

NEW APPROACHES IN REUSABLE BOOSTER SYSTEM LIFE CYCLE COST MODELING

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ABSTRACT

This paper presents the results of a 2012 life cycle cost (LCC) study of hybrid Reusable Booster Systems (RBS) conducted by NASA Kennedy Space Center (KSC) and the Air Force Research Laboratory (AFRL). The work included the creation of a new cost estimating model and an LCC analysis, building on past work where applicable, but emphasizing the integration of new approaches in life cycle cost estimation. Specifically, the inclusion of industry processes/practices and indirect costs were a new and significant part of the analysis. The focus of LCC estimation has traditionally been from the perspective of technology, design characteristics, and related factors such as reliability. Technology has informed the cost related support to decision makers interested in risk and budget insight. This traditional emphasis on technology occurs even though it is well established that complex aerospace systems costs are mostly about indirect costs, with likely only partial influence in these indirect costs being due to the more visible technology products. Organizational considerations, processes/practices, and indirect costs are traditionally derived (“wrapped”) only by relationship to tangible product characteristics. This traditional approach works well as long as it is understood that no significant changes, and by relation no significant improvements, are being pursued in the area of either the government acquisition or industry’s indirect costs. In this sense then, most launch systems cost models ignore most costs. The alternative was implemented in this LCC study, whereby the approach considered technology and process/practices in balance, with as much detail for one as the other. This RBS LCC study has avoided point-designs, for now, instead emphasizing exploring the trade-space of potential technology advances joined with potential process/practice advances. Given the range of decisions, and all their combinations, it was necessary to create a model of the original model and use genetic algorithms to explore results. A strong business case occurs when viable paths are identified for an affordable up-front investment, and these paths can credibly achieve affordable, responsive operations, characterized by smaller direct touch labor efforts at the wing level from flight to flight. The results supporting this approach, its potential, and its conclusions are presented here.

INTRODUCTION

Beginning in mid-2011, NASA Kennedy Space Center began anew its collaboration with the US Air Force Research Laboratory (AFRL). ¹ Collaborative work in 2011 explored the possibility that a life cycle cost methodology could deviate from the traditional product or “what” centered view into “how”. This early exploratory work showed how (1) design/technology, (2) reliability and (3) organizational processes and practices could be organized as drivers, or inputs when considering life cycle outcomes such as near term costs, far term costs, and responsiveness (flight rate capability).

In 2012 a task was formally begun carrying the exploratory work further into a life cycle cost study of a hybrid reusable booster system. This would include developing a new life cycle cost model and performing analysis to assist in understanding the business case for an RBS. This work is described here.

OBJECTIVE

Cost models of large scale projects can serve an assortment of purposes within an organization. Government projects will use cost models in support of ²life cycle management, budgeting processes, changes in course, or to simply quantify and understand past experience before going down some path. A cost model can place an emphasis on the product at hand, past data or analogies, prediction, budget adequacy, confidence in cost and/or schedule, and so on with an emphasis on one factor often meaning less usefulness on others.

For our RBS case, the cost model objectives that would be emphasized are (1) the business case, (2) its actionable characteristics, and (3) examining data within the context of “how” (processes, practices) as well as “what” (the product).

- Assist in maturing the **business case** for the development and operation of a responsive and affordable, Air Force Reusable Booster System (RBS).
- Emphasize tangible, **actionable characteristics** of the whole system, design/technology and organization/industry processes/practices, to inform a potential programs definition and direction.
- Examine historical **data** within the context of “**how**” (processes, practices) as well as “**what**” (the product).

PRELIMINARY RESULTS, SUMMARY BUSINESS CASE FOR AN RBS

The study described herein shows what appear to be abundant options along dual paths that would justify a decision to proceed or formulate a Reusable Booster System program. One path will be called the path of “Effectiveness”, the other “Effectiveness and Efficiency”.

In the paradigm of effectiveness, the main question going in is the need to identify investments such that a relatively small change in these results in a very large change in outcomes. Outcomes of special interest in this paradigm are about responsiveness, being mission capable, readiness and war-fighting potential. If a relatively small change in the envisioned investment, from focusing on the right design, technology or “-ilities” can result in an operating wing 50% smaller than that for a design lacking these investments, then the business case is strengthened.

Further, on sheer quantity, if many combinations of these design/technology options can be identified the case is strengthened that such an investment path is not overly constrained, having to be exactly of a sort. It is only necessary to have enough of the right choices moving in the right direction, not some singular combination. The stakeholders interested in this view would include technology managers, their technologists, and decision makers in general that oversee early research and development.

Alternately, in the paradigm of effectiveness and efficiency, the main question is about how to justify turning investments into a real program, justified on predicted benefits and outcomes, under circumstances where the absolute amounts invested (or available) are also reduced. The relative amount of additional investment that would result in a more responsive or operable system is a moot point in this paradigm, as even the baseline investment is taken to be unacceptable. A small addition to the up-front investment is a small addition atop an impossible starting point.

