Working Title: Systems Engineering Techniques for ALS Decision Making

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Abstract

The ALS Metric is the predominant tool for predicting the cost of ALS systems. Metric goals for the ALS Program are daunting, requiring a threefold increase in the ALS Metric by 2010. Confounding the problem, the rate new ALS technologies reach the maturity required for consideration in the ALS Metric and the rate at which new configurations are developed is slow, limiting the search space and potentially giving the perspective of a stalled program. Without significant increases in the state of the art of ALS technology, the ALS Metric may remain elusive.

This paper is a sequel to a paper published in the proceedings of the 2003 ICES conference entitled, "Managing to the metric: an approach to optimizing life support costs." The conclusions of that paper state that the largest contributors to the ALS Metric should be targeted by ALS researchers and management for maximum metric reductions. Certainly, these areas potentially offer large potential benefits to future ALS missions; however, the ALS Metric is not the only decision-making tool available to the community.

To facilitate decision-making within the ALS community a combination of metrics should be utilized, such as the ESM-based ALS metric, but also those available through techniques such as life cycle costing and faithful consideration of the sensitivity of the assumed models and data. Often a lack of data is cited as the reason why these techniques are not considered for utilization. An existing database development effort within the ALS community, known as OPIS, may provide the opportunity to collect the necessary information to enable the proposed systems analyses. A review of these additional analysis techniques is provided, focusing on the data necessary to enable these. The discussion is concluded by proposing how the data may be utilized by analysts in the future.

Introduction

In his paper entitled, "Managing to the metric: an approach to optimizing life support costs," Drysdale astutely identifies that several aspects of the current perspective on Advance Life Support (ALS) system design are significantly costlier than some other aspects of the ALS system (Drysdale, 2003). Some of the costlier aspects of the system include the cabin volume, the prepackaged food, expendable clothing, and the preparation of food, among several others. However, Drysdale notes that ALS priorities apparently lie elsewhere. Current ALS Metric improvements are not in areas where the ALS Metric costs were highest and in some cases are achieved in areas where minimal impact on the overall ALS Metric will be seen, no matter how large the improvements may be. Drysdale then notes that if large gains are necessary to achieve the ALS Metric goals for the ALS Program, then the large contributors must be targeted. If the ALS Metric goals cannot be achieved in this manner, then it is not likely that they can be achieved at all. In conclusion, Drysdale proposes several changes in ALS System design, focusing on the large contributors to the ALS Metric and shows that it may be possible to achieve the ALS Metric goals - a positive sign for the ALS Program.

Evidently, ALS priorities are not solely focused on achieving metric goals. To ascertain what the priorities of the ALS Program are it is necessary to consider the overall goals of the project, how these goals contribute to the goals of other NASA entities, the goals greater of NASA, and national priorities. From the topmost level, a renewed exploration spirit has been initiated nationwide by the President (Bush, 2004). This has initiated a reorganization of NASA. From this statement by the president ensued a particularly relevant creation of a new office[1], "The Office of Exploration Systems." The responsibilities of this new office shall be to set priorities and direct the identification, development, and validation of exploration systems and related technologies (NASA, 2004a). This falls directly into the NASA goals set by the NASA 2003 Strategic Plan, "Extend the duration and boundaries of human space flight to create new opportunities for exploration and discovery," (NASA, 2003). The President's vision directs that an expedition to the lunar surface occur between 2015 and 2020, where testing of new approaches, technologies, and systems shall occur in an effort to support sustained human exploration to Mars and beyond (Bush, 2004; NASA, 2003).

The ALS Program is a small but critical portion of NASA working towards achieving the above goals. Within NASA, the ALS Program is charged with the research and development of the technologies to enable water purification, air revitalization, processing of solid waste materials, as well as providing a food source for the crew (NASA, 2004b). The ALS Project Plan lists five project objectives (Russo and Henninger, 2002):

1. Provide Advanced Life Support technologies that significantly reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for long-duration missions.
2. Develop and apply methods of systems analysis and engineering to guide investments in technology, resolve and integrate competing needs, and guide evolution of technologies.
3. Resolve issues of microgravity performance through space flight research and evaluation.
4. Ensure timely transfer of new life support technologies to missions.
5. Transfer technologies to industrial and residential sectors for national benefit.

