An Integrated Trade-off Analysis of the Influence of Reliability on Conceptual Design

Mahendra Lodhi[1], Anoop Pratap Singh[2], Harimohan Soni[3]

[1]*Mechanical Engineering Department, Bansal Institute of Science and Technology, Bhopal (M.P.), India.*
[2]*Mechanical Engineering Department, Bansal Institute of Science and Technology, Bhopal (M.P.), India.*
[3]*Mechanical Engineering Department, Bansal Institute of Science and Technology, Bhopal (M.P.), India.*

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Abstract - This article presents research aimed at creating models to assess the system dependability of Unmanned Ground Vehicles by utilising knowledge and data from analogous systems. Conventional reliability methodologies often need comprehensive understanding of a system and are employed throughout later design phases, as well as in development, operational testing and evaluation, and operations. The essential importance of reliability and its influence on acquisition program performance, cost, and schedule necessitates the enhancement of system reliability models throughout the initial design phases. Reliability is frequently seen as an independent criterion, not completely integrated into performance and life cycle cost models. This research aims to include reliability, performance, and cost models inside a trade-off analysis framework during the initial acquisition phases. This study uses functional analysis techniques to evaluate reliability prior to Milestone A and examine the influence of reliability on the performance and cost models of initial system conceptions. This research uses the indexed technological readiness level (TRL) to determine varying dependability levels for design. A comprehensive cost and performance model will guide decision-makers with the implications of dependability prior to selecting a system design for future development.

Key Words: trade off analysis, reliability, life cycle cost, TRL.

1.INTRODUCTION

The United States Department of Defence (DoD) must integrate dependability information prior to Milestone A, as it substantially influences program performance, cost, and schedule projections [1]. This study examines a methodology that employs early life cycle reliability analysis to evaluate performance, cost, and schedule within an integrated model framework for Pre-Milestone A. The objective is to demonstrate the approach by doing a trade-off analysis to find design options for Unmanned Ground Vehicles (UGVs). The study examines the effects of design choices that omit dependability from the performance models. A UGV design tradespace is created to evaluate the feasibility, performance, and cost of design concepts alongside the dependability model of the initial system design. The resulting tradespace will delineate the value contributed by early reliability evaluation.

Our approach concentrated on the creation of parametric models for system performance, dependability, and cost. Value models were developed to evaluate the viability of design options through system-level trade-offs. Subsequently, we illustrated the relationship between cost and reliability, value and cost, and value and reliability. Due to the nature of the study challenge, our access to freely available data was constrained. Consequently, we are utilising hypothetical data to create a case study illustrating potential system performance inside an operational setting. To do this, we analysed pertinent data and information from publications on manned and unmanned vehicle characteristics as a substitute for actual data. Due to the scarcity of design information during the first stages of system idea development. A primary issue for an integrated UGV model is the formulation of suitable parametric reliability and performance models at the initial concept design phase. Comprehending the correlations between technological concepts, decisions, and performance paves the way for integrated models of trade-off analysis. Advancements in UGV technology for military purposes are continuous, and this research can offer valuable insights to decision-makers on the influence of dependability on performance, cost, and timeline during the initial design phases of UGVs. Our study is based on two hypotheses: 1) dependability has not been sufficiently modelled in conceptual design, and 2) modelling reliability in conceptual design yields divergent value and life cycle cost estimations. Our research is on creating a conceptual design framework to model reliability and influence decision-making.

1.1. A Comprehensive Model

The integrated reliability model encompasses reliability in system design feasibility assessment, performance evaluation, and life cycle cost estimations of design concepts to facilitate trade-off analysis. Dependability is included into performance metrics along the mission chain and inside the life cycle cost model by utilising anticipated operational utilisation and assessing the influence of dependability on life cycle cost components [2].