The paradigm of effectiveness and efficiency identifies many combinations of factors, beyond the design/technology of the product, delving into the processes and practices of the performing organizations (industry). Once again, on sheer quantity, many combinations of industry process/practice factors have been identified, supporting the notion that such a program path would not be overly constrained, having to execute the program exactly to a rule. It is only necessary to be in the general area of design/technology and industry process/practice characteristics that are in the realm of low up-front costs, low operations and production costs, but high capability.

APPROACH AND SYSTEM SCOPE

The hybrid RBS chosen for this study is in the 15,000lbm (LEO 28.7deg, 100nm) payload class. Given the exploratory nature of the task, an initial single design point was avoided. In many an exercise of this nature, a chosen architecture is defined to some appropriate level of fidelity (how many engines, what type power supply, the power systems weight, etc.) More design iterations would begin serially after some initial foray was made into that initial design by the assorted analysis disciplines. In this approach the initial single point design would not only be avoided, it would not even be an output.

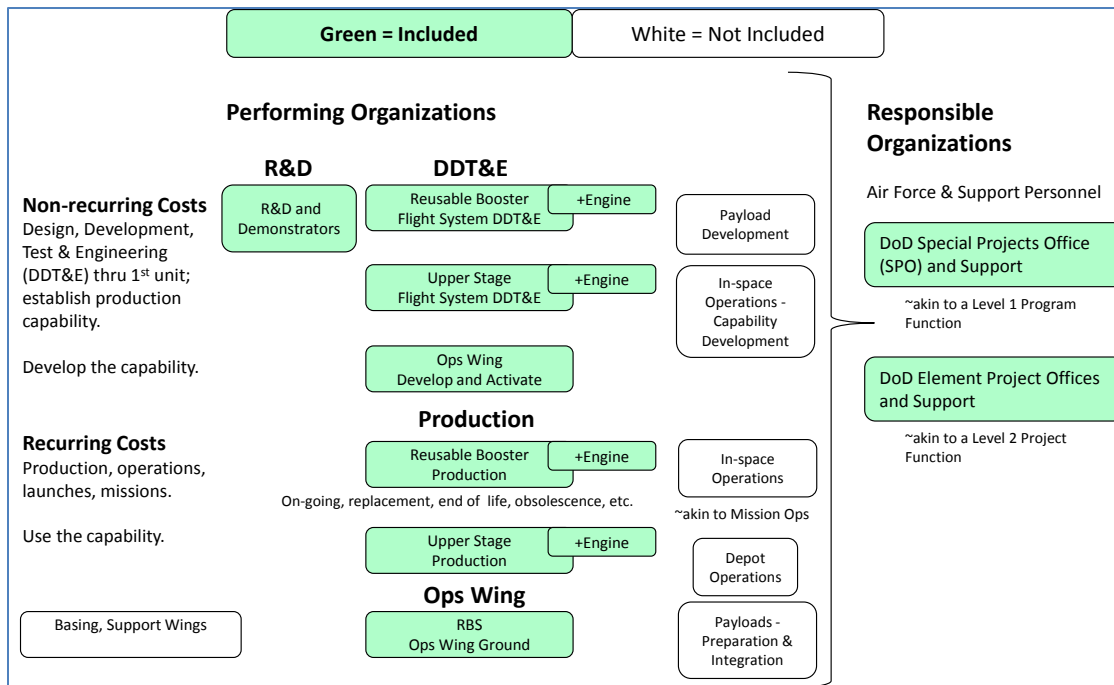


Figure 1: The RBS System/Study Scope

Although the approach described previously would avoid an initial single point design, it was still necessary to define the system (and by relation the studies) scope. The system/study scope is outlined in **Figure 1**. Though not 100% comprehensive at this time (measured in reference to ³Mil-Standards), and not all of the areas received the same level of detailed treatment, the scope addresses most of the areas of discussion that arise at this stage of study and analysis, and then some, based on the analysts experience. (Future study may delve further into areas that received less detail, enter into areas not addressed, or both, according to the resources available).

RECONNAISSANCE – THE BASIS OF ESTIMATE

The basis of estimate of any model for a large scale aerospace project must begin with the accumulation of cost data and a review and understanding of the meaning of that data. Of particular interest to the objectives of this analysis were providing an **actionable understanding**, with as much focus on data within the context of “how” (processes, practices) as well as “what” (the product).

By policy, indirectly, a government acquisition emphasizes “what”, the product, the item, the tangible purchase, acquired deliverable or service. There are good and ample reasons for this emphasis given extremely complex systems and the numerous organizations involved in both government and industry aerospace. The Mil-Standard on Work Breakdown Structures (WBS) points out how “generating and applying uniform work breakdown structures improves communication in the acquisition process”.

Clearly everyone in government or industry involved in the process of getting Product X from idea to reality should always be on the same understanding of “what” they mean when they talk about Product X. Nonetheless, this formal acquisition policy emphasis on “what” can turn attention away from “how” an industrial partner turns an idea into reality. An acquiring government organization (technical or non-technical) may be loath to delve into “how” when outcomes have been so procedurally linked to “what”. This creates a dilemma-as the cost data of projects that are ever more complex shows more and more convincingly that desired project outcomes such as affordability, or responsiveness, up-front or once operational, outcomes on a par with the product, are by necessity about “how”.

