The Effective Use of Metrics in Space Life Support System Trade-Offs

Harry W. Jones[1]
NASA Ames Research Center, Moffett Field, CA, 94035-0001

Engineering metrics are useful in space life support technology selection, but they must be carefully used. Metrics are only part of a complete system trade-off.

Metrics do harm if they cause neglect of other important technical, organizational, or intuitive decision factors. Two metrics have damaged space life support, closure and Equivalent Systems Mass (ESM). Closure measures the fraction of the required system inputs that are produced by recycling system outputs. Increasing closure produces diminishing returns and becomes increasingly expensive. Increasing closure does not directly contribute to providing better life support. ESM measures the total launch mass required to provide life support. ESM includes the mass of the system hardware and of its power, cooling, pressurized volume, spares, and logistics. ESM predicts launch costs, but recently launch costs have been reduced by a factor of 20 or more. System development cost for space hardware is often much greater than launch cost. The past nearly exclusive use of ESM has led to the neglect of Life Cycle Cost (LCC), reliability, cost, and the other engineering factors. Closure and ESM have misguided space life support technology selection for more than twenty years and have adversely affected the expenditure of 100's of millions of dollars.

Metrics can be effectively used three ways in space life support technology selection:

1. **A small set of key engineering metrics for preliminary screening.**
2. **A full set of engineering to guide technical selection.**
3. **Combining engineering metrics with organizational, political, and intuitive decision factors to understand technology selection.**

The past emphasis on closure and ESM served to support recycling life support over resupply and built on the intuitive appeal of a human ecosystem in space.

Nomenclature

ALS = Advanced Life Support
AMCM = Advanced Missions Cost Model
CER = Cost Estimating Relationship
ESM = Equivalent System Mass
FMEA = Failure Modes and Effects Analysis
LCC = Life Cycle Cost
MAUT = Multi-Attribute Utility Theory
MTBF = Mean Time Before Failure
NPV = Net Present Value
Pr(LOC) = Probability of Loss of Crew
SCM = System Complexity Metric
TRL = Technology Readiness Level

I. Introduction

Engineering metrics can be very useful in space life support trade-offs and technology selection, but only if they are correctly developed and used. Depending on how they are selected and implemented, metrics can help organize and support decision making, but they must be part of an open, wide ranging, and deep technical analysis.

Metrics fail if they are used to narrow analysis or are substituted for or cause neglect of other important decision factors. There are two well-known examples of failed metrics in space life support, percent closure and Equivalent Systems Mass (ESM). Closure is an ecosystem parameter, measuring the portion of the required system inputs that are produced by recycling system outputs. Increasing closure produces diminishing returns and becomes increasingly expensive. Increasing closure does not directly contribute to the life support engineering goals of providing life support

---

[1] Systems Engineer, Bioengineering Branch, Mail Stop N239-8.

with sufficient quantity, quality, safety, and economy. Increasing closure seems to be an extraneous goal in itself and can only be achieved at the expense of other goals. ESM measures the total launch mass required to provide some life support function. ESM includes the mass of the system hardware and its power, cooling, climate-controlled volume, and spares and material logistics. ESM is a direct predictor of launch costs, but recently launch costs have been reduced by a factor of 20 or more. System development cost for complex hardware is often much greater than launch cost and operations cost for a multiyear mission are also often much larger than launch cost. And the exclusive use of ESM has caused the neglect of Life Cycle Cost (LCC), reliability, cost, and many other factors. The extraneous goal of closure and the use ESM to exclude all other costs and engineering metrics has misguided space life support trade-offs and technology selection for more than twenty years and adversely affected the expenditure of 100's of millions of dollars.

There are two opposed attitudes about the use of metrics. Most managers and many engineers consider metrics to be useful and even necessary in rational decision making. Some consider the use of metrics to be so fundamentally flawed that metrics are inevitably seriously damaging and should be avoided and resisted to the maximum extent possible.

What would be the effective use of metrics in space life support system trade-offs? The possibilities are:

1. A comprehensive set of metrics that covers all major concerns and provides strong guidance.
2. A limited set of metrics that serves as a preliminary screening check list.
3. No metrics but a process of developing specific requirements and evaluating performance of them.

The developers and advocates of metric based technology selection tools hope and strive for 1, but it is impossible to include all possible aspects of a set of decisions in advance. It seems that new issues continually arise and require modification of the selection tool. Some metrics seem unavoidable, such as Technology Readiness Level. The best approach may be a combination of 2 and 3, which would provide selection support and still allow consideration of all the actual decision drivers. Mistaken assumptions and incomplete requirements are always possible but can be limited by a formal requirements development process such as axiomatic design.

II. Approach

This report will first attempt to develop a comprehensive set of metrics that is intended to provide complete guidance in space life support trade-offs and technology selection. The next topic will be analysis and criticism of metrics. The final area will consider the prevalence of intuition and "gut feel" in most actual decisions.

III. A Comprehensive Set of Metrics

Several past attempts were made to go beyond ESM and establish a comprehensive set of metrics. [1] [2] [3]

A. A hierarchy of overall and contributing metrics

The central goal of life support is "Provide Life Support in Space." The goal of advanced life support (ALS) research is the successful mission use of the developed advanced technology

We can arrange the advanced life support goal and supporting metrics in a top-down hierarchy, as shown in Table 1, ALS Goal and Metrics.