1.1.1 Influence Diagram for Integrated Models

We created an influence diagram (Figure 1) [3] to illustrate the interconnections among stakeholder needs, requirements, system alternatives, technology/manufacturing, integration readiness, stakeholder objectives, models, and simulations utilised for reliability and system performance modelling in the integrated trade-off analysis. The integrated models in the influence diagram utilise prescriptive models (blue), predictive models (green), and prescriptive models (orange). The yellow signifies information that is unlikely to alter in the model. The impact diagram delineates whether the information is a known constant, a choice, an uncertainty, a calculated uncertainty, or a value. The diamond form denotes known constants, the rectangle signifies judgements, the single oval indicates uncertainties, the double oval represents computed

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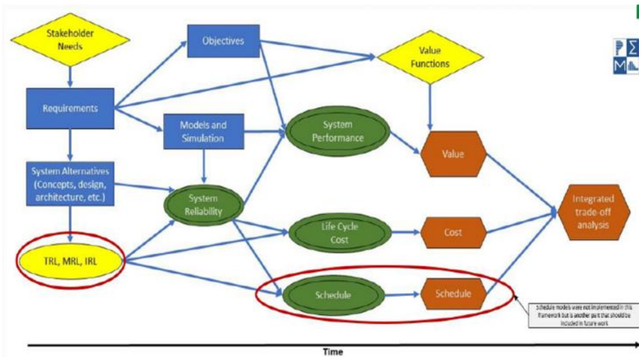
uncertainties, and the hexagon shape reflects the value for the measure of interest. We utilise directed acyclic graphs (where arrows do not create loops in influence diagrams) to represent the flow of information. It is crucial to recognise that knowledge becomes accessible in subsequent phases, as shown by the timeline at the bottom of Figure 1.



Our approach centres on creating an integrated framework of performance models to assess feasibility and evaluate design proposals. Our AFD and ID methodology starts with essential design choices, including the mobility platform, power supply, and sensor kinds. The calculations of the system's dependability, performance metrics, system value, and life cycle costs for all alternatives are utilised to assess the design trade space and conduct a comprehensive trade-off analysis from the design decision.

2. Reliability Modelling

Reliability is conventionally defined as the likelihood that a component or system will execute its designated function for a specified duration when utilised under defined operating conditions [12]. This research defines reliability as the likelihood that a component or system will fulfil specified functions throughout time, contingent upon the functional performance conditions of other interconnected functions. Theoretically, these definitions are identical; nonetheless, it is emphasised that the failure of a component or system is contingent upon the current status of other system components. While the methods of analysis may provide varying figures, the fundamental structural analysis for dependability remains consistent.

$$R_{sys}(t) = \prod_{i=1}^{n} R_i(t) \tag{1}$$

$$R_{sys}(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)) \tag{2}$$

$$R_i(t) = e^{-\lambda i * t} \tag{3}$$

Two fundamental configurations for system analysis regarding dependability are series and parallel architectures. These two structures can be amalgamated to form a series-parallel configuration. This study exclusively examines these categories of structures. The formulas for series and parallel configurations are shown in equations (1) and (2), respectively. This research use the exponential life distribution to characterise the reliability of essential components for the UGV (equation 3). An assumption is that failure is contingent upon the function, shown by the failure rate, λi, where “i” signifies the function. The system's failure rate is essential for determining the number of systems needed for the operational concept and the life cycle cost.

Predicting dependability during the basic design stages of system development is part of our study. We use hypothetical data and functional analysis in our reliability analysis method to check how reliable a design idea is. One of the most important parts of functional analysis is figuring out how the system works so that it can be used in conceptual design. For a UGV, general functions were set up that are used in the system study.

This functional analysis technique is tailored to integrate with technological readiness levels to signify the prospective reliability of a high-level function. This method facilitates the examination of the interconnections among functions and their effects on performance, value, and cost. The Excel INDEX function is utilised for three presumed readiness levels of a certain system component. The dependability of the system is subsequently determined based on its functional structure utilising equations 1 and 2. If a function relies on all functional connections, it is represented by AND logic. If it relies just on a minimum of one function, it is represented by OR logic in the functional connections table. The subsequent equation is employed to convert the reasoning into a reliability estimate grounded in the functional connections. To represent the optimal situation of non-failure, the framework utilises the maximum reliability value of the functional linkages. In determining this value, we sought an optimistic viewpoint for the case study based on the design selections made. Rather to use MAX, one may utilise MIN to assess the worst-case possibilities for dependability performance inside the tradespace.