As early as 1990 it was observed by ^{4,5}McCullough and Balut, reviewing aircraft projects, and industry (contractor) costs that –

“Overhead costs were neither visible nor understood, so common practice was to use poorly documented (sometimes proprietary) factors to “burden” the labor estimates. The practice has persisted, even though direct manufacturing labor has nearly disappeared as a cost driver, and overhead has grown to represent more than half the cost of defense systems, and may rise to represent two-thirds of these costs.”

“Experience at these firms indicates that overhead had grown from about 38 percent of total business in 1973 to about 49 percent by 1987. Extrapolation of this trend indicates that overhead will reach about 54 percent by the year 2000.”

More recently, most of the 84 recommendations in the EELV should-cost review were associated with overhead and indirect costs.

For the RBS system, an immediate natural analogy was to the similarly semi-reusable Space Shuttle. As a program that KSC modelers and cost analyst were intimately familiar with – the data confirmed program wide what was already suspected – that the cost of the effort “close-in”, the nearer to the product (the vehicle turnaround, the production, the materials, etc.) was the smallest part of total expenses.

Other data review included the EELV program, United Launch Alliance, the B-2 Stealth Bomber, and the Space-X Falcon.

These previous terms of costs, making up most of the total costs in our industry, have come to be referred to with assorted, often inconsistent naming - indirect, overhead, non-touch, systems engineering, project, program management, etc. A WBS that is not entirely system and sub-system oriented was defined, shown in **Figure 2**, to clarify terminology, alongside an example of \$10 using historical splits.

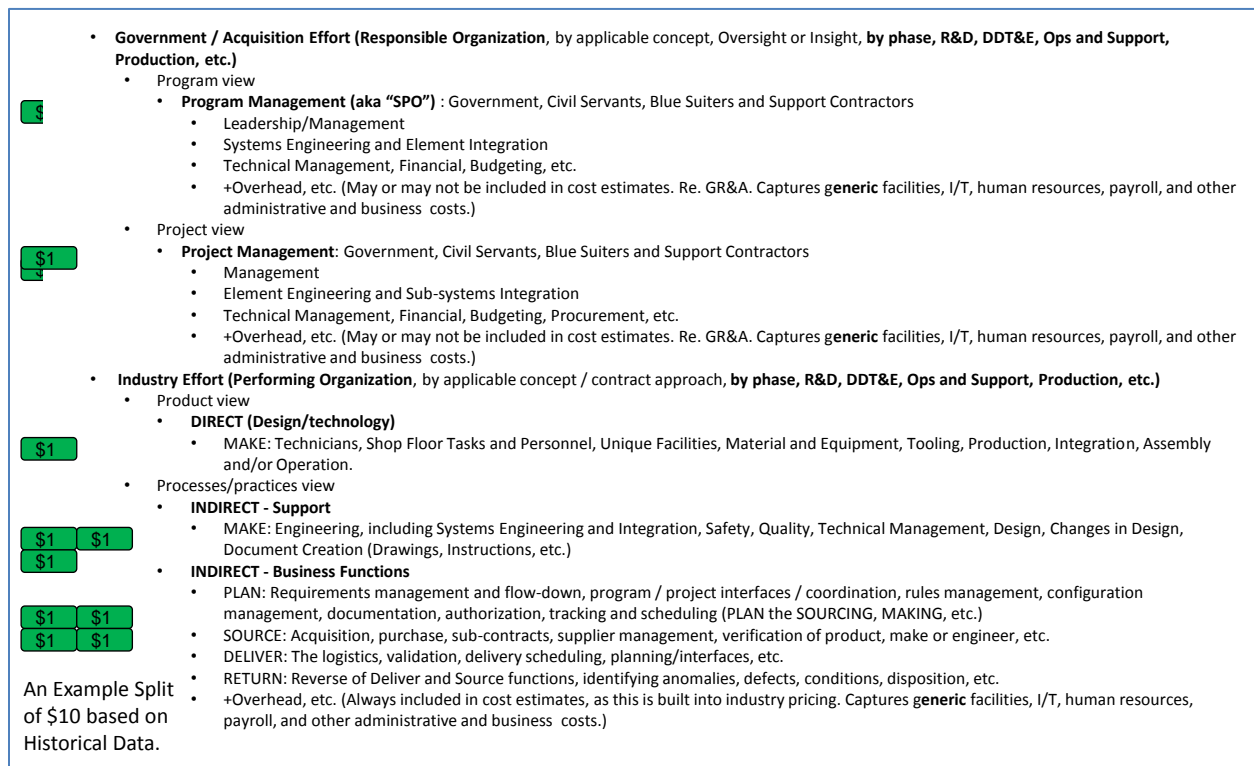


Figure 2: Basis of Estimate – Work Breakdown Structure, Detail

THE RBS MODEL

The 1.0 RBS model would rely on past modeling and analytical expertise. Other models developed by KSC in support of past programs such as the ⁶LLEGO model, contributed greatly, with most of the cost estimating relationships consistent with decision analysis and problem decomposition techniques. As has been observed before when attempting to connect causes to outcomes –

