baseline and Alternative A-3. Alternative A-3 with the presence of two cables and a large cable motion ratio is the worst performing alternative received a rank of 1.

After raw ranks are populated in the table, weights are applied. The weighted scores are determined by multiplying the raw scores by their corresponding weights. Total

cumulative safety scored are determined by summing the weighted values across an alternative. The total scores are shown in Figure 11.

	Total Raw Score	Total Weighted Score
Weights	-	-
Baseline - Legacy System	16	37.5
Alternative A-1 (Double Cable)	32	69.75
Alternative A-2 (rigidStructure)	27	54.5
Alternative A-3 (Single Cable)	28	62.5

Figure 11. Total Weighted Scores

One can see in Figure 11 that all of the alternative scored better than the baseline. Additionally, based on the cumulative weighted scores, Alternative A-1 is the best performing alternative.

A top ranking does not mean that the alternative is the best solution overall. Users should take the scores on the surface and use them to conduct a trade-off analysis and foster a discussion with stakeholders. This selection process should be treated as a pre-requisite to the bigger AoA with ultimate alternative selection still considering feasibility, performance, available budget, and cost.

V. CONCLUSION

In conclusion, the L.E.A.D.S process represents a significant opportunity for advancement of AoA during the conceptual design phase of defense systems, where safety considerations often demand the utmost attention, but are currently overlooked. The process offers a structured approach to prioritize safety objectives, uncover technical risks, which may have the greatest impact to a systems architecture, and ensure the development of robust defense systems.

This thesis achieves its objectives by meticulously detailing the L.E.A.D.S process and illuminating its numerous merits for enhancing the defense system conceptual design phase. The process effectively addresses the goals set forth, yielding substantial benefits for system safety and design evaluation. The L.E.A.D.S process fulfills the objective of enhancing system safety performance by providing a structured framework that actively identifies and mitigates potential technical risks. By systematically examining casualty scenarios and technical safety risks, the process ensures that safety considerations are deeply ingrained in the design process. The process aligns with the goal of systematically evaluating alternatives based on mission-based safety measures. Through its attribute weighting and performance criteria derivation steps, it enables a comprehensive assessment of alternatives' safety implications, ensuring that mission success is intricately tied to safety outcomes. Furthermore, the integration of lessons learned from legacy systems, as facilitated by the L.E.A.D.S process, meets the objective of incorporating valuable insights into the design process. This approach promotes a traceable and informed decision-making process that draws from established safety best practices and successful system experiences.

The L.E.A.D.S process effectively facilitates life cycle technical risk management. By identifying technical risks early on and promoting root-cause analysis, it empowers designers to proactively manage risks throughout the life cycle of the defense system.

In its entirety, the L.E.A.D.S process accomplishes the overarching goal of placing safety as a paramount objective in the evaluation of alternatives. By fostering a culture of

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safety-driven decision-making, the process ensures that defense systems are not only mission-effective but also inherently safe, ultimately contributing to the creation of safer and more reliable defense systems.

The integration of the L.E.A.D.S process into the conceptual design phase of design systems brings forth a range of advantages and benefits. These advantages not only contribute to more robust and safety-conscious defense system development, but also address challenges and complexities that must be carefully navigated to ensure successful implementation. The multiple benefits offered by L.E.A.D.S include the following:

- Enhancing Safety Considerations: The primary objective of the L.E.A.D.S process is to prioritize mission safety objectives. Employing the process and expanding access to legacy system development and operational data can better the development of defense systems that are better equipped to address potential safety risks and mitigate them effectively.

- Informed Safety-Based Decision Making: The L.E.A.D.S process provides decision-makers with valuable insights and information derived from legacy systems. By identifying casualty scenarios and deriving safety performance measure criteria, decision-makers gain a deeper understanding of the safety implications of different design alternatives. This facilitates informed decision making, as the evaluation and scoring of concept design alternatives are based on objective safety criteria rather than subjective judgment.

- Integration of Best Practices and Lessons Learned: The process incorporates a thorough examination of legacy systems, allowing designers to learn from previous experiences and leverage best practices. By studying the successes and failures of existing defense systems, designers can avoid repeating past mistakes and incorporate proven safety measures into the conceptual design phase. This integration of lessons learned helps improve the overall safety performance of the new defense systems.