- Functional Reliability Estimate = MAX (SET{Functional Relationship Reliability} * (TRL Reliability of the Base Function))
- Functional Dependencies Reliability -> Varied Reliability Assessments for Functional Relationships
- Function 3.0 is contingent upon F1.0 or F2.0. The following illustrates the procedure for determining the reliability estimate.
  - o F3.0_Reliability=MAXIMUM (SET {1.0_Reliability, 2.0_Reliability * F3.0_Reliability)

By using our stated reliability relationships, we can readily compute function reliability. In the aforementioned example, we utilise the foundational reliability estimate of function 3.0 and employ the other functions upon which 3.0 relies to ascertain the chance of failure for function 3.0, contingent upon the failure probabilities of functions 1.0 or 2.0. This paradigm resembles series-parallel systems, although greater focus must be placed on the propagation of failure in both forward and backward directions. Due to the intricacy of connections, adequately identifying them may be beneficial in conceptual design.

4.Results and discussion

An approach to life cycle cost and value is discussed in this paper, which also incorporates a fundamental reliability model. We emphasise three primary areas in the integrated modelling framework: cost, value, and reliability. The

preliminary results in the cost vs. value tradespace are presented in the subsequent section, which utilises the technology preparedness levels for the system functions.
The model enables us to index three TRLs and determine the reliability, value, and cost of an alternative for each level. We employ parametric models that are incorporated, as illustrated in Appendix I. The outcome of the integrated modelling framework is a tradespace that evaluates the trade-offs between alternative value, cost, and reliability for a specific design. Dependent variables, including system design value and life cycle cost, would be adversely affected by an inadequately designed system or system alternative.

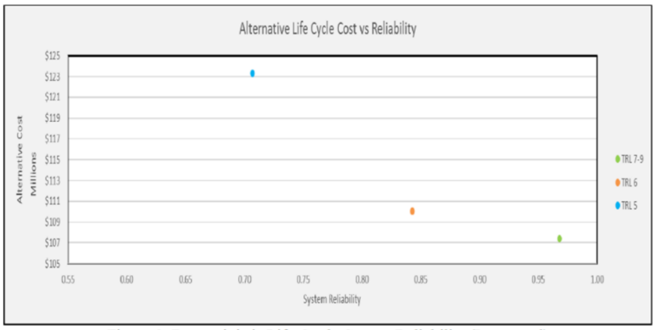


Figure 8. Deterministic Life Cycle Cost vs Reliability (Integrated)

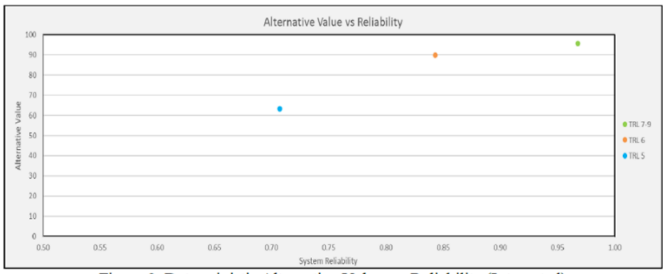


Figure 9. Deterministic Alternative Value vs. Reliability (Integrated)

We aim to compare deterministic analysis with uncertainty analysis of TRL values. As stated in [17], the objective of TRL is to assess the maturity of technological components inside a system. This measurement enables individuals to assess the advancement of technology prior to its implementation.