“...the cognitively demanding task of information combination can be performed by model, typically implemented on a computer. Furthermore, the framework is general enough to incorporate information from diverse sources, including both 'hard' data and 'soft' subjective assessments.” (Kleinmuntz)

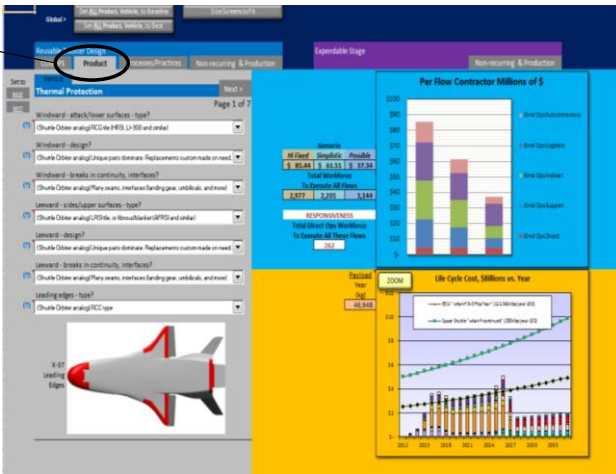
The first task was to break out product from processes/practices. Shown in **Figure 3** is the product input screen (1 of 7) for describing the technology or design (including where emphasized, the reliability) of the RBS.

The RBS LCC Model – Sample Screen

- **Product Inputs (7 Screens, TPS example)**

Most model inputs represent a level of detail that is pre-PDR, high level.

- Some inputs may require more fidelity in system definition.
 - TPS
 - Propulsion (Main + Other)
 - Fluids and Gases
 - Power, Avionics and Health Management
 - Structures
 - Other



Sample screen for illustrative purposes only.
Specific values shown do not represent specific analysis.

- 2 outputs graphs calculate on any change; immediate user feedback.

Figure 3: Product View of the RBS LCC Model

The second task was, similarly, to breakout the view of “how” the product is implemented, as shown in **Figure 4**. In each case about as many variables, or questions (inputs) as a surrogate for measuring a level of detail, were developed for describing the vehicle, system or thing (what) as were developed for “how” the product was to be achieved (developed, produced, operated).

This is a novelty in this RBS LCC model, as a survey of the field of aerospace cost models would invariably find -

- (1) The number of variables, inputs or switches that could be categorized as about “how” would be an order of magnitude fewer than the count of inputs that could be categorized as related to “what”, describing the product. (“How” features and understanding are thus part and parcel of the “what” data in most models, hiding insight there).

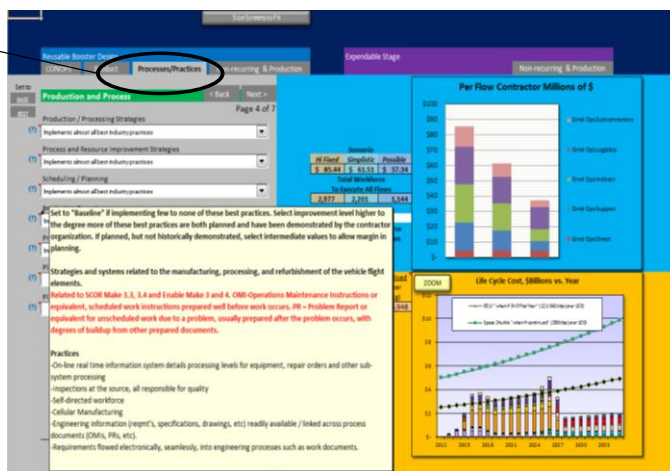
- (2) That even these process/practice switches are relegated to being weak switches, or kept constrained on their range, meaning that even a known answer may not be reproducible when it depends too much on “how”. (The case in point being the recent ^{8,9}review of the “NAFCOM” model when considering a Space-X Falcon 9 development).
- (3) That many “how” variables in cost models, being for government decision makers, or the government acquisition, focus on the program/project management, and the acquisition approach - not industry, where most of the money will be spent.

The RBS LCC Model – Sample Screen

- **Processes/Practices Inputs (7 Screens, Production example)**

Analysts must select inputs descriptive of the expected capability of the performing organization:

- “Best practices” follow a plan, source, make, deliver, return pattern.
- “Agile R&D” and “Agile Product Development”, lead to “Lean Manufacturing/Production” and Advanced Supply Chain Management, segueing into similarly efficient operations.
- Area of the model most likely to evolve significantly in immediate Forward Work – esp. the graphic user interface, and the visibility of input linkages specifically to either early R&D, product development, manufacturing/production, or operations.



Sample screen for illustrative purposes only.
Specific values shown do not represent specific analysis.

Figure 4: Processes/Practices View of the RBS Model

Given the number of variables involved, it became necessary as happens with complex models to find a way to actually perform a useful, repeatable, quantity and quality of analysis, searching throughout the design space for those “aha” moments. For this task it is now possible to employ off-the-shelf tools such as Phoenix Integration ModelCenter (rather than automating or adding features to the analysis capability at the MS Excel level). Automation is thus used to create analysis products that an analyst could not conceivably do manually in any reasonable amount of time. (Some of the analysis runs described ahead would take a typical laptop a few hours – each).

