Spacecraft Complexity Subfactors and Implications on Future Cost Growth

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Abstract - **During the last ten years the Jet Propulsion Laboratory has used a set of cost-risk subfactors to independently estimate the magnitude of development risks that may not be covered in the high level cost models employed during early concept development. Within the last several years the Laboratory has also developed a scale of Concept Maturity Levels with associated criteria to quantitatively assess a concept's maturity. This latter effort has been helpful in determining whether a concept is mature enough for accurate costing but it does not provide any quantitative estimate of cost risk. Unfortunately today's missions are significantly more complex than when the original cost-risk subfactors were first formulated. Risks associated with complex missions are not being adequately evaluated and future cost growth is being underestimated. The risk subfactor process needed to be updated.**

This paper updates the cost-risk subfactors to make them more appropriate for complex systems and integrates them with Concept Maturity Levels in order to provide quantitative estimates of cost risk. The eventual goal is to be able to identify cost risks early enough in the project lifecycle to be "engineered" out of the design.

The approach works over a range of concept complexities ranging from Flagship missions to simple Earth orbiters. A complex system is defined as one containing multiple technical and programmatic elements and interfaces that interact with varying, difficult- to- characterize outcomes. Thirty-three complexity factors are defined in such a way that they can be easily evaluated early in concept development and used in combination with estimated maturity to predict future cost growth. They are grouped into four categories: (1) project technical design complexity, (2) project programmatic complexity, (3) lack of resiliency, and (4) new design challenge.

The data is based on interviews with Project Managers and system engineers on seven recent flight projects. Results indicate that the major factors contributing to a project's complexity can be identified early enough to be useful in reducing development risk. This paper describes the thirty-three complexity factors, how they can be evaluated, and how they can be combined with Concept Maturity Levels to predict future cost growth.

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1. INTRODUCTION

Cost overruns continue to be a major problem within the aerospace industry. One of the primary causes is that it is extremely difficult to accurately estimate costs and assess technical risks during early concept development when there is insufficient knowledge of the system to use traditional estimation tools. Many science commitments and engineering assumptions which will have a major impact on future costs are made during this early stage.

The Jet Propulsion Laboratory (JPL) uses cost- risk subfactors developed ten years ago to validate more conventional model-based and grass-roots cost estimates but these are difficult to use early in the project life cycle and miss many of the cost drivers now embedded in our more complex systems. Several years ago a scale of Concept Maturity Levels, referred to as CMLs [1]–[3], were defined by JPL to characterize concept maturity and to enable identification of areas requiring better definition before costing. The question being addressed was whether the proposed concept was a vague idea sketched on a cocktail napkin or was it backed up with a well thought out and costed architectural design (Figure 1). A set of maturity criteria were defined across twenty-three technical and programmatic categories such as requirements definition, mission design, spacecraft design, risk posture, cost and schedule. The defined criteria become increasingly rigorous at higher levels on the CML scale. Pre-project teams now routinely use the criteria to assess concept maturity prior to initiating proposals and major reviews. A simplified CML scale is presented in Figure 2 and a notional diagram describing how a mission concept evolves as a function of CMLs is illustrated in Figure 3.

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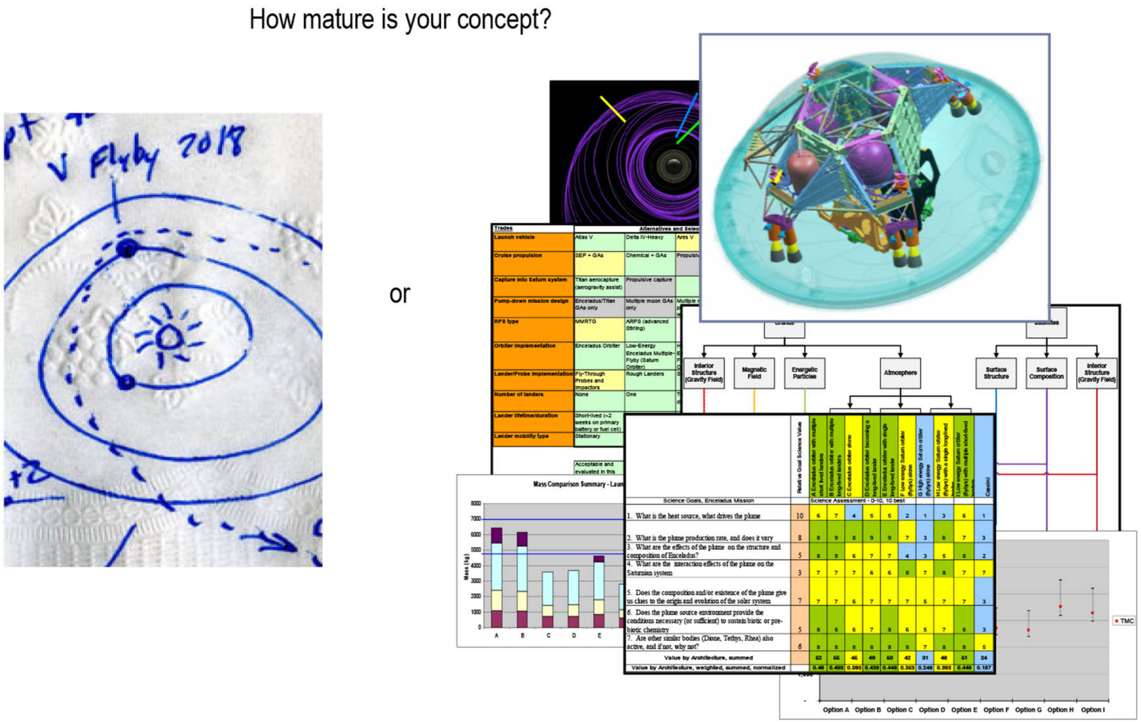

Figure 1. CML assessments can allow an independent observer to determine the level of analysis invested in a mission concept. [3]

