

An Implementation of Automated Structural Design-To-Cost in a Model Based Engineering Environment

Christopher Price and Apinut Sirirojvisuth (PRICE Systems)

Leonor Hagberg, Brig Bjorn, and Daphne Biddle (Lockheed Martin – Missiles and Fire Control)

ABSTRACT:

The integration of Computer-Aided Design (CAD) tools with Cost Analytic tools in a Model Based Engineering (MBE) environment allows designers to quickly and easily estimate the cost of structural designs as they are designing, thereby directly supporting Design-To-Cost. This paper will demonstrate how quick and easy it is to estimate modifications to a structural assembly using such COTS integration environment.

I. Introduction

The Problem

The Aerospace and Defense industry breeds the world's brightest technical minds – engineers in particular – but the attempt to produce the best possible products and systems frequently forces these brilliant minds into specialized disciplines, creating Subject Matter Experts (SMEs) who are very knowledgeable in very specific technical areas of expertise. This specialized focus can keep SMEs from seeing the full impact of their designs on areas outside of their discipline. Model Based Engineering promises to broaden the view of the design engineers, allowing them to easily collaborate with other disciplines and see the results of their designs in multiple functional dimensions of the products they are creating. These functional dimensions include the areas of producibility, safety, reliability, maintainability, affordability, and many other key design area considerations. In the past, all of these activities were performed serially by separate SMEs, with manual, oftentimes disjointed feedback loops. This inefficient process frequently led to product redesign caused by a lack of timely information and a thorough understanding of the design and its impacts across the program disciplines. Integrated Product Teams (IPTs) have eased this difficulty, but the process still requires a significant number of individual interactions within the team before the IPT has the full understanding of the design impact. Model Based Engineering promises to automate many of these manual interfaces in an integrated design environment giving design engineers the ability to see all aspects and impacts of the design decisions made. Many organizations are currently working towards this goal.

The Current State

Historically, organizations have been pressured to adhere to requirements that focus on performance, schedule, and risk. The Affordability team has had less influence on design decisions, and as a result, lifecycle cost assessments are typically a by-product of an already committed design this is too late in the design process to allow Affordability to influence the design decisions (Figure 1).

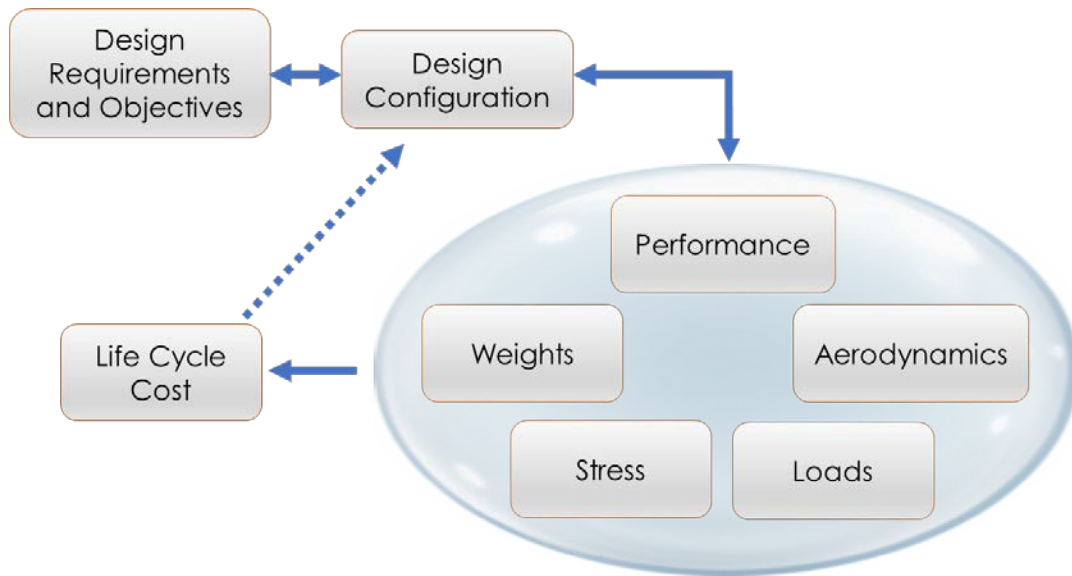


Figure 1. The Conventional Design Process

Design-influencing disciplines are fragmented and decoupled from one another. These disconnects in the design process open the door to error. In addition, the design is inflexible and unable to accommodate rapid changes, and design excursions tend to stay in the mold of previously successful products and technologies. Low-risk alternatives are typically selected but better alternatives may be discovered if the cost and schedule risks are better managed through improved efficiency in the design process.

In the current state of non-model-based systems design, a design engineer creates Computer Aided Design (CAD) models and makes changes as the design evolves. If the design engineer is required to know the cost of the design, the engineer works with a cost analyst to develop a cost model to reflect the CAD model design.

This current-state process is time intensive. The design engineer works individually to make design changes. Then the engineer passes on the information to the cost analyst. The cost analyst incorporates these inputs into the model. Finally, the cost analyst returns the results to the design engineer.

Depending on the workload of the cost analyst, it may be hours or days before the design engineer receives the results of the cost model. Once the results are received, additional time is needed to determine the path forward. Decision-making using non-model-based systems is thus an extremely time-intensive effort.

Figure 2 illustrates the feedback loop between design engineer and cost analyst.