ALS objectives are well aligned with the directives handed down by the President and the NASA Strategic Plan. To enable Martian missions, the ALS Program needs to produce technologies than enable such missions that are low in cost, highly efficient, self sufficient, and minimize resource utilization[2]. In particular, life cycle costs (LCC) are specified by the ALS Program objectives. The ALS Metric, a figure of merit acting as a proxy for launch costs, is certainly a significant portion of the life cycle costs of the system, however it does seem that a significant portion of LCC are currently not considered. Often it is asserted that the necessary data required for life cycle costing is unavailable. In another paper dealing with decision support for ALS, Jones presents existing models currently

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[1] Other changes that were proposed by the President's directive include: the retirement of the Shuttle, development of a new manned exploration vehicle, a plan to return to the Moon by 2015 with both robotic and human missions, and an increased use of robotic missions for space exploration (Bush, 2004).
[2] Perhaps ALS is not as well aligned with respect to the precursor Lunar missions since most technology development and analysis has considered Martian missions as the target, however Lunar missions may be utilized as testbeds for Martian technology. This remains to be seen.

utilized by NASA and the Air Force to estimate costs such as Design, Development, Testing, and Evaluation (DDT&E) Costs; Launch and Emplacement Costs; and Operations Costs (Jones, 2003). The models are top-level in nature, likely due to the limited available data to make such predictions. Nonetheless, Jones was able to show that according to the best models currently available launch costs are not necessarily the largest portion of the LCC of ALS missions; in fact, based on these models research and development costs easily rival the costs of launching ALS systems for high complexity items such as avionics. However, these models may not have been developed considering ALS missions to the Moon or Mars. Thus, it may be less certain that for life support logistics items like bulk gases, water, and food are so costly to develop. Furthermore, launch costs will reach unprecedented highs for missions to Mars due to the extreme differences.

A more comprehensive analysis would be desirable for the ALS (and the greater NASA) community. Although, LCC is an attractive option for industry, it seems that some aspects are not currently tractable to a level high enough to merit the additional expenditure[3]. However, the current approach of systems engineering and analysis based almost entirely on the equivalent system mass (ESM) based ALS Metric is also lacking, especially considering that management decision making is evidently not solely based on metric improvements. Significant portions of the costs of ALS missions are not being considered in analysis and decision-making may benefit from the results from such analysis. To address this need, some techniques often utilized or related to LCC can be added relatively easily to the repertoire of ALS systems analysts. Some of these techniques are briefly outlined here with their data requirements. In addition, since data seems to be lacking, a plan is set forth to collect the necessary data for future analysis within ALS and NASA with some considerations for use of the data, once it is collected.

Analysis Techniques and Data Requirements

LCC is a very comprehensive analysis technique attempting to consider the costs of all aspects of a system from the time the analysis of a new idea begins, through the building and operations phase, and ultimately until the project is disposed of. The determination of metrics, such as the ALS Metric, is a critical intermediary step in the LCC process used for decision-making. To improve decision making in ALS, it may be enough to add some metrics to the analyst repertoire. Ideally, we would focus on metrics that deal with aspects other than launch costs, such as those highlighted by Jones. Models such as those utilized by Jones should be adequate, until there is better data. Two short-term improvements to these models would be useful. (1) Consider the original design uses of these models. If they are not suitable for ALS missions to the Moon or Mars, they should be upgraded in some simplistic manner or all results reported should highlight the potential shortcomings. (2) Attempt to quantify the uncertainty in their predictions based on the uncertainty in input data. Rodriguez et al. (2003a) provide techniques for considering the uncertainty in model output.