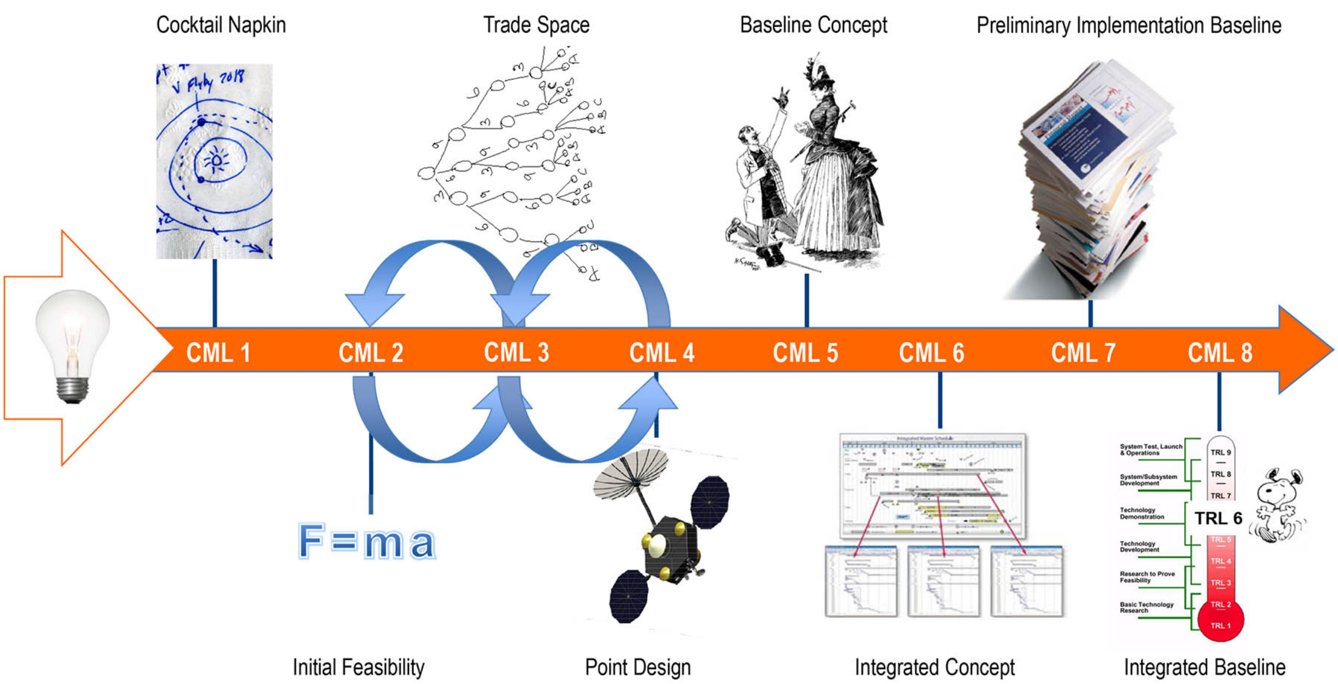

Figure 2. The CML Scale includes loops between Initial Feasibility, Trade Space and Point Design CML Levels reflecting the iterative nature required to mature a mission concept. [3]

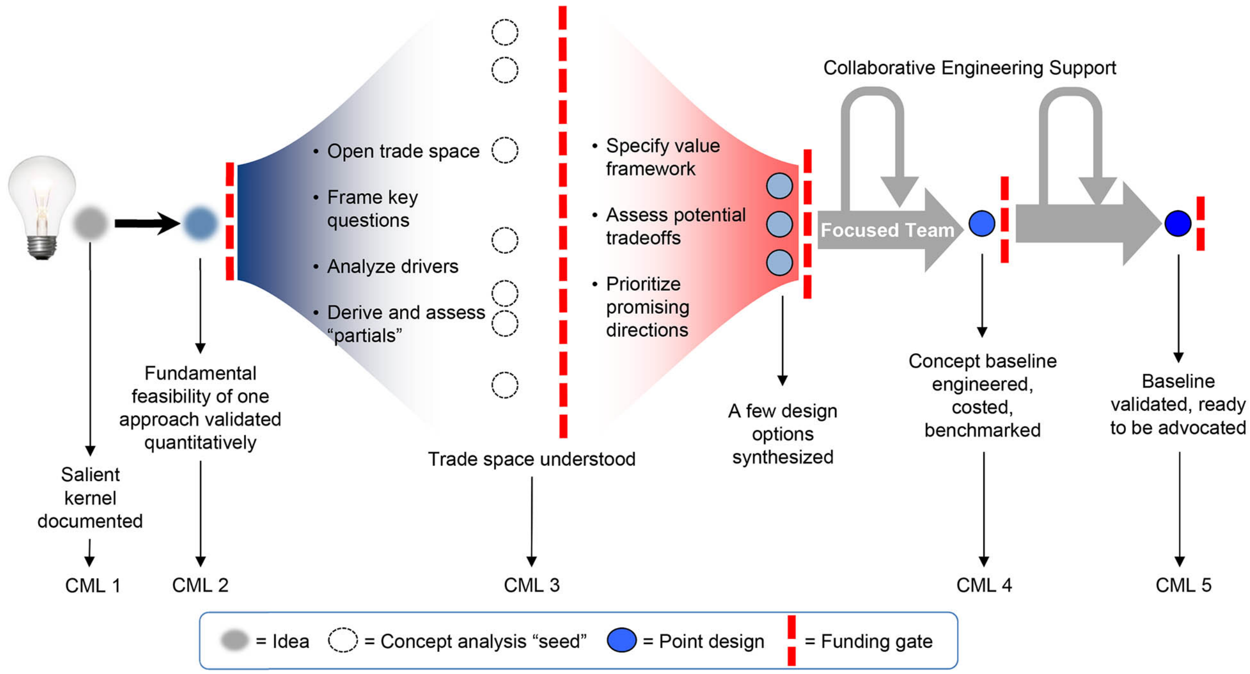

Figure 3. A mission concept starts with a "new idea" and assessment of its feasibility (CML 1 & 2), expands into a number of "seeds" to understand the design's sensitivities (CML 3), and then converges into a point design (CML 4). [3]

Using CMLs to evaluate a concept's maturity has provided a number of benefits in ranking and reviewing concepts. However, it is difficult to correlate CMLs with future cost growth. Cost uncertainty depends on both maturity of the concept at the time of the estimate and on the complexity of the design. This is especially true for more complex systems early in the development cycle. They are hard to characterize and generally contain multiple interactive interfaces and elements that can produce varying and uncertain outcomes. Complexity is on an orthogonal axis from concept maturity. Elements of a complex system may be just as well-known as for simpler systems at a given level of maturity but the complex concept will carry a lot more risk. This greater risk is due to (1) uncertainties in how these elements will interact once the system has been built, and (2) potential difficulties that may be encountered procuring custom components and completing technology and engineering development. Lack of information about such a system leads to poor decisions and costly mistakes.