In deterministic analysis, each function was categorised by the identical TRL level. The integrated framework would then compute dependability, value, and cost for the three Technology Readiness Levels (TRL). The following are the outcomes of the deterministic analysis.
The initial outcomes derive from a deterministic analysis employing the integrated framework. The chart below illustrates a design space with three points. The blue point signifies TRL 5, the orange denotes TRL 6, and the green indicates TRL 7-9. The graphic illustrates the effect of dependability on the life cycle cost of design. Under our specified conditions, when a system possesses the subsequent graphic illustrates the influence of dependability on the value of a system design. This graph clearly illustrates that the integration of dependability influences the performance of a design option, which in turn affects the value of that alternative. Another significant insight is that the value increment is little when dependability improves, due to our framework's sensitivity to underperforming alternatives. As dependability improves, the cost of failure will markedly diminish. Expenses are expected to be minimal as dependability rises. The framework prioritises inadequate dependability. While it was crucial to observe predictable outcomes in system analysis, including uncertainty into the results is as significant. In this instance, uncertainty was characterised as the variation of the TRL range that produces a design space amenable to realistic comparison with deterministic analysis. We may see a certain function as well-developed, assigning it a Technology Readiness Level (TRL) of 7-9 for that determination. Conversely, another function may own technology with a maximum Technology Readiness Level of just 5.

We employed Monte Carlo simulation to develop the mixture design with the SIPmath program from ProbabilityManagement.org [18]. Probability Management defines "probability management" as the depiction of uncertainty using data arrays referred to as Random
Figure 12. Alternative Value Compared to Life Cycle Cost (Non-Integrated)

Information Packets (SIPs) that adhere to the principles of arithmetic and the axioms of probability. SIPmath is an Excel add-in that enables users to do a Monte Carlo Simulation on the index value. The index value is utilised to derive the values of a certain design. A distribution is allocated to each function and a specified TRL range. A discrete uniform distribution was employed to select the index values in this investigation. A discrete uniform distribution was employed due to the selection of three distinct TRL ranges, necessitating an equitable selection of these ranges. A triangle distribution was employed to delineate the range of TRL values, with the lowest and maximum values presented in Appendix II. Triangular distributions were employed due to their utility in scenarios lacking system data, particularly when utilising notional data. The index values for each function were designated as a "Input" for the modelling tool. Upon selection, the SIPmath modeller tool simulates the index value for a predetermined number of trials and automatically records user-defined information. The dependability cells are designated as "output."

Understanding the classification of the point as TRL 5, TRL 6, or TRL 7-9 is crucial. This research categorises mixed design options based on their corresponding reliability ranges. For TRL 5, the range was [.67, .75]; for TRL 6, it was (.75, .85]; and for TRL 7-9, it was (.85, .99]. The values were categorised according to the outcomes of the Monte Carlo simulation. A clear aggregation of points was observable. Another rationale for discarding is that prior interactions with academics suggested the approximate range of data that may be pertinent for further study. Considering these two considerations, we categorised the data accordingly.

The conclusions of the analysis parallel those of the deterministic analysis. A cluster of points dominates the tradespace due to markedly superior dependability, reduced cost, and enhanced value. The following illustrates the correlation between life cycle cost and system reliability, indicating that locations within the TRL 7-9 range exhibit superior reliability and markedly reduced costs compared to the infeasible points depicted un purple. The infeasible locations are those where dependability failed to satisfy the minimal threshold criterion of 0.67 for the TRL 5 baseline. A notable observation from the data indicates a cluster of spots exhibiting comparable dependability levels, but at a potentially elevated cost. Nonetheless, this is just minor, and at a programmatic level, a few million dollars may be inconsequential.

5. Conclusion

The way things are done now, for stability on a certain part or component, static numbers are used. When Monte Carlo Simulation is used to store all the fixed numbers for design choices, this method changes into a dynamic one. In this system, big choices about design were made, and TRL levels showed how levels of reliability changed. The SIPmath tool was used to make a tradespace by listing all the possible design decisions that could be made. The end study shows that the high-level system trade-offs can be used to continue working on reliability modelling methods.

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