Developing a *cost breakdown structure* (CBS) that specifically identifies all costs to be incurred throughout the system life cycle would be a good way to increase the breadth of ALS systems studies and potentially providing a complete LCC analysis in the future (Blanchard and Fabrycky, 1998). This requires that models are be developed to predict the each cost incurred

[3] For a comprehensive description of LCC, refer to Blanchard and Fabrycky (1998).

throughout the life cycle. It is precisely the lack of these models that is preventing the preparation of a comprehensive LCC in ALS. With such models, the models described by Jones could be replaced or upgraded. ESM, for example, could be utilized as a basis in development of a model to predict the costs of launch. Costs of DDT&E, particularly for software, are harder to ascertain[4]. Some considerations for double booking of costs will be required. For example, ESM currently considers many aspects of operations through crew time, logistics, and power. For a complete LCC, and perhaps in preliminary stages, it may be beneficial to have these aspects parsed out for greater resolution in the analysis.

Research, Development, Test and Evaluation[5] life cycles are outlined in the literature by Patterson (1999). By creating a better understanding of the research and development life cycle in ALS, it may be possible to understand the analogous CBS. A key aspect of the DDT&E life portion of the life cycle is that research activity never ends throughout the complete life cycle and that its products are always useful for strategic planning of future activities through a constant feedback loop.

With this understanding, several cost related issues can be considered for collection by the Online Project Information System (OPIS), to be described in more detail later. In particular, we need to collect the input information for whichever models we choose to utilize. With respect to ESM, we need mass, volume, power, cooling, crew time, and logistics information. Inputs vary with the models suggested by Jones, depending on the specific model used. They include the simplistic inputs, such as the mass of electronics and mechanical/structural mass, learning curves, launch dates, labor costs, perceived complexity, mission type, and whether or not the new system is a modification of a previous design (Jones, 2003; SAIC, 2004; NASA, 2004c).

A significant portion of operations costs will be consumed by the provision of reliable and safe systems to the crew. Until highly developed technologies are available, it is challenging to make accurate predictions of the operations costs. It is a currently a fundamental research theme in reliability engineering to attempt to obtain reliability information on technology early in the life cycle of the technology[6]. With the appropriate reliability information for the components of the system, it will be possible to determine what the necessary redundant components may be and the necessary maintenance patterns should be. With this information operations costs can directly be determined. Analogously, reliability information early in DDT&E

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[4] In some respects, perhaps these costs are not so difficult to determine, at least in aggregate form. The annual disbursement of funds to the ALS Program, NASA principal are of DDT&E for ALS missions, is a matter of public record, and can be determined with certainty. In aggregate form, it is most reasonable to spread cost data acquired in this manner equally over the entire ALS Program. LCC analysts should note, however, that such aggregate data would make it difficult to observe the costs and benefits of crosscutting versus highly focused research projects. Greater resolution may eventually be beneficial. This approach would provide costs incurred directly by NASA, which may or may not be the best perspective for the analysis. Such things as institutional taxes are wrapped into these figures and may or may not be interesting from some perspectives.

[5] Research, development, test, and evaluation should be conceptually identical to DDT&E to the reader.

[6] A short introduction to this research is provided in the appendix.

phase of the life cycle can be tremendously useful, and should be stored for future analysis in a platform such as OPIS.

Invariably during an analysis, especially one of such a grand nature as a LCC, some portion of the results may be viewed as suspect. This may be due to several reasons including inadequate input data, weak assumptions, lack of knowledge in a new area, or a rapidly changing environment. Sensitivity analysis considers the extent to which inputs to an analysis can vary without significantly affecting the result. This is often done by selecting the largest contributors to a particular result, as Drysdale did in his 2003 paper. Then the analyst should identify the key input factors that lead to the result and vary them, observing the effect on the overall result. Key input factors can be identified by considering all those that may be expected to vary throughout the project life cycle or those that are determined based on assumptions or data of questionable accuracy. Depending on the structure of the models the various inputs will have differing effects on the results. For example, in ALS, varying the crew size can be expected to have a significant effect on the ESM of a system. Nearly every life support subsystem an ALS System is sized based on the number of crewmembers. It is reasonable to anticipate that the results of an ESM analysis should be especially sensitive to variations in crew size. To properly complete an analysis, LCC or otherwise, a sensitivity analysis should be performed to consider the range of potential outcomes that should be anticipated especially in areas where grand assumptions were utilized.

