The influence of reliability on conceptual design is analysed via the lens of an integrated trade-off analysis.

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.*

---***---

Abstract - This article details studies that used data and information from similar systems to build models that evaluate the reliability of Unmanned Ground Vehicles. The following stages of design, development, operational testing and evaluation, and operations all make use of conventional dependability approaches, which typically necessitate a thorough understanding of the system. Because reliability is so crucial and affects the performance, cost, and timeline of acquisition programs, it is necessary to improve system reliability models throughout the early stages of design. In contrast to performance and life cycle cost models, reliability is often considered as a separate metric. Incorporating cost, performance, and reliability models into a trade-off analysis framework for use at early stages of acquisition is the goal of this research. This study delves into the impact of reliability on the performance and cost models of initial system conceptions, using functional analytic approaches to assess reliability prior to Milestone A. Different degrees of design dependability are defined in this study using the indexed technical readiness level (TRL). In order to help decision-makers navigate the dependability implications of potential system designs, a thorough cost and performance model is available.

***Key Words*:** reliability, life cycle cost, TRL.

1.INTRODUCTION

Due to its significant impact on program performance, cost, and schedule forecasts, dependability information must be integrated by the United States Department of Defence (DoD) before Milestone A [1]. Performance, cost, and schedule are assessed within an integrated model framework for Pre-Milestone A using a methodology that incorporates early life cycle reliability analysis. To show how the method works, we'll conduct a trade-off analysis to identify potential UGV designs. This research looks at what happens when you choose to leave reliability out of your performance models during design. To assess the practicality, efficiency, and affordability of potential design ideas in conjunction with the reliability model of the original system architecture, a UGV design tradespace is established. The value of early reliability evaluation will be outlined in the resulting tradespace.

The development of parametric models representing reliability, cost, and system performance was the primary focus of our methodology. To determine whether design choices were feasible by considering system-level trade-offs, value models were created. Our next step was to show how reliability, value, and cost all relate to one another. Our ability to use publicly available data was limited because of the study's inherent difficulty. As a result, we are building a case study to show how the system could work in an operational environment using fictitious data. In place of actual data, we evaluated relevant data and information from publications on the characteristics of manned and unmanned vehicles.

Because there is a dearth of design knowledge available when brainstorming potential system ideas in the early phases. In the early stages of concept design, one of the most important things to do for an integrated UGV model is to formulate appropriate parametric performance and reliability models. Developing integrated models of trade-off analysis requires an understanding of the relationships between technical ideas, decisions, and performance. The military is always investing in UGV technology advancements, and this study can help decision-makers understand how reliability affects performance, cost, and timeliness in the early stages of UGV design. We postulate that (1) conceptual design has not adequately modelled dependability and (2) that doing so produces different value and life cycle cost estimates. These hypotheses form the basis of our analysis. In order to model dependability and impact decision-making, our study focusses on developing a conceptual design framework.

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].

2. The Modelling of Connections

The possibility that a component or system will perform its intended function for a set time under specified operating conditions is called reliability [12]. This research defines reliability as the possibility that a component or system will fulfil stated functions over time, depending on other interconnected functions' performance conditions. Though equivalent, these definitions stress that a component or system's failure depends on other system components. Although analytical approaches may yield different statistics, structural analysis for dependability remains consistent.

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

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

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

Series and parallel architectures are two basic topologies for system analysis that pertain to reliability. Combining these two structures allows for the formation of a series-parallel arrangement. Only these types of constructions are covered in this research. Equations (1) and (2) display the formulas for series and parallel arrangements, correspondingly. In order to describe the dependability of key UGV components, this study employs the exponential life distribution (equation 3). The failure rate, λi, where "i" represents the function, indicates that failure is dependent on the function, which is an assumption. When calculating the operating concept and life cycle cost, the failure rate of the system is crucial.

Part of our research involves developing reliability predictions for use in the early phases of system design. To determine the dependability of a design concept, we employ a reliability analysis method that makes use of functional analysis and hypothetical data. Determining the system's inner workings for use in conceptual design is a crucial component of functional analysis. General functionalities were established for a UGV and utilised in the system analysis.

A high-level function's future dependability can be represented using this functional analysis method that is specifically designed to work in tandem with technological readiness levels. Using this approach, we can more easily see how different functions affect one another and how much it all ends up costing, in terms of performance and value. One system component is assumed to be ready at one of three levels using the Excel INDEX function. The system's reliability is then ascertained by applying equations 1 and 2 to its functional structure. The AND logic is used to depict functions that depend on all functional connections. To indicate that it depends on at least one function, the functional connections table uses OR logic. A reliability estimate based on the functional connections is obtained by applying the following equation to the rationale. The framework uses the maximum dependability value of the functional links to depict the best state of non-failure. We aimed for a positive case study perspective based on the design choices made when determining this value. If you want to evaluate the worst-case scenarios for reliability performance inside the tradespace, you can use MIN instead of MAX.