2. Definition of Complexity

Complex systems are difficult to cost because they incorporate a number of poorly characterized, difficult-to-quantify subsystems, components, interface designs and/or ambiguous and difficult to implement management/ programmatic approaches. This is especially true during the early stages of concept development where performance, lifetime, environmental and interface design adequacy will not have been demonstrated. Inheritance will not have been validated and technology development will only be partially completed. If there are programmatic interfaces with multiple foreign partners, NASA Centers, government agencies and contractors, additional unknown challenges will be faced.

Because the primary intent of this paper is to help quantify cost uncertainty during early Formulation, the proposed definition of complexity differs slightly from those found in the literature. Most of those definitions have focused on the size, mass and cost of the spacecraft system and on the expensive components and instruments that make up that system. Their objective is to estimate total cost. But because these models are based on design details that are not yet known, they cannot be used until later in the Formulation Phase.

In this paper, complexity is defined as "a set of functions containing **multiple** technical or programmatic **elements,** which (1) are physically or functionally connected, (2) can interact to produce **different outcomes and** (3) are **difficult to characterize and assess** except within the context of the larger system."

3. Complexity Factors

To proceed with quantifying the effect of complexity on cost growth, detailed complexity factors needed to be defined. To do this a typical robotic spaceflight mission was divided into its functional areas and keeping the above definition of complexity in mind, conditions were identified that could lead to design issues, implementation problems and unpredicted cost growths. The functional areas were

- Science requirements
- Spacecraft and payload system architectures

- Ground system design
- Launch vehicle accommodations
- Implementation approach

The assessment resulted in identifying 33 general complexity factors. These were grouped into four categories: (1) project technical design complexity; (2) project programmatic complexity; (3) lack of resiliency; and (4) new design challenge.

The first two categories are characteristic of complex interfaces embedded in the technical and programmatic approaches. They include cases where there are a number of closely coupled, interacting, and poorly characterized design or programmatic elements that can produce multiple, unpredictable and potentially adverse outcomes. Examples of project technical design complexity include cases where there are (1) competing science objectives that can impact spacecraft and/or payload design; (2) lack of modularity and/or design standards, multiple interdependencies and/or "many-to-one" (inputs to output) type interfaces; (3) difficult to characterize operational environment and/or system interactions with that environment; (4) incomplete or difficult to implement requirements and/or ambiguous programmatic constraints; and (5) multiple new inventions with significant technology or engineering developments. Project programmatic complexity occurs when there are inadequate management structures and/or poorly defined lines of responsibility and authority. This can occur when there are multiple sponsors, ill-defined lines of authority, and reliance on multiple foreign partners.

The third category is lack of resiliency. This can occur due to inadequate financial or technical reserves, low schedule margins and overly constricting programmatic constraints affecting implementation. Although lack of resiliency may not, in itself, be a complexity factor it was included because it exacerbates any problem that does occur during formulation and implementation. Examples include insufficient design margin, low programmatic reserves and lack of meaningful fallback options for new technologies.

The fourth category acknowledges the difficulty of making accurate cost estimates with new designs. Design challenge depends on both the scope of the job and the level of experience of the project team. Examples where this type of complexity would exist would be new entry-descent and landing (EDL) approaches, spacecraft designs requiring state of the art attitude control, long mission durations, life-limited components and use of hardware or software with unverified heritage or low technology readiness level (TRL) maturity. Whether a complexity factor was categorized as a project design complexity factor or a design challenge was sometimes based on a judgment call, but this was not deemed important to the overall results.

The resulting list of general complexity factors was screened for thoroughness and accuracy by the authors and critiqued by the JPL Engineering Council, and a number of current and former Project Managers and technical personnel experienced in the design of complex systems. Some changes were identified and incorporated. Table 1 presents the results. Many are similar to the original list of cost risk subfactors [2] but additional factors and enhanced definitions have been added to better characterize risks earlier in the lifecycle and to capture risks associated with complex systems. To keep possible misinterpretations to a minimum, the factors were designed to be addressed with just a binary "yes" or "no" answer or a simple number of occurrences. Nineteen of the thirty-three complexity factors are project technical design factors, four are programmatic, seven address resiliency and three focus on design challenge. A distinction is made between factors that have a major impact and those believed to have only a minor effect. Based on judgment of the authors 24 of the 33 were designated as major contributors and identified as such in the table. Consistent with the weighting used in JPL's Cost-Risk Subfactors analyses [2], major factors were assigned a weight of 3 points while minor factors were assigned 1 point. Factors needing to be scored for each occurrence (e.g., each insufficient technical margin—#24) are also identified in the table. These designations and weightings will be further refined with future correlation analyses after more data is collected. Based on these assumptions a simple Earth orbiter would have a complexity of 10. Mars Science Laboratory would be approximately 100.

Table 1 – Complexity Factors can be used to evaluate multiple design architectures to identify the design with the lowest cost risk

Type	Complexity Factor	Weighting	Complexity Question
Complexity Category: Project Technical Design			
Sub-category: Science & Mission Objectives			
Conflicts	1. Competing science objectives	Major	Are there conflicts or strong interactions among instruments due to S/C configuration, electromagnetic state, viewing time, pointing accuracy, stability vs. slewing, power /data constraints, etc.? How many occurrences of this condition exist?
Incomplete Science Requirements	2. No mapping between quantified science objectives and proposed science measurements	Major	Are there science objectives that do not have a corresponding instrument measurement? How many occurrences of this condition exist?