- Systematic and Structured Approach: The process provides a systematic and structured methodology for evaluating and comparing design alternatives. Each step is well-defined and guides designers through a logical progression. This ensures that safety considerations are systematically integrated at multiple junctures to reduce the likelihood of overlooking known technical risk. Beyond the analysis of alternatives, the deliverables that emanate from L.E.A.D.S can be applied at other junctures of the project. The casualty scenario list can inform survivability parameters for the deeper stages of design, provide justification for derived requirements, create applicable boundary conditions for the design space, and foster planning for the maintainability concept.

Even though L.E.A.D.S can provide benefits, there are challenges such as increased complexity, potential information overload, subjectivity in attribute weighting, and limited availability of legacy system data. Careful planning, resource allocation, and mitigation strategies are necessary to maximize the advantages of the process.

A. LIMITATIONS

There are some process limitations to consider since L.E.A.D.S is still in its infancy stages:

1. Limited Availability of Legacy System Data: Access to comprehensive and accurate data from legacy systems may be limited. The effectiveness of the L.E.A.D.S relies on the availability and quality of historical data related to casualty scenarios, safety records, and operational history. The presence of SMEs is just as decisive in identifying and explaining lessons learned. In some cases, legacy systems may lack detailed data, making it challenging to derive meaningful insights.

2. Incomplete Coverage of Safety Performance Measures: The derived safety-based performance measure criteria may not capture all relevant safety aspects or address emerging safety concerns. Decision makers need to ensure that the selected criteria cover a wide range of safety

considerations and account for evolving industry standards and regulations.

3. Complexity and Resource Intensiveness: Implementing the process requires substantial effort, time, and resources. The complexity and resource intensiveness of the process may present challenges, particularly in cases where project timelines or budgets are constrained. The process primarily focuses on safety-based decision making. Safety considerations should be integrated with other design factors, such as cost, schedule, performance, and operational requirements. Overemphasizing safety without considering other crucial aspects may lead to imbalanced design decisions or result in system designs that are not cost-effective or operationally efficient.

B. RECOMMENDATIONS FOR FURTHER STUDY

To further enhance the effectiveness of the L.E.A.D.S process and validate its applicability across defense lines, the following recommendations for future study are proposed:

1. Conduct comprehensive case studies across diverse defense domains to validate the impact of the L.E.A.D.S process. Analyze real-world scenarios to assess how the integration of safety considerations from legacy systems influences design decisions and mitigates technical risk.
2. Develop quantitative analyses to measure tangible improvement in safety performance achieved through the implementation of L.E.A.D.S. Compare safety outcomes between systems designed using L.E.A.D.S and those designed using the traditional approach to quantify process's effectiveness.
3. Investigate feasibility and benefits of incorporating advanced data analytics techniques to enhance the identification and evaluation of technical safety risks in the L.E.A.D.S process. This involves exploring

the potential synergies between the L.E.A.D.S process and other established risk management frameworks to develop an integrated approach for evaluating safety performance across the defense system life cycle. An example would be including "likelihood" into the scenario weighting process. Inclusion of additional data can enhance identification of technical risks, predict safety-related issues, and offer designers more insight for decision making.

4. Conduct stakeholder survey and interviews to gauge perceptions of the L.E.A.D.S. Explore how decision-markets, design team and subject matter experts perceive the process's benefits, challenges, applicability, and potential areas of improvement.

5. Perform a longitudinal study to assess the long-term impact of the L.E.A.D.S process on defense system performance, safety incident, and life cycle costs. Analyze how the adoption of L.E.A.D.S influences the overall success of a defense program over an extended time frame.

These recommendations can enrich the understanding, applicability, and overall effectiveness of the L.E.A.D.S process. The L.E.A.D.S process stands as a transformative framework that not only bridges existing gaps in the AoA methodology but also introduces a novel approach to safety-based decision-making in defense system design. By systematically incorporating historical safety records, lessons learned, and technical risk identification, L.E.A.D.S sets a precedent for prioritizing safety as a primary objective in evaluating alternatives, thereby contributing to the creation of more resilient, reliable, and mission-effective defense systems.

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