Estimate of Functional Reliability = Maximum (TLL Base Function Reliability * SET{Functional Relationship Reliability})
• Reliances on Other Functions Dependability -> Multiple Dependability Evaluations for Practical Connections
F1.0 or F2.0 must be present for Function 3.0 to be executed. You can see the steps to calculate the reliability estimate in the following.
Set 1.0_Reliability, 2.0_Reliability, and F3.0_Reliability to the maximum value.

We can easily calculate function reliability using our stated reliability relationships. To determine the likelihood of failure for function 3.0 given the failure probabilities of functions 1.0 or 2.0, we use the foundational reliability estimate of function 3.0 and the other functions upon which 3.0 depends in the previous example. While this model is similar to series-parallel systems, it requires more attention to the forward and backward propagation of failure. Because links are complex, it could help in conceptual design to properly identify them.

3.Results and discussion

In this work, an approach to life cycle cost and value is described, and a fundamental reliability model is also incorporated into the discussion. From the perspective of the integrated modelling framework, we place an emphasis on three major areas: cost, value, and reliability. Using the technology preparedness levels for the system functions, the subsequent part presents the preliminary results in the cost versus value tradespace. These results are reported in the next section.
With the help of the model, we are able to index three TRLs and ascertain the cost, value, and dependability of an option for each level. We make use of parametric models that are incorporated, some examples of which can be seen in Appendix I. The integrated modelling framework will produce a tradespace as its final product. This tradespace will analyse the many value, cost, and reliability trade-offs that are associated with a particular design situation. A system or system alternative that is improperly designed would have a negative impact on dependent variables, such as the value of the system design and the cost of the system during its whole functional life.

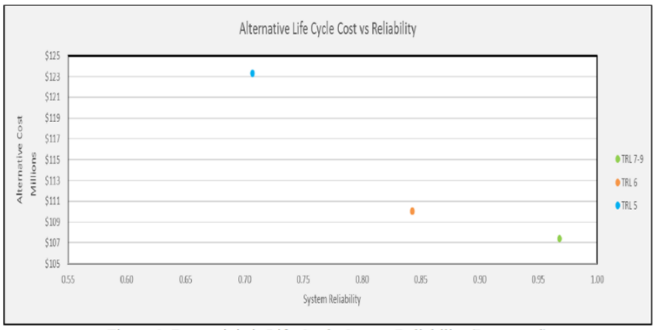

Figure 8. Deterministic Life Cycle Cost vs Reliability (Integrated)

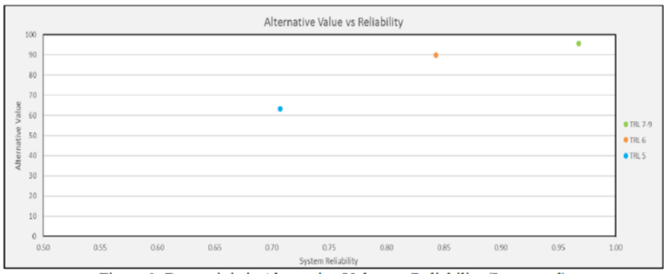

Figure 9. Deterministic Alternative Value vs. Reliability (Integrated)

Our goal is to evaluate TRL value uncertainty analysis in comparison to deterministic analysis. The goal of TRL is to determine how developed a system's technological components are, as mentioned in [17]. Prior to its adoption, this metric allows people to evaluate the progress of technology.

Every function was assigned the same TRL level in deterministic analysis. The three Technology Readiness Levels (TRLs) would thereafter have their reliability, value, and cost calculated using the integrated framework.

Conclusions drawn from the deterministic analysis are as follows.
An integrated framework deterministic analysis yields the first results. The following diagram shows a three-point design space. The green dot represents TRL 7-9, the orange dot TRL 6, and the blue dot TRL 5. This graphic shows how dependability affects the LCC of a design. When a system meets our requirements, the following graphic shows how reliability affects the design's value. This graph makes it very evident that a design option's performance is affected by the incorporation of dependability, which impacts the value of that choice. Because our paradigm is sensitive to underperforming alternatives, another important observation is that there is little value increment when reliability improves. There will be a dramatic drop in the cost of failure as reliability increases. As reliability increases, costs should remain low. Inadequate reliability is given precedence by the framework. Including uncertainty into the results is just as important as seeing predictable outcomes in system analysis. Here, uncertainty was defined as the range of possible TRL values that yields a design space that can be reasonably compared to deterministic analysis. In some cases, we may consider a function to be fully developed and give it a Technology Readiness Level (TRL) between 7 and 9. On the other hand, a different department might have tech that can only handle a Technology Readiness Level 5 at most.

We used the SIPmath tool from ProbabilityManagement.org to conduct Monte Carlo simulation and build the mixture design [18]. The term "probability management" is defined in the field of probability management as the statistical representation of uncertainty through the use of Random
Picture 12. Value of Alternatives in Relation to Life Cycle Cost (Separate)

Secure Information Packets (SIPs) that follow standard mathematical and probabilistic procedures. This index value can be subjected to a Monte Carlo simulation with the help of the SIPmath Excel add-in. The values of a specific design are derived from the index value. Every function and a certain TRL range receives a distribution. To choose the index values for this study, a discrete uniform distribution was used. Since three separate TRL ranges were chosen, it was necessary to pick them fairly, hence a discrete uniform distribution was used. The range of TRL values was defined using a triangular distribution; the lowest and highest values are shown in Appendix II. Because of their usefulness in situations without system data, especially when using notional data, triangle distributions were used. The modelling tool's "Input" was the index values for all functions. When you use SIPmath as your modeller, it will automatically capture user-defined data while simulating the index value for a set number of trials. The cells that measure reliability are called "output."

That the point is classified as TRL5, TRL6, or TRL7-9 is an important understanding. This study sorts mixed-design alternatives according to the dependability ranges that correspond to them. The intervals for TRLs 5-7 were [.67,.75], [.75,.85] and [.85,.99], respectively. Based on the results of the Monte Carlo simulation, the values were classified. It was easy to see that the points had accumulated. Prior interactions with academics indicated the approximate range of material that may be relevant for further investigation, which is another argument for dismissing. Our data categorisation was based on these two factors.

Findings are consistent with the deterministic analysis. Because of their far higher reliability, lower cost, and increased value, a cluster of points controls the tradespace. Locations within the TRL 7-9 range show lower costs and better reliability compared to the infeasible spots shown in purple, as shown in the accompanying graph of life cycle cost vs system reliability. A place is considered infeasible if its reliability does not meet the TRL 5 baseline's minimal threshold requirement of 0.67. An interesting finding in the data points to a group of locations with similar reliability scores, but maybe higher prices. However, this is quite small, and a few million dollars might not even matter when it comes to programming level.

4. Conclusion

According to the current method of doing things, static numbers are utilised in order to provide stability on a certain element or component. The transformation of this method into a dynamic one occurs when Monte Carlo Simulation is utilised to store all of the fixed numbers for design decisions. In this system, significant decisions were made about the design, and the TRL levels demonstrated how the levels of reliability increased over time. For the purpose of creating a tradespace, the SIPmath program was utilised to compile a list of all the potential design choices that may be made. The conclusion of the study demonstrates that the high-level system trade-offs can be utilised to persist in the development of reliability modelling techniques.

REFERENCES

[1] Department of Defense Instruction. (2015). DoDI 5000.02. Operation of the Defense Acquisition System. Washington, DC: U.S. Department of Defense.
[2] E. Specking et al., "Assessing Engineering Resilience for Systems with Multiple Performance Measures," Risk Anal., vol. 39, no. 9, pp. 1899–1912, Sep. 2019, doi: 10.1111/risa.13395.
[3] Howard, R. A., Matheson, J. E. 2005. Influence diagrams. Decision Analysis, 2(3), 127-143.
[4] M. Cilli and G. S. Parnell, "Understanding Decision Management," in Trade-off Analytics: Creating and exploring the system tradespace, G. S. Parnell, Ed. Hoboken (N. J.): Wiley, 2017, pp. 180–181.
[5] Web of Science Group. (2021, July 7). Trusted publisher-independent citation database. Web of Science Group. https://clarivate.com/webofsciencegroup/solutions/web-of-science/.
[6] T. Kurtoglu and I. Y. Tumer, “A graph-based fault identification and propagation framework for functional design of complex systems,” J. Mech. Des. Trans. ASME, vol. 130, no. 5, 2008, doi: 10.1115/1.2885181.
[7] T. Kurtoglu, I. Y. Tumer, and D. C. Jensen, “A functional failure reasoning methodology for evaluation of conceptual system architectures,” Res. Eng. Des., vol. 21, no. 4, pp. 209–234, 2010, doi: 10.1007/s00163-010-0086-1.
[8] A.-R. Short, A. D. Lai, • Douglas, and L. Van Bossuyt, “Conceptual design of sacrificial subsystems: failure flow decision functions,” doi: 10.1007/s00163-017-0258-3.

[9] L. Jing et al., "Conceptual Scheme Decision Model for Mechatronic Products Driven by Risk of Function Failure Propagation," doi: 10.3390/su12177134.
[10] I. Tumer and C. Smidts, "Integrated design-stage failure analysis of software-driven hardware systems," IEEE Trans. Comput., vol. 60, no. 8, pp. 1072–1084, 2011, doi: 10.1109/TC.2010.245.
[11] M. Augustine, O. Prakash Yadav, R. Jain, and A. Rathore, "Cognitive map-based system modeling for identifying interaction failure modes," doi: 10.1007/s00163-011-0117-6.
[12] Ebeling, C. E. (2010). In An introduction to reliability and maintainability engineering (pp. 23–23). essay, Waveland.
[13] Ebeling, C. E. (2010). In An introduction to reliability and maintainability engineering (pp. 175–177). essay, Waveland.

[14] Parnell, G. S., Johnson, E. R., Parnell, G. S., & Tani, S. N. (2013). In Handbook of decision analysis (pp. 196–196). essay, John Wiley & Sons.
[15] Kirkwood, C. (1997). Strategic Multiple Objective Decision Analysis with Spreadsheets. Belmont, CA: Duxbury Press.