Type	Complexity Factor	Weighting	Complexity Question
Sub-category: Mission Design			
Difficult to Predict Operational Environment	3. Unpredictable operational environments that interact with the system	Major	Will the spacecraft be operating in an environment that is not well defined?
Difficult to Implement Requirements	4. Planetary ascent and escape	Major	Is a planetary (non-Earth) ascent required?
	5. Significant planetary protection or contamination control requirements requiring sterilization or other severe measures	Major	Does the project have significant planetary protection or contamination control requirements (e.g., Earth orbital debris)? How many occurrences of this condition exist?
Sub-category: Flight System Architecture			
Lack of Modularity or Design Standards	6. Lack of modularity in flight system functions, subsystems or instruments	Major	Does the spacecraft lack modularity (e.g., complicated physical interfaces, distributed logic, shared embedded functions, “many inputs-to-single output interfaces”)?
	7. Non-standard design approaches	Major	Will the project have non-standard (e.g., diverse approaches for implementing redundancy, lack or standards, etc.) design approaches? How many different types of non-standard design approaches exist?
Difficult to Implement Requirements	8. Significant change in surface mobility architecture	Major	Does the “rover” have mobility requirements (e.g., major increase in range, new mobility approach, automated route planning based on multiple sensor inputs, etc.) that exceed past capability?
	9. New Entry, Descent & Landing (EDL) design architecture	Major	Is a new EDL capability needed?
Difficult to Implement Requirements *(continued)*	10. Severe attitude control requirements	Major	Are there severe attitude control (e.g., femto-radian and nanometer metrology required for SIM; or extreme stabilization of 0.01 pixel required for Kepler; unique dual spin configurations, etc.) requirements? How many different types of severe attitude control requirements exist?
	11. Difficult-to-simulate verification environment	Minor	Is the verification environment difficult to simulate?
	12. Life-limited articulation requirements	Minor	Are there any life-limited articulations (e.g., bearing surfaces with low life margins)? How many occurrences of this condition exist?
	13. Long mission durations	Minor	Is the prime mission longer than 5 years?
	14. New nuclear generator design	Major	Does the spacecraft use a new (i.e., never operated in space) nuclear generator design?
New Inventions	15. Low TRL technology developments	Major	Does the spacecraft depend on any technology that is ≤ TRL 4? How many occurrences of this condition exist?
	16. Unvalidated Heritage Assumptions	Major	Does the project’s heritage assumptions include a) unverified claims, b) inappropriate prior application, c) lack of pedigree, d) parts obsolescence, e) loss of vendor capability? How many hardware or software heritage assumptions fall into this category?
Sub-category: Launch Vehicle Accommodation			
Ambiguous Program Constraints	17. Accommodate multiple possible launch vehicles	Minor	Does the project have to keep the option of using an alternate launch vehicle?
Sub-category: Ground Systems			
Difficult to Implement Requirements	18. Ground system data processing requirements potentially exceeding current capability	Minor	Do the ground system data processing requirements exceed current capability?
	19. New ground system interface	Minor	Are there new ground system interfaces?

Type	Complexity Factor	Weighting	Complexity Question
Complexity Category: Project Programmatics			
Sub-category: Management			
Multiple Sponsors and/or Partners	20. Multiple Centers or government agencies	Major	Are multiple NASA Centers or government agencies involved in this project?
	21. Major foreign partner contributions	Major	Are there major deliverables from foreign partners directly to JPL? How many occurrences of this condition exist?
Poor Lines of Authority	22. Poor allocation of key functions to design and /or design to implementing organization	Major	Is there a poor allocation of key functions to design (e.g., too many functions assigned to single component and/or implementation responsibility assigned to unqualified or overly stressed implementing organization)? How many occurrences of this condition exist?
	23. Lack of well-defined roles and lines of authority	Major	Are roles and lines of authority well defined?
Complexity Category: Lack of Resiliency			
Sub-category: Margins			
Insufficient Design Margins	24. Insufficient technical margins	Major	Are there sufficient margins (i.e., recommended in Design Principles[1] or Pre-Project Principles and Practices [P4][1])? How many occurrences of this condition exist?
Insufficient Programmatic Reserves & Margins	25. Less than recommended cost reserves	Major	Are cost reserves at the recommended levels (compared to Cost Risk Subfactors and/or Flight Project Practices [FPPs][1])?
Insufficient Programmatic Reserves & Margins	26. Less than recommended schedule margin	Major	Are schedule margins at the recommended levels (Compared to Rules of Thumb and/or Flight Project Practices [FPPs][1])?
	27. Constrained launch schedule	Major	Does the project have a constrained launch schedule?
	28. Closely linked time-critical events	Minor	Does the project have closely linked time-critical events?
Sub-category: Design Constraints			
Lack of Technology Fallback Options	29. No meaningful fallbacks (if there is new technology) or descopes within Baseline Mission	Major	Does the project have fallback options or acceptable descopes for each new technology? If no, then how many new technologies have no fallback option?
Co-Manifested Payload	30. Co-manifested on same launch vehicle with another payload	Minor	Is the spacecraft co-manifested with another spacecraft?
Complexity Category: New Design Challenge			
Sub-category: Experience and Scope			
Lack of Experience	31. No experience implementing equivalent encounter / orbit insertion sequences	Major	Does the implementation team have recent and relevant experience in developing this type of mission, flight system and payload? (As an example, a negative response would be given by a JPL team if the desired mission incorporated the use of aerocapture to achieve Martian orbit.)
Scope of Job	32. Challenging trajectory	Minor	Does the mission require a challenging trajectory (e.g., low thrust, formation flying, low-mass targets, ill-defined target orbit, multiple gravitational assists, etc.)?
	33. Major spacecraft separations, reconfigurations and deployments	Major	Does the spacecraft change its configuration (e.g., different EDL, S/C or rover reconfiguration, probe separation or ground sampling procedure, etc.)? How many occurrences of this condition exist?