To enable the analysis of sensitivity ranges anticipated data values are necessary, especially in the early stages of research and development. Such practices are already utilized in the Baseline Values and Assumptions Document, where nominal data values are presented with expected ranges (Hanford, 2002). Other useful information that may be useful for sensitivity analysis describes how the data may vary. What probabilistic distribution best represents the data? What is the standard deviation or variance?

Collection of Necessary Information for Decision Support

A wide array of information describing the ongoing research activity in ALS is being compiled into the OPIS database (Levri, et al., 2003). This information will be input and updated regularly directly by the principal investigators (PI) responsible for the research activity, creating a historical record of ALS activity. The baseline objective of the OPIS database is to make ALS research project information readily available to the members of the ALS Community. In doing so, several other possibilities emerge, including decision support for current researchers, prospective researchers, and the management of the ALS Program. It is proposed that the additional information described above could also be stored in OPIS to improve the analyses described previously.

Decision support that would be beneficial for researchers is similar for both the current and prospective researcher. In each case, the researcher desires a more complete perspective of the state of the knowledge in ALS. With this knowledge, researchers can sculpt ongoing or proposed research to better fulfill the needs of ALS. In this respect, the enhancement of the transfer of information, similar to that currently provided on the World Wide Web, may be sufficient to enable decision support for researchers. Online tools and innovative graphical user interfaces can be made available to PI to expedite input of the information into the database. This is critical as the information to be requested by OPIS will be far-reaching and detailed in nature. In addition, often researchers from the ALS Community are asked to submit short biweekly and quarterly reports to provide regular updates of current activity, as well as yearly and final reports for wrapping-up of research findings over the long term. It has been proposed that the OPIS interface could be utilized to expedite the reporting process by interactively generating reports for the PI's online.

Once such data is stored in OPIS, it can be made searchable to the ALS Community. Dynamic interfaces can be constructed to attractively present the data to the users. It has been proposed to allow PI's to prepare home pages to describe their projects. This will allow some latitude in personalization of how their work is presented to the community. Furthermore, OPIS can become a web portal to the ALS Community, where users not only could personalize how they are viewed by the community, but they can personalize how they view the community. An example of personalized web viewing is the MyYahoo! web page within the Yahoo.com® web portal (Yahoo! Inc., 2004). Users can individually choose the content of the MyYahoo! web page to suit their personal web browsing habits. Therefore, users of OPIS could choose to view any portion of the OPIS database on a regular basis. For example, a wastewater-processing researcher may choose to view news regarding other relevant wastewater processing projects and provide links directly to relevant solid waste processing project home pages. In addition, based on user preferences and user browsing habits it is possible to generate individualized recommendations for areas within OPIS that users may interest the user (Linden, et al., 2003).

With respect to management, the provision of effective decision support will need to go beyond an effective web portal and generation of browsing recommendations, although these could certainly still be provided to management users. The most critical decisions made by management involve the distribution of resources, often in the form of research funding, throughout the ALS Community. Multiple metrics, including LCC, would be beneficial for this process. Not only will management require pertinent project information on a timely basis, but also information regarding how effectively the funds were used would be highly beneficial.

Information that should be stored in OPIS should include the inputs to the various models used at the research project level. Cost data should include predicted costs made by researchers as well as actual costs incurred by NASA. Over time, with such historical data, ALS systems analysts can complete a greater portion of the CBS described above. With data describing a wider perspective of NASA ALS, the uncertainty of predictions can be determined, enabling sensitivity studies.