Table 1. ALS metrics hierarchy

Successful mission use of advanced life support technology			
Safety	Availability	Performance	Life Cycle Cost
# of criticality 1R failures Pr(LOC) Hazards temperature pressure toxic substances	TRL	Function quantity quality Other microgravity contamination noise flexibility commonality	Launch cost - ESM mass volume mass power mass heat rejection mass resupply, spares mass Development cost complexity SCM Operations cost "-ilities" maintainability reliability

The second row of Table 1 contains the four system attributes that are required for flight selection leading to the successful mission use of ALS technology. A new ALS technology will be flown if it provides better overall safety, availability, performance, and cost. Weighting these criteria to compare unlike systems may be difficult. Below the supporting goals of safety, availability, performance, and life cycle cost are the factors or metrics that contribute to them. These can be used in the detailed evaluation of alternate systems. The table includes nearly all the selection metrics gathered in a literature search. [1]

Safety is the most important hardware selection determinant. As part of the Failure Modes and Effects Analysis (FMEA), each system and component will have its potential failures defined and the criticalities of the potential failures rated. A FMEA starts bottom-up and defines the failure modes and causes, their expected frequency, and their criticality for each component. The severities of the effects are indicated by standard criticality ratings.

The first three criticality ratings are defined as follows:

Criticality 1: Single failure point that could result in injury or loss of life.

Criticality 2: Single failure point that could result in loss of mission.

Criticality 1R: Redundant hardware items, which if all failed could result in injury or loss of life.

The usual requirement for a manned space system is that there are no potential failures of critically 1 or 2. Operational life support systems may have several potential failures of criticality 1R.

The Probability of Loss of Crew, Pr(LOC), due to a system failure is determined by the system's failure rate. The overall mission is usually assigned a target Pr(LOC), which can be allocated and traded off between mission phases and functions. Pr(LOC) is a stronger and more useful top level metric while FMEA is useful in redundancy design. A preliminary hazard analysis can be conducted as part of the safety check.

The availability of hardware for mission use is usually measured by its Technology Readiness Level (TRL). TRL appears to be the most important single factor in space system hardware selection for several reasons. A technology with a TRL of less than 5 was not considered in ISS technology selection would not usually be considered in system selection. TRL 5 indicates that components were validated in a relevant environment, as in a bench test prototype. The TRLs of good candidate technologies usually increase with time, as further research and development is funded. Since continued investments are directed toward technologies promising better safety, performance, or cost, a high TRL suggests that the other criteria will also be high.

Performance means meeting the functional performance requirements, specifically the product quantity and quality. The other listed components of performance are microgravity sensitivity, contamination potential, noise level, flexibility in use, and commonality of application.

ESM combines the factors contributing to launch mass and cost in a single mass number. ESM includes the mass of the flight hardware, the equivalent masses of the spacecraft power and the pressurized volume the hardware uses, the mass of the heat rejection capacity required, and the mass of resupply and spares. ESM includes mass, **m**, volume, **v**, power, **p**, cooling, **c**, and logistics, **l**. More precisely ESM is equal to the sum of the system mass, **m**, the equivalent mass of the required volume, ESM(**v**), the equivalent mass of the required power supply, ESM(**p**), the equivalent mass of the required cooling system, ESM(**c**), and the mass (M) of the materials and spares logistics, M(**l**).

$$\mathrm{ESM(system)} = \mathbf{m} + \mathrm{EM}(\mathbf{v}) + \mathrm{EM}(\mathbf{p}) + \mathrm{EM}(\mathbf{c}) + \mathrm{M}(\mathbf{l}) \qquad (1)$$

Development cost is usually estimated using parametric cost models based on cost estimating relationships (CERs) relate development cost to a system's quantitative characteristics. The most common cost determining parameters are the system dry mass and the number to be produced.

Johnson Space Center developed the AMCM (Advanced Missions Cost Model) to improve on models based only on mass. The AMCM is appropriate early in conceptual design where little detailed data is available. The model is a single CER using mass, quantity, mission type, number of design generations, and technical difficulty to estimate the total system cost for design, development, test, and production.

The AMCM formula for the cost of DDT&E and production in millions of 1999 dollars is:

$$\mathrm{Cost} = 2.82\ Q^{0.59}\ M^{0.66}\ 80.6^{T}\ G^{-0.36}\ 1.57^{D} \qquad (2)$$

Q is the total quantity of development and production units, M is the system dry mass in kilograms, T calibrates for the type of mission (2.14 for human habitat, 2.4 for crewed planetary), G is the hardware generation (1 for new design, 2 for second generation), and D is the estimated difficulty (0 for average, 2 for very difficult, and -2 for very easy). [4]

Difficulty and design cost increase with complexity, which is related to the total number of subsystems and subsystem interfaces. Complexity is a whole system property that can increase as the square of the number of components or connections, rather than linearly. Higher system complexity increases design effort and is associated with more difficult maintenance and repair. A new System Complexity Metric (SCM) predicts design cost and failure rates.

The SCM is defined to be the sum of the number of nodes, N, in the system block diagram plus the number of one-way interactions, I, between the nodes. SCM = N + I. SCMs are easily determined by direct inspection of high level block diagrams of life support systems. System cost can be expected to increase directly with SCM. The system MTBF (Mean Time Before Failure) is the inverse of the system failure rate. MTBF = 1/f. The system MTBF can be expected to increase as SCM decreases. Since the system SCM can be determined by direct inspection of the system block diagram, it is not expected to be subject to adjustment or dispute. SCM can provide an early ranking of preliminary systems designs. [5]

Operations cost includes the material and spares, ground systems, mission control and planning, data analysis, and crew training. Space operations costs can be estimated as a percentage of the system development cost. The Johnson Space Center estimated the yearly operations cost for manned spacecraft as 10.9% of the total design, development, and production cost. [6]

B. Use of the metrics in technology selection

The ALS metrics hierarchy in Table 1 can be tailored to the particular application and used as a checklist. Each quantitative metric can be measured, computed, or estimated. Each qualitative metric can be described for each candidate technology and the technologies can be compared and perhaps scored. Following this checklist process should provide useful support for technology selection.

There are two common but unsatisfactory ways to use the metrics. The first is to use only one single decision factor. Advanced life support research has long used ESM nearly exclusively. ESM is the major factor determining launch cost but using only ESM in technology selection is assumes that all other metrics other details can be ignored.

The second unsatisfactory approach is to screen candidates using the criteria in order of importance. This is called “elimination by aspects.” The space station technology selection process first eliminated technologies having low Technology Readiness Level (TRL). Then prototypes were developed to the same prototype TRL and used to evaluate performance, safety, and cost factors. Using the most important factor first, with a hard cutoff, might eliminate a technology that is far superior in other aspects. Considering only technologies with high TRL makes it difficult to choose innovative systems.

Using only one of the criteria, or screening using the criteria one by one, is less likely to produce the best result than comparing all alternatives using all criteria. One method that scores, weighs, and combines all of the metrics is multiple criteria decision making, sometimes called Multi-Attribute Utility Theory (MAUT). Technologies can be compared by overall score, by aggregate scores on safety, TRL, performance, and ESM or LCC, and by individual metric scores.

The radar and difference charts illustrate multiple decision criteria and facilitate multicriteria decision making. [3] Both the radar and difference charts help develop and communicate technology comparison insights. The radar chart shows the trade space that the alternatives occupy. Every alternative is shown by one polygon on the radar chart. The set of polygons gives an overview of all the alternatives and their relative strengths and weaknesses. The points plotted on each axis define the range of scores for that particular factor. Connecting the outer-most neighboring points by straight lines determines an outer performance boundary, the set of the best values for all the criteria.

Figures 1 and 2 show the radar and difference charts for two carbon dioxide removal technologies, 4BMS and revised 2BMS. [3] The four metrics are shown with equally sized axes, corresponding to equal weighting.

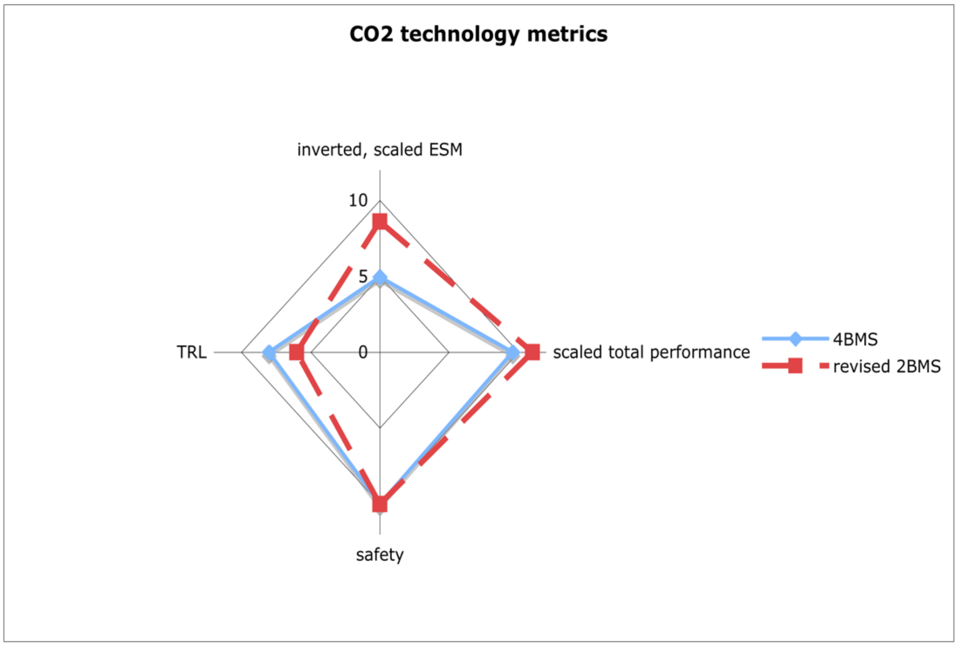

Figure 1. 4BMS and revised 2BMS carbon dioxide removal technology metrics. [3]

Figure 1 shows the TRL, safety, and scaled total performance metrics for the 4BMS and for the revised 2BMS. Higher TRL, safety, and performance are desirable, but higher ESM is not. The ESM is inverted and scaled to provide a positive metric. Except for TRL, the 4BMS now on ISS has lesser or equal metrics than the revised 2BMS.

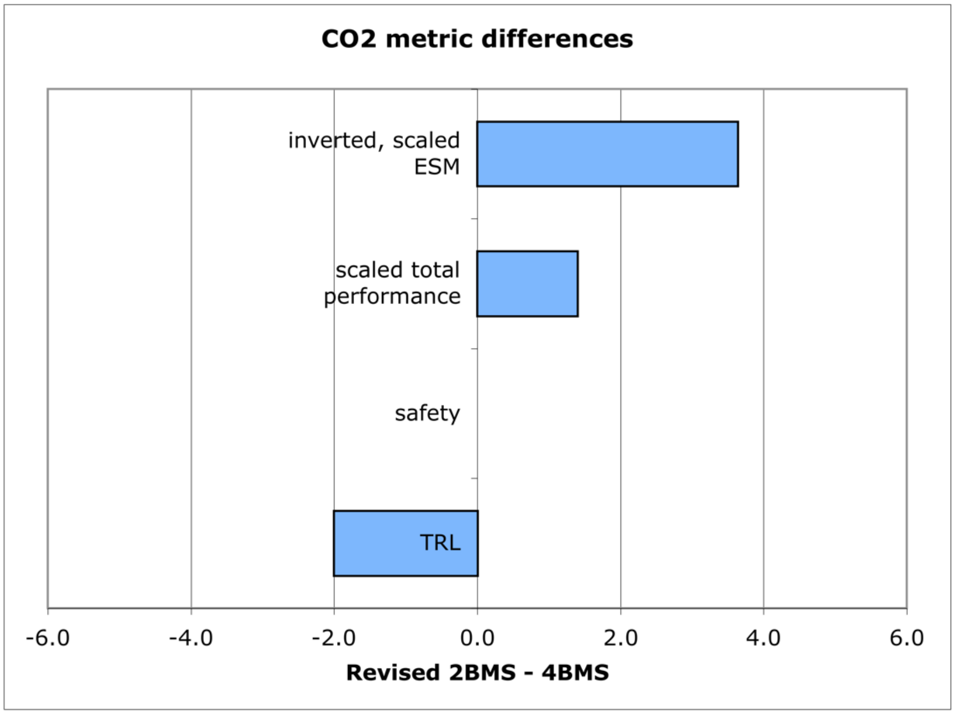

Figure 2. Difference in carbon dioxide removal metrics, revised 2BMS minus 4BMS. [3]

The difference chart of Figure 2 shows the revised 2BMS metric values minus the 4BMS values. It makes clear that the revised 2BMS has much better ESM and total performance than the 4BMS, with equal safety but lower TRL.

The process of using multiple criteria in decision analysis can be made ineffective by several errors. Common decision analysis problems include:

1. Missing criteria
2. Missing data
3. Dependent or correlated criteria
4. Different criteria used for different alternatives
5. Predetermined or biased decisions
6. Undocumented rationales for criteria, weighting, scoring, and selection

IV. Applying Metrics

The use of metrics for technology and research project selection has had a complex history.

A. Mathematical versus intuitive methods

The early technology portfolio selection models developed before 1980 were designed to maximize composite objective functions using mathematical techniques such as linear programming or multiattribute decision analysis. Multiple criteria that require intelligent trade-offs were combined in rigid formulas. These early methods were difficult to understand and required experts to implement. Most organizations that used such models relied more on intuition and engineering common sense. The reason is that human insight, intuition, and "gut feel," rather than reason, are more persuasive than poorly understood theories. [7]

In the later 1900's ranking and selection used simpler and more intuitive methods, such as peer review, scoring using criteria, and consideration of strategic balance. These are user-friendly and acceptable for existing groups within organizations rather than for single decision makers. But simple methods are less impressive. The transparency of simple methods stimulates challenges their results. The early hope that projects can be selected could be done by formal objective mathematical methods has been replaced by acceptance of an inevitable subjective group process.

Unfortunately, human intuition is not infallible. Humans tend to be overconfident, to underestimate uncertainty, to be excessively risk adverse, to ignore sunk costs due to loss aversion, to select alternatives using only the most salient differences, to select data to confirm past decisions, and to be influenced by irrelevant, perhaps unconscious motives. Some studies have shown that human decision errors and biases can result in such poor project decisions that random project selection is better. The potential problems of the inevitable intuitive approach indicate a need to also use more objective ranking and selection methods.

B. There are no proven good methods

The main reason for the limited use of formal project selection methods is simple. Despite the plausibility of the mathematical project selection methods, there are no proven and generally accepted methods. There is simply no reliable data or empirical evidence establish a formal rational approach to technology selection. No one has shown that formal selection techniques actually improve decisions. This justifies management keeping personal responsibility for project selection. Many believe that personal expertise and inspiration rather than systematic research are responsible for technical advance.

The problems using formal project selection methods include resistance to the process as well as lack if proof that any method works, and the frequent management override based on "gut feel."

The unselected are strongly motivated to find fault with the selection method and seek exemptions for their own projects. Highly successful research are exceptional and seem each to succeed in its own way, which makes it difficult to identify shared success criteria. The metrics of Table 1 seem more a list of problems to be avoided that predictors of success. It is certainly possible that, even after the list of project selection metrics has been considered, engineering judgment and management intuition could still be a better guide. If management does override formal selection results based on "gut feel," they are seen as being done merely for show.

Because of the difficulties using formal project selection, researchers have spent less effort in developing them and more in how the process is actually performed and effect it has. The project selection process is seen as a way to coordinate and strengthen an organization, as a way to enhance communication and create an atmosphere of fairness and cooperation.

Regardless of the difficulties in developing and applying a project selection methodology, There seems to be no alternative. Research and technology development projects are absolutely necessary. Some project selection process must be used. Scientists, engineers, and technical managers are not likely to abandon the belief that careful, analytical project selection will produce more successful projects. Funders and customers expect due diligence and a serious approach to project selection. Awareness of the difficulties may help avoid some typical errors and bad project selection rules and give better project selection results. Using accepted logical methods helps to gain the organizational benefits of rational legitimacy and open communication.

Many users of project selection methods do achieve positive effects and are well satisfied with their methods. The way that project selection methods are established and operated affects their acceptance. Process legitimacy can be bolstered by an open and honest attempt to make the best decisions using reasonable, acceptable methods. Satisfied users typically apply a balanced combination of methods.

C. Satisfactory project selection methods

A survey of US technology research organizations concluded that the organizations that were satisfied with their project selection used an open formal process that was applied to all projects at the same time. [7] These businesses used multiple explicit formal portfolio selection methods that were supported by senior management and were consistently applied to all projects simultaneously using well-defined rules and procedures. Satisfactory project portfolios had high value, were well aligned with strategy, and were well balanced between long and short term, high and low risk, and across applications and technologies. The more popular project selection methods were Net Present Value (NPV) (used by 77%), resource allocation by strategic goals (65%), scoring (38%), checklists (21%), and scatter diagrams (41%). All the businesses used more than one project selection method and the probabilities add to 242%, so 2.4 is the average number of methods used. This survey considered organizations' self-reported satisfaction with their project selection methods and with the resulting selected group of projects. It did not attempt to ascertain if the selected projects were actually any better than those that might have been selected by other methods or randomly. [7]

D. Nontechnical "gut feel" organizational success factors

Some organizational factors strongly affect the success probability of research projects, even though they are not strictly technical. These include:

1. High level management support
2. Perceived high probability of success/low risk of failure
3. Favorable market and competitive environment/high relevance and need
4. Affordability
5. Strong organizational expertise, technology, and marketing
6. Good research planning
7. Good proposed personnel and leadership
8. Fit with current products and projects

These nontechnical organizational success factors do not appear in the Table 1 criteria or other formal selection methods, but they probably strongly influence management "gut feel." Risk and uncertainty are rarely discussed, let alone analyzed, but they are often strongly intuited and decisive.

V. Past misuse of metrics in space life support

The fundamental problem with the past use of metrics in space life support has been the use of a single metric that reflects only one of many important project selection factors. In two cases the metric is no longer relevant or never was relevant to the purpose of providing life support.

The three metrics that have been used in space life support are system closure, Equivalent System Mass (ESM), and Technology Readiness Level (TRL). These metrics have been used at different times to justify life support research projects or select technology. Increased closure, lower ESM, and higher TRL all suggest better life support, but improving one of them will usually not improve the others or lead to overall better life support. Increasing closure tends to increase ESM rather than reduce it. Decreasing ESM may incur excessive development cost or performance penalties. Requiring higher TRL technology could lead to the use of older less capable systems and detract from improving closure or ESM.

A. Closure

The system closure metric for life support is the percentage of all life support material - oxygen, water, food, and other supplies for the crew - that is provided by recycling rather than supplied from Earth. The early goal of life support R&D was to approach a totally closed human ecosystem, independent from Earth. Closure is an important concept in ecosystem theory and artificial ecosystem design. At the time that the space station was being developed, the future life support system for the Moon and Mars was expected to include food production, waste recycling, and ultimately to be totally closed except for leakage.

Increasing the closure of space life support makes human space exploration more independent from Earth and reduces the expense of launching life support materials to sustain the crew. However, increasing closure is subject to diminishing returns and exponentially increasing costs. The most abundant and easiest to treat wastes, such as condensed atmosphere water or hygiene water, are treated first. Methane produced from exhaled carbon dioxide or human solid waste both are more difficult to recycle and are a much smaller part of the total ecosystem material circulation. Growing food is obviously needed for full closure but requires a large greenhouse, power for lights, and massive supporting equipment. Achieving high levels of material closure is theoretically appealing but is not cost effective.

B. Equivalent System Mass (ESM)

Equivalent System Mass (ESM) was previously defined as the total launch mass needed to provide and support a system. There are four serious and fundamental problems with the ESM metric. First, ESM reflects only launch cost, giving a partial and biased view of life support cost. Second, ESM comparisons made for technology selection are unreliable and can be distorted, as has happened in ESM reporting. Third, reducing ESM has guided life support R&D in a direction away from solving more urgent problems. Fourth, the use of the flawed ESM metric instead of multiple metrics or a systems engineering approach gives an unfortunate impression of misguided management.

C. Technology Readiness Level (TRL)

Technology Readiness Level (TRL) was previously discussed. It reflects the stages in technology development from proof-of-concept through prototype to flight. A good candidate technology will have its TRL increase as continuing investments are made. The space station technology selection process first eliminated all but the highest TRL technologies, which is appropriate for a flight mission. Selecting the highest TRL technologies is not appropriate in selecting research projects. Low TRL alternates may be rejected prematurely. Changed missions and requirements often require new approaches.

The government technology development process modeled by advancing TRL has a fundamental problem. Development should satisfy the customer, but government research splits the customer in two, the actual current funding program and the hypothetical future mission user. Government research programs develop technology to be used later by potential future missions. The research effort develops early prototypes but does not flight qualify systems. Yet missions do not want to use technology that is not flight qualified. This causes the technology transfer problem, the mid-TRL gap. Because the user is not involved, the user-needed technology is not developed. The operative research program goal is to fund current projects, not to provide systems for future missions.

The objective of space life support research should be the development and demonstration of high TRL flight qualified systems that are superior to the current space station systems. It seems that bad metrics, a distorted selection process, and unsuitable research projects are the result, the symptom and not the cause, of a technology development process that has gotten off track because of lack of user input.