Note: [1]JPL Internal guidelines and requirements for designing and managing space mission concepts and projects

As can be seen, most of the above factors can be determined early in concept development (CML 1–3). However, there are some exceptions. Risk factors associated with overly complex project organization and ambiguous lines of authority will not be known until teams are formed at the beginning of the proposal phase (CML 4–5). Heritage assumptions won't be completely validated, new technology and/or significant engineering development won't be completed, and the adequacy of cost, schedule and technical margins cannot be fully assessed until after a robust formulation phase (CML 6–8). However, early assessments can identify these as open areas that should be continually monitored so that these high-risk areas do not become actual issues.

4. PROJECT COMPLEXITY RATINGS

In order to verify that complexity could be estimated and quantified, interviews were held with JPL Project Managers and system engineers on seven recent project teams (Projects 4, 5, 6, 8, 9, 10, and 11 in Tables 2 and 3). A three-step process was followed. Each team was briefed on the above definition of complexity and provided several examples spanning the complexity spectrum. They were then asked to rate the complexity of their project and eleven others on a scale that ranged from 10 to 100. To normalize their responses they were told to assume that a simple Earth orbiter carrying a well-developed, passive science payload would rate as a 10 and that Mars Science Laboratory (MSL), generally acknowledged by all as the most complex of JPL missions, was estimated at 100. Inputs were solicited from multiple Project Managers for each project to determine if a consensus on a project's complexity could be reached and to calibrate the opinions of the individual Project Managers. During the interviews the Project Managers appeared to be familiar with the development challenges faced by the other 11 projects as a result of personal interactions within the project manager community and briefings received during monthly and quarterly Project Manager Reviews. (These problems were essentially all the result of one or more of the complexity factors identified in Table 1.) The projects assessed include Cassini, MER, Pathfinder, Phoenix, Juno, MRO, SMAP, Kepler, GRAIL, OCO, CloudSat and OSTM. Names have been removed due to programmatic sensitivities. The complexity ratings and spread of results from the interviews for each of the twelve projects are presented in Table 2. The reasonably close spread indicated a fairly broad agreement among the Project Managers and system engineers that were interviewed and strengthened the argument that a project's complexity can be quantified.

The last step of the process occurred at the end of the interviews when each team was asked to assess their project against each of the 33 complexity factors. The projects were asked to declare whether a factor applied or did not apply to their project. As can be noted in Table 1 the questions were phrased to require a simple yes or no answer or, when appropriate, the number of occurrences. The initial intuitive self-assessment and the subsequent detailed responses to the 33 complexity factors are believed to be reasonably independent. The detailed questions were objectively phrased and dealt with specific elements within the project development. Furthermore, the projects didn't have an opportunity to see or evaluate the total list of 33 factors before the interview and didn't know which were considered "major" vs. "minor". It is highly unlikely that their responses on the applicability of the 33 factors would have been biased by their initial subjective estimate of overall complexity.

After each Project completed their self-appraisal, the major and minor contributors were counted, weighted and summed. The results were shown to the project but no changes were made. A comparison between the intuitive assessment of complexity and the subsequent detailed assessment computed using the 33 factors is presented in Table 3 for the seven interviewed projects. They are presented in descending order. About half of the initial intuitive estimates were higher than the subsequent detailed assessments and half were lower.

Table 2. Project Manager Initial Estimates of Project Complexity

Project	Average Appraisal from All Interviews (mean $\pm$ 1 σ)
Project 1	82 $\pm$ 15
Project 2	82 $\pm$ 12
Project 3	71 $\pm$ 14
Project 4	68 $\pm$ 12
Project 5	62 $\pm$ 13
Project 6	56 $\pm$ 11
Project 7	45 $\pm$ 8
Project 8	40 $\pm$ 16
Project 9	36 $\pm$ 9
Project 10	26 $\pm$ 5
Project 11	23 $\pm$ 11
Project 12	23 $\pm$ 3

Table 3. Detailed Complexity Ratings

Project	Project's Initial Self- Appraisal (intuitive)	Project's Detailed Self- Appraisal (based on Complexity Risk Factors)
Project 4	75	91
Project 6	70	68
Project 5	50	48
Project 8	50	32
Project 9	25	26
Project 10	25	19
Project 11	15	30

Linear regression analysis comparing the two assessments indicates a reasonably good correlation with an R^2 value of 0.79 (Figure 4). The dotted line on the plot would indicate a perfect fit. The solid line was generated using a linear least squares best fit. The correlation with the intuitive assessments validates that the 33 factors do a reasonably good job of assessing concept complexity. Since any estimate of concept complexity by early development teams would have to be based on the 33 factors (or a major subset), all further discussion of complexity in this paper is based on estimates that have been or could be achieved using the 33 factors.

Although more data obviously needs to be collected, it appears that complexity can be reasonably well quantified early in the development lifecycle by assessing the 33 factors. Performance attributes, architectural concepts, instrument and technology approaches that incur high cost risk can be identified during the early trade studies required to reach CML 3 and modified or "engineered out" of the approach before significant resources are expended and before commitments are made to the science team, instrument developers and NASA Headquarters. Performance modifications, design alternatives, analyses and tests can be focused on the high risk areas. Backups can be identified for high risk technologies and instruments and high heritage components can be incorporated into the design.