With this information, it is proposed that several relationships could be generated using the data within OPIS, utilizing a combination of data mining techniques including fuzzy descriptors of quantitative values. The ideal relationships that would be useful for management decision-making include the models for CBS, however we are not limited to these. With data mining techniques, any aspect of the OPIS system could be investigated for useful information (Fayyad, et al., 1996). Potential relationships are described by Eqns. (1), (2), (3), however the character of the actual relationships identified could take any conceivable form.

$$C_\gamma^x = f(\gamma_o, s_1, \ldots, s_m, a_1, \ldots, a_n)\,. \qquad (1)$$

$$T_\gamma^x = f(\gamma_o, s_1 \ldots, s_m, a_1, \ldots, a_n)\,. \qquad (2)$$

$$\Delta ESM_{\gamma}^{x} = f(\gamma_o, s_1, \ldots, s_m, a_1, \ldots, a_n)\,. \qquad (3)$$

C_{γ}^{x} is cost to the ALS Program to improve the technology readiness level (TRL) of technology x to level γ from γ_o, based on the states s_i, which are not necessarily directly related to technology x, and actions a_i. Similarly, T_{γ}^{x} is the time required to improve technology x to TRL level γ from γ_o, based on the same factors. ΔESM_{γ}^{x} represents the change in ESM when TRL is improved to level γ from γ_o.

If the relationships such as those described by Eqns. (1), (2), and (3) could be ascertained, managers would have tremendous tools to utilize during decision making. For example, the expected change in the ALS Metric could be considered prior to investment in a technology, much like Drysdale proposes. Perhaps a relationship can be identified between PI cost estimates and actual expenditures. Relationships would not need to be deterministic in nature; in fact, if a range of values with confidence limits could be provided, managers would have much more information to deal with than they currently do. Consider further, the possibility that research centers or types of research centers, a state variable, could be identified as particularly proficient in a certain type of research or research dealing with technologies of specific TRL. Perhaps, the ALS Program would be most proficient at raising TRL from level 5 to 6, whereas universities are a better investment for TRL's 1 - 4. Certainly, relationships describing time will be hugely beneficial when developing timelines and allocation of resources considering deadlines.

Summary

To maximize the potential for effective decision support within the ALS community, a wider array of metrics could be utilized. Development of a cost breakdown structure may go a long way towards providing the wider perspective of ALS necessary to enable effective decision support. The inputs to the various cost models within the cost breakdown structure describe the additional data that should be collected within the OPIS database. Data should be collected the project level and predicted as well as actual costs should be stored for later correlation. With such an expansive data set data mining may be a way to extract relationships that may otherwise be difficult to ascertain. In the short term, models such as those described by Drysdale and Jones may be utilized to ascertain the costs. In some cases, these models may not provide the resolution desired of a cost breakdown structure and, in some cases, the assumptions of these models are not completely transparent, which will need to be considered in the near future.

Some aspects of life cycle costs still need to be considered. In the past, dollar cost figures have not generally been made available to analysts, as they have been considered private and sensitive information. Furthermore, the cost of getting new ALS technologies approved for flight is extremely high, especially compared to a redesign or retrofitting of an existing flight approved technology. A life cycle perspective is exactly the perspective necessary to enable ALS technologies to prove their worth over existing NASA technology designed for short-term missions, however if cost data continues to be unavailable to analysts, either reasonably proxies will need to be identified or an arrangement needs to be created to share anonymous cost information with analysts.

Another issue related to life cycle costs has not yet been seriously considered, but may offer interesting perspectives for decision makers in ALS or even at the national level. Return on investment can be utilized to justify the potentially large investment for long-term missions to the Moon or Mars. Returns, however, are not always measured in dollar values. National pride, increased interests in space, science, mathematics, and technology are all significant returns, but it is challenging to convert these into returns on the initial investment. Nonetheless, NASA is very interested in returning value to the taxpayer in the form of technology transfer; it has been reported that returns on the Apollo program may have generated a return on investment for the US economy as high as 10 to 1. It should be expected that sustainability technologies for highly constrained scenarios, such as ALS missions, could enter the commercial marketplace. As natural resources on Earth dwindle the value of conservation should increase, making ALS technologies applicable even on Earth, perhaps creating a significant return on investment. Such an analysis would certainly be beneficial to justifying the expenditures on the ALS Program.