RESULTS AND DISCUSSION – EFFECTIVENESS VIEW

Shown in **Figure 5** is an example run (using genetic algorithms) where some output of up-front cost is plotted against some output of far term cost (or ~ benefit). (Note that inputs are specific to and contained inside each point in the scatter, and are not on the axes). There are various dilemmas with the design space explored if the purpose is to proceed into a program using some form of this in a business case. Although a (relatively) small amount of increase in the up-front cost (Y-axis), coupled with the right investment directions for operability, can buy a significant improvement in responsiveness, the actual total up-front amount may be funding that is simply not tenable (appealing, justifiable, etc.) Alternately the view is invaluable if the program is a technology program, wanting insights into investment directions. Each point in the scatter plot contains the numerous technology choices/inputs or “genes” for a design the output of which are the costs on X and Y.

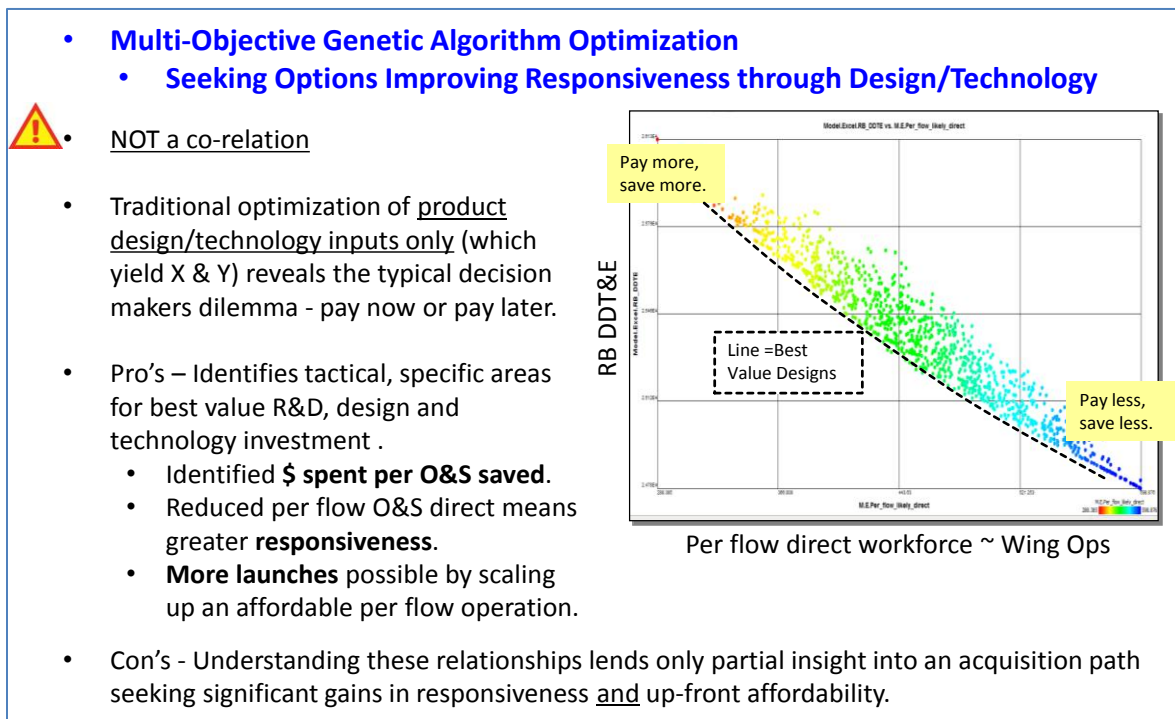


Figure 5: Traditional Optimization of Design/Technology (Only) vs. Costs Near and Far

Some caveats about the prior analysis results –

- (1) These results do not integrate risk, confidence or related uncertainties (in the data, or cost estimating relationships). This will be considered in forward work.
- (2) In lieu of a time specific analysis and set of variables (such as an integral discrete event simulation, or some type of joint cost and schedule confidence level, a “JCL”) the responsiveness is considered improved as regards model feedback when the direct, close-in wing ops workforce requirement (on the X-axis) is reduced.

RESULTS AND DISCUSSION – EFFECTIVENESS AND EFFICIENCY VIEW

Allowing the automated search of the design space to also alter the process/practice variables, the “how” to achieving the product, will yield very different results, shown in **Figure 6** vs. **Figure 5**. It is now possible to achieve the responsiveness and the recurring operations and production cost improvements for far less up-front investment (research, design, development, test, engineering, operations and production development, setup and acquisition, etc.) This inverts the slope of the scatter, as the genes of a design start at the traditional up-front and far term levels, but seek to explore all options that improve both. (While novel in the consideration of complex, large scale aerospace projects, where primes, cost-plus contracts, protected industries, and other non-market factors weigh in, this is actually the expected result, as best practices evolve this trend in competitive circumstances.)