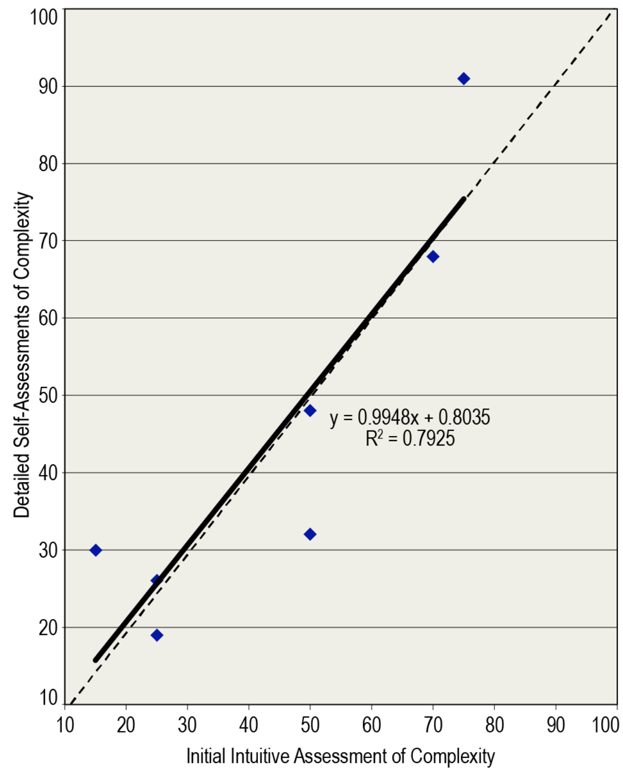

Figure 4. Correlation between Project Initial Intuitive Assessment and Subsequent Detailed Self-Assessment

5. COST GROWTH VS. COMPLEXITY

The authors next attempted to determine the impact of complexity on a project's ability to make accurate cost estimates. The complexity ratings used were based on the 33 factors. But the accuracy of a cost estimate depends not only the complexity of the project, but on the maturity of the concept at the time of the estimate. Cost estimates that were documented at different points in the lifecycle and therefore at different maturity levels were collected. The estimates included reserves if the project felt they were going to utilize them (in all cases they were included). The first documented estimates are usually made at CML 5 and included in the Step 1 Proposal or, if it is an assigned mission, presented at the Mission Concept Review. This is prior to any commitment to NASA Headquarters, which does not occur for competed projects until the Step 2 Concept Study Report is submitted (CML 6) or, for assigned projects, at the Preliminary Design Review (PDR; CML 8). Even so they are included in Figures 5–9 to present a full picture. Figure 5 presents the data for medium and small projects of less than \$500M. Figure 6 adds a flagship mission and illustrates continued cost growth significantly beyond PDR (CML 8). It is believed that this occurred because the project faced an unusually large number of challenges and was unable to resolve all their technical issues during the Formulation Phase.

Efforts were made to remove cost growth due to external conditions. This was done by working with JPL cost data records (CADRes) and the projects to identify the individual contributors to cost growth, their magnitude and whether the contributor occurred due to conditions outside of the control of the Project Manager (e.g., launch vehicle slips, funding hold-backs, program redirection, etc.). Due to a major shift in Center management responsibilities directed by NASA in the middle of implementation, the authors were not able to normalize Kepler cost growth so it is not included on the plots. Names have been removed due to programmatic sensitivities.

These cost data can be converted into calculations of future cost growth (F.C.G.), in percent, at various points in the lifecycle (L.C.) as follows:

$$\text{F.C.G.} = \frac{\text{final cost} - \text{estimate at L.C. point} \times 100}{\text{estimate at L.C. point}} \qquad (1)$$

Future cost growth above a project's first estimate is plotted against concept complexity in Figure 7. The first estimate is normally made at a maturity of CML 5. For assigned missions the estimate is presented at the Mission Concept Review. For competed missions it is documented in the Step 1 Proposal. In the cases considered there was one exception. One of the projects delayed estimating costs until CML 6. It is identified in the figure with the note "Based on CML 6 Estimate." This might explain why their cost growth seems lower than average. Regression analysis was conducted using a second order polynomial with the intercept through zero. Results indicate a reasonably good fit with an R^2 of 0.65. It is clear that at this relatively low level of maturity (CML 5) cost uncertainty increases as complexity increases and it is very likely increasing at a rate higher than linear.

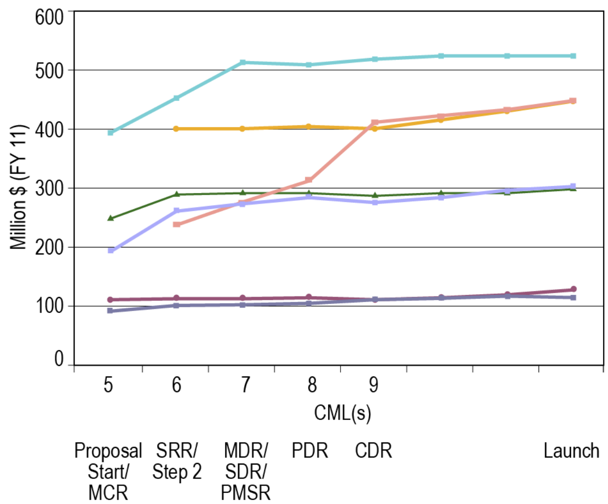

Figure 5. Project Development Cost Estimate vs. Time of Estimate for Medium and Small Projects

Based on references in the literature [4]–[6] this is not surprising but more data from large, complex New Frontier and flagship missions is needed before any firm conclusions can be made, especially for missions that are as complex or more complex than MSL.

Even though the data is limited, useful assessment can still be accomplished. Complexity can be calculated by identifying the applicable complexity factors in Table 1, and then weighting and summing them to get a quantitative estimate of complexity. That value can then be used with Figure 7 to get an approximate measure of cost risk. If the risk is too high, specific risk factors can be eliminated or mitigated by changing the implementation approach prior to making any formal or informal commitments to NASA or the scientific community.

6. Cost Growth vs. Complexity and Concept Maturity

The above section describes an approach for estimating future cost growth based on complexity early in the development cycle. But to better support project management and cost assessment later in the lifecycle, the authors next attempted to correlate future cost growth with complexity at higher levels of project maturity (CML). The relationship between cost uncertainty and maturity can conceptually be represented as an "S Curve" (Figure 8). During early concept development (CMLs 1–3) the focus is on mission definition, trade studies, payload and system architectures, not on obtaining a detailed understanding of the design, interfaces or performance. Not much is learned during this period that will reduce cost risk and, as a result, the cost uncertainty curve remains fairly flat. Once a point design is selected, the focus shifts to design, analysis, risk reduction and cost estimation (CMLs 4–8). This reduces technical risk and cost uncertainty and the curve correspondingly bends downward. If the Formulation Phase is successful in retiring most of the development risk, the curve begins to flatten out after the Preliminary Design Review (PDR). The curve approaches zero at the time of launch.