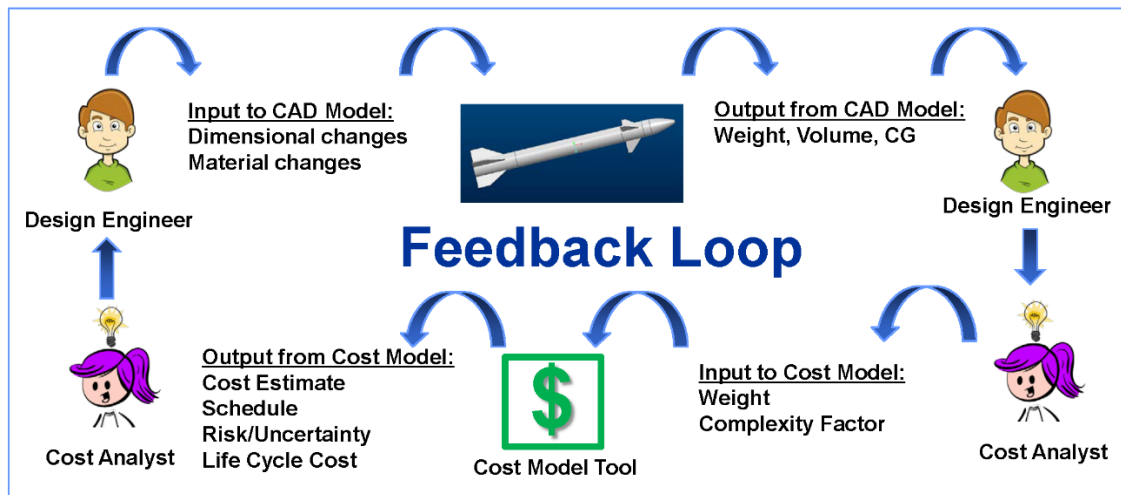


Figure 2. Feedback Loop for Design Engineer and Cost Analyst

Using a conventional design process, a design engineer takes 30-60 minutes to make changes to a CAD file, depending on the complexity of the part. A cost analyst takes roughly the same amount of time, depending on the complexity of the changes. But the true disadvantage of non-model-based systems is the span time it takes to turn around results. The span time between a design engineer and cost analyst can easily grow to hours or days, depending on complexity of changes and priorities for each.

The Solution – Future State

As tools evolve to become more collaborative and easily integrated, the processes for developing solutions will evolve as well. A highly integrated and collaborative environment, where analyses are dynamically driven by current engineering data rather than by static snapshots, enables real-time feedback on the cost of solutions and the root causes of cost drivers. A wider set of solution options emerges. Additionally, management gets visibility into critical system parameters, especially cost, with traceability to requirement sources. The transparency from all sides aids an optimization of the system design, providing a system solution of greatest value to the Customer.

For cost estimators, this new environment means a marked improvement on how their critical work is performed. High-quality and up-to-date design data is readily available to support cost estimates. Integrated environments support continuous integration of data and real-time feedback between

functional disciplines regarding the impacts of design decisions on cost, producibility, supportability, schedule, performance, and risk. The design engineer and Program Management are able to examine those parameters that are of most value to the Customer. Specialists spend less time chasing down data and can more quickly examine the key selection criteria that the Customer has identified as of most value to their needs.

Figure 3 [ref1:] depicts a notional future state MBE environment where specific design processes and models are integrated to support automated feedback loops to the design engineer. This figure also emphasizes that Life Cycle Cost, which was traditionally performed at the end of the design cycle, is now integrated into the design process, allowing for early LCC estimates during Concept Development.

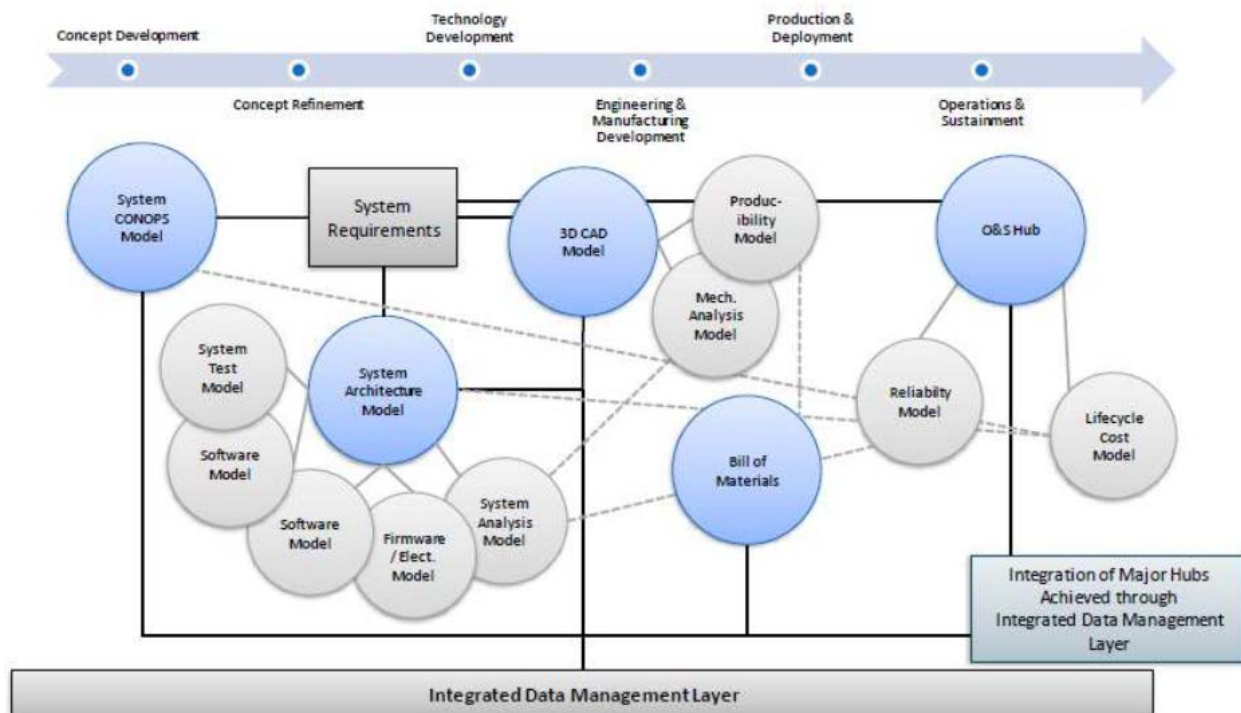


Figure 3. A Notional MBE Environment

This paper presents a case study on the integration of Affordability with Structural Design in a Model Based Engineering environment.

II. The Integration of Structural Design and Affordability in a Model Based Engineering Environment – A Case Study

Notional High-Velocity Missile Sizing and Analysis

The goal of this case study is to advance the existing design process by developing a new paradigm consisting of an interconnected and rapid response design environment. We will use a notional High-Velocity Missile (HVM) design task to demonstrate the up-front work required to set up representative models for performance analysis, structural design, CAD model, and lifecycle cost analysis. These disciplinary models can then be integrated in a Model-Based Engineering environment using COTS

Integration MBE Environment tools. These tools are required to enable analysis automation, instant design feedback, and rapid design exploration to then estimate the relative value for a family of design alternatives. These models and their purpose are capture in the following section:

The CAD Model

For this case study, we designed an inert missile using a popular CAD software tool. The missile has four components: Body, Tail, Fins, and Nose (see Figure 4).

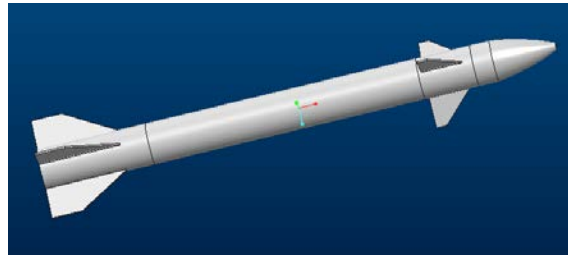


Figure 4. Inert Missile Designed in a Popular CAD Software Tool

A timeline of creating the inert missile in CAD is shown in Table 1.

Table 1: Timeline of Creating CAD File of Inert Missile

	Time (minutes)
Set up CAD environment and mass properties	10
Create missile body	5
Create missile nose	15
Create missile fins	10
Create missile tail	10
TOTAL	50

The overall dimensions of the inert missile are shown in Table 2.

Table 2: Overall Dimensions of Inert Missile

	Overall Dimensions
Length	38 inches
Diameter	3 inches
Volume	70 cubic inches
Weight	6.89 pounds
Material	Aluminum 6061

We designed this case study to show how information can be moved from one application to another within the Model Based Environment. Specifically, we show how technical data (weight in this case) is transferred from the missile CAD model to a parametric cost estimation model (described later in this paper).

Figure 4 shows the HVM component layout and basic parameters used to construct its geometry. A simplified missile consists of tail, body, fin, and nose sections. The variation in body height, body diameter, wall thickness, and payload height determine the overall performance of the rocket.

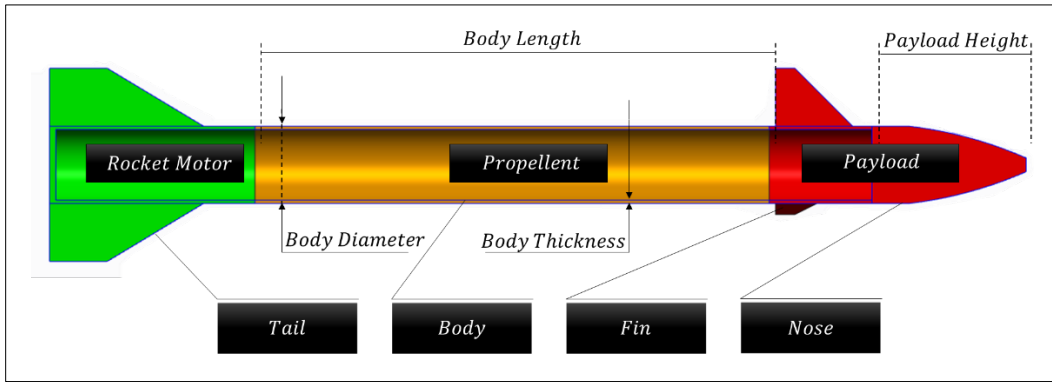


Figure 4: Component Layout and Basic Geometry Parameters

Performance Model

The analysis of missile performance is based on an application of momentum theorem, also known as ideal rocket equation or Tsiolkovsky rocket equation [ref2:], which describes the motion of the vehicle, represented as a point mass. The diagram of forces during flight is shown in Figure 5. As shown, a vehicle mass m_v experiences drag in the direction of its flight path (θ) and thrust in the thrust vector angle (α) relative to horizontal plane. The propellant is stored in the body of the missile and consumed at the rate \dot{m} .

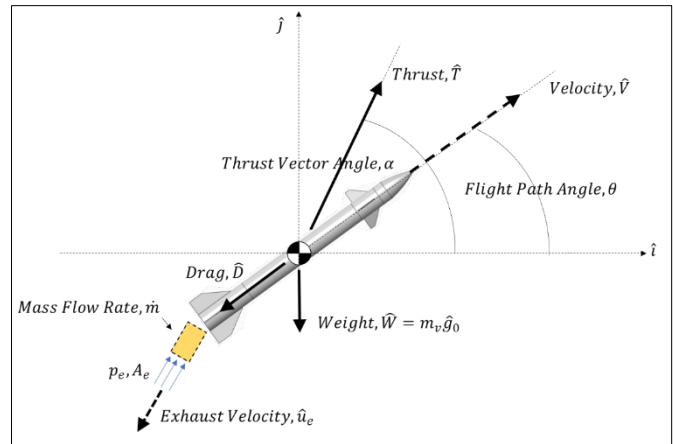


Figure 5. Force Diagram for Missile Performance Analysis

Consider the forces acting on the system during flight:

$$\sum \hat{F} = \hat{T} + \hat{D} + \hat{W}, \quad \hat{T} = \hat{A}_e(p_e - p_0) + \frac{dm}{dt} \hat{u}_e \cong \frac{dm}{dt} \cdot I_{sp} \cdot \hat{g}_0, \quad \hat{D} = \frac{\rho \hat{V}^2 C_D A}{2}, \text{ and } \hat{W} = m_v \hat{g}_0$$

Vehicle flight simulation is developed using a Python program to integrate the equations of motion over time. Each time step, the simulation calculates the vehicle mass (m_v), propellant mass (m_p), coordinate velocities (u, v), orientation (θ), altitude (alt), distance (dis), and acceleration (\hat{a}), along with the vehicle state vector (S). As time step advances in the simulation, the vehicle state vector is updated to (S^*) and become the new state for the next time step:

$$S = \begin{bmatrix} m_v \\ m_p \\ u \\ v \\ \theta \\ alt \\ dis \end{bmatrix}, \quad \hat{a} = \frac{\hat{T} + \hat{D} + \hat{W}}{m_v}, \quad \Delta\hat{V} = \hat{a}\Delta t, \quad \dot{m} = \frac{T}{Isp}, \quad S^* = \begin{bmatrix} m_v - \dot{m} \\ m_p - \dot{m} \\ u + a_i\Delta t \\ v + a_j\Delta t \\ \text{atan}\left(\frac{v + a_j\Delta t}{u + a_i\Delta t}\right) \\ alt + V_j\Delta t \\ dis + + V_i\Delta t \end{bmatrix}$$

In addition to supplying values for each element in the state vector, several fixed parameters that do not change over the course of the simulation are required. These simulation constants are shown in Table 3.

Simulation Ground Rules and Constants

- ***Isp***: The specific impulse of a rocket engine determines how effectively a rocket uses propellant. The typical value for a high-velocity, high-altitude rocket is between 120 and 300 for ammonium perchlorate-based (APCP) propellant.
- **α** : The thrust vector is assumed to be fixed and independent of flight trajectory to simplify the vehicle dynamic, thus allowing drag force to be properly calculated.
- ***Thrust factor***: For early sizing analysis, the thrust produced is assumed to be constant throughout the flight and equal to a factor of total vehicle mass. This factor is set so that as the vehicle mass sizes up or down due to changes in physical dimensions, the thrust produced will be enough to overcome drag and gravity. This rubberized engine thrust will then determine the fuel burn rate.
- **Cd, ρ, \hat{g}_0** : Drag coefficient, air density, and gravitational acceleration are assumed to be constant throughout flight.

Table 3. Simulation Constants

Parameter	Description	Unit	Value
<i>Isp</i>	Specific Impulse	s	180
α	Thrust vector angle	deg	45
<i>Thrust factor</i>	Ratio of thrust to vehicle mass	–	1.5
<i>Cd</i>	Drag coefficient	–	0.12
ρ	Air density	kg/m ³	1.225
\hat{g}_0	Earth's gravitational acceleration	m/s ²	9.81

Output metrics

Figure 6 illustrates the HVM simulated flight trajectory. The flight path starts with a constant-thrust burn period defined by the red data points, followed by a free-fall period in blue. The total distance (range), max altitude, and terminal velocity are also captured for further analysis. This simple 3-DoF model is appropriate for the early conceptual phase, when overall performance is the main interest. A full vehicle dynamic, 6-DoF or higher-order model may be required when considering the ability of a more detailed vehicle design to perform target acquisition and flight control.

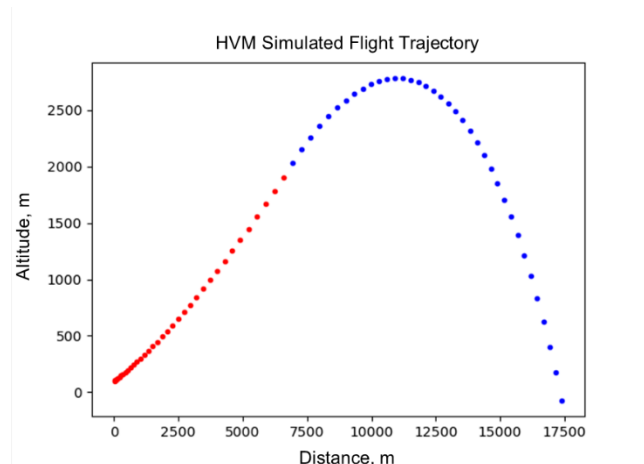


Figure 6. HVM Simulated Flight Trajectory

The Cost Model

The outputs from the CAD model can be transferred to a parametric cost estimation tool to provide feedback to the designer on the impact of changes to cost. Parametric cost models are powerful estimating tools in this sense, as they easily support the rapid and accurate cost estimation of multiple designs.

In a parametric cost estimation tool, the key required inputs are a Product Breakdown Structure (PBS), weight (from the CAD model), and complexity of structure. Table 4 illustrates the cost model setup.

Table 4. Parametric Cost Model Setup

Need a heading here	Parametric Cost Model Setup
Operating Environment	Airborne Missiles
Start Date	March 2018
Number of Prototypes	5
Number of Production Units	5000
Worksheet Set	A
Weight	According to CAD file
Complexity of Structure	Conceptual Calculator

Once the cost model was set up, the next step was to input weight and complexity factors for each CAD variation.

Figure 7 shows a parametric cost model of an HVM missile where component weights, manufacturing processes, and materials will determine amortized unit production cost.

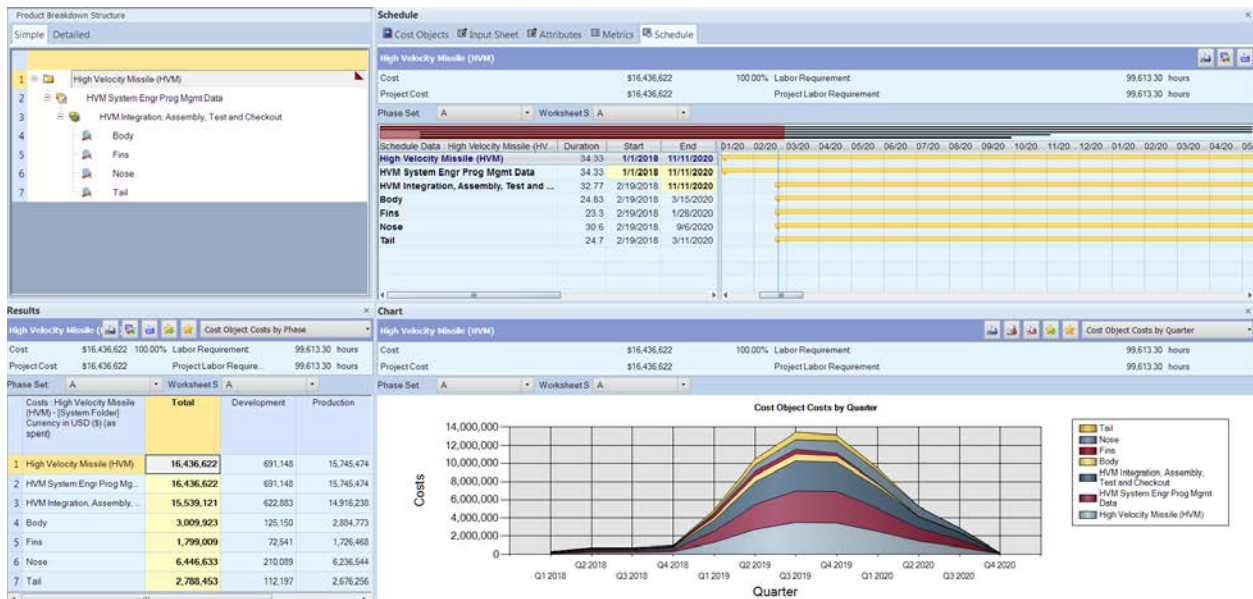


Figure 7. Parametric Cost Model

Model Based Engineering (MBE) Environment

This section describes the final stage of pulling the analyses together. The design engineer's first step is to understand the possible sources of design variations and ensure that those design parameters are exposed within the MBE environment. Examples of design parameters and design process flow are illustrated in Figure 8. The next step is the linkage of relevant inputs and outputs between modules to allow complete automation of data flow. Setting up a reusable and expandable design process is the key to future MBE processes. The COTS Integration Environment tool enables SMEs to be virtually co-located to communicate the changes in design and receive rapid feedback between key functional disciplines and selection criteria. Figure 9 is a screenshot of the completed MBE environment ready for various design studies and trade-off analyses.

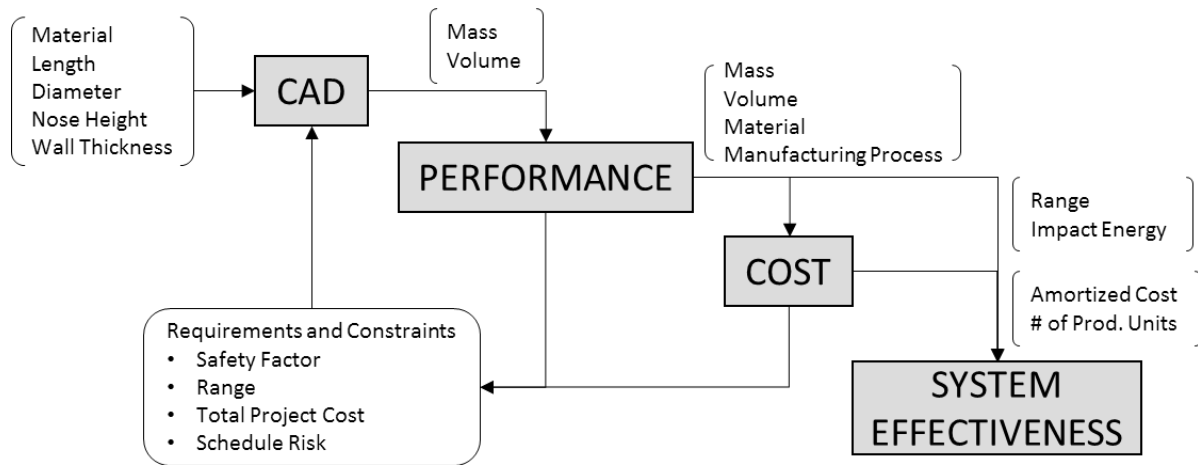


Figure 8. Notional Conceptual Design Process

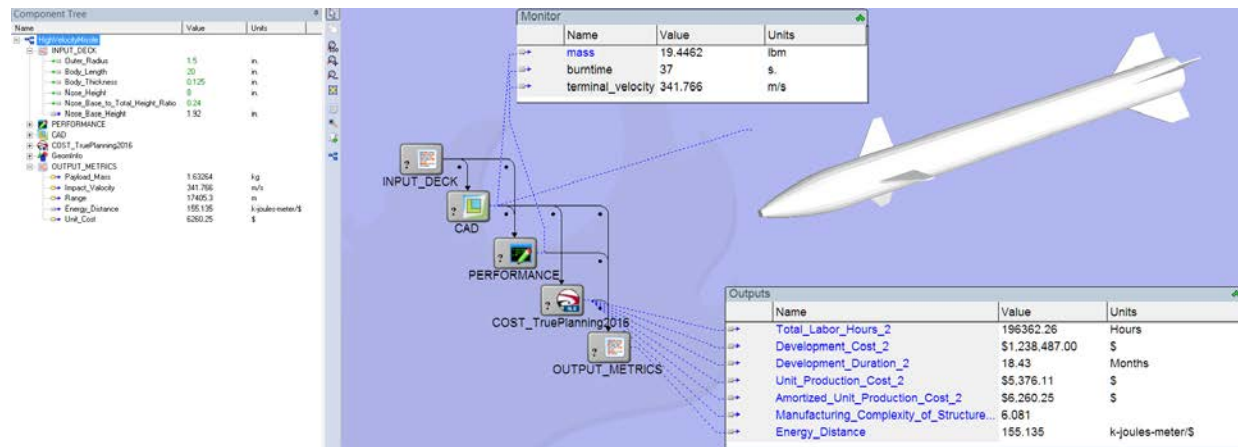


Figure 9. MBE in COTS Integration Environment Tool

Independent Variables, Design Constraints, and Risk Factors

In an MBE environment such as this, a single design iteration can provide feedback to the design engineer in seconds, as opposed to the hours or days it can take using the conventional design process. Moreover, the integration of missile performance and metrics gives the design engineer valuable insight into which architectures provide the most value, in a rapid fashion.

In this paper we demonstrate a missile conceptual design study where a change in one or more of the input parameters triggers a recalculation of performance, cost, and a composite measure of system efficiency. Table 5 lists the input parameters, and the baseline, min, and max values used for this study. In addition, design constraints can be imposed where only the alternatives that meet all the requirements are considered. For the purposes of this study, we include three representative design constraints found in this type of design: minimum values for range, impact energy, and structural factor of safety. Finally, external risk can be factored in to see whether changing those risk factors will severely impact the design choice, allowing a more robust solution to emerge. For simplicity, we assume Total

Project Cost to be the only external risk factor faced by the program manager, where the customer has the absolute power to dictate what they are willing to spend on a project. Of particular interest is the inclusion of a detailed cost estimating module where materials and manufacturing process selections are inputs to the cost model in addition to the structural weights. Table 6 illustrates how material and process selection can influence design decisions. For example, a first-order approximation based on material yield strength is used to determine appropriate wall thicknesses depending upon the material selected. Another example is the use of an internally calibrated complexity factor for each combination of material and manufacturing processes. The integration of a detailed cost estimate into the MBE environment eliminates the need for the Cost Analyst to manually respond to every design change. The time saved can be used more productively to improve model accuracy and scope as the program progresses.

Table 5. Design Variables and Their Value Ranges

Parameter	Unit	Baseline	Min	Max
Body Length	inch	15	10	20
Body Diameter	inch	3	1	5
Wall Thickness	inch	1.5	1	3
Nose Height	inch	6	5	10
Production Unit	unit	1000	100	5000
Material	–	Aluminum, Steel, Titanium		
Manufacturing Process	–	Casting, Hi/Low Precision Machining		

Table 6. Material and Process Factors for Cost Analysis and Safety Factor Determination

Item	Material 1	Material 2	Material 3
Material Description	Aluminum 6061-T6511 [ref3:]	S31266 Stainless Steel [ref4:]	Titanium Ti-6Al-4V [ref5:]
Yield Strength (GPA)	276	470	570
Density (lb/in ³)	0.097	0.296	0.160
Relative Wall Thickness for same safety factor	1	0.587	0.484
Casting Process Complexity	5.890	6.050	6.130
Machining Process Complexity	6.140	6.300	6.380
Precision Machining Complexity	6.490	6.670	6.750

Objective Function

An objective function, or value function, is a mathematical formulation that combines outputs from all design disciplines into a single equation, called HVM System Efficiency (HVM-SE). The HVM-SE value represents how well a design alternative performs compared to others. It is defined as the ratio of Total Utility over Total Project Cost. The equation below expands on the definition for each metric. Care must be taken when using this type of formulation to ensure that design constraints and customer requirements are considered. Implicitly, only alternatives that pass certain criteria are included, or a penalty function can be imposed on the design alternatives that do not meet those requirements.

$$\begin{aligned}
 \text{HVM System Effectiveness} &= \frac{\text{Total Utility}}{\text{Total Project Cost}} \\
 &= \frac{\text{Impact Energy} * \text{Range} * \text{Total Unit}}{\text{Total Development and Production Cost}'} \\
 &= \frac{(1/2 \cdot m_v \cdot V^2) * \text{Range}}{\text{Amortized Unit Cost}'} \quad \frac{\text{kJ} \cdot \text{m}}{\$}
 \end{aligned}$$

Generative Design

The ultimate goal in the conceptual design phase is to filter out an infinite number of design alternatives to a manageable, countable subset as quickly and as informedly as possible. The first step in that direction is to use a methodology called Parameter Scan, where the combination of all extreme values for both discrete and continuous design variables is studied. This study can be effectively used to eliminate design variable(s) that do not contribute to acceptable design outcomes. In this case, although stainless steel allows wall thickness to be reduced by half compared to aluminum, the low strength-to-weight ratio contributes to an excessively high structural weight which contributes to higher cost for the same performance. All stainless steel designs are inferior in terms of system efficiency. Thus, only aluminum and titanium will be considered further. Figure 10 shows the comparison between these three materials using Parameter Scan analysis. The design extremes that meet the range, energy, and cost requirements are highlighted in red. Since none of the stainless steel options meet the criteria, that material can be safely eliminated from further considerations.

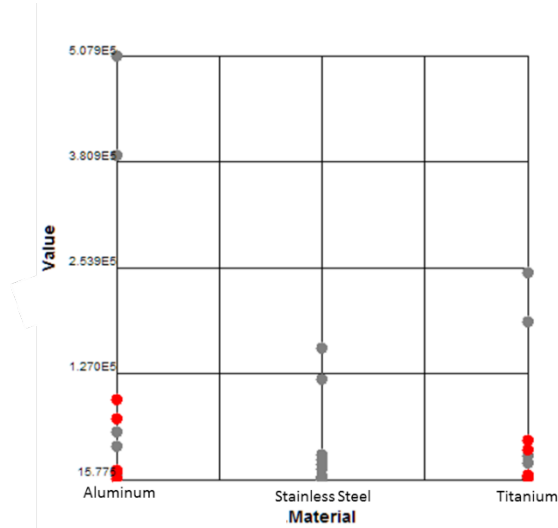


Figure 10. Comparison of Material Selection Based on Parameter Scan Analysis

A more detailed study can be done using the Design of Experiment (DOE) methodology to discover the variation of design outcome based on the change in independent design variables, and to understand the interaction that exists within differing domains of analyses. Sensitivity Analysis is one of the results from DOE, where a Pareto plot shows variable influence on system efficiency (Figure 11). The relative importance of each design variable is shown.

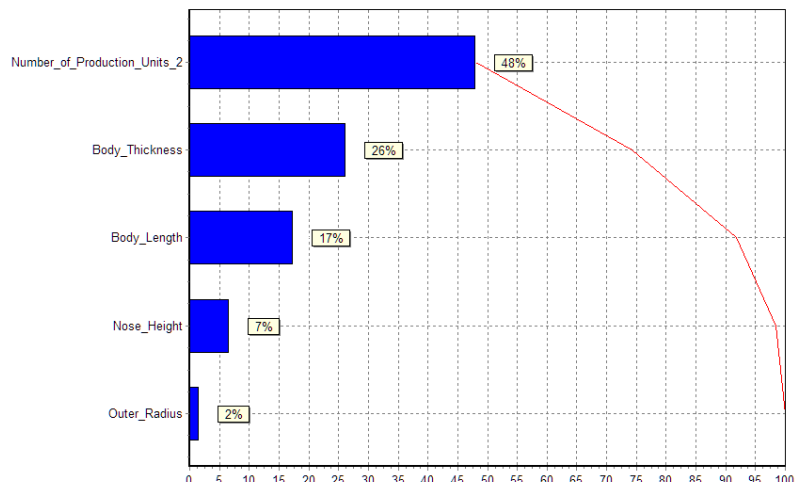


Figure 11. Pareto Plot of Variables' Relative Influences to System Efficiency

Finally, once the parameters' sensitivity and the degree of interaction are better understood, a feasible design space can be established for each discrete variable, in this case, one for aluminum design, and one for titanium. Figure 12 shows an example of a feasible space for aluminum designs. Four design limits/constraints are superimposed to establish the infeasible design under the covered area. Also shown along the border of each constraint is the direction of a more stringent requirement. The uncovered area (i.e., white space) defines the feasible design space. The gradient of increasing system efficiency is shown by the green contour plot, with the direction of improvement shown by the gray arrow. The design engineer is now empowered to make a preliminary informed decision to include or discard certain design alternatives as he or she sees fit.

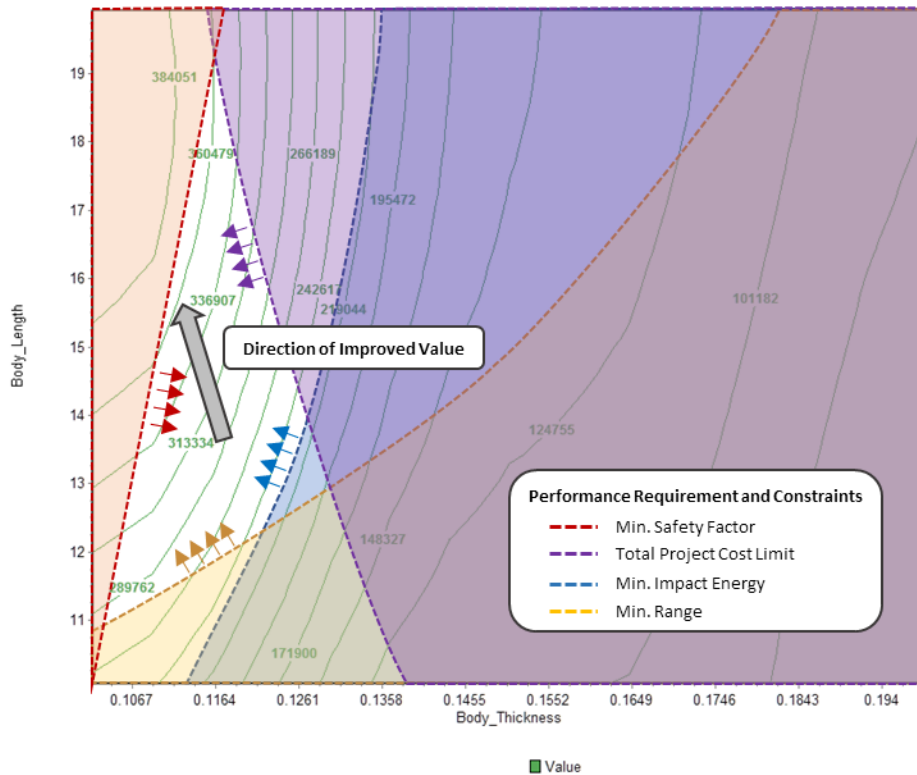


Figure 12. Feasible Design Space for Aluminum Design

Risk-Adjusted Design Selection

It is generally understood that however the system value function is defined, the best value design should be the one selected in the end. But because of the conceptual nature of the early design study, focusing on best value is not always possible since the early phases of the design are accompanied by high uncertainty in the requirements and a fuzzy view of the end goal. One example faced by government contractors and Original Equipment Manufacturers (OEMs) is the fluidity of the total available funding, which is often considered as Rough-Order-of-Magnitude (ROM) in the beginning. It is evident throughout this study that Total Project Cost has a monumental impact on the ability for a design engineer to choose some viable, risk-based alternatives in the early phases. Figure 13 shows a Pareto Frontier of designs that perform best under different production volumes.

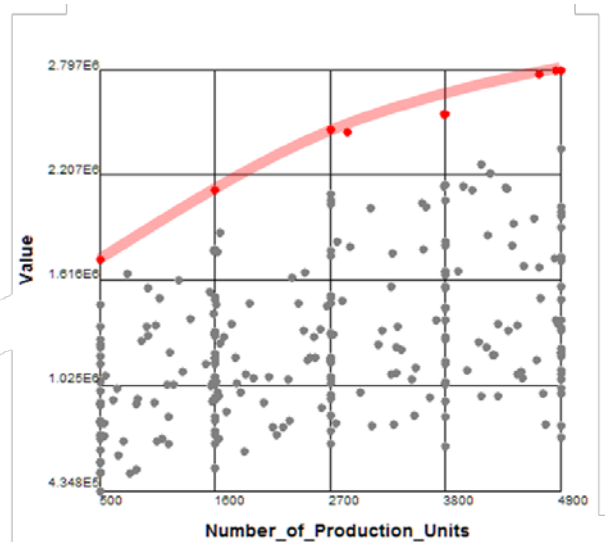


Figure 13. A family of robust design alternatives under external risk

Result

Currently, at the conclusion of a conceptual design phase study, the design engineer carries the burden of freezing some aspects of the design so that further detailed analyses can begin. An MBE methodology can effectively communicate design choices and the supporting rationale to decision makers. Figure 14 provides an example of an MBE-enabled methodology to effectively communicate design choices and the data behind the designs. It can also highlight the impact of risk on decision making. For example, the designer could suggest the most likely wall thickness and nose height values for a particular total project cost. In the figure, as the production quantity increases from 500 to 4900 units, Total Utility increases at a faster pace than Total Project Cost, leading to a higher overall Value, as shown on the left vertical axis. The corresponding best Wall Thickness and Nose Height values are shown on the vertical right axis. Increasing production volume typically gains the benefit of economies of scale, also called learning curve effect. However, production unit cost is tightly related to how much the customer is willing to pay for the entire project, i.e., total project cost. Unfortunately, using the conventional design process, engineers and program managers do not have enough bandwidth to explore every design option under various external uncertain situations, nor do they have enough flexibility to react to changes appropriately. A combination of detailed cost/affordability analysis and MBE technology can be a step toward a more effective dialog between customer and design organizations. The MBE process supports the US Government Accounting Office (GAO) Cost Estimation Best Practice [ref6:] by providing a rigorous cost sensitivity analysis based on cost and technical / performance parameter trades.

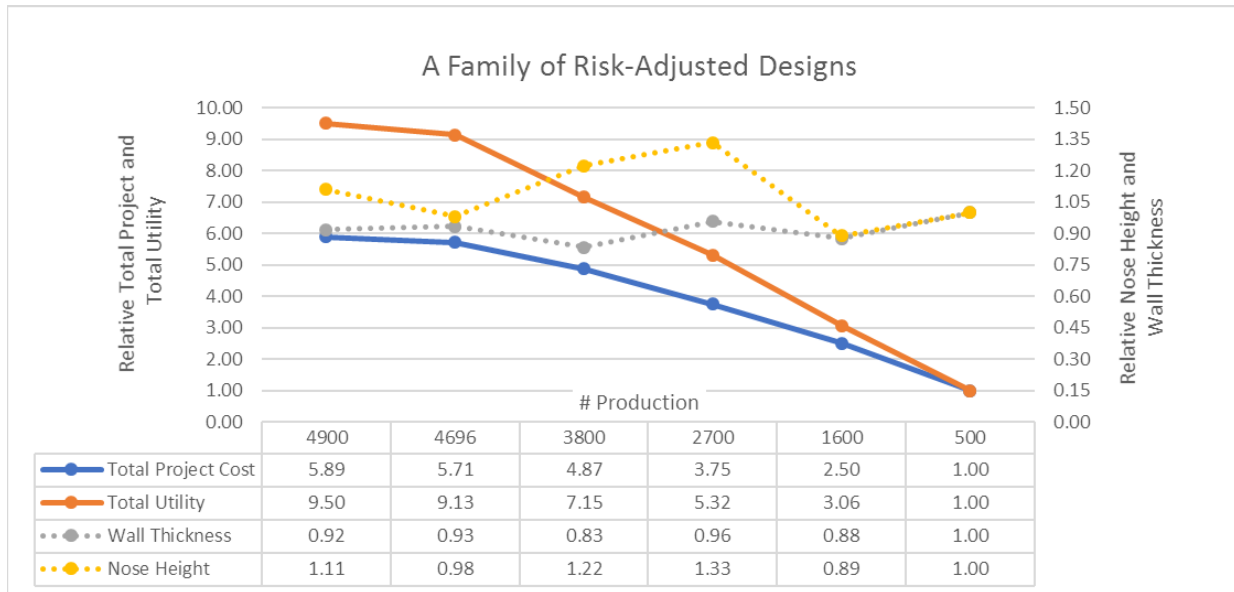


Figure 14. A Family of Best Design Alternatives Based on Number of Production Units for HVM

III. Summary

This case study demonstrates the value in moving from a conventional design process to a Model Based Engineering process. In addition to a significant time savings, the MBE process provides additional value in terms of the integration of performance measures, to allow the design engineer the ability to quickly optimize the design to achieve a balance of performance and affordability.

This case study also included a conventional design time study (Appendix A), which demonstrates that the MBE process results in a significant time savings in performing trades – seconds versus hours-to-days. Using this as motivation Government, industry, and tool vendors are moving towards an integrated environment. This research demonstrates that even on a small scale, there is significant benefit to a higher degree of integration among design and analysis tools in the development of complex systems.

References

[Ref1] Hart, Laura; Lockheed Martin; July 30, 2015; “Introduction To Model-Based System Engineering (MBSE) and SysML”, Presentation at the Delaware Valley INCOSE Chapter Meeting; <https://www.incose.org/docs/default-source/delaware-valley/mbse-overview-incose-30-july-2015.pdf>

[Ref2] Tsiolkovsky rocket equation, https://en.wikipedia.org/wiki/Tsiolkovsky_rocket_equation

[Ref3] Aluminum 6061-T6511 mechanical properties, <https://www.azom.com/article.aspx?ArticleID=2863>

[Ref4] S31266 Stainless Steel mechanical properties, <https://www.makeitfrom.com/material-properties/UNS-S31266-Stainless-Steel>

[Ref5] Titanium Ti-6Al-4V mechanical properties, https://en.wikipedia.org/wiki/Titanium_alloy

[Ref6] GAO Cost Estimating and Assessment Guide, <https://www.gao.gov/products/GAO-09-3SP>

APPENDIX A: Current State Design Cycle Times and Sample Design Variations

To emphasize and attempt to quantify the time savings of moving from a conventional design process (current state) to an MBE process, we performed a conventional design process time study.

CAD Model Variations

To study the difficulty of non-model-based systems, we measured the time it took to vary the geometry and mass properties (length, diameter, and material) of the CAD missile.

First, we varied the length of the missile body while keeping the diameter and material properties the same. See Table A1 for length variations and results.

Length Variation	INPUT			RESULTS	
	Length	Diameter	Material	Weight (lb)	Time to Modify CAD Model
Control Group	38	3	Aluminum	6.89	-
Trial 1 - Length	42	3	Aluminum	7.30	8 min
Trial 2 - Length	46	3	Aluminum	7.74	10 min
Trial 3 - Length	50	3	Aluminum	8.18	9 min

Table A1. Length Variations of Missile Body

Second, we varied the diameter of the missile body while keeping the length and material properties the same. The diameters of the nose, fins, and tail were changed accordingly to match the missile body. See Table A2 for results.

Diameter Variation	INPUT			RESULTS	
	Length	Diameter	Material	Weight (lb)	Time to Modify CAD Model
Control Group	38	3	Aluminum	6.89	-
Trial 1 - Diameter	38	3.5	Aluminum	11.05	15 min
Trial 2 - Diameter	38	4.5	Aluminum	13.73	20 min
Trial 3 - Diameter	38	5	Aluminum	17.01	24 min

Table A2. Diameter Variations

Third and last, we varied the material of the missile body while keeping the length and diameter the same. The change in material also changed material properties such as density and weight. With the change in material to the missile body also came changes to the nose, fins, and tail. See Table A3 for results.

Material Variation	INPUT			RESULTS	
	Length	Diameter	Material	Weight (lb)	Time to Modify CAD Model
Control Group	38	3	Aluminum 6061-T6511	6.89	-
Trial 1 - Material	38	3	Aluminum Beryllium 38AL-62Be	5.33	25 min
Trial 2 - Material	38	3	Titanium Ti-6Al-4V	11.25	12 min
Trial 3 - Material	38	3	Aluminum Composite A356.0 T6P	6.82	15 min

Table A3: Material Variations

With the time study done on creating a CAD model and varying its geometry and mass properties, we now know the effort and time it takes to turn around changes in the CAD tool. On average, it took 15 minutes to change the CAD model.

Cost Model Variations

This section describes the cost modeling process, and turnaround time for the designer to get feedback on their design.

A time study timeline analysis of the process to go from a CAD model to a parametric cost model is shown in Table A4.

Length Variation	RESULTS	
	Weight (lb)	Time to Modify Cost Model
Control Group	6.89	-
Trial 1 - Length	7.30	10 min
Trial 2 - Length	7.74	12 min
Trial 3 - Length	8.18	9 min

Diameter Variation	RESULTS	
	Weight (lb)	Time to Modify Cost Model
Control Group	6.89	-
Trial 1 - Diameter	11.05	8 min
Trial 2 - Diameter	13.73	7 min
Trial 3 - Diameter	17.01	9 min

Material Variation	RESULTS	
	Weight (lb)	Time to Modify Cost Model
Control Group	6.89	-
Trial 1 - Material	5.33	9 min
Trial 2 - Material	11.25	8 min
Trial 3 - Material	6.82	10 min

Table A4: Time study of CAD model input into Parametric Cost Model

With the time study timeline analysis being completed to develop an independent cost models for each trial, we now know the effort and time it takes to turn around changes in the cost model. On average, it took 8 minutes to change the cost model.