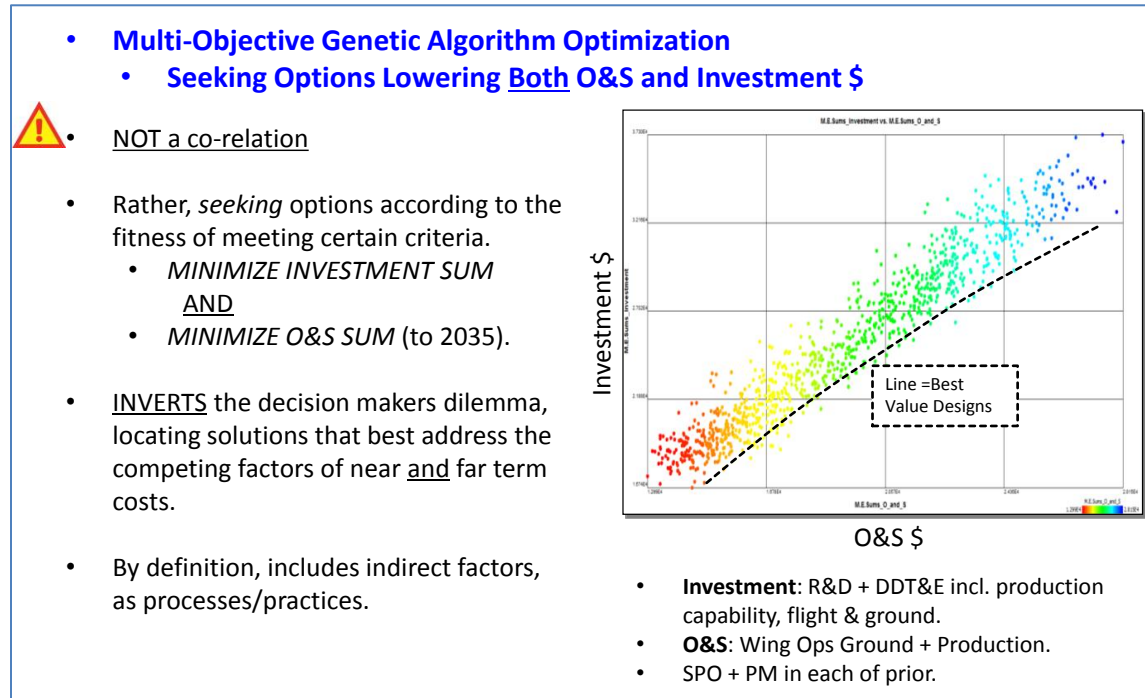


Figure 6: Comprehensive Optimization of All Variables Affecting Costs Near and Far

Interpreting the prior results -

- (1) The search starts at a baseline configuration that is higher LCC in the upper right and eventually winds its way down to the lower LCC space in the lower left (**Figure 7**). That lower LCC space is lower LCC as much for having reduced up-front cost as for having reduced future costs. The decision maker’s dilemma of insufficient up-front funding is thus addressed, pointing the way to programs that can achieve significant future improvements even in highly constrained funding situations. (Albeit, understanding how to retire one dilemma creates a new challenge, discussed ahead).
- (2) The results on the lower-end of the LCC (lower left) are ¹⁰consistent with other studies, but with more detail within, working toward a more actionable understanding. This detail could eventually inform acquisition / proposal assessment, concepts of operations for program offices, and business models for acquiring (government) and implementing (industry) organizations.
- (3) Any point on the scatters can be examined further, it’s genes (or “data deck”) capturing all the necessary information with which to explore further. This is shown in **Figure 8**. (The data can be loaded back into the MS Excel RBS LCC model automatically, further minimizing human error, generating graphs (**Figure 9**), for further analysis, etc.)

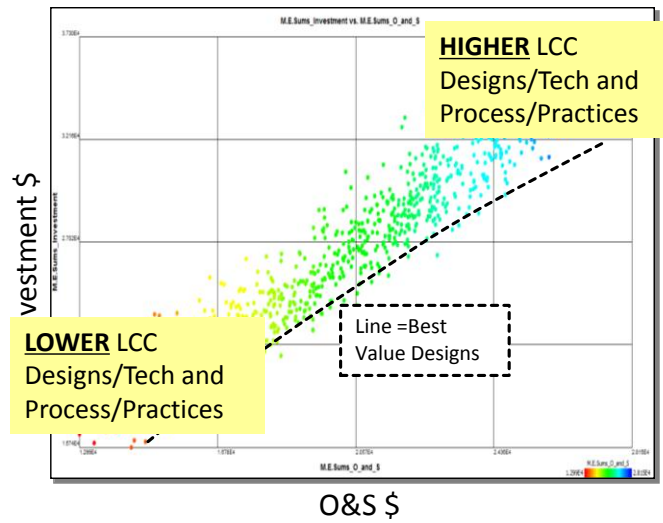
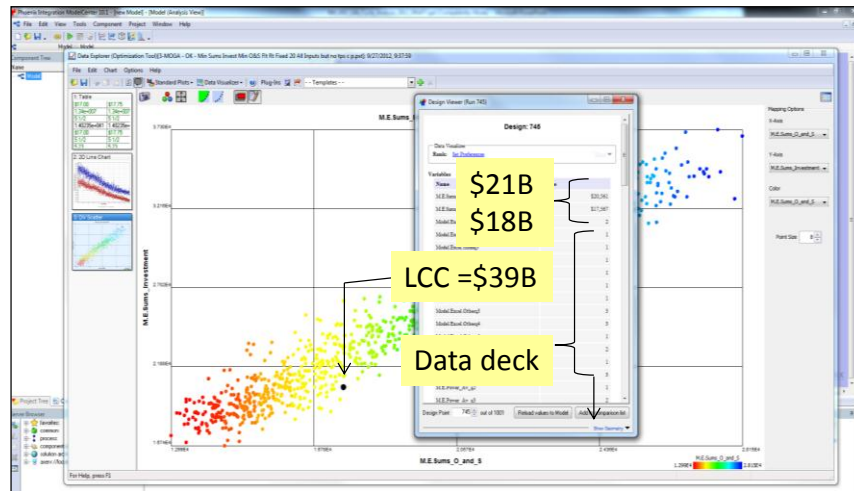