Extending this line of reasoning to projects with different complexities, they could be represented by a family of "S Curves." Each curve would correspond to a different complexity. Curves representing projects with higher complexity would fall higher on the plot, having higher cost uncertainty at the low CMLs. They would require a steeper downturn and greater level of evaluation during

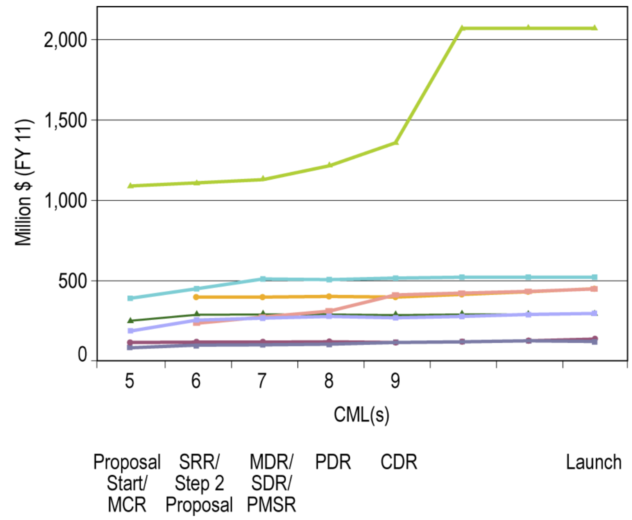

Figure 6. Project Development Cost Estimate in M$ (FY 11) vs. Time of Estimate for All Projects in Study

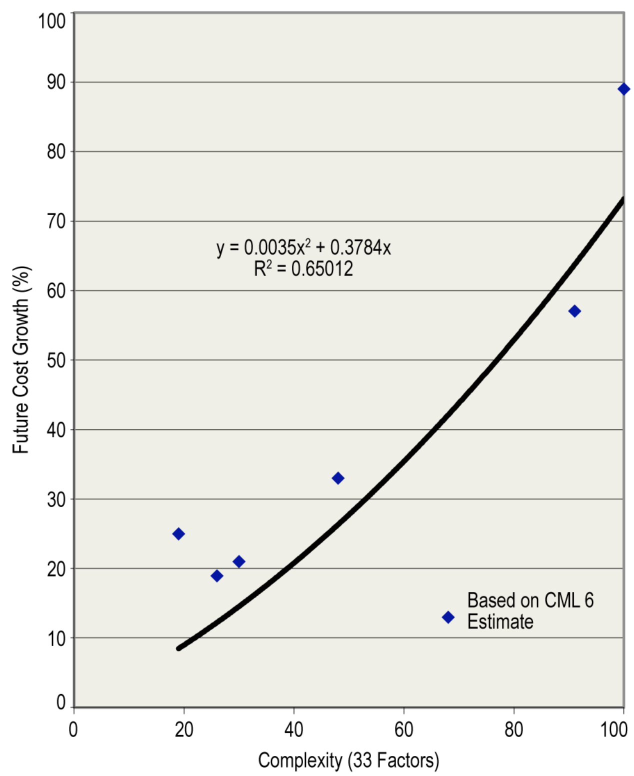

Figure 7. Cost Growth (from original documented estimate) vs. Complexity

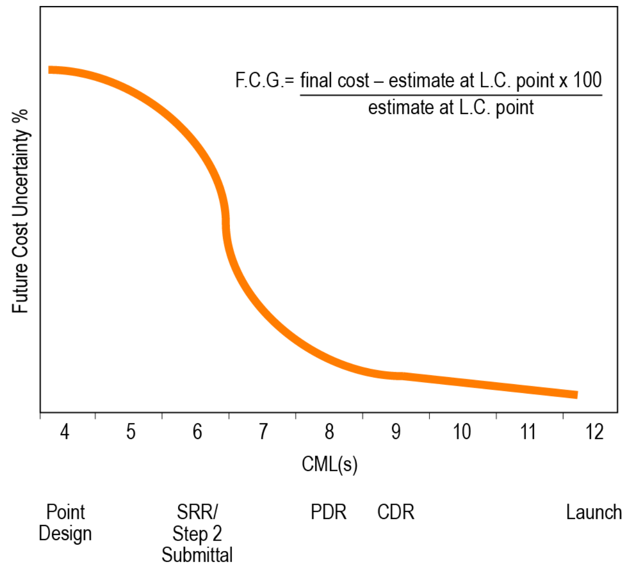

Figure 8. Cost Uncertainty vs. Concept Maturity

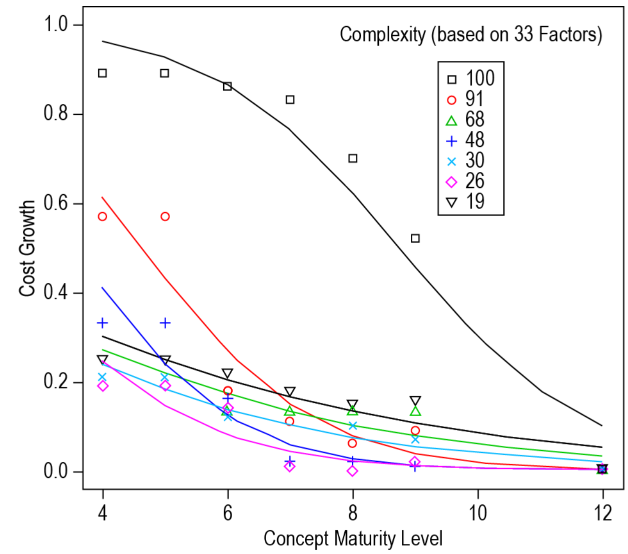

Figure 9. Cost Growth vs. CML Maturity for Projects with Varying Complexity

Formulation. In order to accomplish this they require more time and resources than the typical 15–20% provided during Formulation. If cost or schedule constraints make this impractical, reserves ought to be increased above the typical 30–35% [4]–[6]. Most of the cost growth for complex missions occurs due to design risks which have not identified and mitigated during Formulation. Unresolved problems are a lot more expensive to fix during the Implementation Phase when flight hardware is being built.

Cost growth for the selected projects, each with a different complexity, are plotted against concept maturity in Figure 9.

The curves in Figure 9 are generated from regression analysis using a logit function based on maximum likelihood. It appears from this limited data that the impact of complexity on cost estimation accuracy is most pronounced at early stages of concept development and most significant for missions with complexities approaching 100.

It should also be noted from Figure 9 that the cost uncertainty decreases for even the most complex systems as the concept matures. If a new mission were designed as a near-duplicate of MSL, and other factors necessary for achieving high inheritance were satisfied (no obsolescence of parts, same processes, vendors, etc.) the cost risk would be very low.

7. Conclusions

The major conclusions are that:

1. Significant cost risks can be identified early in the lifecycle by assessing complexity and "engineered out" of the implementation approach before selecting a concept, submitting a proposal or making any cost commitments.
2. Concept complexity can be quantified by assessing thirty-three complexity factors.
3. The uncertainty of a cost estimate depends on both the maturity of the concept at the time of the estimate and the complexity of the design and implementation approach.
4. Complexity has the most influence on cost estimation accuracy early in the development lifecycle, especially for highly complex systems.
5. Data is limited but it appears that quantified values of concept complexity and concept maturity (CMLs) can be used to generate estimates of future cost growth.

Additional comments:

1. Cost uncertainty is larger than generally acknowledged at CML 5.
2. Cost estimation problems will continue to plague complex projects well after PDR unless more resources are allocated to solve technical issues during Formulation. Reliable baselines can, however, be achieved, even for complex missions, prior to PDR, if inheritance, technology maturation, engineering development and interface design issues are fully identified and addressed. Designing missions that can make full use of inheritance from recent missions can significantly reduce complexity and cost growth.
3. More data is required on New Frontier and Flagship missions.

8. References

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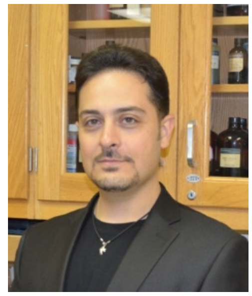
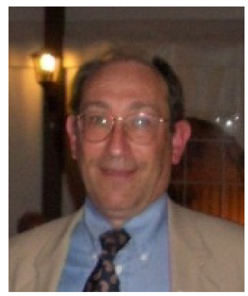
BIOGRAPHIES

Jeff Leising *has 44 years of experience at JPL in varying engineering, project and program management positions. He has worked for NASA on unmanned space flight projects to the Moon, Mars, Venus, Mercury, Jupiter, Saturn, Uranus and Neptune. He has also worked with DOE in solar photovoltaic and solar thermal energy, DOT in electric and hybrid vehicle development and DOD in tactical information fusion. In his last position he managed Office 154, Project Formulation, supporting proposal teams and new projects as they establish plans and requirements, identify risks and reserve postures, and establish integrated baselines. His technical background is in propulsion, system engineering, and management processes. Jeff graduated from Cornell University with Bachelors and Masters in Mechanical Engineering. He retired in December 2011.*

Randii Wessen *has been an employee of the California Institute of Technology's Jet Propulsion Laboratory for twenty-eight years. Dr. Wessen is currently a Senior Technical Staff Member to JPL's Innovation Foundry. Prior to this Dr. Wessen was the Navigator Program System Engineer, the Telecommunications & Mission Systems Manager for the Mars Program, Manager of the Cassini Science Planning & Operations Element, the Galileo Deputy Sequence Team Chief, and the Voyager Science Sequence Coordinator for the Uranus & Neptune encounters. Dr. Wessen received his Bachelors of Science in both Physics & Astronomy from Stony Brook University, a Masters of Science in Astronautics from the University of Southern California, and a Doctorate in Operations Research from the University of Glamorgan, Wales, United Kingdom. He co-authored the books "Neptune: the Planet, Rings and Satellites" & "Planetary Ring Systems."*



Raymond Ellyin *is currently the Mission Assurance Manager of CHARM (CubeSat Hydrometric Atmospheric Radiometer Mission), a CubeSat radiometer Earth orbiting mission scheduled to launch in February of 2014. He is a member of the biotechnology & planetary protection group at JPL. He earned his Bachelors Degree in physics and mathematics from UCLA in 2002. He went on to earn his M.S. and Ph.D. degrees in 2005 and 2012 respectively also from UCLA. In addition, Dr. Ellyin currently holds a faculty position at Demirdjian High School teaching physics & mathematics.*



Leigh Rosenberg *is a JPL Principal Engineer in the Mission Systems Concepts Section. Previously, he was the Group Supervisor of JPL's Cost Engineering Group. He was also a charter member of JPL's Advanced Design Team (Team X). He has worked at JPL in cost estimation and systems engineering for the last 35 years. He has developed the original JPL Team X engineering cost estimation methodology. He has coordinated the cost estimation of various competitive proposals including the Stardust, Genesis, and Deep Impact projects. He created the Parametric Mission Cost Model, which is used to generate parametric WBS mission costs for JPL space missions. He is currently a member of NASA Cost Analysis Division Executive Cost Analysis Group. He is also the Editor of the latest update to the NASA Cost Estimating Handbook.*

Adam Leising *is a doctoral candidate at Stanford University. He possesses an MPhil in Technology Policy from Cambridge University and a BS in Chemistry from UC San Diego. He studied complex systems theory in Beijing, China within the Complex Systems Summer Program, which is administered by the Santa Fe Institute and the Chinese Academy of Sciences Institute for Theoretical Physics.*

ACKNOWLEDGMENT

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.