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Appendix: Preliminary Reliability Assessment
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Two major obstacles remain for rigorous reliability assessment of ALS systems: (1) the lack of reliability data due to either prohibitive cost or low technology readiness and (2) the lack of a finalized system design perspective of an anticipated ALS system. The reliability analysis proposed here offers the opportunity to develop a preliminary reliability assessment of ALS systems and components and to develop techniques to consider the early phase reliability of a system.

Current reliability analysis procedure does support the ability to develop reliability bounds on a system, even with limited information of the system configuration (Barlow and Proschan, 1974). For example, such analysis can be enhanced with the identification of cut sets and path sets, which can likely be identified. Cut sets are defined as a minimal set of components within a system that if each component within the set is failed, the overall system is ensured failure. Conversely, a path set defines a minimal set of components, which if operational, will ensure that the system will be operational, regardless of the condition of other components outside the pat set. It can be shown that k cuts sets K and s path sets S define the reliability bounds within which the true reliability of the system must lie. Eq. (4) depicts the current reliability bounds available through the use of cut sets and path sets, where $\coprod_{i=1}^{n} p_i$ is known as the *parallel of* p_i and is equal to $1-\prod_{i=1}^{n}(1-p_i)$.

$$\prod_{j=1}^{k}\coprod_{i\in K_j} p_i \le R(\underline{p}) \le \coprod_{j=1}^{s}\prod_{i\in S_j} p_i \qquad (4)$$

With cut and path sets, the opportunity exists to further the existing state of reliability analysis. Can other analytically sound solutions be developed to further reduce the length of the reliability bounds currently obtainable? Perhaps, with some assumptions regarding the system configurations already mentioned above, further information might be garnered. In addition, it may be possible to develop more information by considering multiple states, such as off-nominal operational states, as proposed above with respect to the structure functions.

For example, by coupling the limited data with anecdotal knowledge and perceptions of systems, it may be possible to utilize Bayesian techniques to leverage the sparse data. Bayesian decision analysis is often used in engineering analysis owing to its ability to incorporate human experience and knowledge with scarce experimental data in order to develop better-informed distributions regarding the actual distribution of the process under consideration (Soboyejo, Orisamolu, and Soboyejo, 2001; Soboyejo, et al., 1998; Soboyejo, 2002; Soboyejo, 2001; Sullivan, et al., 2001). Eq. (5) demonstrates the formal statement of Bayes Theorem, where $\Pr(A)=\sum_j \Pr(B_j)\Pr(A|B_j)$.

$$\Pr(B_i|A)=\frac{\Pr(B_i)\Pr(A|B_i)}{\Pr(A)} \qquad (5)$$

In this methodology, prior beliefs are quantified into the Prior Distribution $\Pr(B_i)$ of the random variable. The experimental data is cast in the form of the Likelihood function, which determines the probability of the obtaining the set of experimental data under the assumption of the prior $\Pr(A|B_i)$. The expression results in the evaluation of the posterior (or updated) density $\Pr(B_i|A)$, which can now be used for decision-making.

With the availability of large amounts of data, the posterior density asymptotically resembles the density calculated by frequentist approaches (such as most likely estimation).

The choice of prior density and the experimental setup govern the ease of use of the Bayes Theorem. Several technologies (such as the Entropy method) are available for the derivation of the prior density for the purpose of this study.

In addition, it would be useful to generate information regarding the failure distribution early in the investigation of a new technology. As mentioned above, collaboration has been established with existing wastewater processing and air revitalization research projects in the form of preliminary life testing of components and/or the consideration of existing data and the manner in which it was collected. For instance, is it possible to determine if a subsystem had an increasing or decreasing failure rate during its early experiments? Was its failure rate increasing or decreasing on average? This type of information is useful for reducing the length of reliability bounds. Furthermore, this may be useful for developing system procedures, such as maintenance policies, or perhaps for determining the optimal types of system redundancy.

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