D. Metrics issues

Experience in life support confirms that metrics can be corrupted and work misdirected. Closure and ESM have been manipulated and, because they do not measure the true objectives, have misguided research. TRL has usefully helped guide space station technology selection, but conducting research to advance TRL can neglect user input and commitment.

Why were these metrics used? A metric provides a formal, predictable, and controllable decision process. A metric is simpler, requires less data, and is easier to compute than a full trade-off study. The objective of analysis is often to support a known decision, and in this case a fudgeable metric is sufficient.

The fact that life support research has had the wrong goals apparently explains why it has not emphasized developing the systems actually needed for future missions. But this obvious logic is wrong, backwards. In the theoretical systems engineering approach, the goals are set and then projects selected. In practice the projects come first. Researchers have technologies they want to develop and managers a need to expand programs. The metrics are adopted to help advocate the projects. The misuse of metrics is a symptom rather than the cause of misguided research. The life support metrics support internally inspired technology driven projects. The objective should be to develop systems to meet external, higher level, long-term mission objectives.

Life support research has advocated the wrong goals, increasing closure or reducing ESM, rather than providing the higher reliability more operable hardware that mission designers would prefer. Using single partial metrics to manage is a mistake. The better way to manage research is to use multiple metrics or even the full systems engineering process to develop systems that meet user needs.

VI. NASA is both a rational and a natural organization

The problem of selecting technology programs has been studied for decades without resolution. The rational methods for selecting projects are convincing but not widely used and not found to be effective. Technology development has been largely determined by natural human self-interest and often with questionable results.

Organizations are both rational and natural systems. NASA's technology development should account for and make the best of both. The rational accepted goal of NASA's research programs is developing, selecting, and completing projects to produce useful new technology. The natural human goals of self -interest and organizational growth should be aligned to support the rational goal.

Successful developing advanced technology development requires two things. First, the goal of producing genuinely new technology must be strongly established and maintained over the long term. This is difficult because research is costly, its results are uncertain, and new technology may benefit rivals and even damage the developer organization and its members. Because of these risks, commercial companies tend to focus on incremental improvements of existing products. Major advances often depend on government agencies, universities, and government funding. Second, an effective research organization must align natural goals with the overall rational goal. This is difficult because there is no clearly effective research management methodology and because urgent personal and organizational needs easily divert funding. People and the organization should be able to meet their own natural goals only by serving the rational goal of meeting the customer's needs.

A. Organizations are systems

Modern organization theory describes organizations as rational and natural systems. Not either or, but both all the time. [8] The traditional concept of an organization as a well-designed rational machine operating independently and efficiently is attractive but unrealistic.

Early students of bureaucracies and corporations considered organizations as instruments that could be rationally designed to accomplish their assigned goals. The organization was to carry out a planned set of processes. It was assumed that the environment was stable and the organization could control events.

Sociologists viewed organizations as natural human systems. Like villages, tribes, and nations, organizations are organic systems, collectives that somehow evolved in spontaneous, indeterminate, evolutionary processes. An organization can be thought of as an artificial life form, with its own survival as its overriding goal. Political and economic power operate in real time to set the actual organizational goals. [8]

NASA is a <u>rational structure</u> intended to perform a function

NASA is a <u>natural human system</u> of people in groups

The rational/natural aspects are different points of view or "frames" that provide useful alternate backgrounds for interpreting a single complex organizational reality.

B. NASA is a rational structure and a natural human system

The visible, public, accepted NASA is a rational structure. The organization charts, budgets, reporting systems, project plans, and standard management procedures of NASA define its rational structure. Knowing and working within this structure is essential.

In any organization, the fundamental barrier to achieving a shared rationality is the inevitable conflict over goals. Funding must be divided between near term applied research and higher risk advanced development. These conflicting goals cannot be easily balanced and reconciled.

An organization is a natural organic system, a group collective that seems to have a life and goals of its own. An organization naturally attempts to grow and expand while coping with competitors. It evolves spontaneously, often changing its original mission. Organizational survival is the overriding goal, sometimes the only goal.

New inventions, research, new ideas, even mere hints of better approaches are all serious challenges to an on-going activity. Organizations rarely innovate. Most large organizations are implacable enemies of the future, which inevitably brings their decline and fall. New technologies nearly always emerge from small start-ups, organizations that are deliberately designed to produce innovations sometimes intended to disrupt the status quo.

The rational structure view is more simple, logical, and appealing than the natural human system perspective. A rational design creates distinct subsystems, well-defined hierarchical layers, and clear interfaces. Evolved natural organic systems are less easily separable into distinct layers and subsystems, since they have more complex interconnections and interactions. As adjacent layers in an evolved natural system, people and groups cannot be clearly separated. Each higher level of organization has new emergent properties. The whole is more than the sum of its parts.

The rational structure view and the natural human system perspective are two different pictures of a single reality. Both are true, and both are necessary for understanding. Their seeming conflict is resolved only by accepting both.

Consider Einstein's statement, "Everything should be made as simple as possible, but no simpler." Einstein received the Noble prize for establishing the wave-particle duality of photons. The wave theory of light explained most observed phenomena and was widely accepted, but it could not account for the photoelectric effect. Einstein showed the photoelectric effect was explained by the particle theory of light. Light photons are not either waves or particles, but both wave-like and particle-like, depending on what is observed. Similarly, the organization and the people in it cannot be separated. Both the rational and natural human systems approaches are needed to fully understand an organization.

C. Problems of natural human project selection

What is the natural, human project selection process? Some ideas can be gained from the observed problems of natural project selection:

1. Decisions are political.
2. Decisions are strongly influenced by the top management.
3. Decisions are based on personality and organization.
4. Decisions are perceived to have been made in advance.
5. Decisions are thought to be made unfairly and dishonestly.
6. Decisions are based on ad hoc "gut feeling."
7. Decisions are influenced by departmental loyalties, conflicts in goals, and differences in perspectives.
8. Decisions are hampered by an unwillingness to openly share information.

Politics, lack of trust, conflict, and concealment are symptoms of individual self-interest and competition between groups. What is the usual result of the natural, human political project selection process? Individuals and groups try to and usually succeed in preserving their current projects.

One purpose of rational project selection is to try to limit the natural, human project selection process. A formal, fair project selection system can define goals, stimulate innovative ideas, focus attention on key issues, stimulate open communication, establish consensus, and gain support for the selected projects. Since a good project selection system looks fair and reasonable, it can help prevent the damage caused by excessive politics.

D. Sunk cost errors

The most common natural human mistake in project management is to continue to fund obvious failures Sometimes managers reduce the funding of successful projects to increase that of failing projects. All past costs are called sunk costs. Rational economic decisions ignore sunk costs. The amount of money already spent on a project should not affect the decision to spend more. But cancelling a project seems to suggest that the money spent has been wasted. People do not like to admit following the wrong path.

E. Goal conflicts

The sunk cost, politics, and other problems can be considered as irrationalities found in natural human organizations. But citing human irrationality condemns people for not conforming to theory. In fact, the rational organization model is partial and incomplete. It assumes that common goals can be agreed on and that a rational process can be developed to achieve them. This fails because goal conflicts inevitably motivate power politics.

Goal conflicts are the cause of organizational politics. Political action takes place for reasons of self-interest. Looked at practically, politics is the necessary process used to resolve goal conflicts. Decisions must be made somehow when facts, reason, and compromise fail.

Bolman and Deal define the political framework of organizations:

1. Organizations are <u>coalitions</u> of diverse interest groups and individuals,
2. They have <u>different goals</u> and beliefs,
3. The important <u>decisions allocate scarce resources,</u>
4. Scarce resources and different goals cause <u>conflict,</u>
5. Goals and decisions emerge from <u>bargaining and struggle</u> for resources. [9]

VII. The cases for and against depending on intuition

Many decisions are made by intuition, or "gut feel." Intuition can sometimes help to improve decisions but should not be trusted without examination.

A. Two kinds of decision making, rational and intuitive

The human mind apparently has two parallel and complementary decision making systems, designed for different kinds of problems. Kahneman in “Thinking fast and slow,” defined these as System 1 and System 2. System 1 is associative, holistic, subconscious, automatic, easy, and fast. It is used for quick response in familiar situations and includes the common decision biases and heuristics. It is usually considered partly innate or hard wired, primitive, and inferior to System 2. System 2 is analytic, controlled, conscious, logical, difficult, and slow. It is used to consider complex social and technical problems and often uses mathematics, logic, and science. It is learned through culture and formal teaching and is expected to be revised based on reason and evidence. [10]

It has been usual to prefer and advocate the use of System 1 in management and technical problems, but recently intuition has become more favored. In addition to quick judgments in simple situations, such as same or different, gain or loss, friend or foe, intuition also includes pattern recognition and reaction to learned complex patterns, such as chess positions or common social situations. People learn to recognize complex situations unconsciously and can develop strong emotionally felt reactions to them that they cannot readily explain. A person who has dealt effectively with similar situations for many years will develop a subject area expertise and trained judgment that can produce highly effective decisions. Strong respected top managers often lead successfully simply by following their gut.

B. Support for using intuition

Intuition is a judgment that comes to mind with a feeling of rightness, but without clear reasons or justifications. We know what to do but can’t explain why it’s right or how we determined it. Intuition should be checked against reality, hard facts, and logical inference. Correct intuition and sound rational analysis should give the same answer and are best thought of as two parallel systems of knowing, System 1 and System 2. When intuition and reason disagree, it is often because intuition reflects subconscious factors not accessible to reason, suggesting that rational analysis is limited. The strong conviction produced by intuition explain why it often dominates and distorts rational thinking. [11]

Insight provides a person with a self-convincing solution to a problem. The solution often comes suddenly and unexpectedly after a period of uncertainty and worry. Insight seems to require an incubation period that enables non-conscious processes to operate freely without rational analysis. Scientific insights may occur at a “eureka” moment. [11] Insight allows managers to sense when a problem exists, quickly find a plausible solution without analysis, and check the results of rational analysis. The result of a complex rational analysis is usually accepted only if its results agree with intuition.

C. Problems using intuition

Kahneman’s system 1 fast thinking jumps to an intuitive conclusion using some heuristic, a mental shortcut or instinctive rule-of-thumb that solves problems quickly without taking time to think. Fast thinking produces systematic common and repeatable errors because it relies on generally useful heuristics that are built into the human brain. The heuristics described by Kahneman include anchoring, attribute substitution, availability, framing, loss aversion, overconfidence, and the sunk cost fallacy, all of which strongly bias decision making.

Avoiding rational analysis could be motivated by one heuristic of intuitive thinking, specifically overconfidence. Three other human heuristics that particularly affect project selection are loss aversion, myopia, and inside view overconfidence. Loss aversion refers to the fact that losses are felt much more strongly than gains of the same objective value. People will risk gambling gains, “house money,” more readily than their own money. Myopia refers to valuing near term gains much higher than long term gains. People often prefer taking \$100 now to \$120 in a year, implying that their required interest rate is more than 20%. Inside view overconfidence refers to the fact that people consider their own chance of success in their own projects much higher than the statistical average. These heuristics are not economically rational.

D. Intuitive judgment should be combined with rational analysis

Intuitions are emotionally charged judgments based on rapid, nonconscious, and holistic associations. When people make intuitive judgments, they often experience strong and positive emotions such as excitement and awareness that produce strong confidence in the decision. [12]

Intuition can be effective for certain types of tasks where the decision maker has appropriate domain knowledge. Intuition seems appropriate for unstructured management decisions, which involve strategy, commitment, and leadership. Complex problems such as political and ethical judgments call for intuition because there are no well accepted System 2 decision rules for dealing with them. System 2 is effective when there are clear objective criteria of success within some well-defined and self-contained conceptual system. [12]

Management intuition should be listened to but not accepted without confirming rational analysis. Considering the prevalence of flawed heuristics and hidden agendas, management judgment should be treated as a plausible suggestion to be evaluated. Intuitive judgment should be checked with formal analytical tools such as multi-attribute decision analysis. [11] It is important to recognize the strength and prevalence of intuitive decision methods, but it is necessary to check them with alternate rational analysis.

Advocates of intuitive decision making often assume intuition will be used together with rational analysis. Some suggest that intuition should be recorded first, followed by an analytical assessment. Others prefer doing rational analysis first, and then allowing time for subconscious processing to produce a gut reaction. Combining intuition and rationality "is the ultimate skill in today's organizations." [12]

VIII. Conclusion

Many different approaches to project selection are used, but the main categories are computing technical metrics, considering organizational factors, and relying on intuition. Although some technical project selection methods are widely used, none of them are clearly effective. Even organizations that use these methods depend more on intuition and common sense. Yet intuition is flawed. People tend to be overconfident, to underestimate uncertainty, to be risk adverse, to not ignore sunk costs, to consider only the more obvious factors, to ignore data that conflicts with assumptions, and to be overly influenced by personal and even subconscious motives. Human decision errors and biases can result in poor project decisions.

The best approach to technology seems to be to explicitly include and try to balance the three basically unavoidable approaches: computed technical metrics, acknowledged organizational factors, and the results of intuition. The life support metrics are given in Table 1 and some organizational success factors listed in Section IV. It is important to openly consider the acknowledged organizational factors rather than have them disappear into intuitive "gut feel." Understanding a particular intuition may be too difficult.

"Gut feel" and judgment can seem obviously influenced by self-interest and politics, but this can occur without the conscious awareness of the intuitive person. Improper decision rules and unrecognized biases can similarly affect judgement while remaining subconscious. Probing management intuition will be difficult to do openly. External analysis of hidden or possibly disreputable motives would not be well accepted. Open general discussion of possible biases may help.

It seems that making project selections requires one responsible decider, and that even if the decider deigns to explain the decisions, the explanation does not have to satisfy the interested parties. Unless the process is convincingly fair and credible, people will continue to believe that the hidden agenda is always the largest factor in any trade-off for technology section.

References

---

[1] Jones, H., "Multiple Metrics for Advanced Life Support," SAE 1999-01-2079, 29th International Conference on Environmental Systems.

[2] Jones, J Jones, H. (2005) "Project Selection for NASA's R&D Programs" 35th International Conference on Environmental Systems, SAE 2005-01-2916.

[3] Jones, Jones, H., (2010) "Using radar charts to select life support technology," International Conference on Environmental Systems, AIAA-2010-6015.

[4] Guerra, L., and R. Shishko, "Estimating the Cost of Crewed Space Systems," in W. J. Larson, and L. K. Pranke, eds., *Human Spaceflight: Mission Analysis and Design,* McGraw-Hill, New York, 2000.

[5] Jones, H., "The System Complexity Metric (SCM) Predicts System Costs and Failure Rates," ICES 2020-223, International Conference on Environmental Systems, ICES 2020.

[6] Jones, H. W., "Equivalent Mass versus Life Cycle Cost for Life Support Technology Selection," 2003-01-2635, 33rd ICES (International Conference on Environmental Systems), 2003.

[7] Cooper, R. G., Edgett. S. J., and Kleinschmidt, E. J., "Portfolio management for new product development: results of an industry practices study," R&D Management (Industrial Research Institute, Inc.) Volume 31, number 4, 2001.

[8] Scott, W. R., *Organizations: Rational, Natural, and Open Systems*, Prentice Hall, Upper Saddle River, New Jersey, 2002.

[9] Bolman, L. G., and Deal, T. E., *Reframing Organizations: Artistry, Choice, and Leadership*, Wiley, San Francisco, 2003.

[10] Kahneman, D., *Thinking, Fast and Slow*, Farrar, Straus, and Giroux, New York, 2011.

[11] Hodgkinson, G. P., Sadler-Smith, E., Burke, L. A., Claxton, G., and Sparrow, P. R., "Intuition in Organizations: Implications for Strategic Management," Long Range Planning 42, 2009, pp. 277-297.

[12] Dane, E., and Pratt, M. G., "Exploring Intuition and Its Role in Managerial Decision Making," Academy of Management Review, Vol. 32, No. 1, 33–54, 2007.