Figure 7: From High LCC to Low LCC

- Example: A single design points data deck from the prior “seeking” run.



- Ref. BoE. – 23 years, through 2035. Phasing in flights starting mid-2020’s.
- **Investment:** R&D + DDT&E incl. production capability, flight & ground.
- **O&S:** Wing Ops Ground + Production.
- SPO + PM in each of prior.

Figure 8: A Specific Set of Inputs Viewable for Exploring Further

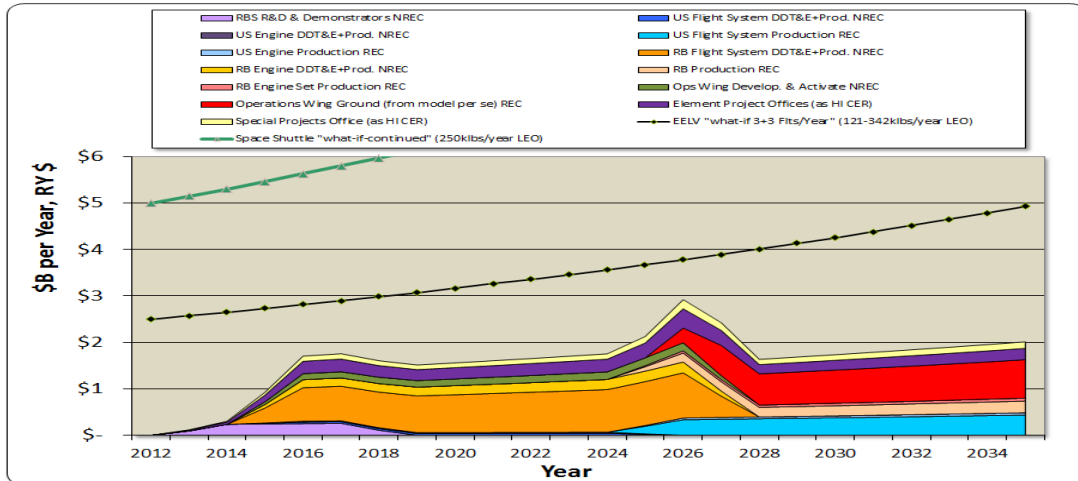


Figure 9: The Prior Example Design Point Loaded Automatically Back into the Original RBS LCC MS Excel Model

SUMMARY AND CONCLUSIONS

It is possible to structure aerospace project cost models in such a way as to avoid the pitfalls of product centric views. Product centric views are susceptible to being cost models that avoid addressing the cause of most costs. Process/practice emphasis in causality, where decisions reign, can be achieved by exploring historical cost data within the proper context and using decision analysis techniques for establishing relationships at manageable levels of detail. Automation, the use of "models of models", can make these techniques manageable, while still preserving a sense of simplicity for the analyst or stakeholders receiving the results of such analysis.

FUTURE WORK

Work in 2013 has focused on collecting and addressing feedback on the 2012 results. As a result, current work includes:

- Especial emphasis on improving the process/practices section of the model.
- Improve the models:
 - User interface.
 - Level of fidelity as appropriate to the analysis phase, pre-acquisition.
 - Transparency of estimating relationships.
 - Ease of being modified by either the developer or new users.
 - Usefulness as a learning tool, independent of an analyst generating results.
- Develop "top-10" lists of:
 - Prioritized technology specifics and directions
 - Prioritized industry process/practice specifics and directions
- Develop prioritized list of further upgrades.

The process/practice section of the model is receiving special attention in 2013 work. Evolving towards more recognizable foundations, this section will be refined anew around source material such as the DoD Integrated Product and Process Development Handbook, the Manufacturing Readiness Levels Deskbook, the Lean Aerospace (Advancement) Initiative, the Lean Enterprise Model, the Supply Chain

Readiness Levels study, numerous lean product development practice compilations, and more. **Figure 10** shows the notional approach to this part of the model/methodology upgrade.

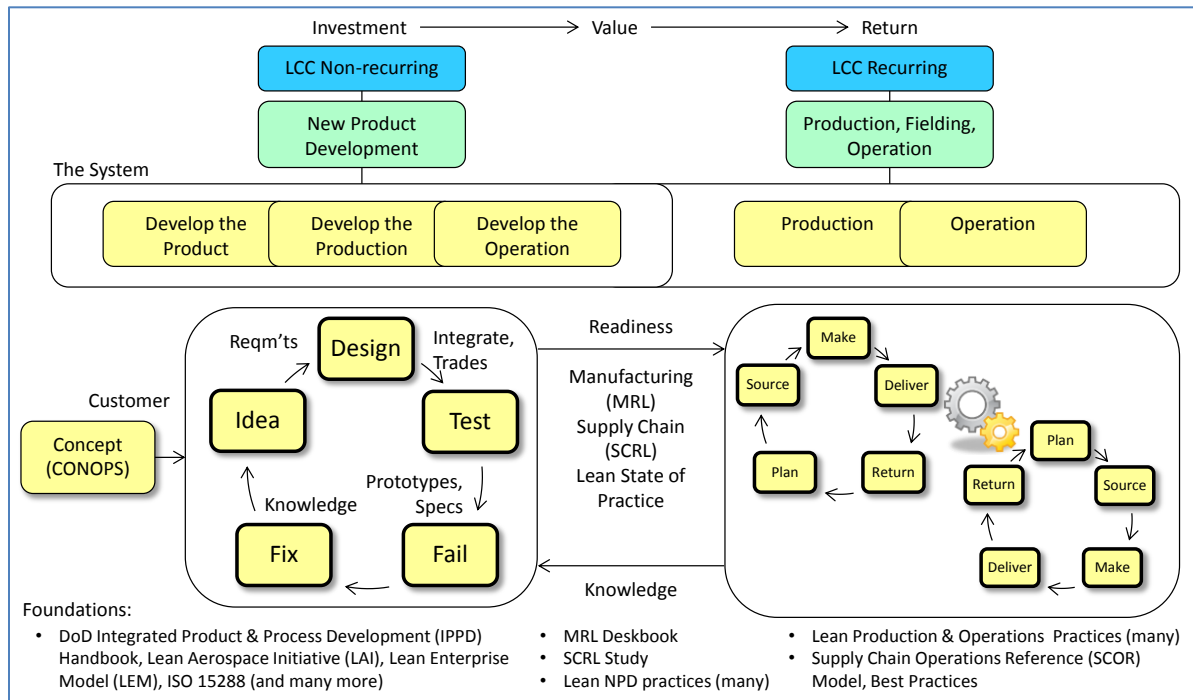


Figure 10: RBS LCC Model Process/Practices Methodology Upgrade in Progress

At the end of 2013, the plan is to distribute the model across a broader, external stakeholder community. Numerous collaborative discussions to that end have already begun.

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REFERENCES

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- ¹ “Air Force Reusable Booster System, A Quick-Look, Design Focused Modeling and Cost Analysis Study”, Edgar Zapata, National Aeronautics and Space Administration, Kennedy Space Center, Florida. Presented at the 2011 Joint Army Navy NASA Air Force (JANNAF) conference.
- ² “DoD Life Cycle Management (LCM) & Product Support Manager (PSM) Rapid Deployment Training”, available at: [https://acc.dau.mil/adl/en-US/399891/file/58190/PSM%20RDT%20\(v10%20Tailored%2014%20Jun%2011\).pdf](https://acc.dau.mil/adl/en-US/399891/file/58190/PSM%20RDT%20(v10%20Tailored%2014%20Jun%2011).pdf), viewed on 2/25/13.
- ³ Department of Defense Standard Practice Work Breakdown Structures for Defense Materiel Items”, MIL-STD-881C, October 2011. (Reinstated after 3 October 2011 and may be used for new and existing designs and acquisitions.)
- ⁴ “Trends in a Sample of Defense Aircraft Contractors Costs”, James McCullough, Stephen Balut, Institute for Defense Analysis, 1990.
- ⁵ “Estimating Fixed and Variable Costs of Airframe Manufacturers”, Stephen J. Balut, Thomas P. Frazier, James Bui, 1991.
- ⁶ The Kennedy Space Center Launch and Landing Effects Ground Operations (LLEGO) model. Information at: <http://science.ksc.nasa.gov/shuttle/nexgen/Models/LLEGO.htm>, viewed on 2/25/13.
- ⁷ “Decomposition and the Control of Errors in Decision Analytic Models”, Don N. Kleinmuntz, Sloan School of Management, Massachusetts Institute of Technology, May 1988. Also available at <http://18.7.29.232/bitstream/handle/1721.1/47217/decompositioncon00klei.pdf?sequence=1>. Viewed on 2/25/13.
- ⁸ “Falcon 9 Launch Vehicle NAFCOM Cost Estimates”, NASA Associate Deputy Administrator for Policy, August 2011.
- ⁹ “Commercial Market Assessment for Crew and Cargo Systems Pursuant to Section 403 of the NASA Authorization Act of 2010 (P.L. 111-267)”, April 27, 2011.
- ¹⁰ “Determining Logistics Ground Support Manpower Requirements for a Reusable Military Launch Vehicle, Thesis, Sydney C. Michalski, Captain, USAF, AFIT/GLM/ENS/07-09, Department of the Air Force, Air University, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio (APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED).