A RISK-INFORMED MANUFACTURING INFLUENCED DESIGN FRAMEWORK FOR AFFORDABLE LAUNCH VEHICLES

A Dissertation
Presented to
The Academic Faculty

by

Tyler Reid Milner

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Aerospace Engineering

Georgia Institute of Technology
May 2016

A RISK-INFORMED MANUFACTURING INFLUENCED DESIGN FRAMEWORK FOR AFFORDABLE LAUNCH VEHICLES

Approved by:

Professor Dimitri Mavris, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Olivia Pinon
School of Aerospace Engineering
Georgia Institute of Technology

Professor Daniel Schrage
School of Aerospace Engineering
Georgia Institute of Technology

Professor Graeme J. Kennedy
School of Aerospace Engineering
Georgia Institute of Technology

Mr. J. Scott Sparks
Nonmetallic Materials and
Manufacturing Division
NASA Marshall Space Flight Center

Date Approved: April, 1st 2016

To my beautiful wife,

Victoria,

my inspiration and motivation.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank those who have provided support and encouragement throughout my academic journey. First, I would like to thank my committee members; Dr. Dimitri Mavris, Dr. Olivia Pinon, Dr. Daniel Schrage, Dr. Graeme Kennedy, and Mr. Jeffery (Scotty) Sparks. I appreciate the time and input you have provided to help shape this thesis. I would like to extend a special thanks to my advisor, Dr. Mavris, for inviting me to contribute to such a great team. The experiences I have gained through ASDL are invaluable.

In addition to my committee members, I would like to thank Mr. Stephen Edwards, my research engineer. Stephen, thank you for your willingness to be a sounding board for many hours whilst this thesis was in its infancy. I always left our discussions excited and confident about a new perspective you afforded me through providing a fresh perspective on something I had been banging my head on for what seemed like weeks.

To my colleagues at ASDL, it is only as a result of our camaraderie, shared triumphs, and pain that I have made it through this process with some semblance of sanity. To the people of room 119, it was a pleasure sharing an office with you. I thoroughly enjoyed our humorous discussions and much needed venue to vent my frustrations. Special thanks to Nathan Knisely and Alicia Sudol who shared in the emotional roller coaster that is quals.

Thank you to my family and friends who provided ample encouragement. And a thank you to my wife, Tori, for all her support and kind words which motivated me throughout this process.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS . . . . **v**

LIST OF TABLES . . . . **x**

LIST OF FIGURES . . . . **xi**

NOMENCLATURE . . . . **xviii**

SUMMARY . . . . **xxii**

I INTRODUCTION **1**

- 1.1 Definition of Key Terms 3
- 1.2 Motivation 9
- 1.3 Background 15
- 1.4 Problem Statement 24
- 1.5 Research Objective 25
- 1.6 Organization of the Dissertation 27

II LITERATURE REVIEW **29**

- 2.1 Launch Vehicle Design Process 30
- 2.2 Industry Standards and Guidelines 34
  - 2.2.1 Project/Program Planning during Conceptual Design 34
  - 2.2.2 Risk Assessment Requirements and Guidelines 37
  - 2.2.3 Conceptual Design Analysis Methodologies 45
- 2.3 Review of Technology Assessment Methods for Conceptual Design . 54
  - 2.3.1 Technology Identification, Evaluation, and Selection (TIES) . 54
  - 2.3.2 Abbreviated Technology Identification, Evaluation, and Selection (ATIES) 56
  - 2.3.3 Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA) 57
- 2.4 Gap Identification 65
  - 2.4.1 Shortcoming of Expectations and Prescribed Practices During Conceptual Design 65

2.5 Manufacturing Influenced Design (MInD) 73
2.6 An Alternative Perspective on the Program Life Cycle 77

III METHOD DEVELOPMENT 81

3.1 Portfolio Theory 81
3.2 Solution Approach 83
3.3 Research Question 1: How can the value of a launch vehicle manufacturing technology portfolio be assessed? 88
  3.3.1 Research Question 1.1: Mission Critical Performance 93
  3.3.2 Research Question 1.2: Quantifying Risk 98
3.4 Research Question 2: Affordability Distributions 104
  3.4.1 Integrated Methods for Affordability Analysis 105
  3.4.2 Summary of Integrated Methods for the Generation of Affordability Distribution 109
  3.4.3 Research Question 2.1: Generating Phase Estimating Relationships. 110
  3.4.4 Traditional Cost Estimating Methods 111
  3.4.5 Traditional Scheduling Techniques 116
  3.4.6 Summary of Traditional Methods 118
  3.4.7 Research Question 2.2: Launch Vehicle Decomposition 121
  3.4.8 Research Question 2.3: Aggregation of Elements into a System-Level Perspective 126
  3.4.9 Hypothesis 2.3 141
3.5 Exploration Upper Stage Manufacturing Influenced Design (EUS MInD) 143
  3.5.1 Process-Based Cost Tool Selection 144
  3.5.2 P-BEAT 146
  3.5.3 Higher Fidelity Analyses Necessitated by Process-Based Cost Estimation 151
3.6 Experiment 1: Verifying Process-Based Cost Utilization 157
  3.6.1 Purpose 157
  3.6.2 Approach 157

3.6.3 Results 170
3.7 Experiment 2: Integration Phase Estimating Relationships 205
3.7.1 Purpose 205
3.7.2 Approach 205
3.7.3 Results 208
3.7.4 Experiment 2 Summary 222
3.8 Research Question 3: Probabilistic Affordability Distributions 223
3.8.1 Research Question 3.1: Determining Uncertain Attributes . . 224
3.8.2 Research Question 3.2: Assessing Appropriate Forms Uncertainty Distributions 230
3.8.3 Research Question 3.3: Propagating Uncertainty 233
3.9 Experiment 3: Generation of Probabilistic Affordability Distributions 236
3.9.1 Purpose 236
3.9.2 Approach 237
3.9.3 Results 243
3.9.4 Summary 250
3.10 Research Question 4: System Level Probabilistic Affordability Curves 251
3.11 Experiment 4: Generation of System-Level Probabilistic Affordability Distributions and Their Use in Decision Making 252
3.11.1 Purpose 252
3.11.2 Approach 252
3.11.3 Results 257
3.11.4 Correlation Analysis 260
3.11.5 Summary 271
IV METHODOLOGY OVERVIEW 273
4.1 Problem Definition 274
4.2 Schedule Permutation Enumeration 275
4.3 High-Fidelity Analysis to Enable Element Deterministic Affordability Curve Generation 276

4.4 System-Level Probabilistic Affordability Distribution Generation through Monte Carlo Simulation 277
4.5 Evaluation and Selection 280

V APPLICATION & RESULTS 282

5.1 Problem Definition 284
5.2 Schedule Permutations 285
5.3 Element Assessment 286
5.4 System Affordability Projection 289
5.5 Affordability Comparison 292

VI CONCLUSION 303

6.1 Summary of Findings 303
6.2 Contributions 309
6.3 Future Work 310
6.3.1 Application to SLS Sensor Problem 314

APPENDIX A — SCREENSHOT OF EXCEL-BASED HOUR TRANSLATOR 317

APPENDIX B — EXPERIMENT 1 FIT EQUATIONS 318

APPENDIX C — EXPERIMENT 2 351

APPENDIX D — MATLAB CODE 357

REFERENCES 385

VITA 402

LIST OF TABLES

1 A Selection of Canceled NASA Space Programs [216] 13

2 Notional Technology Impact Matrix(TIM) (Adapted from [116]) . . . 56

3 Relevant variables and ranges of k-factors for a commercial airliner . 63

4 Rocket equation elements distinguished as mission or vehicle parameters 96

5 Technology Readiness Level Summary [130] 129

6 Advancement Degree of Difficulty (AD^2) Summary [14] 136

7 Technology Readiness Level Used in PBEAT [204] 150

8 P-BEAT Engineering Disciplines and Development Processes [204] . . 159

9 P-BEAT Engineering Disciplines and Development Processes continued 160

10 Baseline Tank Attributes for Use Case 166

11 Metallic Tank Design Attributes Matrix of Alternatives for DOE . . . 167

12 Metallic Tank Process Attributes Matrix of Alternatives for DOE . . 167

13 System-Level TRL's for Various Concepts Based Upon the Minimum TRL Present in the System 209

14 Characterization of Integration for Technology Readiness Levels . . . 214

15 Characterization of Uncertain Attributes in P-BEAT 225

16 List of Scaling Factors Used to Generate Probabilistic Distributions for Launch Vehicle Elements by Scaling Fuel Tank Outcome 254

17 EUS Fuel Tank Alternatives for Method Application to Real World Problem 285

18 Sample Problem: Metallic Tank POS for Each Start Scenario 299

19 Sample Problem: Composite Tank POS for Each Start Scenario . . . 299

20 Sample Problem: Metallic Tank Optimum Start Scenario for Funding Constraints 300

21 Sample Problem: Composite Tank Optimum Start Scenario for Funding Constraints 301

LIST OF FIGURES

1 Visualization of Comparison Between Current JCL Method and Improved Insight Provided by Methodology Developed Herein 4

2 Human Space Flight Development Programs [209] 14

3 Conceptualized Project Life Cycle [114] 16

4 Average Technical and Programmatic Growth for Select NASA Programs [19, 114] 17

5 Life Cycle Cost Committed, Cost Incurred, Knowledge, and Ease of Change [79] 18

6 Amortization Curve 20

7 Planned Block Upgrades to the SLS [adapted from [164, 12, 117, 108, 168]] 22

8 Notional Cumulative Cashflow for a Typical Aircraft Manufacturer [135] 27

9 Conceptualized Project Life Cycle 30

10 General Life Cycle Phases [103] 32

11 Comparison Between Project Life Cycle Phases of Various Entities [114, 103] 33

12 DoD Risk Management Process [63] 38

13 Risk Reporting Matrix [63] 40

14 NASA's Risk Informed Decision Making Process and Its Interaction With the Continuous Risk Management Process [65] 42

15 Probability Density Function with Requirement Overlaid [65] 43

16 Launch Vehicle Conceptual Design Analysis Process [5] 46

17 Launch Vehicle Conceptual Design Analysis Process Relevant to Achieving First Flight 47

18 Primary Body Structures for The EUS (Formerly named the Dual Use Upper Stage) [58] 48

19 Typical Conceptual Design Process Tools Applied to Space Vehicles (adapted from [101]) 50

20 Technology Identification, Evaluation, and Selection (TIES) Methodology) [116] 55

21 Abbreviated Technology Identification, Evaluation, and Selection (ATIES) Methodology [43] 57

22 Design Structure Matrix for a Bimese TSTO ROSETTA Model) [59] 58

23 Visualization of All Feasible Trends for Commercial Airliner Example 64

24 NASA's Joint Confidence Level [109] 66

25 Notional Traditional Cost and Schedule Estimate Generated During Conceptual Design 70

26 Notional Time-Phased Constraints and Initial Expenditure 71

27 Notional Time-Phased Expenditure for a Program Experiencing Cost Overrun, Schedule Slippage, or Cancellation 72

28 A Typical Aircraft Product and Process Development Flow [122] . . . 75

29 Recategorization of Program Life Cycle Phases 79

30 Trades Facilitated by Proposed Methodology 80

31 NASA's Risk Informed Decision Making Process [65] 84

32 Georgia Institute of Technology Integrated Product and Process Development (IPPD) Methodology [197] 85

33 Aggregate Design Decision Support Process (adapted from [197, 65]) 86

34 Generic Manufacturing Technology Design Decision Support Process . 87

35 Generic Manufacturing Technology Design Decision Support Process . 89

36 Uncertainty and Risk [adapted from [65]] 99

37 Taxonomy of Uncertainties in the Development of Space and Launch Vehicles [186] 100

38 Notional Affordability Risk Assessment 103

39 Rayleigh PDF (left) and CDF (right) for Various Time-Scale Parameters (α) [119] 107

40 Cost Estimating Methodology Selection Chart [151] 112

41 Relationship Between Project Funding and Project Budget [155] . . . 119

42 Overview of Exploration Upper Stage Key Subsystems [58] 123

43 Overview of NASA Space Launch System Core Stage [165] 124

44 Research and Development Degree of Difficulty (R&D^3) [131] 130

45 Technology Needs Value (TNV) Weightings and Descriptions [133] . 131

46 Integration Readiness Level [191] and System Readiness Level [193] . 134

47 Summary of the Spacecraft Time to Delivery Model [71] 138

48 Overview of Information Flow for Process-Based Cost Estimation [58] 144

49 Comparison Between Life Cycle Phases 147

50 P-BEAT Analysis Flow 149

51 EUS MInD Analysis Overview 154

52 Final EUS MInD Framework 156

53 Gantt Chart Depicting P-BEAT Development Process Order and Dependencies with Notional Task Durations 163

54 NASA Metallic Tank Design Concept [112] 165

55 Select Tables from NASA Workforce Profile for Start of FY2016 [4] . 170

56 Normalized Annual Expenditure for Al-Li 2195 Baseline LH_2 Tank Configuration 171

57 Normalized Expenditure and Timeline per Phase for Al-Li 2195 Baseline LH_2 Tank Configuration 172

58 Normalized Payload Mass for All LH_2 Tank Design Configurations . . 173

59 Normalized Expenditure and Timeline per Phase for All LH_2 Tank Configurations 174

60 Distribution of Phase End for All LH_2 Tank Configurations 176

61 Distribution of Percent Expenditure per Phase for All LH_2 Tank Configurations 177

62 Scatterplot Matrix Depicting Total Cost and Total Duration Variations as a function of Independent Design Manufacturing Variables 180

63 Scatterplot Matrix Depicting Phase-Specific Affordability Variations as a Function of Independent Design Manufacturing Variables 181

64 Mean Annual Expenditure as a Function of Dome Fabrication 183

65 Mean Annual Expenditure as a Function of the Barrel Panel Fabrication184

66 Mean Annual Expenditure as a Function of the Number of Barrel Panels185

67 Mean Annual Expenditure as a Function of TRL 186

68 Tornado Plot of Independent Variable Impact on Variability of Affordability 187

69 Multi-Stage Regression Procedure for a Candidate Weibull Distribution and Data for 26 Programs [31] 188

70 Options for Fitting Weibull Distributions 189

71 Attempted Weibull Distribution Fits to PDF 190

72 Attempted Weibull Distribution Fits to CDF 190

73 Fitting Error for Weibull Distribution for Each Design Phase 193

74 Weibull Distribution Fit to Phase Milestones and Expenditure PDF . 193

75 Options for Fitting Weibull Distributions to Phase Milestones and Expenditure PDF 195

76 Options for Fitting Weibull Distributions to Phase Milestones and Expenditure CDF 195

77 Actual by Predicted Plot and Summary Statistics for Linear Fit to α 196

78 Actual by Predicted Plot and Summary Statistics for Linear Fit to β 196

79 Summary Statistics for Neural Network Fit to α and β 198

80 Actual by Predicted Plot for Neural Network Fit to α and β 198

81 Residual by Predicted Plot for Neural Network Fit to α and β 199

82 Actual by Predicted Plot and Summary Statistics for Linear fits to End of Preliminary Design, Detailed Design, and First Build Phases . 200

83 Actual by Predicted Plot, Summary Statistics, and Residual by Predicted for Second Order Polynomial fits to End of Preliminary Design, Detailed Design, and First Build Phases 201

84 Summary Statistics for Neural Network Fit to End of Preliminary Design, Detailed Design, and First Build Phases 202

85 Actual by Predicted Plot for Neural Network Fit to End of Preliminary Design, Detailed Design, and First Build Phases 203

86 Residual by Predicted Plot for Neural Network Fit to End of Preliminary Design, Detailed Design, and First Build Phases 204

87 Annual Expenditure for Integration of Al 2219 Tanks for Various Design Concepts When System TRL = Minimum TRL 210

88 Annual Expenditure for Integration of Al 2024 Tanks for Various Design Concepts When System TRL = Minimum TRL 210

89 Annual Expenditure for Integration of Al-Li 2195 Tanks for Various Design Concepts When System TRL = Minimum TRL 211

90 Annual Expenditure for Integration of Al-Li 2090 Tanks for Various Design Concepts When System TRL = Minimum TRL 211

91 Annual Expenditure for Integration of Ti-6Al-4V Tanks for Various Design Concepts When System TRL = Minimum TRL 212

92 Annual Expenditure for Integration of IM7/977-2 Tanks for Various Design Concepts When System TRL = Minimum TRL 212

93 Annual Expenditure (*top*), Standard Deviation, and Range (*bottom*) for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7 216

94 Scatterplot Matrix of Normalized Expenditure for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7 217

95 Distribution of Normalized Phase Expenditure for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7 218

96 Distribution of Phase End for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7 219

97 PDFs and Average Fitting Error 221

98 CDFs and Average Fitting Error 222

99 Activity Permutation Example: Compatibility Matrix for Three Compatible Tasks 227

100 Time Slot Allocations for Tasks With Full Compatibility 227

101 Three Fully Compatible Tasks for Activity Permutation Example . . 227

102 Time Slot Allocations for Tasks With No Compatibility 228

103 Time Slot Allocations for Tasks With Full Compatibility 229

104 Lognormal Probability Density Function [222] 232

105 Triangular Probability Density Function 233

106 Gantt Chart Depicting Optimistic (Parallel) P-BEAT Development Process Order and Dependencies with Notional Task Durations . . . 239

107 Gantt Chart Depicting Pessimistic (Serial) P-BEAT Development Process Order and Dependencies with Notional Task Durations 240

108 Uncertainty in Total Cost (2011 USD) 241

109 Phase Durations for Optimistic (*top*), Pessimistic (*bottom*), and Expected (*middle*) Task Order Permutations 242

110 Phase Durations Resulting from Uniform Distribution 244

111 Likelihood of Sampling Pessimistic ($x = 0$), Expected($x = 0.5$), and Optimistic($x = 1$) Distributions for x-bounds of 0.15 246

112 Phase Durations Resulting From Triangular Distribution With Likelihoods Determined From Notional SME Input 247

113 Phase Durations Resulting From Triangular Distribution With Likelihoods Determined From Standard Deviation 247

114 Probabilistic Affordability Distribution for One Fuel Tank Concept With Highlighted Total Cost Statistics (*top*), and Highlighted Cases Which Form Bounds (*bottom*) 249

115 Notional Constraint Diagram 256

116 Affordability Constraint Diagram 257

117 Robust Affordability Constraint Diagram 259

118 Comparison of Total Cost Distributions for One Constraint Scenario . 260

119 Correlation for Expenditure During Preliminary Design 262

120 Correlation for Expenditure During Preliminary Design 263

121 Differentiation Between Correlations for Optimistic and Expected (left) and Pessimistic (right) Task Order Permutations 264

122 Correlation for Expenditure During Preliminary Design 265

123 Correlation for Non-Cumulative Expenditure and Phase Duration for a Selection of DDTE&P Plans 266

124 Correlation for Cumulative Expenditure Up to the End of Detailed Design 268

125 Correlation for Cumulative Expenditure Up to the End of First Build 269

126 Correlation for Cumulative Expenditure and Phase End for a Selection of DDTE&P Plans 270

127 Comparison of Schedule Milestone Distributions for One Constraint Scenario 272

128 Binned Uniform Distribution with Optimistic, Expected, and Pessimistic Task Order Permutations 286

129 Sample Problem: Normalized Payload Mass Comparison 288

130 Sample Problem: Al-Li 2195 Fuel Tank Probabilistic Element Distribution 290

131 Sample Problem: IM7/977-2 Fuel Tank Probabilistic Element Distributions . . . 291

132 Sample Problem: System-Level Probabilistic Affordability Distribution for Al-Li 2195 Tank Concept . . . 294

133 Sample Problem: System-Level Probabilistic Affordability Distribution for IM7/977-2 Tank Concept . . . 295

134 Sample Problem: Al-Li 2195 Concept System Affordability Distribution for Flat, Increasing, and Decreasing Funding Constraints . . . 297

135 Sample Problem: IM7/977-2 Concept System Affordability Distribution for Flat, Increasing, and Decreasing Funding Constraints . . . 298

136 Sample Problem: Comparison between Al-Li 2195 (left) and IM7/977-2 (right) System Affordability Distributions . . . 302

137 Sensor Installation Affected Area . . . 315

138 Summary Statistics . . . 354

139 Actual by Predicted . . . 355

140 Residual by Predicted . . . 356

NOMENCLATURE

ACO	NASA Marshall Space Flight Center's Advanced Concepts Office
AD^2	Advancement Degree of Difficulty
APAS	Aerodynamic Preliminary Analysis System
ASDL	Aerospace Systems Design Laboratory at Georgia Institute of Technology
ATIES	Abbreviated Technology Identification, Evaluation, and Selection
CDF	Cumulative Distribution Function
CDR	Critical Design Review
CER	Cost Estimating Relationship
CONSIZ	Configuration Sizing Program
CPM	Critical Path Method
CRM	Continuous Risk Management
DDTE&P	Design, Development, Testing, Evaluation, and Production
DES	Discrete Event Simulation
DFA	Design For Assembly
DFM	Design For Manufacture
DFMA	Design For Manufacture & Assembly
DoD	Department of Defense
DOE	Design of Experiments
EAL	Engineering Analysis Language
ECSS	European Cooperation on Space Standardization
ET	Space Shuttle External Tank
EZDESIT	Computer routine for finite element sizing
FEA	Finite Element Analysis
FSW	Friction Stir Weld

GAO	Government Accountability Office
IBS	Integral-Blade Stiffened
IMS	Integrated Master Schedule
INCOSE	International Council on Systems Engineering
INTROS	Integrated Rocket Sizing
IRL	Integration Readiness Level
ITI	Integrated Technology Index
JCL	Joint Confidence Level
KDP	Key Decision Point
LaRC	Langley Research Center
LCC	Life Cycle Cost
LEO	Low-Earth Orbit
LH_2	Liquid Hydrogen
LLO	Low Lunar Orbit
LO_2	Liquid Oxygen
LVA	Launch Vehicle Analysis
MCS	Monte Carlo Simulation
MER	Mass Estimating Relationship
MInD	Manufacturing Influenced Design
MINIVER	Miniature version of the JA70 Aerodynamic Heating Program, H800
MLI	Multi-Layer Insulation
MoA	Matrix of Alternatives
MPS	Main Propulsion System
MSFC	Marshall Space Flight Center
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane

P-BEAT	Process-Based Economic Analysis Tool
PBS	Product Breakdown Structure
PDF	Probability Density Function
PDR	Preliminary Design Review
PER	Phase Estimating Relationship
PERT	Program Evaluations and Review Technique
POS	Probability of Success
POST	Program to Optimize Simulated Trajectories
R&D^3	Research and Development Degree of Difficulty
RIDM	Risk Informed Decision Making
ROSETTA	Reduced Order Simulation for Evaluation of Technologies and Transportation Architecture
RSE	Response Surface Equation
SAIC	Science Applications International Corporation
SDR	System Definition Review
SLI	Space Launch Initiative
SLS	Space Launch System
SMART	Solid Modeling Aerospace Research Tool
SME	Subject Matter Expert
SOFI	Spray-On Foam Insulation
SRL	System Readiness Level
SSME	Space Shuttle Main Engine
SSTO	Single-Stage to Orbit
TFU	Theoretical First Unit
TI	Technology Index
TIES	Technology Identification, Evaluation, and Selection
TIM	Technology Impact Matrix

TLI	Trans-Lunar Injection
TNV	Technology Need Value
TRL	Technology Readiness Level
VAB	Vehicle Analysis Branch
VVT	Verification, Validation, and Testing
WBS	Work Breakdown Structure
ΔV	Change in Velocity
g_0	Gravitational Constant
I_{sp}	Specific Impulse
m	Mass

SUMMARY

Launch vehicle development programs have experienced significant difficulties in achieving first flight. Optimism during the initiation of these complex programs, coupled with the innovative nature of the technologies they employ, has resulted in a long list of programs unable to remain within the national means. A recent example of this challenge is the Constellation program which was canceled in 2011 due to excessive cost overruns and schedule slippage. The budgetary constraints currently placed on NASA's Space Launch System (SLS) highlights the need for a greater emphasis on affordability. Where affordability is defined in this research as the ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals given that performance requirements are met. The proposed research aims to address the gap between current practices and an affordability-centric design approach by capturing manufacturing technology effects on the affordability of the baseline vehicle concept.

Historically, cost overruns and schedule slippages escalate once production begins and are only truly realized at the first launch of a system. These trends, based upon systems which leveraged traditional materials and processes, suggest a shortcoming in the ability of current practices to assess manufacturing implications during the early design phases. The advent of advanced materials and the new process required to fabricate parts from them, further challenges these practices, and threaten to exacerbate the already excessive overruns experience once production begins. Manufacturing technologies, such as composite materials, automated fabrication processes, and the use of stiffener concepts, can no longer be considered independently. This observation leads to the conclusion that improvements in vehicle affordability can only be realized by bringing manufacturing information forward into the Conceptual Design phase.

The goal of this research is to support the development of affordable launch vehicles by quantitatively capturing the effects of manufacturing technology selection during Conceptual Design. A manufacturing influenced design methodology is combined with established techniques of time-phasing and risk propagation to evaluate the expected affordability of a launch vehicle baseline concept.

The method is benchmarked against expected performance and affordability trends established in literature. The experiments used to build this methodology provide interesting insight into the excess risk typically carried into Preliminary Design due to a lack of the temporal nature of cost. Fundamental implications include the notion that the most expensive candidate (i.e. the highest total cost) does not correspond to the candidate with the highest annual cost insurance. Furthermore, the assessment of risk — within the traditional total cost domain — by overlaying vertical constraints onto uncertainty distributions results in the inclusion of many unaffordable candidates.

The final chapter of this thesis applies the method to a relevant launch vehicle, the Exploration Upper Stage (EUS) of the SLS Block IB, which is currently in its Conceptual Design phase. This chapter compares two viable candidate manufacturing technologies based on affordability criteria established herein. The application of this methodology provides the decision maker with a significant amount of information previously unavailable and affords her additional degrees of freedom regarding appropriate Design, Development, Testing, Evaluation, and Production (DDTE&P) planning. This will ultimately enable the selection of an affordable vehicle baseline which will be robust to uncertainty in congress-appropriated funding and thus circumvent risks associated with government program cancellation.

CHAPTER I

INTRODUCTION

The methodology developed herein aims, above all else, to inform decisions during Conceptual Design to circumvent launch vehicle program cancellation. Historically, NASA's launch vehicle development programs have been unable to reach first flight. While many of these programs experienced technical challenges, cost overruns and schedule slippages were the primary reason for cancellation. As much as $22 billion is believed to have been "lost" to these programs.

The background and literature review, performed in Chapters 1 and 2 highlight the need to provide additional affordability insight during Conceptual Design to realize a more realistic representation of affordability and its inherent risk. Furthermore, a thorough review of current guidelines and best practices reveals three major gaps in the methods and requirements of Conceptual Design.

1. The conceptual baseline is selected through performance-centric analysis, with little development planning or manufacturing insight. This portrays a significant lack of collaboration between designers and manufacturers of a system.
2. Conceptual risk analysis is based on a single subject matter expert (SME) generated work breakdown structure (WBS) and master schedule.
3. There is a mismatch between the required risk assessment (Joint Confidence Level) and the true — temporal — nature of affordability risk.

To achieve a risk-informed state during the selection of a conceptual baseline, a quantitative manufacturing influenced design (MInD) environment is used to infuse producibility considerations. This MInD environment enables a decision maker to capture the manufacturing implications which result from design decisions. Furthermore, a custom-built add-on is used to generate high-level parametric work breakdown structures which capture the temporal nature of cost (expenditure). The addition of manufacturing and development planning considerations facilitate the selection of conceptual baseline which is robust to uncertainty in funding — which stems from congressional appropriations subject to the demagoguery of the political arena — and meets the required performance thresholds.

The major findings of this thesis include three aspects. Firstly, **the concept with the greatest total cost does NOT necessarily have the highest annual cost throughout a development program**. This elicits the notion that **uncertain expenditure curves are NOT photographically scaled**, which leads to the second finding. Phase estimating relationships fail to accurately describe the behavior of affordability curves. The final, and most profound, finding is most aptly stated as a consequence of not using this methodology. The joint cost-schedule risk is not described by a vertical requirement line overlaid on an uncertainty distribution; this traditional approach results in the passage of a significant amount of affordability risk from Conceptual Design into Preliminary Design. The use of the methodology developed herein inherently reduces the epistemic risk; **if this methodology is not used, a development program stands a higher chance of being canceled due to a gross underestimation of affordability risk provided by the traditional conceptual analysis methods.** The disparity in risk is shown in Figure 1, which compares the Joint Confidence-Level perspective (currently required by NASA programs) and the perspective provided by the methodology developed herein. The JCL method does not consider the temporal budget phasing constraints, and thus considers all points in the lower left quadrant as meeting the total cost/schedule constraint. However, when the temporal nature of the constraints is captured — enabled by the methodology developed herein — a significant amount of this quadrant does

not meet the annual funding constraints. This depicts the fact that the traditional approach significantly underestimates the affordability risk of a concept.

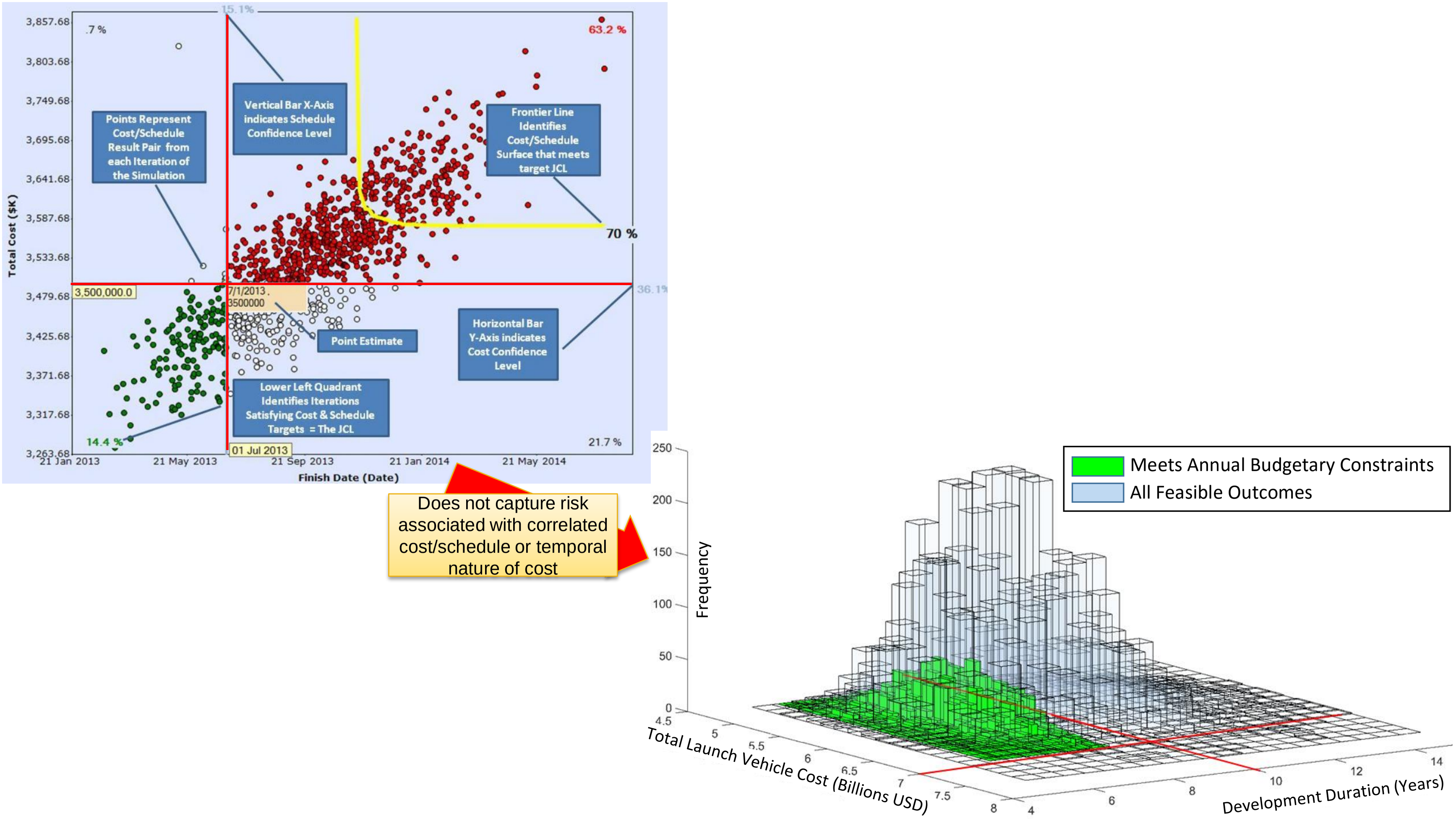
1.1 Definition of Key Terms

Prior to the development of the basis of this thesis, it is necessary to clarify terms which shall be used frequently herein. This section serves to develop the specific definitions of key terms and the metrics upon which much of the discussion and analyses are based.

Technology and Manufacturing Technology

Within the context of complex systems, a technology is an item of interest added to a system to improve some aspect of the design. For instance the Boeing 787 has incorporated a large amount of composite materials to save weight. Similarly, the Space Shuttle external tank changed to an aluminum-lithium material to save weight. Ultimately, during early design phases, the technologies that are identified as candidates of interest are aimed at improving one (or sometimes several) design feature(s). While these candidates often are initially analyzed for their design benefits, the practical nature of precisely how a particular technology will be implemented is overlooked. Namely, the technologies are seldom assessed based upon manufacturing traits.

Historically, the focus of introducing technologies has been to improve performance. A glimpse at the evolution of the space shuttle external tank (ET) epitomizes the performance-centric approach of traditional technology infusion. The original version of the ET was constructed of aluminum 2219, and weighed 76,000 pounds. In 1983 a redesign of the tank, intended to reduce weight to increase the payload capacity — a measure of performance— began. The redesigned tank was 10,000 pounds lighter; where much of the weight savings was accomplished by changing the structural stiffening of the hydrogen tank, and changing the fabrication processes. The



Does not capture risk associated with correlated cost/schedule or temporal nature of cost

Figure 1: Visualization of Comparison Between Current JCL Method and Improved Insight Provided by Methodology Developed Herein

third generation ET, dubbed the super lightweight tank, was achieved by fabricating the tank out of a newly developed material, namely aluminum-lithium (Al-Li) 2195. Again, this effort aimed at reducing the structural weight in order to increase the payload capacity of the shuttle. These efforts reduced the weight of the ET by another 7,500 pounds, achieving a total empty weight of 58,500 pounds [73, 150]. The Space Launch System (SLS) core stage is a prime example of this transition from a performance-centric view on technology infusion, and perhaps the beginning of an era in which manufacturing considerations take center stage. The SLS core tanks — similar in size and design to the hydrogen tank contained within the Space Shuttle ET — will be fabricated from aluminum 2219 instead of the lighter Al-Li 2195. This selection reduces the SLS payload capacity by three tonnes and decreases flight costs by $30 million per launch. [206].

Manufacturing technology, on the other hand, revolves around the identification of materials, fabrication processes and their interrelation which often drives cost AND performance. The key distinction here is that a technology, in the traditional sense is aimed at identifying “What can I add to improve performance or decrease cost?” while the manufacturing technology takes this particular idea one step further by also asking “How can I manufacture to facilitate improved performance and reduced cost?”

NASA has been studying the technical feasibility and economic viability of composite cryogenic tanks since 2011; composites promise 30-40% reduction in weight AND a 25% reduction in cost over the Al-Li counterparts [112, 138]. These new materials, coupled with advanced stiffening concepts, and new fabrication techniques challenges the traditional approach to technology selection; It is no longer a matter of “should I use one material over the other?” Instead, the matter of *HOW* such materials will be implemented and the repercussion involved in that selection. The decision to fabricate from composites, over metallics, brings about an entirely new, and previously inapplicable, set of fabrication techniques. Forming, cutting, and welding are replaced with lay-up, ply tailoring, bonding, and curing. These intricacies must be captured in order to provide the decision maker with sufficient information to select the material, a relevant structural stiffening concept, and the appropriate fabrication and assembly processes for the components which comprise a system.

Affordability

The term "Affordability" has various definitions, differing between academia, industry and government guidelines. What follows is an enumeration of affordability definitions taken from industry and academia, and a discussion which will arrive at a formal definition to be used throughout this dissertation.

Affordability is defined as the following:

1. The Defense Acquisition Guidebook "The ability to allocate resources out of a future total budget projection to individual activities" [64].

2. The INCOSE systems Engineering Handbook states that Affordability and life cycle cost are synonymous [103].

3. Programmatic documents for the NASA Space Launch System states that affordability is:

   "The ability to develop and operate the SLS within the national means to sustain funding for the program [157]."

   Implies we will remain under the mandated funding curve at all points in the life cycle of resultant systems [157].

4. NASA policy requirements list affordability as the ability to meet program schedule and budgetary constraints [152].

Academic works provide the following definitions:

5. The balance of benefits provided or gained from the system to the cost of achieving those benefits[135].
6. a cost-to-benefit ratio, which relates to the desired benefits and the capital investment required to achieve those benefits [197, 116].

Affordability, specific to NASA missions, has evolved towards considering the life cycle cost of an alternative, and ensuring that the cost remains within the national budget. Combining these perspectives, for the purpose of this thesis, affordability is *The ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals.*

Risk and Affordability Risk

A variety of definitions exist in literature, a selection of relevant definitions are listed below.

1. A measure of the inability to achieve overall programmatic objectives within cost, schedule, and technical constraints [114]
2. The combination of the probability that a program/project will experience an undesirable event and the consequences, impacts, or severity of this event, should it occur [114]
3. Risk is the potential for performance shortfalls [144].
4. Risk is operationally defined as a set of triplets [65]

   The *scenario(s)* leading to degraded performance with respect to one or more performance measures

   The *likelihood(s)* of those scenarios

The *consequence(s)* that would result if those scenarios were to occur

Each of the definitions above capture the primary measurement parameters of risk, the likelihood and consequence. These risks, however, can be evaluated based on two perspectives relevant to this thesis: 1) on a programmatic level or 2) on a mission to mission basis. The second perspective is more applicable to systems during the operational phases of their life cycle, where system details are well-known to the operators. At this point, risk assessment is simply an evaluation of the likelihood(s) and consequence(s) of potential failure modes. The programmatic perspective is more applicable to systems in early phases of design, where risk is evaluated based upon the probability that the program will meet requirements and objectives. In this case, the consequences are cost overruns, schedule slippages, or complete cancellation of the program.

With the focus of this thesis revolving around affordability implications of manufacturing technology infusion, it is a logical extension that the risk most applicable within the context of this thesis is affordability risk. Defining affordability as *the ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals*, provides a logical point of departure for defining affordability risk.

Affordability Risk is therefore:

The *likelihood* that a launch vehicle program exceeds the budget ceiling, misses schedule goals, or any combination of the two which could lead to program cancellation

1.2 Motivation

The planning fallacy refers to a readily observable phenomenon: the conviction that a current project will go as well as planned even though most projects from a relevant comparison set have failed to fulfill their planned outcomes [30]

Affordability has become a major focus in the acquisition of large scale systems for both commercial and government based aerospace entities. Cost and schedule overruns occur frequently, despite the availability of guidelines, tools, and concern from customers and contractors alike [104]. The Boeing 787 Dreamliner program has been plagued with issues which began during development, and have persisted to date. Redesigns, supplier issues, and part shortages have caused a three year delay in delivery and incurred a $24 billion cost overrun [181, 86]. Similarly, the Airbus A380 incurred cost overruns initially estimated at $6 billion and schedule slippage of nearly two years [1].

Government based entities, such as the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA), have historically placed great emphasis on performance; often providing optimistic estimates on costs and schedule. [52, 53, 19]. The repercussions for not meeting performance requirements have been far more severe than exceeding cost and schedule goals. This notion has provided justification for programs to allow cost overruns and schedule slips, which can be clearly seen upon inspection of recent government programs [52]. In 2009, the set of nearly 100 major weapon system development programs pursued by the DoD had a cost overrun of $296 billion and schedule slippage, on average, was 22 months [199]. The Government Accountability Office's (GAO) most recent assessment of DoD weapon systems shows that, despite having completed 10% of the 2009 programs, cost overruns are now $403 billion with an average delay of 27 months [218]. The development programs which NASA has completed since 1977 have averaged 50%

cost growth, with the more expensive programs, such as launch vehicles, experiencing the greatest growth [51].

There are several factors which differentiate the goals and business practices of government and commercial industries. First and foremost is the business case distinction; commercial entities weigh the value of an alternative based upon profitability metrics (such as return on investment, time to break even, etc.), while government based entities weigh value based upon intangible metrics (such as scientific discovery, innovation, and space exploration) [135, 162, 49]. While Research and development efforts are managed as sunk costs for both entities, commercial companies expect to recover these (through order down payments, launch customer partnerships, and risk-sharing supplier agreements) over the life cycle of the product, when government entities have no such expectation [107]. Finally, the budgetary environment in which each operates is significantly different. Commercial entities typically have an inflow of revenue to offset overruns in one (or several) projects. The consequence, therefore, for cost overruns and schedule slippage is a delay in profitability for a project, and in rare cases a project may never reach a state of profitability. Commercial entities typically have ample free cash flow at their disposal which can be allotted to a project that experiences overruns. Government entities have no free cash flow at their disposal to allot to a project which is exceeding its budget. Government entities request funds from Congress, who ultimately sets annual budgets for each government entity. Each entity then has to re-balance their portfolio when funds approved do not match funds requested. In the case of NASA, if one program begins to approach cost overruns, then a decision must be made as to either maintain schedule by increasing program funding or to mitigate the cost overrun by allowing the schedule to slip [78]. Increasing funding often means either requesting additional funds from Congress, or reducing funds (and thus incurring delays) to other programs. With appropriation cycles occurring annually there is a need for government agencies, like NASA, to take particular care in planning complex product development programs, such as launch vehicles, with an emphasis on affordability. Therefore, it is imperative to realize cost and schedule risks associated with a program's development and production, as early in the design process as possible.

Launch vehicles are immensely expensive to design, develop and operate, typically in the multi-billion dollar range and usually require eight to ten years to develop [28, 39, 196]. For example, the Falcon 9 currently under development by SpaceX, is touted as a "cheaper" alternative, with an estimated development cost between $1B and $3B [102, 156]. Furthermore, launch vehicles are not produced in a quantity large enough to benefit from learning curve effects, thus the design, development, testing, and evaluation (DDT&E) costs cannot be amortized over a large production lot [143].

A brief glimpse into the history of NASA's space flight development programs exemplifies the challenges associated with achieving affordable launch vehicles. Beginning with an effort to augment the Space Shuttles payload capabilities, and prevent an "all eggs in one basket" policy, the DoD and NASA began a National Aero-Space Plane (NASP) program in 1982. The program called for the development of two single-stage to orbit (SSTO) vehicles, capable of taking off from Dulles Airport, accelerating up to Mach 25, and achieving low Earth Orbit. The program was officially endorsed by President Reagan in 1986 and in the subsequent years it struggled to achieve its technological and schedule goals. Competing budgetary priorities and the slow technical progress ultimately led to its cancellation in 1992 [67]. In conjunction with the NASP program, the DoD and NASA pursued a heavy-lift launch vehicle option, the Advanced Launch System (ALS), to reduce the cost of placing large payloads in orbit [124]. In 1989 the ALS was canceled due to a shift in funding priorities and a realization that the promised cost savings could not be achieved [125]. The National Space Transportation Policy of 1994 gave NASA the responsibility to guide government and industry technology decisions for a next generation reusable launch system. The X-33 and X-34 technology demonstrators were the two most noteworthy programs which NASA developed in response to this policy [125]. "The X-34 would demonstrate reusable multiple-stage technologies for small payloads, while the X-33 would test reusable single-stage-to-orbit technologies capable of provisioning the Space Station [148]." Both the X-33 and X-34 were canceled in early 2001 due to technology development problems, and concerns that additional costs did not justify the potential benefits of the programs [149, 125, 67]. Focus was shifted to a new five-year study to develop the most promising path to shuttle replacement, the Space Launch Initiative (SLI). The SLI was a collaboration between NASA and industry, and was yet another short-lived program which did not make it through design [67]. Focus was shifted to an Orbital Space Plane, which was later canceled when NASA's Exploration System Architecture Study was created in response to President George W. Bush's Vision for Space Exploration [205]. NASA's efforts then turned to the development of Ares and Orion vehicles under the Constellation program, which was canceled in 2010 due to technical challenges and unreliable/inconsistent funding [179, 180]. "The most difficult and most persistent challenges involved cost, schedule, and organization [179]." Table 1 summarizes these cancellations, and provides some perspective on the monetary investments. The cancellations discussed are just a selection of space vehicles which have failed to successfully complete development activities since the early 1990's, as shown in Figure 2, reported to amount to $20B in investments [209]. A more in depth history is presented in [125, 67].

NASA has fallen into a perpetual "start-stop-restart" cycle in which it is unable to achieve first flight for space transportation systems in an affordable (timely and cost-effective) manner [205]. The implications are more than the monetary investments already discussed, as scientific and independent repercussions have also resulted from these perpetual cancellations. The Constellation program was canceled in 2010, the Space Shuttle was retired in 2011, and the Space Launch System (SLS) — a heavy lift

Table 1: A Selection of Canceled NASA Space Programs [216]

Program	Investment	Year	Overview
ALS[125]	$3B	1987-1990	Canceled due to funding cutbacks that shifted program requirements.
NLS[125]		1991-1993	Canceled due to lack of congressional support
X-33[107]	$1.2B	1996-2001	Canceled due to significant technical and budgetary problems.
X-34[107]	$219M	1996-2001	Canceled due to budgetary considerations.
SLI[67]		2000-2004	Canceled due to lack of governmental support.
Ares I[89]	$9B	2005-2010	Canceled due to poorly phased funding that resulted in cost increases and schedule slips. Canceled due to poorly phased funding that resulted in cost increases and schedule slips.

launch vehicle under development and currently planned to replace the Space Shuttle — will not reach its first manned flight until 2021 [206]. This represents a decade period in which the U.S. has no independent means to access space. NASA will pay nearly $1B to Russia to secure U.S. astronaut access to the International Space Station (ISS) [46]. This agreement only covers six round-trips between now and Fall of 2017, at which point NASA expects to switch to a U.S. commercially operated (and certified) spacecraft. Until a commercial vehicle becomes available and achieves full certification, NASA will have to expand current contracts, at more than $70M per round trip, to train and ferry astronauts to the ISS [46].

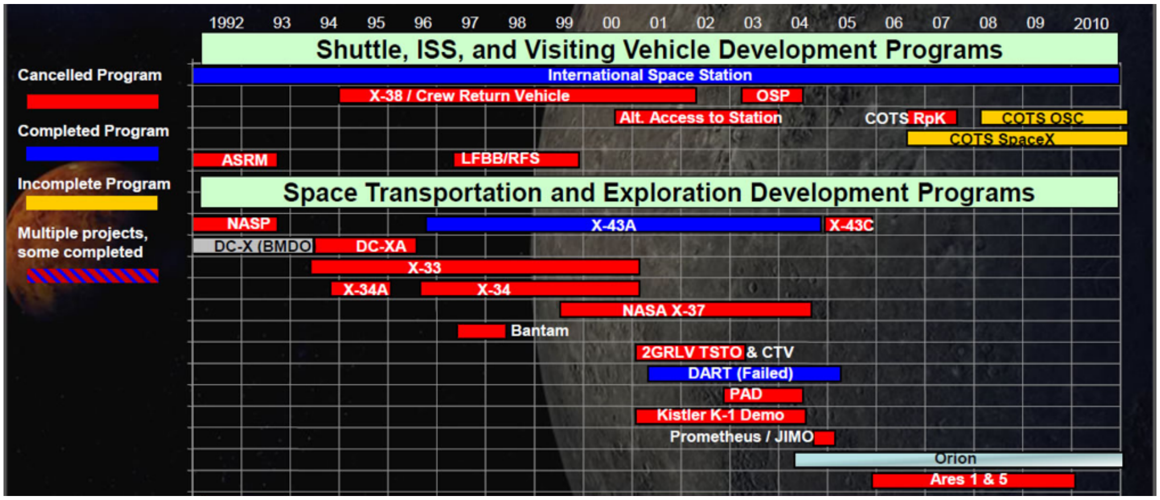


Figure 2: Human Space Flight Development Programs [209]

The SLS program was established by the NASA Authorization Act of 2010, and will be the first exploration class vehicle since the Saturn V, nearly 50 years ago [206]. Lessons learned from the many canceled programs, particularly the Constellation program, are being employed to champion affordability for the SLS program [206, 157]. As established in Section 1.1, affordability in this context is the ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals. Therefore, the ability to understand cost AND schedule risk is critical to the development of a launch vehicle and its ability to reach first flight, despite constrained funding [60]. One common thread amongst the canceled programs is the desire to infuse new technologies, often to provide greater performance. With a paradigm shift occurring, the technology infusion problem has shifted from "How can I perform better?" to "How can I make this endeavor more affordable." Current studies suggest that the key to providing more affordable vehicles may be found by infusing manufacturing technologies, and assessing their impacts early in the design process [35, 49]. This gap between cost, schedule, and budget and realizing an affordable vehicles, in light of technology infusion, is the primary motivation for the initiation of this thesis research. The following section will provide background information regarding overruns and risk assessment in order to identify the specific problem which the proposed research shall address.

1.3 Background

After identifying the gap in the ability of current practices to identify risk associated with launch vehicle development, and available funding, two motivating questions have been derived to guide this research. In order to answer these questions it is necessary to perform a deep dive into two areas; historical cost and schedule data for space programs, and the current design and risk assessment methods employed by NASA. Each of these two areas aims to provide a solution to the following two motivating research questions:

Motivating Research Question 1

What drives the cost and schedule overruns which have led to so many launch vehicle cancellations?

Motivating Research Question 2

How can the drivers of cost and schedule overruns be captured?

NASA project life cycles follow an evolutionary series of steps, beginning with Formulation and proceeding through to Implementation, if the project is given authority to proceed (ATP). Formulation establishes a cost-effective program which demonstrates capability of meeting Agency's and mission directorate's goals and objectives. Implementation is the cost-effective execution of the program plan. There are seven phases which comprise the full life cycle of a project; Formulation consists of pre-conceptual, conceptual, and Preliminary Design phases while Detailed Design, fabrication, operation and sustainment, and closeout are the phases which form the Implementation portion of a project life cycle [114].

A series of key decision points (KDPs) and reviews occur throughout the life cycle. KDPs are the events at which the decision authority determines the readiness of a program/project to progress from one phase to another, with KDP-C as the official ATP from Formulation to Implementation. While a series of reviews occur within each design phase, there is only one review which marks the end of design and the start of fabrication, the Critical Design Review (CDR). Figure 3 provides a conceptual representation of NASA's project life cycle, which is explained in greater detail in Section 2.1.

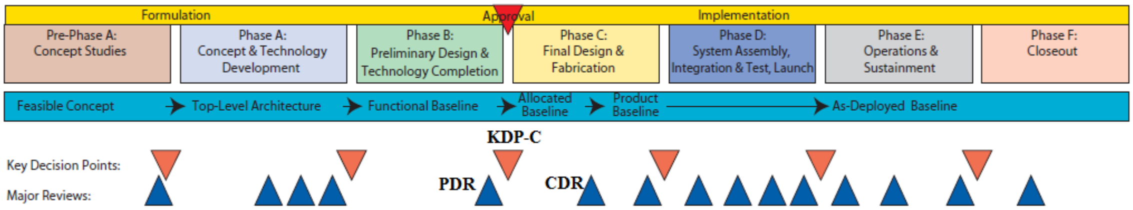


Figure 3: Conceptualized Project Life Cycle [114]

Bitten, Freaner, and Emmons published two studies on the evolution of initial concept designs and their relation to cost and schedule growth of a selection of NASA programs launching between 2000 and 2009. They reveal significant growth in both technical and programmatic metrics from the estimates which are developed during Phase A conceptual studies [19, 82]. They conclude that there is a lag between the realization of technical growth and the realization of cost and schedule growth. Figure 4 presents their results, overlaid with the project life cycle from the NASA systems engineering handbook. It is evident that, while the majority of technical growth occurs prior to the start of fabrication and integration (marked by the CDR), the majority of cost and schedule growth occurs during these phases and isn't realized until launch. These studies postulate that there is inherent optimism in the initial concept design which can manifest as an underestimation of the complexity of the system. Furthermore, the desire to launch as early as possible can lead to a "success-oriented" schedule [19]. The Constellation lessons learned, published a year after Bitten's study, confirms these postulations. "The reality is that Agency flagship programs like Constellation must be robustly planned (e.g.‘elastic’) vs. optimally planned (‘inelastic’) [180]”.

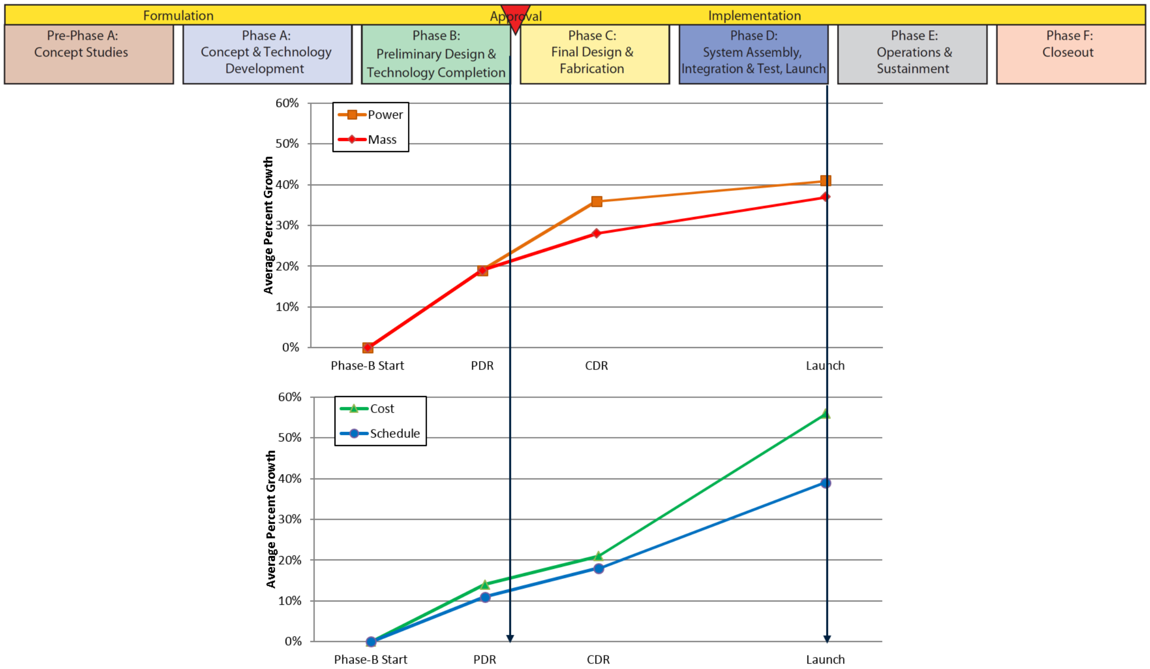


Figure 4: Average Technical and Programmatic Growth for Select NASA Programs [19, 114]

The trends identified through Bitten, Freaner, and Emmons research suggest that the “Paradox of Sequential Design” is the foundation of many space programs at NASA. This term was coined by Sobieski to represent the notion that, as knowledge about the design increases, the engineers ability to influence the design decreases. He claims that the efficacy of optimization loops is greatly diminished when this serial design approach is followed [211]. This notion was expanded upon by Fabrinsky in the early 1990’s to include the implications regarding cost incurred and cost committed. Whilst little is known about a system at the onset of a program, it is the decisions made within the early design phases which lock in potentially undesirable traits that are only realized, once production begins, when changes are extremely costly [114, 115, 79, 136]. As much as 90% of a system’s life-cycle cost is committed by the start of production, with as much as 80% locked in by the end of Conceptual Design

[114, 20]. Figure 5 portrays the trends common to the “Paradox of Sequential Design” described by Sobieski and Fabrinsky.

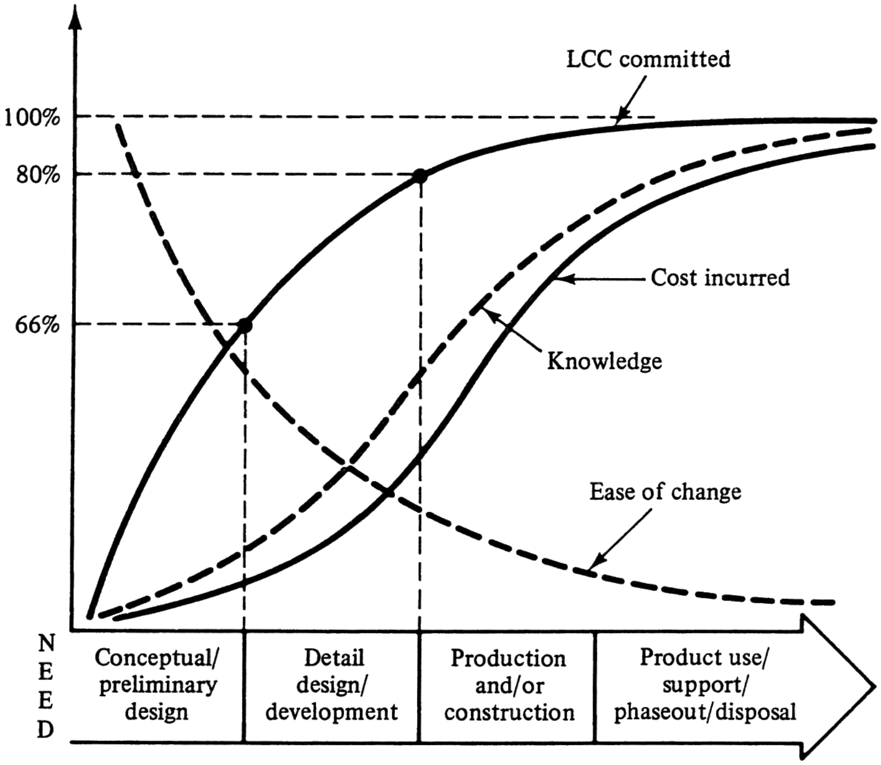


Figure 5: Life Cycle Cost Committed, Cost Incurred, Knowledge, and Ease of Change [79]

In 1990 Schrage and Rogan qualitatively established the benefits of concurrent engineering to the “Paradox of Sequential Design” [198]. Concurrently engineering both the product and processes facilitates greater availability of knowledge early in the design phase where engineers have sufficient design freedom to influence the evolution of the design. The ability to maintain influence over the design for a longer duration becomes invaluable when the products in question are highly complex and involve new technologies.

In 2010, Accenture performed a research based study aimed at discovering the factors needed to achieve high performance in the aerospace and defense industry. The study included a survey of forty aerospace and defense executives, from both commercial and military sectors. One key finding establishes that a majority of the executives believe the basis of their competitive advantage is the capacity to deliver innovative products [61]. Innovative products, especially in the aerospace industry, require advanced technologies, which often aim to increase performance with a tendency to also increase both cost and risk to the manufacturer and operator [200]. NASA's vision [160] "to reach for new heights and reveal the unknown so that what we do and learn will benefit all humankind," suggests that their products will not only be technologically advanced, but revolutionary beyond other industry endeavors.

The advent of advanced materials and new manufacturing processes, particularly composites and their processing technologies, challenges the traditional design approach [200]. The sequential design approach was formed from decades of aluminum-dominated designs and manufacturing practices. Engineers could accurately estimate design mass by leveraging size-based relationships, and then accurately predict the cost based upon the system mass [122]. In this design approach the manufacturing aspects would not be considered until the end of the Detailed Design phase, just prior to the start of production [122]. Thus the impact of early design decisions was never assessed relative to the cost of producing a system.

To fully appreciate the challenges NASA's launch vehicles face, over advanced aircraft for instance, a brief thought experiment will prove greatly beneficial. Assume that the cost to develop and produce a launch vehicle (such as NASA's SLS) and an aircraft (say the Boeing 787) is equivalent. Where the program development cost and unit production cost is \$25billion and \$500million, respectively[1]. If the effect of learning, whereby the cost to produce a unit decreases as the number of

---

[1] The production costs of these programs is not representative. As of 2013 the 787 costs approximately \$200million to produce [81], and the SLS is expected to cost more than \$1billion. While neither Boeing nor NASA have published any official numbers, the development efforts of each is reported to be in the mid-\$20billions [40, 8]

units produced increases, is ignored, a clearer representation may be presented. To determine the average cost incurred by the manufacturer, to produce a unit, the program development cost is typically amortized over the entire production lot. Thus, for any size production quantity the unit cost may be determined from Equation 1.

$$AverageUnitCost = \frac{ProgramDevelopmentCost}{NumberofUnitsProduced} + UnitProductionCost \tag{1}$$

Equation 1 suggests that as more units are produced the average unit cost asymptotically approaches the actual unit production cost. This trend is shown in Figure 6, for the Boeing 787 versus NASA SLS thought experiment, where the average unit cost of producing a single unit is an unaffordable proposition, the average unit cost drops to 150% of the unit production cost once 100 units are reached.

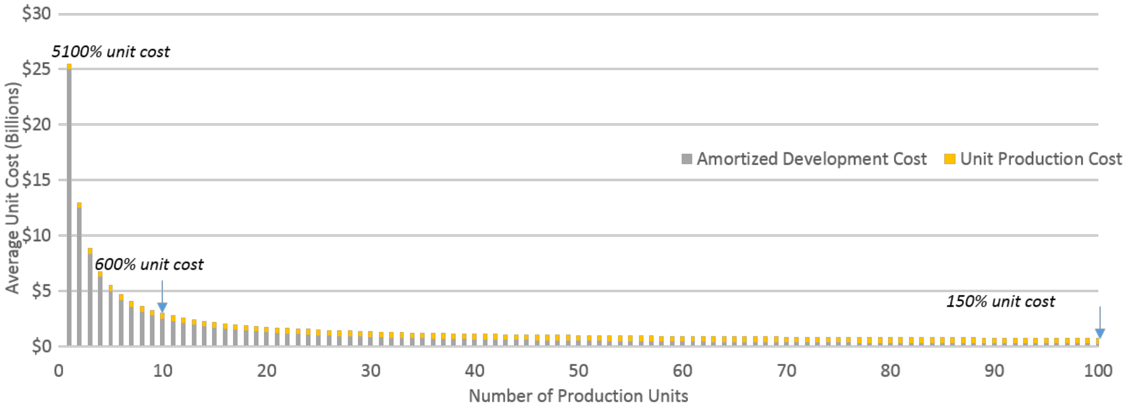


Figure 6: Amortization Curve

The key distinction between the NASA SLS and the Boeing 787 is the evolution of the program throughout its lifecycle. The Boeing 787-8 was the first in the family of aircraft to be introduced, followed by two variants, the 787-9 and the 787-10 [22]. As of the writing of this thesis, the family of aircraft has amassed orders exceeding 1000 [23]:

1. 787-8 — 467

2. 787-9 — 465

3. 787-10 — 139

With regard to the thought experiment and Equation 1, the contribution of the amortized development cost is approximately 35%, for the 787-10, and 10% for the -8 and -9 variants. At the current production rates reported by Boeing the production of these three variants will continue well into the 2030's, especially as additional orders are anticipated [21].

The NASA SLS program plan also includes a family of three variants. The first variant, designated as the "Block I," is expected to achieve its first launch in 2018, followed by a second launch in 2020's [164, 145, 108]. The first launch will be unmanned and serve as a system readiness test, while the second flight will be manned and undoubtedly incorporate design changes identified from the test launch. To date, only these two missions have been approved [164]. An additional 5 missions have been proposed, which provides insight into the expected evolution of the SLS. The third launch, which is expected no sooner than 2023, is expected to be the first launch of the second SLS variant, the "Block IB" [12]. This variant will include the addition of the Exploration Upper Stage, which will increase both the launch performance and the in-space capability, and is considered an intermediate step towards the final SLS variant. Launches four, five, and six are expected to be the same "Block IB" configuration before the final variant, the Block II, is debuted in the 2030's [10]. The final variant will incorporate advanced boosters to the "Block IB" configuration, and provide the final performance increment needed to facilitate sending astronauts to Mars [164].

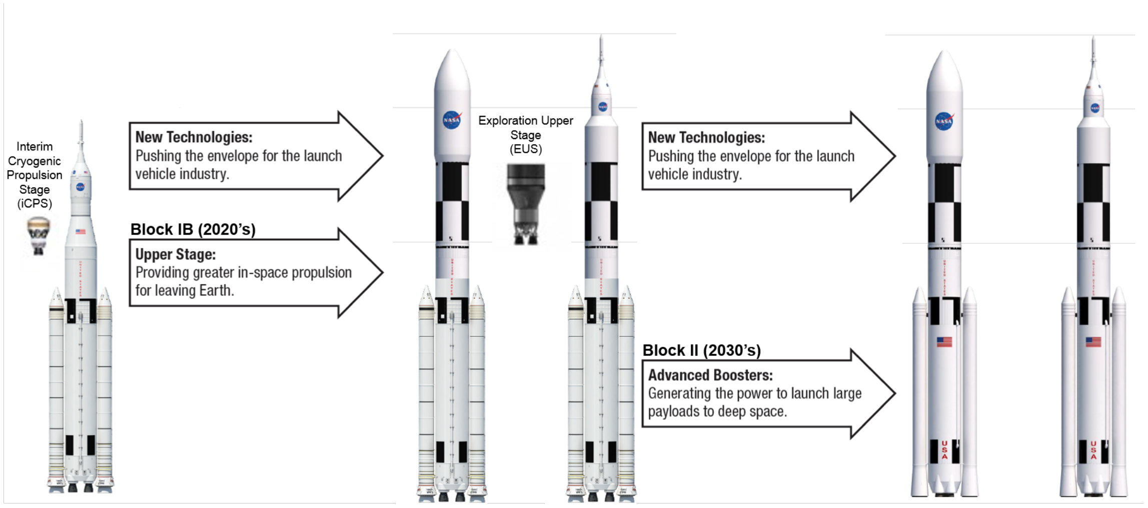


Figure 7: Planned Block Upgrades to the SLS [adapted from [164, 12, 117, 108, 168]]

Flights one to four will leverage the current stock pile of sixteen Space Shuttle Main Engines (SSMEs) to power the core stage, at four engines per flight [164]. While NASA anticipates a restart of SSME production, the agency has not finalized acquisition plans to manufacture them [40]. This engine was designed specifically for the Space Shuttle; as such some of its features include reusability and robust performance in-atmosphere and on-orbit [3]. With the SLS being an expendable launch vehicle — whereas the Space Shuttle was a reusable launch vehicle, orbiter, and reentry vehicle — the SSMEs are over-designed for SLS operation, and a redesign to provide more appropriate performance to the SLS is expected [11].

In reviewing the seven SLS missions — for which information is presently available — there will be at least four different vehicle configurations, assuming that none of the test flights necessitate any redesigns. Furthermore, each of the block upgrades will require additional development expenses which are not currently included in estimates. With no more than two identical versions of each configuration, it is clear that the SLS will operate under a continuous improvement paradigm where each vehicle will be an improvement over the last. Thus, in returning to the thought experiment between the SLS and the 787, the tiny production quantity of the SLS dictates that the average unit cost is dominated by program development costs. It may therefore be concluded that the SLS program, which will most likely operate under a *continuous improvement paradigm* and never exit the development phase of the design lifecycle.

This continuous improvement paradigm coupled with the low production quantities and exorbitant costs and time associated with the development of launch vehicle necessitates more thorough planning during early design phases. Furthermore, the advent of advanced materials and new manufacturing technologies requires a fundamental shift in the traditional design process, specifically bringing the production aspect forward and considering design, development, testing, evaluation, and production (DDTE&P) simultaneously. Thus, one may postulate an answer to the motivating research questions:

Motivating Research Question 1

What are the main drivers of cost and schedule overruns that have led to so many launch vehicle cancellations?

The cause of such overruns is the inadequate consideration of both manufacturing technologies **AND** the required DDTE&P planning performed during Conceptual Design.

A variety of methods have been developed to improve the quality of early Conceptual Design, particularly by expanding the ability to explore more of the architecture space, and expanding the use of optimization during design [47, 27, 48]. These methods, however, typically operate only on the metrics/parameters available in a particular design phase. They do not address the appropriateness of certain metrics, nor do they prescribe methodologies to determine appropriate values for the metrics which are instrumental to strategic planning. These methods do not generate the information necessary to assess the impact of manufacturing technologies during the early phases of design.

Significant growth (both technical and programmatic) occurs immediately after initial estimates are generated, and a lag exists between the realization of technical growth and the realization of cost and schedule growth. This suggests that, in order to produce an affordable vehicle, a significant amount of technical planning must be performed early. While many methodologies champion the need to assess risk early on, few provide guidelines on developing tangible metrics to guide affordable launch vehicle system realization up until first flight. One major breakthrough in providing more realistic technical assessment in early design phases is the Manufacturing Influenced Design (MInD) methodology developed at Georgia Institute of Technology, and discussed in Section 2.5.

1.4 Problem Statement

The primary motivation for this research is the challenge that launch vehicle programs have experienced, historically, in reaching first flight. The inability for these programs to maintain affordability stems from inadequate DDTE&P planning which has resulted in the many cancellations — from schedule slippages and cost overruns, due to optimism in initial estimates of technology capability, and the cost and time associated with planning maturation through to first launch.

The current practices and expectations (reviewed in Section 2.2) for Conceptual Design analysis and planning consider only the total life cycle cost (LCC), total project/program duration, and the risks attributed to these totals. The information contained in Chapter 2 elucidates the methods used during Conceptual Design, with an emphasis on the details included in technical analysis, and the extent of the planning activities required to progress into Preliminary Design. Section 2.4 identifies two major flaws in the current practices:

1. The technical analysis is performed at a level of detail incapable of providing

insight into manufacturing aspects, which ultimately drives program planning.

2. The cost analysis performed during Conceptual Design often provides only a "feeling" of the program costs, and include limited,if any, planning considerations.

Thus, an observed solution to the second motivating research question may be posed:

Motivating Research Question 2

How can the drivers of cost and schedule overruns be captured?

Considering a lower level of technical detail during Conceptual Design —namely Manufacturing Influenced Design — AND will facilitate the inclusion of planning considerations to realize the affordability of a launch vehicle.

The historical perspective, provided in 1.3, shows that programs are canceled long before the total LCC is achieved as a result of the cost accrual exceeding the appropriated budget. These highly constraining funding profiles bolster the need to generate accurate time-phased cost estimates during Conceptual Design through the creation of risk-aware development strategies. Thus, an overarching research question has been developed to guide this research.

Overarching Research Question

How can Conceptual Design studies be adapted to realize the affordability of a launch vehicle up to first flight?

1.5 Research Objective

The goal of the proposed research is to improve upon current affordability and risk assessment methods for Conceptual Design. Specifically, improvements shall be made to facilitate the selection of an affordable strategic plan during launch vehicle baseline concept selection to better understand the implications of achieving first flight. This goal is presented at a high level by the primary research objective of this thesis, given below.

Research Objective

Support the development of affordable launch vehicles by quantitatively capturing the effects of manufacturing technology selection during Conceptual Design

To meet this overarching research objective, the following series of requirements have been derived:

Develop a methodology which has the following characteristics:

1. Flexible and scalable to apply to complex systems such as launch vehicles.
2. Robust to uncertainty in inputs.
3. Quantitative means to select an affordable portfolio of manufacturing technologies
4. Produce a quantitative forecast of both cost AND schedule risks associated with a development plan.

To begin satisfying these requirements it is beneficial to envision the end state, and thereafter develop the research questions (by finding the gaps between what is needed and what is currently available) to realize the end state. Commercial aircraft manufacturers have, for many years, assessed the business case of a potential aircraft candidate through a cumulative cash flow approach [135, 88]. The premise of such a concept is to provide a visualization of the life cycle cash flow associated with developing and marketing a new aircraft. This single visualization shows the required capital investment (i.e. the sunk cost) and expectation of revenue and profitability (from sales forecasts) for an aircraft concept. Figure 8 shows a notional aircraft manufacturers cumulative cash flow. In more recent years, emphasis on risk and uncertainty methods has yielded an uncertain cumulative cash flow, which captures programmatic uncertainties and propagates them onto the cumulative cash flow [49]. Thus, the methodology proposed herein seeks to provide the Conceptual Design team the ability to assess the implications of DDTE&P strategic planning decisions upon the LCC of a launch vehicle during baseline selection.

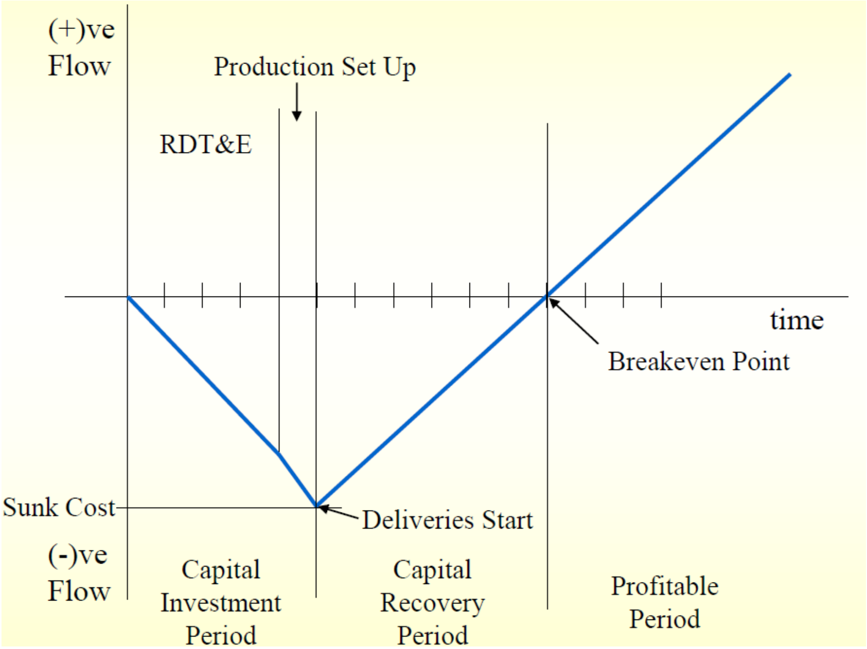


Figure 8: Notional Cumulative Cashflow for a Typical Aircraft Manufacturer [135]

1.6 Organization of the Dissertation

The remaining sections of this thesis will cover relevant literature, a description of the proposed methodology, and the development of the experimental plan for the proposed research. Chapter 2 begins with a brief description of the launch vehicle design process, followed by the presentation of current industry standards and practices for planning and risk management during early stages of design.

The purpose of this chapter is to establish the current methods used in industry, beginning with two background questions:

Background Research Question 1

How are launch vehicle DDTE&P strategies generated?

Background Research Question 2

How are these strategies used in the down selection to a baseline vehicle configuration?

Thereafter, a review of technology assessment techniques often leveraged in Conceptual Design and a discussion on their applicability to manufacturing technologies is presented. Chapter 2 concludes with a critique of the industry standards and relevant technology assessment methods and identifies a gap which the proposed methodology aims to bridge. Chapter 3 begins with a brief overview of the approach followed to develop the proposed methodology, and is followed by the elicitation of research questions and hypotheses which are tested by subsequent experimentation.

Chapter 4 provides an overview of the developed framework which is then leveraged, in Chapter 5, to compare the real-world implications of composite material use for cryogenic propellant storage. This dissertation is then concluded with a summary of findings, a discussion on the contributions of this thesis, and the potential future work opportunities it has provided.

CHAPTER II

LITERATURE REVIEW

Whether any particular future mission flies is linked to its perceived value (as measured by society's willingness-to-pay) at some future date [201]

The ability to achieve first flight hinges upon a program's ability to remain affordable, and deliver a vehicle that remains affordable throughout its life. The historic cancellations — presented in the previous chapter — suggest that a huge challenge exists in maintaining the affordability of a program up until the first vehicle is delivered. As such, the focus of this thesis is on the program life cycle up until the first launch. Operations and Support shall be considered beyond the scope of this work; including these aspects in future works, will provide a complete perspective of a programs affordability.

This chapter reviews relevant literature in the area of risk management and launch vehicle development practices with emphasis on affordability assessment. It begins with a brief discussion of the launch vehicle design process which will clarify the specific life cycle phases discussed throughout this thesis. Thereafter, an overview of relevant risk and affordability requirements will be provided; beginning with current risk assessment guidelines and practices prescribed by government entities, and followed by a review of technology assessment methodologies leveraged during Conceptual Design.

The intent of this review is to establishing the current state-of-the-art practices in affordability risk assessment during early design. This chapter will help identify the gaps to be addressed by this research, and will discuss the theory behind the methods to be used in the proposed solution.

2.1 Launch Vehicle Design Process

The life cycle of a launch vehicle evolves through seven distinct phases, beginning in formulation phases and then proceeding through to the implementation phases. These seven phases may also be categorized in terms of the type of work being performed; phases in which the system design is still evolving, and phases where the design is considered fixed. The launch vehicle design process consists of four phases: Pre-Conceptual Design, Conceptual Design, Preliminary Design, and Detailed Design [20, 114].

CDR	Critical Design Review
CERR	Critical Events Readiness Review
DR	Decommissioning Review
FRR	Flight Readiness Review
KDP	Key Decision Point
MCR	Mission Concept Review
MDR	Mission Definition Review
ORR	Operational Readiness Review
PDR	Preliminary Design Review
PFAR	Post-Flight Assessment Review
PIR	Program Implementation Review
PLAR	Post-Launch Assessment Review
PRR	Production Readiness Review
P/SDR	Program/System Definition Review
P/SRR	Program/System Requirements Review
PSR	Program Status Review
SAR	System Acceptance Review
SDR	System Definition Review
SIR	System Integration Review
SRR	System Requirements Review
TRR	Test Readiness Review

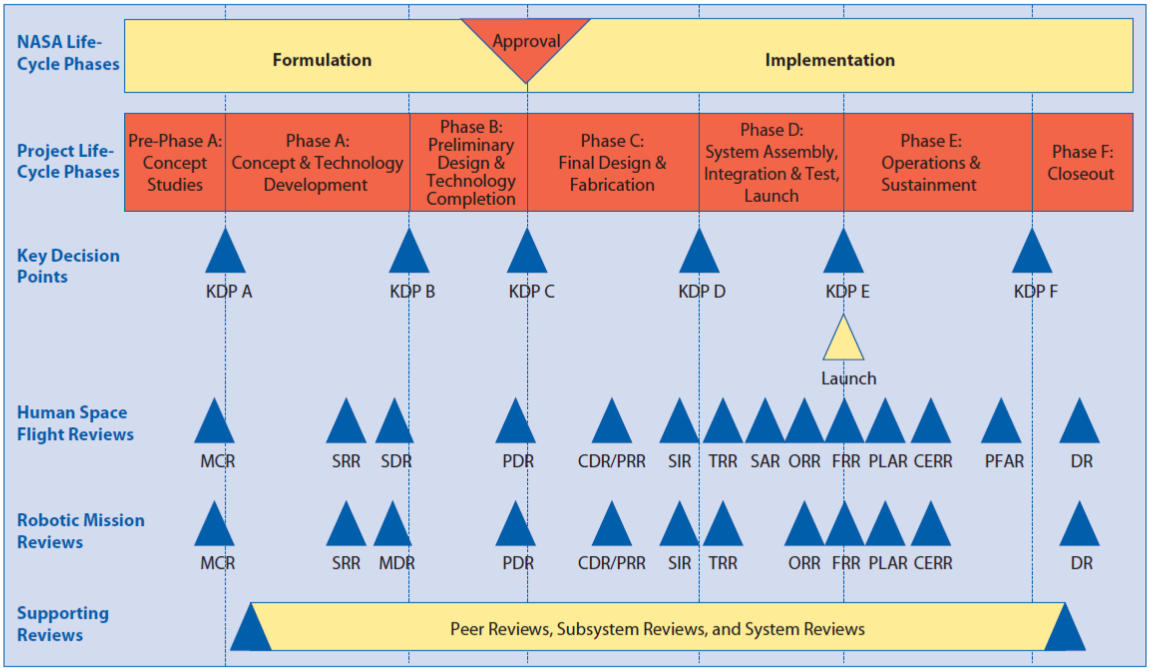


Figure 9: Conceptualized Project Life Cycle

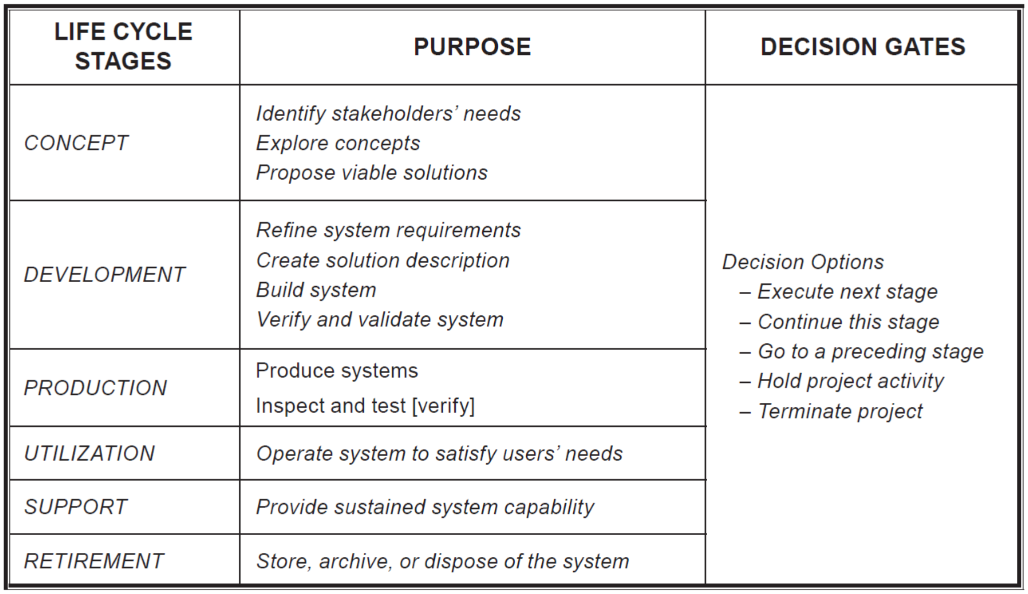
The first phase, pre-Conceptual Design, focuses on producing a broad spectrum of ideas and alternatives for missions from which new programs and projects can be selected. Design studies examine feasible vehicle concepts for general missions of interest and are usually performed continuously by concept study groups [114]. Baseline vehicle architecture selection is typically performed at the end of pre-Conceptual Design or during Conceptual Design [227].

The second phase, Conceptual Design, consists of a more detailed study into the feasibility and desirability of a suggested new major system [114]. During these conceptual studies the emphasis shifts from feasibility to optimality, and more detailed analysis is performed using top-level sizing to produce estimates of performance, cost, technology development needs and risk [20]. The number of feasible concepts is narrowed as the design process progresses through this phase, typically culminating in the selection of a single baseline concept [20, 114].The technical team is expected to generate a technical cost and schedule estimate based upon the work required to satisfy the technical requirements of the project [114].

The third design phase, Preliminary Design, is characterized by increased fidelity analysis of all significant subsystems [20]. Project level performance requirements are used to develop a complete set of system and subsystem design specifications for flight and ground elements [114]. The baseline may evolve throughout this phase, encountering refinements to subsystem design or fundamental architecture changes. The development of engineering test items may be necessary to derive data to demonstrate new technologies or for the evaluation of project risk [114] The end of this phase is marked by a Preliminary Design review (PDR) where all phase efforts are used to establish a final design-to specification for the system. Hereafter, no fundamental design changes are expected, only successive refinements [114].

During the fourth phase, Detailed Design, all hardware and software specifications for the system are generated [20, 114]. These specifications facilitate the production of test articles and further detailed analysis to verify system performance and increase the confidence that the design will function as expected [114]. Over and above these design refinements, manufacturing, integration, operations and support plans are considered. This phase is bisected by a critical design review (CDR), which marks the completion of fully defining a system, and the beginning of flight hardware fabrication. Hereafter, the hardware is assembled, integrated, and tested before performing first launch, and thus entering the operations and sustainment phase, during which it performs its designated mission [114]. Figure 9 depicts a conceptualized project life cycle; showing the evolution of the system, the decision points which act as gates between phases, and the major reviews which occur throughout. Further detail regarding the design evolution may be found in [20, 114, 175].

The project life cycle phases, as described above, differ between U.S. government entities, international councils, and commercial industry, but ultimately follow a single evolutionary progression, as described in the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook, and Figure 10. Figure 11 shows a comparison of these phases for various entities, with a typical decision gate process overlay.



LIFE CYCLE STAGES	PURPOSE	DECISION GATES
CONCEPT	*Identify stakeholders' needs* *Explore concepts* *Propose viable solutions*	*Decision Options* *– Execute next stage* *– Continue this stage* *– Go to a preceding stage* *– Hold project activity* *– Terminate project*
DEVELOPMENT	*Refine system requirements* *Create solution description* *Build system* *Verify and validate system*	
PRODUCTION	Produce systems Inspect and test [verify]	
UTILIZATION	*Operate system to satisfy users' needs*	
SUPPORT	*Provide sustained system capability*	
RETIREMENT	*Store, archive, or dispose of the system*	

Figure 10: General Life Cycle Phases [103]

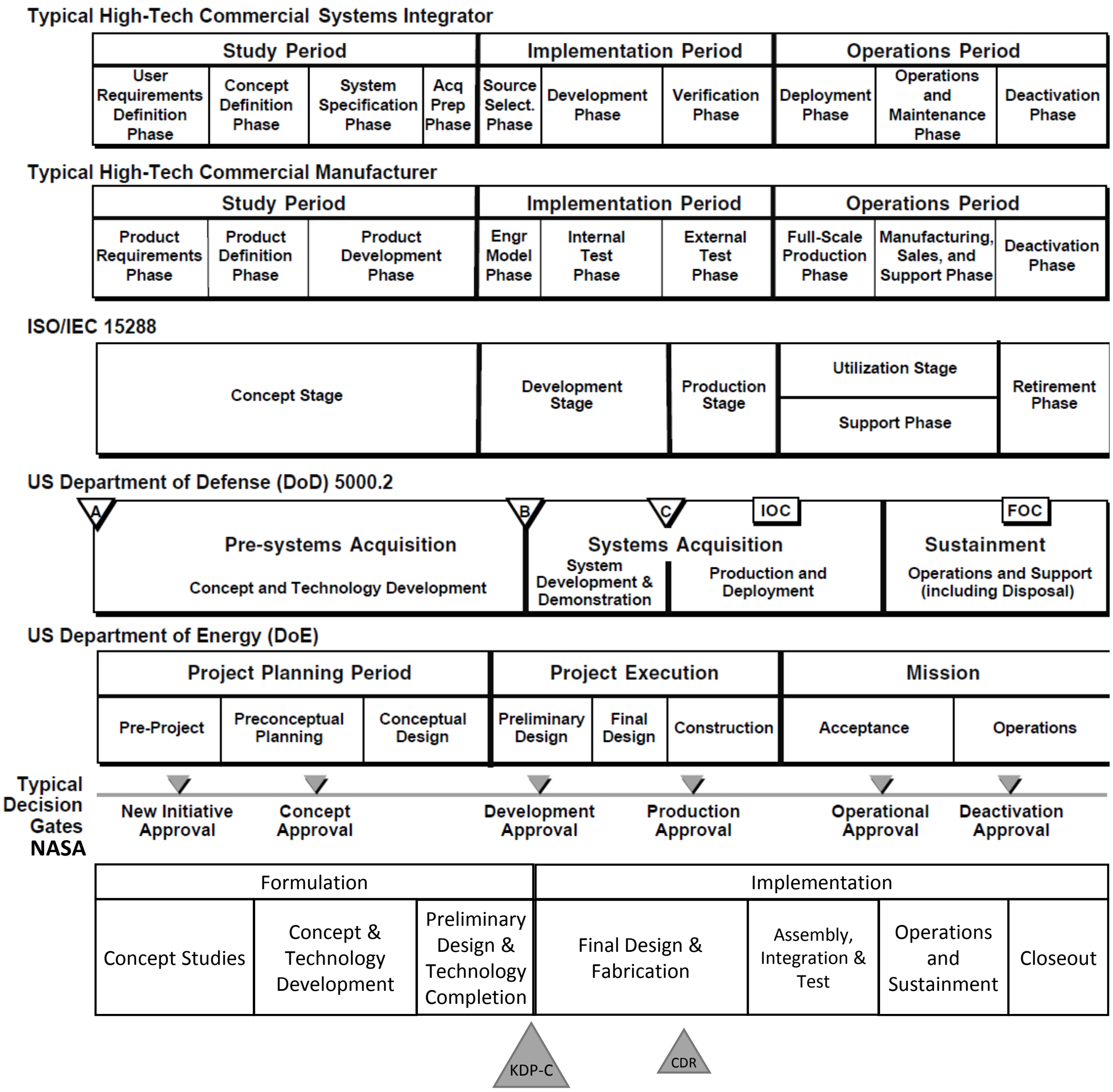


Figure 11: Comparison Between Project Life Cycle Phases of Various Entities [114, 103]

The major distinction between each of the life cycle phases is where and how often critical reviews occur[1]. For example, Milestone B of the US Department of Defense process marks the first review where an affordability analysis and initial

---

[1] Note: These phase boxes are not scaled to represent any progression of time. They have been scaled within the typical decision gates. While it is possible to assert that an entity has a greater amount of detail—based on how soon a decision gate occurs— this representation cannot provide any indication of the time duration between these decision gates. The time duration will differ for every program and will most likely increase proportionally with the complexity of the program in question.

summary-level development plans are due [64]. NASA, on the other hand requires the first summary-level plan and affordability analysis at the end of the "Concept & Technology Development" phase, and a second, more detailed version of both at key decision point (KDP)-C. This warrants a more in-depth discussion of planning, affordability, and risk standard of the relevant launch vehicle entities.

2.2 Industry Standards and Guidelines

Having established the design phases through which a launch vehicle evolves, it is necessary to determine how the information matures through these phases, and what development planning techniques are currently used to capture life cycle affordability. A review of government guidelines and documentation has been performed to determine the current best practices for project/program planning and risk assessment during early design phases.

2.2.1 Project/Program Planning during Conceptual Design

The applicable standard used by the Department of Defense (DoD) is the Defense Acquisition Handbook, which contains guidelines for both the program manager and systems engineer [64]. These guidelines are intended to apply for all DoD programs and projects and does not specifically cater to launch vehicles. Milestone B, as shown in Figure 11, is the first point in the lifecycle where affordability, planning, and risk assessments are expected. This handbook prescribes the development of a work breakdown structure (WBS) to manage risk and meet program objectives while balancing cost and schedule. The program schedule is generated based upon functional relationships between activities, which are arranged to identify the critical path of the program. The critical path consists of the planned activities which drive the project duration, forming the longest path to program completion. Each of these processes is subject matter expert (SME) driven, and therefore manual in nature. The Defense Acquisition Handbook, however, does not explicitly describe the scope of the estimates to be provided at each milestone within the project. It suggests that the caliber of the estimates will increase as the system progresses through its life cycle, and therefore implies that the early estimates will be simplistic/summarizing in nature and will become more detailed (and therefore more accurate) as the system materializes [64].

The International Council on Systems Engineering (INCOSE) Systems Engineering Handbook represents an industry-wide guideline. Like the DoD practices, it also recommends the generation of a WBS and loading resources by associating activities and summary costs particular to the WBS items [103]. The first affordability estimate, and risk assessment is prescribed to occur by the end of the "Concept Stage," as depicted in Figure 11. Like the DoD Acquisition Guidebook, the INCOSE Systems Engineering Handbook also prescribes the use of arranging activities to determine the critical path of the program. While the planning process guidelines herein recommend developing these estimates as early as possible and tailoring them to a particular program, they allude to a manual (subject matter expert) approach and present no expectation of plan scope at these, and later, project milestones.

Within NASA standards, the planning exercise consists of two parts: program/project planning and technical planning. Technical planning refers to an effort led by the systems engineer to identify, define, and develop plans for performing decomposition, definition, integration, verification, and validation of the system. The program/project planning, led by the program/project manager, concentrates on managing the overall program/project life cycle and provides the available budget allocated from the program, and the desired schedule for the project to support overall program needs [114]. NASA's Space Flight Program and Project Management Handbook describes the program/project level planning guidelines, dictating that a baseline project plan is due by the SDR. Some key aspects of this plan include a summary Integrated Master Schedule (IMS), technical performance measures, and progress reporting procedures. The summary IMS contains the logical relationships for the various project elements and displays the critical path along with all milestones and expected reviews [163]. The NASA's Systems Engineering Handbook provides the technical planning guidelines, suggesting that only once the technical effort begins to coalesce can specific planning activities (and efforts) be defined. This document prescribes the development of a product breakdown structure (PBS) — a hierarchical depiction of the entire system architecture — which is then expanded in the form of a WBS — which depicts the applicable work effort necessary to complete the project and thus develop, produce, and operate, the product [114, 95]. "Each WBS model represents one unique unit or functional end product in the overall system configuration and, when related by the PBS into a hierarchy of individual models, represents one functional system end product or 'parent' WBS model [114]." While both documents are general in nature, they do suggest that planning is to be done at the schedule level, and then resources allocated to that schedule. However, they also suggest that the estimates — which ultimately form the baseline WBS and IMS — provided at the end of the Conceptual Design phase will be based heavily upon subject matter expertise and the selected baseline vehicle [114].

The industry trend for design efforts have shifted focus towards affordability approaches. NASA and INCOSE suggest the use of a resource loaded WBS in an attempt to capture the LCC of a system. Despite their agreement that the best time to mitigate excessive cost and schedule overruns is early in the design phase, there is no expectation that a detailed/baseline WBS be generated before the end of Preliminary Design, suggesting that the baseline vehicle concept is selected without significant consideration of DDTE&P planning. This lack of consideration undoubtedly locks in unforeseen cost and schedule risk which will result in growth — analogous to that show in Figure 4.

2.2.2 Risk Assessment Requirements and Guidelines

The Department of Defense Risk Management Guide for DoD Acquisition establishes the expected practices for managing risks throughout the life cycle of a program, with an emphasis on reducing the life cycle cost of a system. The main emphasis is on continuous risk management (CRM): “continuously identifying and measuring the unknowns; developing mitigation options; selecting, planning, and implementing appropriate risk mitigation; and tracking the implementation to ensure successful risk reduction [63].” This process, depicted in Figure 12, consists of five key activities and is designed to occur iteratively, re-evaluating risks as a project/program evolves through its life cycle. The key activities are:

1. Risk Identification
2. Risk Analysis
3. Risk Mitigation Planning
4. Risk Mitigation Plan Implementation
5. Risk Tracking

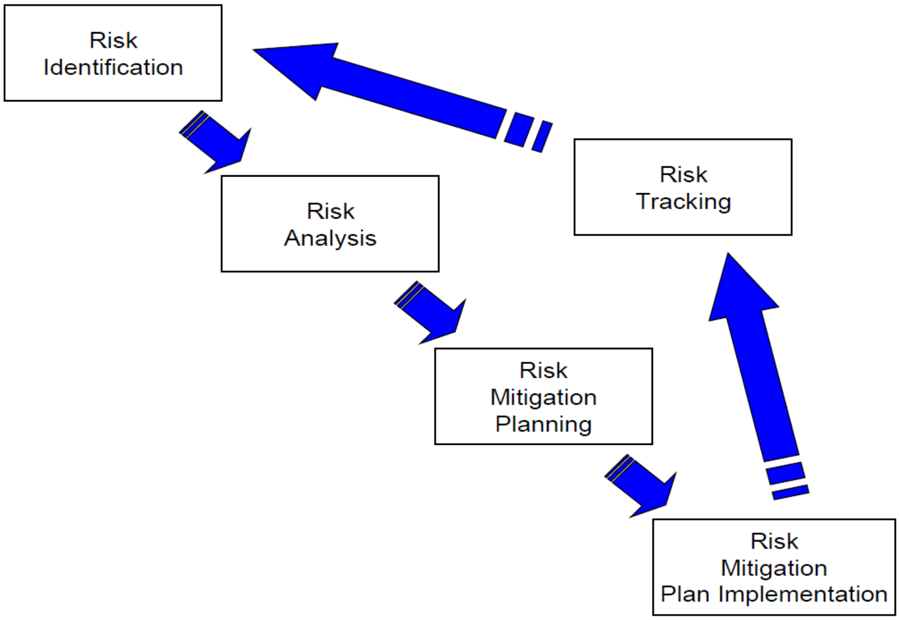
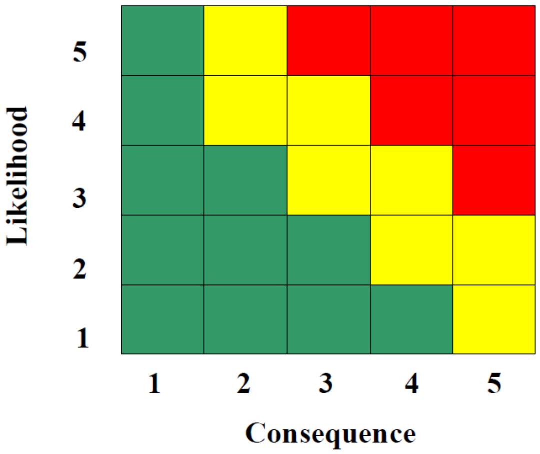


Figure 12: DoD Risk Management Process [63]

The risk identification activity revolves around examining each element of a program in order to identify potential root causes and set the stage to manage them. This identification process revolves around decomposing the WBS into as detailed a list of product and process elements, examining them, and enumerating an exhaustive list of "what could go wrong?" scenarios for each [63]. The risk analysis process aims to answer the question of "How big is the risk?" for each of the scenarios identified. This analysis process is largely qualitative in nature, prescribing the use of subject matter experts to identify potential risk scenarios and assign a likelihood and consequence to each. Both are evaluated on an ordinal scale of one to five — where one is the least likely (or lowest consequence). These are then reported onto what is often referred to as a "5x5 Risk Matrix," shown in Figure 13, which visually depicts the risks associated with the identified scenarios and is an extremely commonly used tool. This visualization enables the quick identification of the most risky scenarios, as well as the prioritization of risk mitigation planning and the implementation of those plans. The level of risk is thus defined as the product of the likelihood of a scenario occurring and the consequence associated with that scenario if it were to occur [63]. The risk mitigation planning activity seeks to establish an approach for addressing each potentially unfavorable scenario to reduce risks to acceptable levels given program constraints and objectives. This activity culminates in the selection of an appropriate plan which dictates:

1. What should be done
2. When it should be accomplished
3. The party responsible for each action
4. The funding required to implement the plan

Thereafter, the plan is implemented with an aim of ensuring that the risks associated with each scenario, and addressed by activities in the mitigation plan, are successfully mitigated. This activity is complemented by risk tracking, which establishes metrics to facilitate systematic monitoring of the risk mitigation process and evaluating the performance of risk mitigation actions against established metrics [63]. The level of detail available depends heavily upon the program life cycle phase in which these activities are performed. As such, this process is iterative such that as the program progresses through its life cycle, the risk mitigation plans may evolve to capture new risk scenarios which arise as more knowledge of the system is gained. Since the activities rely heavily upon a detailed WBS, “there must be enough detail to allow a general estimate of the effort required and technological capabilities needed based on system complexity.” **This alludes to the need to establish a baseline vehicle configuration *before* the first iteration of CRM may be performed [63]. There is no indication that specific expectations for the scope of risk estimates are due at any milestone within the life cycle of a program.**



5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨	🟨	🟥
2	🟩	🟩	🟩	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨
	1	2	3	4	5

Figure 13: Risk Reporting Matrix [63]

The INCOSE systems engineering handbook prescribes a continuous risk management (CRM) process identical to that of the DoD, as shown in Figure 12. The minor difference with INCOSE is that, while each of the five activities identified in the CRM process serve the same purpose as those followed by the DoD, no one method is prescribed. Instead, each section includes a brief mention of applicable methods available in literature, but ultimately conclude that leveraging subject matter expert knowledge and historical data is more appropriate for most projects [103]. **Akin to the DoD handbook, no specific expectations on the scope of estimates at key milestones is presented, nor is any threshold for the acceptable level of risk presented in order to ensure that an initiated program succeeds.**

NASA's primary guidelines are contained in the NASA Risk Management Handbook and NASA Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners, and are considerably more extensive than those prescribed by the DoD and INCOSE [66, 213]. While both the DoD and INCOSE champion a CRM approach, NASA expands the definition of risk management to include risk informed decision making (RIDM), a complementary process to CRM [65]. RIDM is concerned with the analysis of important and/or direction setting decisions, while CRM stresses the management of risk during implementation. “RIDM helps to ensure that decisions between alternatives are made with an awareness of the risks associated with each, thereby helping to prevent late design changes, which can be key drivers of risk, cost overruns, schedule delays, and cancellation [65].” The RIDM process consists of six steps, categorized into three parts: identification of alternatives, risk analysis of alternatives, and risk-informed alternative selection. An illustration of the RIDM process and its interface with the CRM process is shown in Figure 14

The first step of the process is to establish an understanding of expectations, and to derive performance measures which capture this expectation. This step represents the flow down of requirements into objectives and constraints by which alternatives may be evaluated. The second step represents an exhaustive effort to identify all possible alternatives for the problem of interest. Step three entails the identification and selection analysis methodologies which link the inherent uncertainty in a particular alternative to uncertainty in the achievement of the objectives. Once these methods have been established, the alternatives identified in step two are analyzed such that each alternative possesses a probabilistic representation of the performance measures and objectives identified on step 1. Step 5 establishes the levels of risk tolerance and desired performance commitments by which each alternative shall be compared. The final step consists of the downselection process through which a final “Risk-Informed” alternative is chosen. This final alternative is then passed into the CRM process, as described above [65].

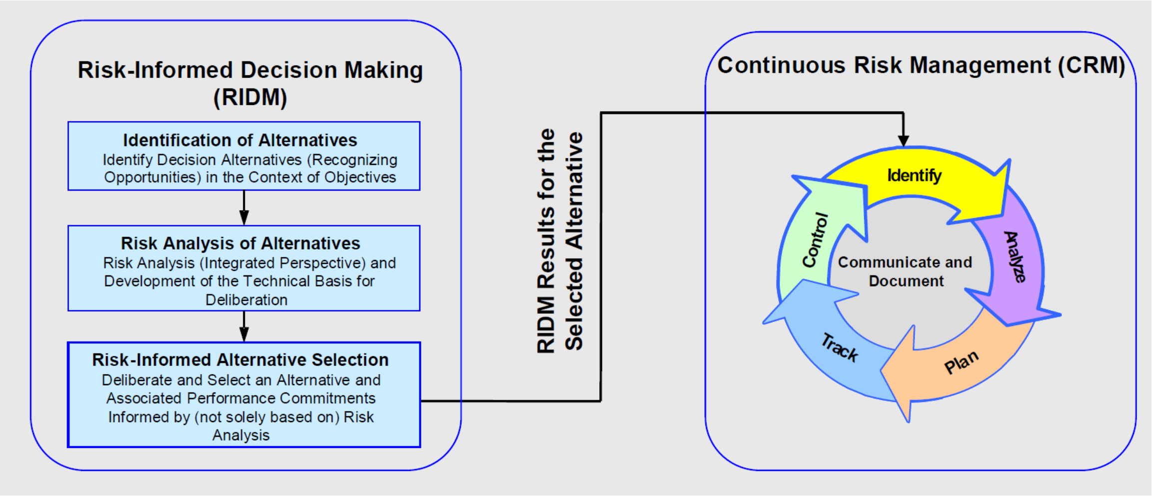


Figure 14: NASA's Risk Informed Decision Making Process and Its Interaction With the Continuous Risk Management Process [65]

NASA's risk management guidelines stress the importance of quantitative analysis, and thus prescribe the use of probabilistic analyses to quantify uncertainties and risks [65, 153]. The primary output of this analysis is a probability density function which graphically presents the likelihood that a particular value, for a performance metric of interest, will be achieved. The appropriate requirement is then overlaid on this figure to provide a representation of the risk associated with achieving this requirement [65]. A notional example is shown in Figure 15, in which performance measure X must be less than or equal to the requirement, thus the risk is the integral of the shaded area. NASA documentation clearly describes the expectations for deliverables needed to pass from one phase into another (through the completion of the KDP reviews). One key metric used to define the programmatic risk is the Joint Confidence Level (JCL), which represents the probability that the program will be completed at or below the estimated cost AND at or below the projected schedule. At the end of the Conceptual Design phase (by KDP-B shown in Figure 3) only the range of confidence on the total LCC and expected completion date is to be established for the selected baseline vehicle configuration. These estimates are then refined during Preliminary Design; in order for the program to proceed into the implementation phase, NASA programs are required to establish a 70% JCL [159, 154]. The selected vehicle configuration must show a 70% likelihood of achieving first launch within the allotted time frame *and* within the available budget. If this threshold is not met, then the program is "kicked" back into Conceptual Design where a new baseline must be established in order to meet the JCL requirement.

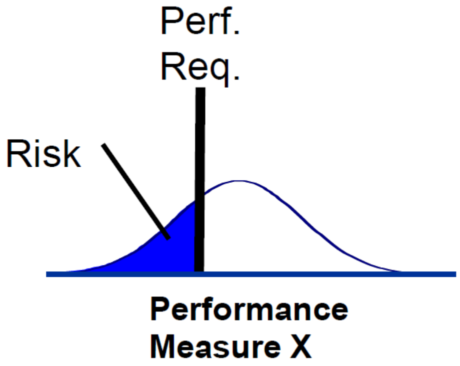


Figure 15: Probability Density Function with Requirement Overlaid [65]

The review of these documents represent a survey of the current state-of-the-art guidelines prescribed by the very entities which embark on the design, development, and implementation of launch vehicles. While all three entities stress the importance of life cycle affordability and the need to assess risks early, only the NASA documentation provides specific analysis guidelines, expectations, and requirements as a function of the program's evolution through its life cycle phases. However, these requirements do not emphasize the value of generating the schedule — upon which the LCC and risk analyses are based. In establishing the expectations of industry, a series of observations are developed:

Observations from Conceptual Design Best Practices

1. NASA is the only organization which prescribes the expectation of the estimates (and their scope) due at each milestone throughout the life cycle of a program/project.

2. While the maturation of a program follows the same general life cycle phases,

NASA's guidelines suggest the program evolves — from Conceptual Design to Preliminary Design — more rapidly and thus the initial affordability and risk assessment is due much sooner than the other entities.

3. The program affordability and risk assessment — expected at the end of the Conceptual Design phase by all entities — is based upon a single WBS, which is generated by subject matter experts around a single baseline vehicle configuration.

4. Since none of the entities reach further back than the selected baseline configuration, the activities which comprise the WBS are extremely dependent upon the constituents that define the baseline vehicle configuration.

5. The affordability and risk assessment includes at most (per the more stringent NASA standards) the range of the TOTAL project duration and TOTAL LCC (based upon optimistic and pessimistic task durations).

6. The total program duration is determined through the application of the critical path method, which allows the schedule risk to be determined solely based upon the critical path activities.

7. Given the current approach to assess affordability, it is not possible to determine how much of the risk is a result of the selected DDTE&P plan, and how much is directly related to the vehicle concept itself.

8. While there is a desire to assess time-phased cost, the best practice documents do not provide the means to generate such information.

Having established the expectations as set forth by the very entities responsible for managing launch vehicle programs, it is necessary to delve into the inner workings of the technical team responsible for generating initial cost and schedule estimates for launch vehicles during Conceptual Design.

2.2.3 Conceptual Design Analysis Methodologies

The methodology by which the technical team performs Conceptual Design studies, to facilitate the selection of a baseline vehicle configuration, differs between entities. While the specific analysis tools differ from team to team, the end goal is often the same; to select a baseline vehicle configuration which meets the design requirements and possess a certain value, as established relative to decision maker criteria (a combination of performance, affordability, and programmatic metrics). The following sections present Conceptual Design methodologies and the analysis tools leveraged by various entities, and is followed by a series of observations regarding the current ability to capture DDTE&P planning considerations as well as the impacts of various advanced materials, processes, and structural stiffening concepts.

2.2.3.1 NASA Marshall Space Flight Centers Advanced Concepts Office

The Advanced Concepts Office (ACO) at Marshall Space Flight Center (MSFC) consists of a team of systems engineers and multi-disciplinary design engineers. This is the technical team whose responsibilities include concept definition, integration, and analysis of Earth-to-orbit transportation systems (i.e. launch vehicles) and in-space transportation systems. This team develops models of the concepts used to define the systems and subsystems of a spacecraft. For launch vehicles these models include a weights and sizing tool, a structural loads analysis tool and an ascent performance (i.e. trajectory) tool. Cost, reliability, and operations models are also included in order to provide a complete picture of the concepts to be evaluated and to understand how to fund technology development. An example of the analysis tools used to evaluate launch vehicle concepts is shown in Figure 16, and a description of the tools relevant to the scope of this thesis, shall now be discussed. The blue boxes represent the system model: the analysis tools used to develop a physical size and description of a launch vehicle. The green boxes represent cost estimation tools, each applicable to different stages of a vehicles life cycle, the pink box represents operational analysis and thee red box includes reliability and safety risk analysis.

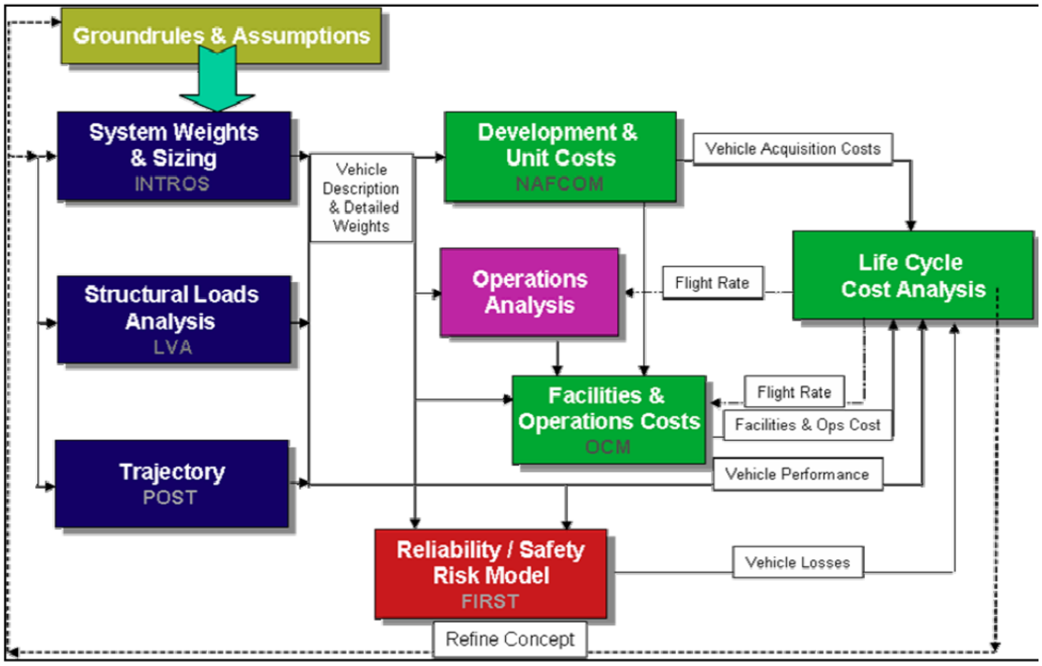


Figure 16: Launch Vehicle Conceptual Design Analysis Process [5]

The focus of this thesis is the considerations which contribute to achieving first flight. Thus the operations aspect of the analysis, while important, is beyond the scope of this thesis. Therefore, only one of the three green — cost — boxes is relevant: the "Development & Unit Costs." Figure 16 may be augmented to highlight the analysis areas relevant to this thesis, as shown in Figure 17, before a discussion on the tools themselves is presented.

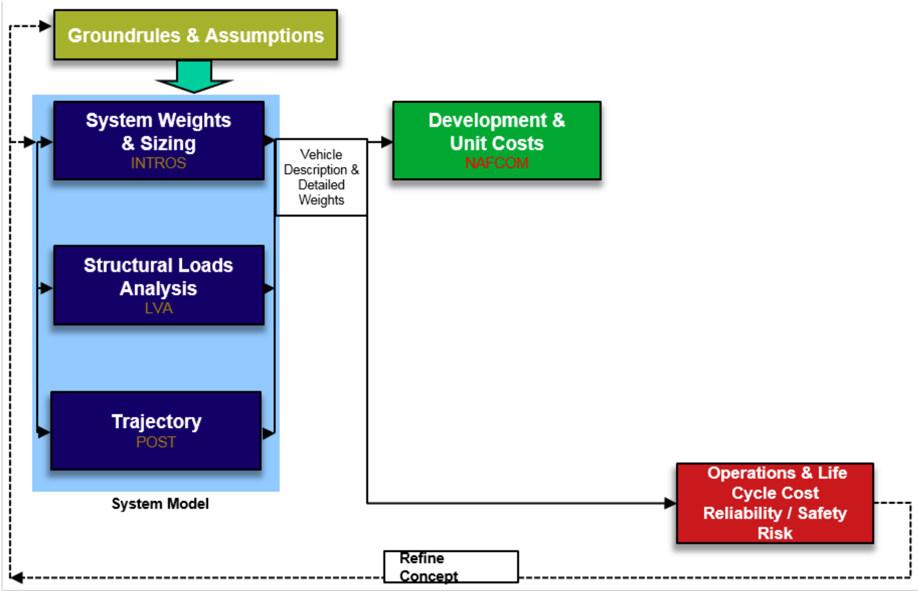
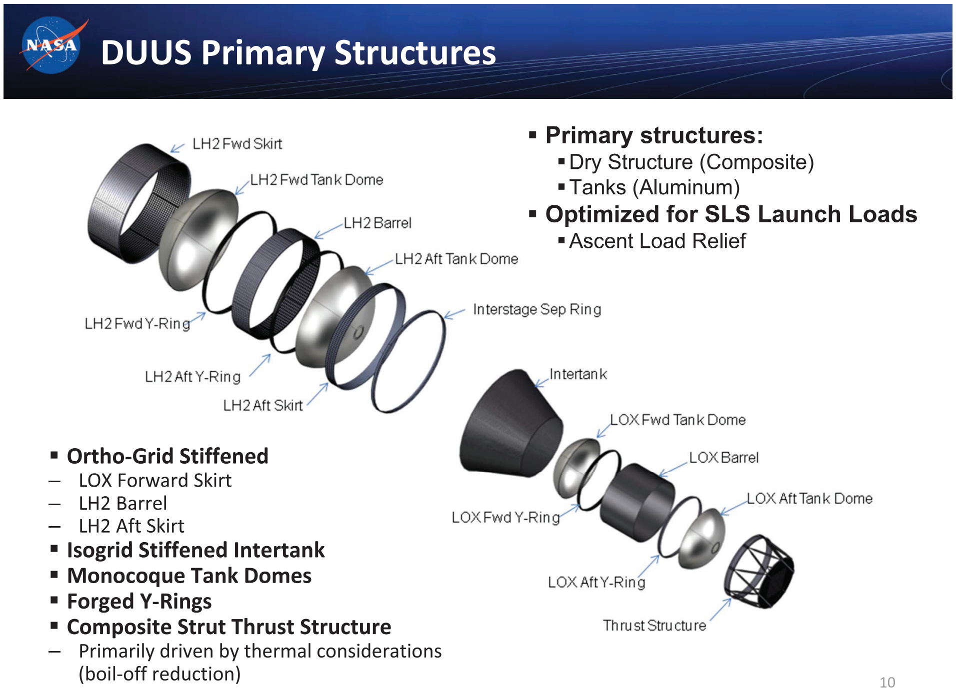


Figure 17: Launch Vehicle Conceptual Design Analysis Process Relevant to Achieving First Flight

The system model, for launch vehicle analysis, is composed of three tools: INTEgrated ROcket Sizing Model (INTROS) , Launch Vehicle Analysis (LVA), and Program to Optimize Simulated Trajectories (POST). These three tools form an iterative analysis capability which sizes a vehicle (INTROS and LVA) and then attempts to fly that vehicle (POST) to the desired orbit [5, 57].

INTROS is an Excel-based tool which leverages mass estimating relationships (MERs) to establish gross lift-off mass and scale geometric layout sketches to size a launch vehicle. This tool forms the foundation for vehicle sizing. It determines a complete vehicle mass breakdown based upon the user-defined geometry of the primary body structures, engine characteristics, and the desired orbit information. LVA is a stand-alone application which leverages closed-form equations and first principles to model structural elements and vehicle components at a higher level of fidelity than INTROS. This tool leverages material properties and structural load cases to determine masses, but is limited to primary structural elements [5]. Primary structural elements include: tanks, skirts, intertank, interstage, and thrust/attach structure. Figure 18 provides a visualization of these structures for the Exploration Upper Stage (EUS) proposed for the SLS. These primary values are used to update INTROS such that secondary and tertiary masses (for example: electrical systems, avionic and hydraulic systems, fairings, and so on) may be recalculated to match the higher fidelity primary structures. POST is a program which simulates and optimizes point mass trajectories for high-thrust aerospace vehicles, most commonly used for ascent trajectories. POST will then take key sizing parameters from INTROS and optimize the trajectory flown in an attempt to reach the desired orbit. Failure to reach the desired orbit is indicative of performance shortfalls in the design and will require an iterative resizing effort until the mass injected into the desired orbit (as simulated) is within 300 pounds of the desired payload specified in INTROS [57].


DUUS Primary Structures

- **Primary structures:**
  - Dry Structure (Composite)
  - Tanks (Aluminum)
- **Optimized for SLS Launch Loads**
  - Ascent Load Relief

- **Ortho-Grid Stiffened**
  - LOX Forward Skirt
  - LH2 Barrel
  - LH2 Aft Skirt
- **Isogrid Stiffened Intertank**
- **Monocoque Tank Domes**
- **Forged Y-Rings**
- **Composite Strut Thrust Structure**
  - Primarily driven by thermal considerations (boil-off reduction)

Figure 18: Primary Body Structures for The EUS (Formerly named the Dual Use Upper Stage) [58]

The final analysis tool of interest is that used to determine the development and production cost, the NASA/Air Force Cost Model (NAFCOM). NAFCOM is a parametric estimating tool for space hardware, applicable to both crewed and uncrewed spacecraft, and launch vehicles. This tool leverages cost estimating relationships (CERs) — based upon an extensive historical database of NASA and Air Force space projects — which correlate historical cost to mission characteristics [137]. These relationships are heavily dependent upon system weight, which greatly restricts the applicability to advanced materials and processes, where the cost vs. weight trends are not captured by the traditional CERs [115]. NAFCOM leverages the masses generated by INTROS and LVA, as well as some engineering management, complexity and team experience inputs, to estimate DDT&E cost, flight unit cost, and production cost.

2.2.3.2 NASA Langley Research Center's Vehicle Analysis Branch

The Vehicle Analysis Branch (VAB) at Langley Research Center (LaRC) is comprised of a team of "discipline SMEs with a systems analysis perspective" [166]. This is the technical team which performs system studies at the conceptual and early Preliminary Design stages on launch vehicles and in-space transportation systems [166, 101, 36]. The VAB leverages its own analysis methodology, outlined in Figure 19, to define a specific vehicle concept. Similar to the analysis tools used by ACO, Langley's VAB tools include a weight and sizing tool, structural analysis, trajectory and propulsion tool, as well as aerodynamic and thermal analyses. While cost and operations are shown as part of the analysis, these are depicted to occur only once the program passes into the Preliminary Design phase.

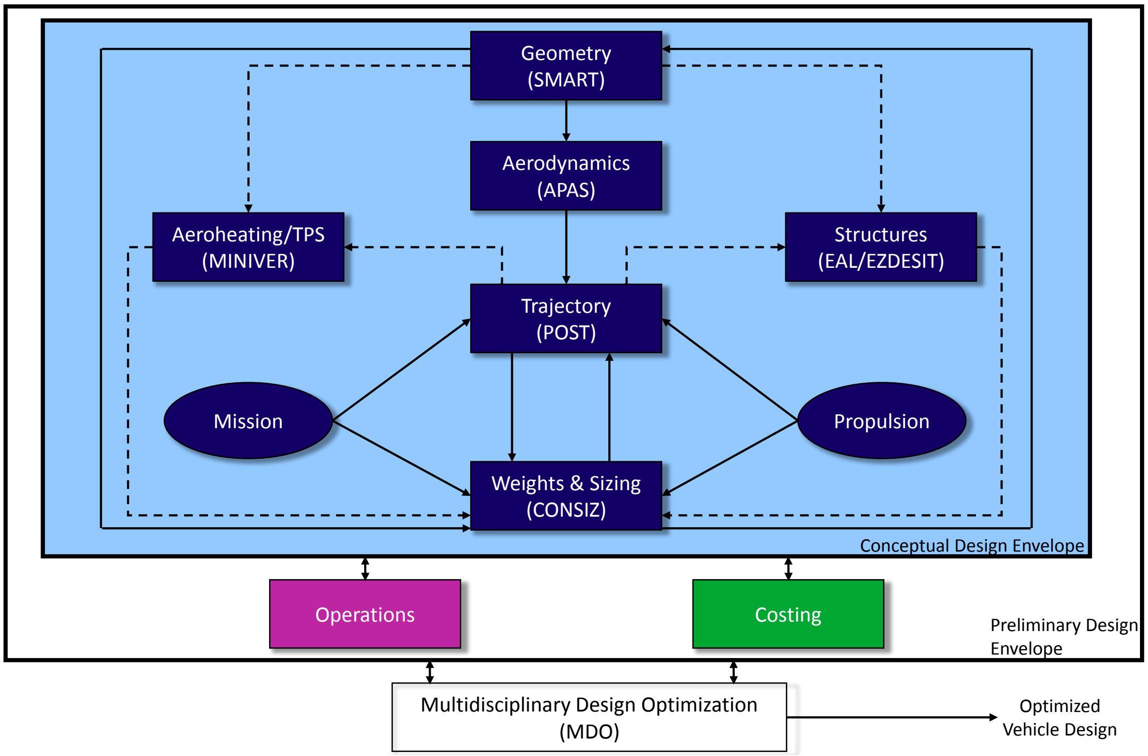


Figure 19: Typical Conceptual Design Process Tools Applied to Space Vehicles (adapted from [101])

The design process begins with the geometric modeling using Solid Modeling Aerospace Research Tool (SMART), developed in house by VAB [101]. SMART enables a rapid 3-dimensional surface representation of a vehicle concept for use in aerodynamic and structural analysis [139]. Once a geometric description of the vehicle concept has been generated, it is fed into Aerodynamic Preliminary Analysis System (APAS) which calculates the pressure distributions, force and moment coefficients for a range of atmospheric conditions. The aerodynamic conditions are passed on to POST, which is used to analyze the trajectory subject to mission-specific constraints. The primary output from POST includes in-flight conditions and propellant requirements to achieve the desired mission. The geometry, aerodynamics, and trajectory information is utilized to determine the size and weight of the vehicle concept. Configuration Sizing program (CONSIZ) uses historically based MERs to calculate the weight of each component, the gross vehicle weight, and the c.g. of the vehicle

[121, 101]. These four tools — SMART, APAS, POST, and CONSIZ — are used iteratively to converge on a design concept to be used in more detailed analysis.

The central column of the design process, depicted in Figure 19, represents the initial system model, which provides rapid analysis capabilities to establish an initial estimates of the mass and size of a vehicle concept. This converged estimate is then refined in an expanded environment (represented by the dashed lines in Figure 19) in which structural and heating analyses are used. In light of the significant time and resources required to leverage computational fluid dynamics (CFD) during early design, a miniature version of the JA70 Aerodynamic Heating Program, H800 (MINIVER) is used to size the thermal protection system thicknesses or assess material capabilities [101, 126]. MINIVER leverages theoretical and empirical correlations to compute the local flowfield and heating rates over basic airframe shapes [106, 126, 110]. The structural analysis is typically a multistep process involving the generation of a finite element mesh, mapping aerodynamic and inertial loads, and then calculating the panel thicknesses required to alleviate the estimated stress on each portion of the finite element grid [101]. The finite element model and detailed grid are established based upon the output parameters of SMART and the specified material properties. The aerodynamic loads are provided by APAS and the inertial loads are provided by POST and then the stresses are calculated through a finite element analysis program (FEA). Engineering Analysis Language (EAL) is a high-order command language for structural, fluid, and thermal FEA [224]. The scope, inner workings, and a series of studies leveraging EAL may be found in [34, 223, 134, 32], amongst many others, suggesting extensive use of EAL as an FEA tool within NASA LaRC. Other programs, such as the commercially available Patran, are becoming more widely used FEA software, which could also be used to provide the stresses. EZDESIT, a panel sizing program, is used in conjunction with a finite element model to determine the required thickness—and by extension the expected weight— necessary to withstand the stresses of each finite element panel [37, 101].

The more detailed analyses, namely aeroheating and structural, are used to enrich the initial estimates and potentially identify aspects that may require redesign [101]. This tiered approach, coupled with the known resources required to perform FEA, suggest that concept pruning occurs before the more detailed tools are used to refine the initial estimates. This downselection would undoubtedly be based upon performance, namely vehicle weight and each concept's ability to perform the required mission, as determined by historically-based MERs and first principles. Furthermore, the requirement to select a baseline concept by the close of Conceptual Design—as described in Section 2.2— coupled with the exclusion of cost and operations analyses within the Conceptual Design envelope of the LaRC design process, shown in Figure 19, suggests that a baseline vehicle configuration is selected without consideration for cost.

The review of the methodologies leveraged during Conceptual Design elicits several observations:

1. The Conceptual Design methodologies are performance based, often providing a reasonably accurate estimate for vehicle weight and mission capability.
2. The heavy reliance upon historical data limits the accuracy of these tools to evolutionary vehicle concepts — configurations similar to those contained within the historical data upon which the estimates are based.
3. The accuracy of these tools becomes questionable when a revolutionary concept is analyses — this essentially requires extrapolation from the historical data to provide an estimate whose accuracy cannot be validated.
4. At best, the Conceptual Design methodologies provide a ”feel” for the cost of a configuration.

5. Most notably, these tools lack insight into the manufacturing aspects which ultimately drive costs and schedule.

The perspective presented in chapter 1 establishes the importance of technology infusion into highly complex systems such as launch vehicles. Furthermore the advent of advanced manufacturing technologies challenges the traditional aluminum-based design approach and now requires early design studies to incorporate more manufacturing-centric analysis. There is a need to consider the implications these technologies have on DDTE&P activities, particularly for launch vehicles which, over the past twenty years have had a plethora of cancellations due to affordability overruns. An affordability paradigm shift is occurring such that technologies are sought to reduce cost and schedule instead of improving performance characteristics. While the industry standards discussed in Section 2.2 stress the importance of performing analysis at a lower-level and building estimates from the bottom-up, none of them reach any further back than the baseline concept — selected towards the end of the Conceptual Design phase — when developing a program plan, WBS, and the affordability and risk assessment. Instead, subject matter experts generate a single plan, tailored to each project, based solely upon the baseline vehicle selected during Conceptual Design, which meets all performance requirements. It is worth noting that not every feasible point (from a performance standpoint) is analyzed from a cost perspective. Typically, only a select few of the most promising configurations — from a performance perspective — are passed through to assess cost implications. Furthermore, the analysis which ultimately culminates in the selection of the baseline vehicle is sequential, and does not provide the capability to either consider automated program planning or the implications that technology infusion would have on a program plan. The literature presented thus far provides sufficient information to develop a suitable answer to the background research questions formulated in Section 1.6:

Background Research Question 1

How are launch vehicle DDTE&P strategies generated?

Background Research Question 2

How are these strategies used in the down selection to a baseline vehicle configuration?

1. A single DDTE&P strategy — in the form of a PBS-centric WBS — is generated by subject matter experts and based exclusively upon the baseline vehicle selected towards the end of Conceptual Design. These plans are tailored to each program/project, and will become more detailed as the design progresses through its life cycle phases.
2. This manual process, and the lack of scheduling analysis during the selection of the baseline vehicle, suggests that limited trades — regarding affordability, manufacturing technology infusion, and DDTE&P strategies — are performed when evaluating baseline candidates.

This review of the industry best practices and the methods employed during Conceptual Design yields a gap which this thesis seeks to bridge. The fundamental issue at hand is the ability to assess manufacturing technology impacts during Conceptual Design. As such, a review of currently available technology assessment methods is necessary to determine their applicability to bringing manufacturing considerations forward in the design process.

2.3 Review of Technology Assessment Methods for Conceptual Design

2.3.1 Technology Identification, Evaluation, and Selection (TIES)

The TIES methodology was developed as a means to account for the impacts of technologies during early Conceptual Design phases. As described by its originators;

"The nine step process known as TIES provides the decision maker/designer with the ability to easily assess and balance the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations [116]." This process is visually represented in Figure 20.

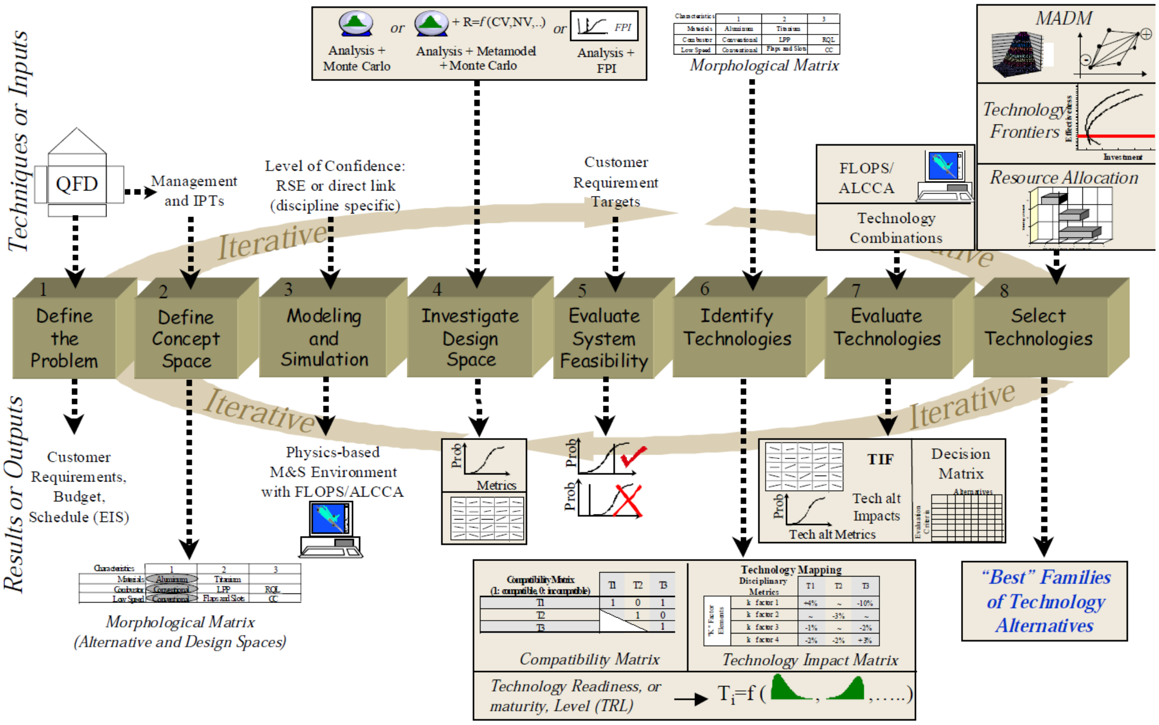


Figure 20: Technology Identification, Evaluation, and Selection (TIES) Methodology) [116]

TIES requires the selection of a baseline candidate configuration into which technologies will be infused to meet customer requirements. Technologies are identified and their impacts quantified in the form of a technology impact matrix (TIM) which maps a technology's effect on key intermediate or output variables. These impacts, termed 'k-factors,' modify disciplinary technical metrics; in essence, they simulate the benefits and/or detriments associated with infusing a particular technology into the candidate baseline vehicle configuration. An example of this is shown in Table 2, where k-factors of three technologies are mapped to four disciplinary metrics. A reduction to the disciplinary metric is represented by a negative percentage, while an

Table 2: Notional Technology Impact Matrix(TIM) (Adapted from [116])

Disciplinary Metrics	Technology 1	Technology 2	Technology 3
k_1 (O&S Costs)	+4%		-10%
k_2 (Drag)		-3%	
k_3 (RDT&E Cost)	-1%		-2%
k_4 (Fuel Burn)	-2%	-2%	+3%

increase to the metric is represented as a positive percentage.

Within the TIES formulation, each technology is considered to be independent which allows the designer to select any combination of compatible technologies and assess their impacts on the disciplinary metrics. The k-factors are assumed additive, and are derived by the summation of technology impacts documented in the TIM for the selected technologies.

2.3.2 Abbreviated Technology Identification, Evaluation, and Selection (ATIES)

The ATIES methodology is an augmentation of the ASDL-developed TIES methodology. As the originator describes: "...the main feature of ATIES is the much simpler nature of the process. In ATIES, more focus is given towards evaluation and selection rather than identification [43]."

ATIES includes six steps, and removes the additive limitation of TIES, allowing for multiplicative and more complex functions of k-factor impacts for a mix of technologies. The ATIES method is shown in Figure 21.

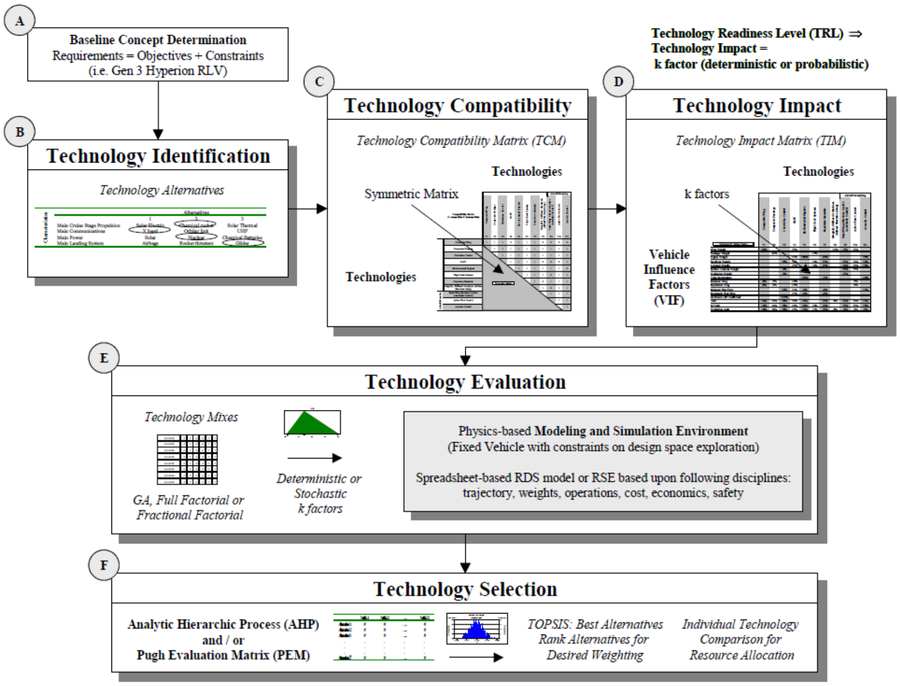


Figure 21: Abbreviated Technology Identification, Evaluation, and Selection (ATIES) Methodology [43]

2.3.3 Reduced Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA)

ROSETTA is a modeling process for advanced space transportation technology investment, prescribed for use as the modeling and simulation environment used during the "Technology Evaluation" step of the ATIES method [59]. The analysis hinges upon the use of response surface equations — statistical regressions of inputs to each output of analysis codes —which have been gathered into an excel-based framework. Weight-based cost model (NAFCOM), a net-present value economic model (CABAM), and structural and performance models which rely upon historical regressions and first order principles only, are leveraged within this framework, as outlined in Figure 22.

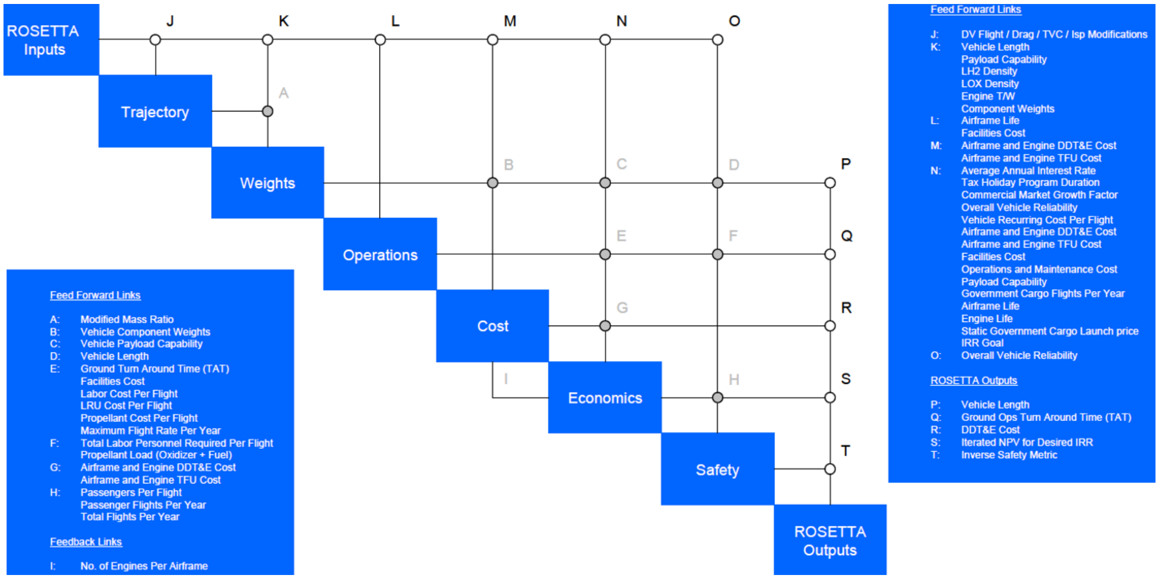


Figure 22: Design Structure Matrix for a Bimese TSTO ROSETTA Model) [59]

In review of these technology assessment methods, a few shortcomings have been identified.

1. Temporal constraints are missing. Namely, how the selection of particular technologies affects the manufacturer's ability to deliver the system on time.
2. Both TIES and ATIES hinge upon the ability to create Response Surface Equations (RSEs) of a modeling and simulation environment which adequately captures the impact that varying inputs has on the response. These RSE methods imply:
    (a) The selection of a baseline vehicle fixes the shape/form of the RSE.
    (b) The impact of each technology on these responses must be known /quantifiable; their impact is assessed by "tweaking" coefficients of the fixed shape RSE.
    (c) The modeling and simulation environments that are traditionally used for

space systems during early Conceptual Design (Section 2.1) are predominantly based upon high-level historical data. This implies that these environments are incapable of providing meaningful variations in the responses when lower-level details are varied. This incapability can be attributed to two factors:

i. The resolution of the information contained within these tools is too high-level to capture more detailed aspects of a design. For instance, a cost analysis program may ask whether the manufacturing processes are novel or well established, but cannot provide any distinction between two novel or two well established processes.

ii. The historical data upon which these tools are built may be devoid of any relevant/similar systems when comparing lower-level design details. Within the context of the SLS program — there is only one historical system that bears similarity to the SLS program, and that is the Saturn V. At a high level, these systems are similar in size, mission requirements, and configuration. However, when delving into the lower-level aspects, it becomes evident that new materials, new structural stiffening techniques, and new fabrication processes exist over those employed on the Saturn V. Thus at a very detailed level, these systems may be considered dis-similar. These dissimilarities would then bring into question an estimate that is generated without considering the subtleties.

While both TIES and ATIES stress the need to leverage physics based modeling and simulation environments; these methods have an underlying flaw which prevents them from adequately capturing manufacturing technology considerations. A practical illustration shall elucidate this flaw.

Both methods leverage response surface methodology to create surrogates which describe the relationship between a response and the independent variables, over a limited range, which affect them. These relationships are termed Response Surface Equations (RSEs), and are generated from a given dataset. Perhaps the most well-known surrogates amongst aerospace students are those presented in Raymer's Aircraft Design: A Conceptual Approach. The latter chapters of Raymer's text present a series of aircraft weights and sizing RSEs as well as a collection of cost relationships recommended for use during conceptual sizing and cost estimation[182]. For illustrative purposes, a selection of these equations is presented below.

$$W_{wing} = 0.0051(W_{dg}N_z)^{0.557}S_w^{0.649}A^{0.5}\left(\frac{t}{c}\right)_{root}^{-0.4}(1+\lambda)^{0.1}(\cos\Lambda)^{-1}S_{csw}^{0.1} \tag{2}$$

$$H_{engineering} = 4.86W_e^{0.777}V^{0.894}Q^{0.163} \tag{3}$$

$$H_{manufacturing} = 7.37W_e^{0.82}V^{0.484}Q^{0.641} \tag{4}$$

where:	W_{dg}	design gross weight, lbs
	N_z	ultimate load factor
	S_w	trapezoidal wing area, ft^2
	S_{csw}	control surface area (wing mounted), ft^2
	A	aspect ratio
	$(t/c)_{root}$	thickness-to-chord ratio at wing root
	λ	wing taper ratio
	Λ	wing sweep at 25% mean aerodynamic chord
	W_e	empty weight, lbs
	V	maximum velocity, knots
	Q	production quantity

Equation 2 is an RSE which defines the wing weight of a cargo/transport aircraft as a function of several design variables, most of which are based upon the geometry of the wing. Raymer presents numerous RSE's for fighter, cargo/transport, and general aviation type aircraft. For each aircraft, the total empty weight would be determined by summing all the component weights as follows

$$W_{empty} = W_{wing} + W_{fuselage} + W_{tail} + W_{avionics} + ... \tag{5}$$

Equations 3 and 4 are estimations of the required engineering and manufacturing hours which contribute significantly to the cost research, development, testing and evaluation (RDT&E) of a production lot of aircraft [182]. These hour estimates are multiplied by respective hourly wrap rates to estimate the engineering and manufacturing costs, respectively, before being combined with the other cost-specific RSEs to arrive at a complete RDT&E+flyaway cost, as shown below.

$$RDT\&E + FlyawayCost = H_E R_E + H_M R_M + ... \tag{6}$$

where:	H_E	engineering hours
	R_E	average engineering wrap rate
	H_M	manufacturing hours
	R_M	average manufacturing wrap rate

TIES and ATIES prescribe augmenting these RSE's with technology impact ("k") factors which operate on either intermediate or independent variables. The application of these is shown in Equations 7 and 8, operating on intermediate variables, and Equations 9 and 10, operating on independent variables; where the mapping of these impact values would be identified per technology, and organized in the form of a TIM, shown in Table 2. Raymer prescribes a similar approach to that of operating on the intermediate variables, Equation 7 and 8. The equations presented are applicable to traditional aluminum aircraft. In the case of weights, a table of "fudge factor" ranges is provided for a selection of structural concepts; for instance, if an aircraft's wing and fuselage are to be fabricated from advanced composites, then the wing weight should be multiplied by 0.85-0.9, and the fuselage weight by 0.9-0.95 [182]. The same applies to the cost estimating relationships furnished in Raymer, where the engineering hours estimates are multiplied by a "fudge factor" which is to account for the increased difficulty of fabrication.

$$W_{empty} = k_1 W_{wing} + K_2 W_{fuselage} + k_3 W_{tail} + k_4 W_{avionics} + ... \tag{7}$$

$$RDT\&E + FlyawayCost = k_5 H_E R_E + k_6 H_M R_M + ... \tag{8}$$

$$W_{wing} = 0.0051((k_1 W_{dg})N_z)^{0.557}(k_2 S_w)^{0.649}(k_3 A)^{0.5} k_4 \left(\frac{t}{c}\right)_{root}^{-0.4}(1+\lambda)^{0.1}(\cos\Lambda)^{-1}(k_5 S_{csw})^{0.1} \tag{9}$$

$$H_{manufacturing} = 7.37(k_6 W_e)^{0.82}(k_7 V)^{0.484}(k_8 Q)^{0.641} \tag{10}$$

The major flaw with this approach is the fact that the form of the equation does not change. The multipliers simply shift these curves up or down depending on whether the technology (in this case using composite materials instead of aluminum) is an improvement or detriment to each intermediate/independent variable, as determined through populating a TIM. Applying the "fudge factor" method prescribed by Raymer to a commercial transport aircraft for the case of infusing advanced composite materials will further elucidate this flaw. Table 3 lists the relevant variables and ranges of k-factors for use with, Equation 10. The goal of such advanced composite infusion would be to reduce the weight of the aircraft, while still meeting customer requirements; therefore the production quantity and maximum velocity are fixed for this example.

Figure 23 portrays the trend which would be applicable to an all metallic aircraft, as well as the complete set of trends which would result from any combination of weight and cost "fudge-factors" (k_1 and k_6) as evaluated with Equations 7 and 10,

Table 3: Relevant variables and ranges of k-factors for a commercial airliner

Variable	Range	Description
V	500 knots	Maximum velocity for commercial airliner, transonic range
Q	100	production quantity for commercial airliner
R_M	\$75.00	average manufacturing wrap rate
k_1	0.85-0.9	weight reduction due to infusion of advanced composites into structures
k_6	1.1 - 1.8	cost increase due to complexity of advanced composites

respectively. These trends are what we would expect to see, as an aircraft becomes larger (and thus heavier) the cost to manufacture the components becomes more complex. In the case of composites, however, the shape of the trends should have the ability to change. The prime example can be seen by the large autoclave recently acquired by Boeing in order to fabricate and cure composite structures for the 787 family of aircraft. There exists, however, a size limitation beyond which this autoclave (and for that matter all existing autoclaves) can no longer be used; in these cases, the manufacturer may be force to switch to an out of autoclave process. While the relationship between the labor required to cure using one method or another is unknown, this would ultimately correspond to one of two options. Either a discontinuous jump from one trend to another, or a change in the trend entirely once the autoclave threshold is surpassed.

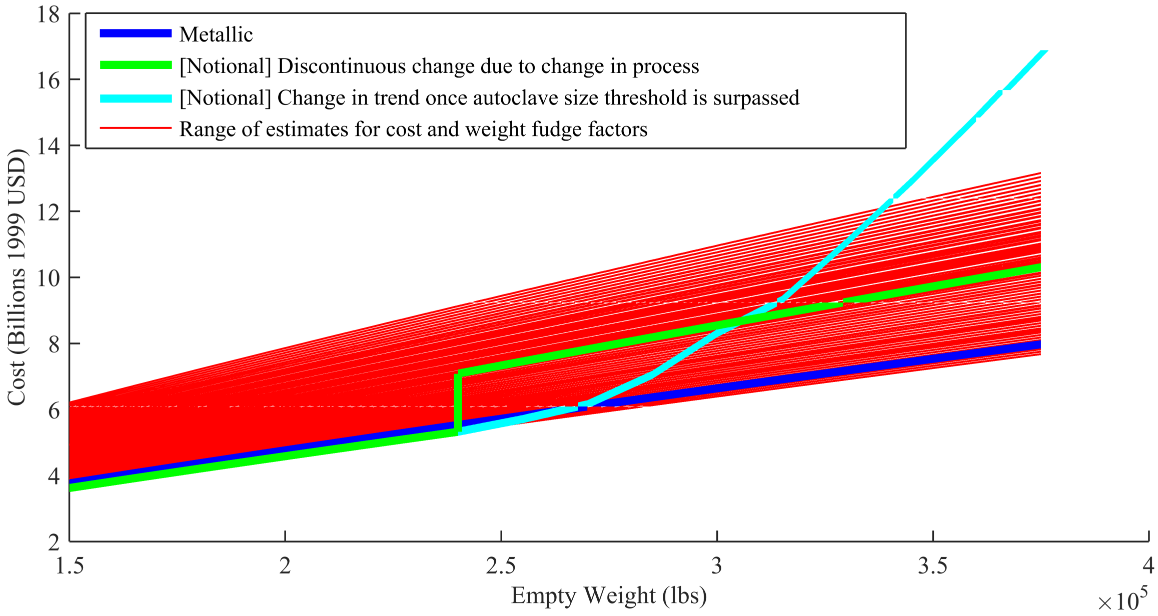


Figure 23: Visualization of All Feasible Trends for Commercial Airliner Example

It is necessary to concede that it is possible to determine the appropriate "fudge factor" required to adequately represent a specific material and a specific process within Raymer's framework. However, in order to do so one would need to gather sufficient data pertinent to the material and process pair in order to create a regression from which a reasonable range of "fudge factors" can be extracted. In the case where the material and process is novel, or too few relevant examples exist to adequately create statistical regressions, then the **explicit modeling of technology** is absolutely essential to categorizing the effects on cost, schedule and performance.

Having established the shortcomings in the analysis typically used during Conceptual Design, a summary of the gaps identified in the best practice documents and the shortcomings of the current design phase categorization shall now be discussed.

2.4 Gap Identification

2.4.1 Shortcoming of Expectations and Prescribed Practices During Conceptual Design

The best practices have begun to emphasize the importance of affordability and the risks associated with assessing the risk associated with the funding environment in which government entities operate. This is particularly true for NASA, who has produced several risk-related guideline documents in the past decade alone, and whose definition for affordability inspires this research. Affordability has become *The ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals.* A desire to quantify the affordability of an alternative, and have this metric bear more importance in the decision making process is described in each of the best practice documents. NASA's guidelines are the most extensive, and shall now be summarized to provide a "best-in-class" process which will serve as a point-of-departure in the development of a new methodology.

NASA's guidelines require that, by the end of Conceptual Design, a range of affordability risk be presented for the vehicle configuration which shall pass into the Preliminary Design phase and ultimately on to production and operation. This range is designed to provide the decision maker with the boundaries which enclose the space in which all possible variations of cost and schedule can fall (i.e. cost and schedule risk). A notional representation of this deliverable, referred to as a Joint Confidence Level (JCL), is shown in Figure 24. This visualization represents the uncertainty of total cost and total schedule for a specific concept. The uncertainty is a result of the propagation of both attribute uncertainty and critical path duration uncertainty. Fundamentally, the gray "crosshair" represent the total cost and total duration constraints, whose values are called out in yellow boxes on the y and x-axis, respectively. The joint-confidence is expressed as the proportion of points which meet these constraints simultaneously. These are portrayed as green in Figure 24, where the white points meet only one constraint, and the red meet none. The confidence level required to pass from conceptual to Preliminary Design phase is 70%, which dictates that 70% of the points meet both the cost and duration constraint. Practically speaking, a concept whose JCL is 70% has a 70% likelihood of remaining within the cost and schedule constraints.

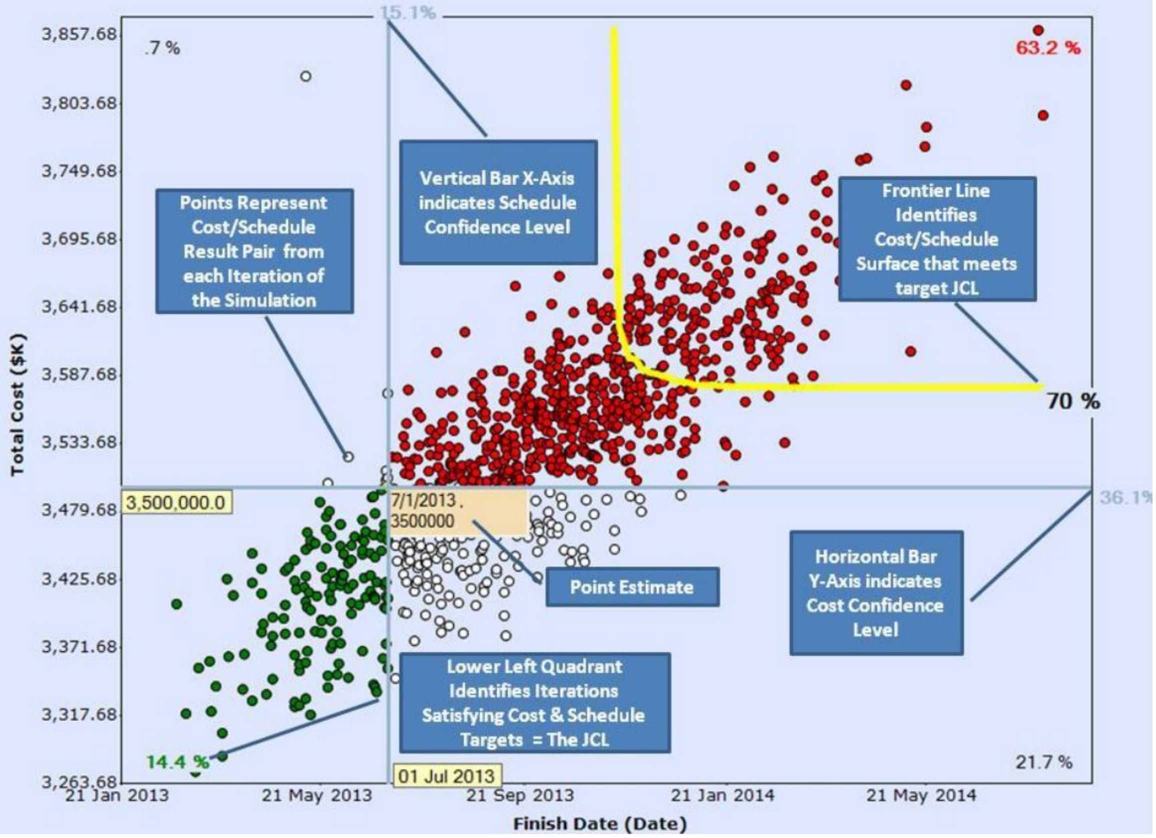


Figure 24: NASA's Joint Confidence Level [109]

The process by which this result is generated starts with establishing the baseline vehicle configuration, a performance dominated analysis as described in Section 2.1. Once this configuration is established, subject matter experts compile a *single* WBS, describing, at a summary level, the work necessary to complete the program. The time aspect is determined through the development of an integrated master schedule, and identification of the critical path based upon functional relationships between tasks. Each task is assigned an optimistic, pessimistic, and expected duration, which allows for the development of a triangular probability distribution on task duration. The cost aspect is determined by summing the hours required and multiplying by an estimated labor rate. The JCL range diagram (Figure 24) is then generated by running a Monte Carlo simulation, which chooses a duration for each task — based on a random draw from each tasks triangular probability distribution — and aggregates the total program duration and the likelihood of it occurring [109].

This summary of the "best-in-class" standards, upheld by NASA, brings to the forefront one resounding observation regarding the gap between the prescribed practices and the desire to select affordable and risk-aware design.

Gap Identification

The current best practices FAIL to inform decisions made during Conceptual Design in regards to the implications that manufacturing technologies have on actual cost profiles and program schedules.

1. The process for vehicle design and down selection to a baseline is a serial process that excludes planning considerations and culminates in a hand-off to the program planning team.
2. There is no practical feedback between the planning group and the vehicle design group.
3. While this process is sufficient for vehicle designs which are similar to those built historically, the infusion of new manufacturing technologies invalidates the ability of the tools, typically used during Conceptual Design, to predict the required program planning and thus assess affordability.
4. While trade-off analyses are performed, in order to be effective in picking the right baseline during Conceptual Design, the decision maker requires information which is not currently available because they do not include:
    (a) **The expenditure behavior as a function of time, and thus insight into whether a program/project has the potential for becoming unaffordable**
    (b) process implications resulting from material selection (e.g. aluminum welding techniques are not applicable to titanium alloys or composites)
    (c) fabrication implications from detailed structural design selection (e.g. number of panels/gores which comprise each tank barrel/dome, or the method by which structural stiffening shall be applied)

The historical perspective in Section 1.2 describes the repetitive cycle that launch vehicle development programs have followed for nearly fifty years: A program is initiated and progresses for two-to-four years before it becomes unaffordable and is eventually canceled. Its successor would champion a more affordable approach but ultimately follow the same path. It is clear that the fundamental flaw stems from the affordability analysis which provides information at no-greater detail than a total program cost. This total cost represents the integration of all costs which are expected to occur during the life of a program. Thus, *by only considering the total expected costs and launch date, insight into the manner in which those temporal cost are incurred cannot be attained.*

A brief thought experiment is presented to more distinctly describe the disparity between the current state of program cost and schedule estimates and the desired state. Initial cost and schedule estimates, as generated by the traditional analysis approach, are point-values representing the expected uncertainty in the LCC of a program and an expected first launch date. These values are represented in the JCL visualization in Figure 24. An additional piece of information, not explicitly called out in the JCL method, is the notion that within the uncertainty there is an expected value. This point value would ultimately fall within a range of confidence bands, and if the location of this value is within the constraint crosshair, then the program may be approved and pass into Preliminary Design even if JCL is less than 70%. A visualization of this expected cost and schedule point is shown in Figure 25, where the red point represents the low confidence cost/schedule estimate, the green the high confidence cost/schedule estimate, the orange the expected value, and the dashed black box the region in which all other points are contained. This is to say that if five different vehicle concepts were being traded, each would have a chart similar to that of Figure 25 which would inform the decision makers downselection to a final baseline candidate which passes into Preliminary Design.

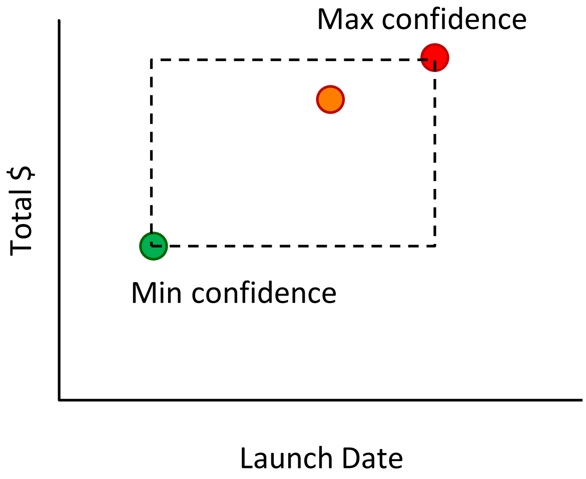


Figure 25: Notional Traditional Cost and Schedule Estimate Generated During Conceptual Design

If the problem at hand is considered on a practical basis, each project will be subject to annual budgetary constraints as well as a first launch deadline. Thus it is necessary to develop a second visualization which includes a temporal view of the problem at hand. The maximum budget and schedule constraints, representing the national means, are determined based on the expected annual support from Congress and the duration said support will be provided. Program managers often incorporate cost and schedule reserves, to account for cost growth and schedule delays, should they occur. Figure 26 represents the constrained temporal space in which programs are expected to operate. Under the traditional approach, only a total expenditure would be known, as visualized in Figure 25; the program would be approved and expenditures would begin, represented by the green curve. As is indicative of the many programs discussed in Section 1.3, expenditures would occur at a rapid rate and reach the reserve threshold within the first few years. At this juncture, represented by the thin vertical red line, it is realized that the cost vs time trajectory that has been committed to is in conflict with the constraints set on the program.

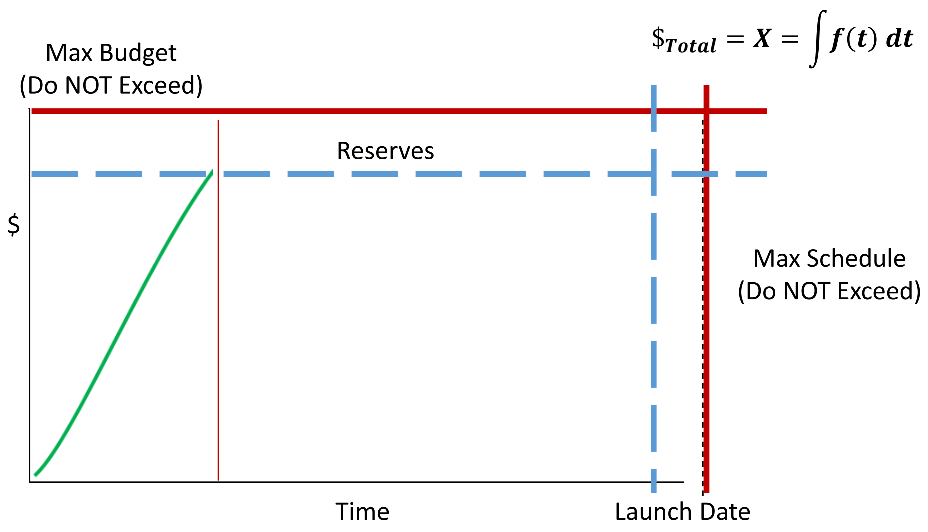


Figure 26: Notional Time-Phased Constraints and Initial Expenditure

This time-perspective of expenditure brings to light the realization that cost and launch date are not adequately described by a single point, as in Figure 25. Instead, cost has a time evolutionary nature, the integral of which would equate to the single point cost estimate. Figure 27 shows the notional time evolutionary behavior of cost as f(t). At the juncture when the cost trajectory is realized to conflict with the constraints, three options exist which allow the program to proceed. The first, depicted by the thin red-dashed line, is to continue on this trajectory and incur cost overruns. This pure-cost overrun would require solicitation of additional funding either through congressional appropriations directed to the program, or by sacrificing funding from other programs. The second option, depicted by the thick orange-dashed line, is to extend the timeline such that the budget ceiling is not exceeded in any one year, while the launch date is pushed back to accommodate the delay in work. The third option would be to implement a combination of the first two options where both schedule delays AND cost overruns are incurred. Alternatively, this juncture represents the chronological point at which program cancellation becomes a viable option if additional funding and schedule delays are unacceptable i.e. the program becomes unaffordable.

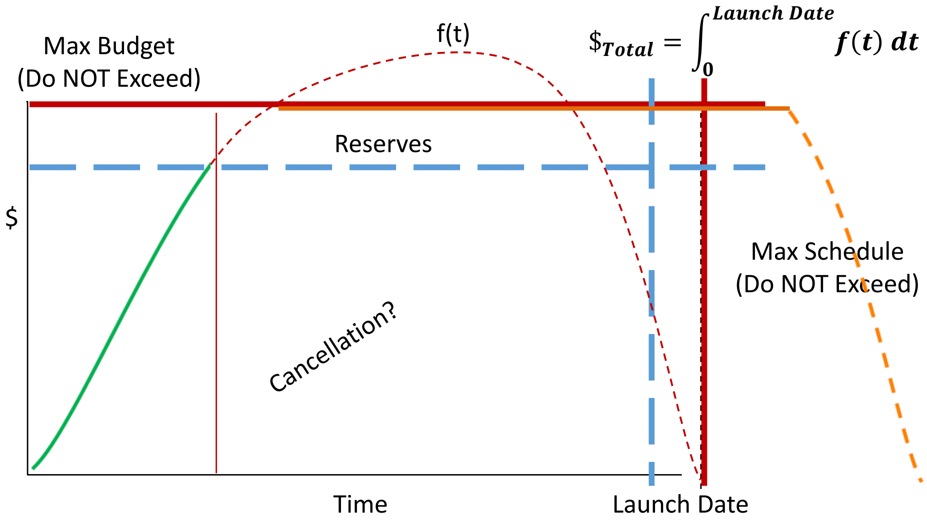


Figure 27: Notional Time-Phased Expenditure for a Program Experiencing Cost Overrun, Schedule Slippage, or Cancellation

The importance of assessing affordability in today's budgetary environment suggests that it is absolutely necessary to generate time-phased diagrams, similar to Figure 27, which portray the cost evolution of a program with time. The notion of assessing the implications of manufacturing technologies and their required DDTE&P plans, suggest that the problem is more detailed than a program-level phasing representation. Since manufacturing technologies may be infused into any number of structural elements, the program-level phase diagram is an aggregation of element phase diagrams, which vary based on the manufacturing technologies infused in each. Thus, a solution to the second motivating research question, presented in Section 1.3, may be established:

Motivating Research Question 2

How can the drivers of cost and schedule overruns be captured?

Decomposing a system in order to develop subsystem [cost] phase diagrams and aggregating them will provide a time-evolutionary understanding of cost throughout the lifecycle of a program. Furthermore, this perspective will capture the impact of manufacturing technologies on subsystems; providing insight into cost and schedule drivers as well as identifying opportunities for affordable technology infusion

The identification of these gaps provides justification for the research objective, repeated below. The approach of assessing affordability of a system based upon the aggregation of sub-elements, into which manufacturing technologies may be infused, allows for the decision maker to perform trades not currently possible. These trades are driven by questions relating to specific technology infused elements, the DDTE&P plan which describes a specific combination of elements, and the impact that changing manufacturing technologies has on program level affordability.

Research Objective

Support the development of affordable launch vehicles by quantitatively capturing the effects of manufacturing technology selection during Conceptual Design

---

2.5 Manufacturing Influenced Design (MInD)

Manufacturing considerations traditionally become the focus of design efforts during the late stages of aerospace system design, once structural elements are well defined [35]. The advent of advanced materials and new manufacturing processes necessitate that manufacturing trades be performed earlier in the design process, and more harmoniously with design trades. The MInD methodology integrates manufacturing-centric cost analysis tools with the traditional multi-discipline design tools leveraged during early trade studies.

The traditional Conceptual Design process, as described in Section 2.1, leverages weight-based cost analysis tools to determine point-estimates of LCC, development cost, and production cost. The equations presented by Raymer — Equations 6,8, and Figure 23 in Section 2.3 — are examples of the weight-based equations upon which these traditional tools are based. Thus, these tools are restricted to a proportional relationship between weight and cost; cost monotonically increases with weight. Advanced materials such as composites, however, provide a reduction in weight and typically increase cost over metallic counterparts [214]. Furthermore, tooling and redesign costs associated with the support of advanced materials are considerably larger contributors to cost than in the past, especially for low-volume production systems such as launch vehicles. As a result, cost is no longer proportional to weight, but to material and the selection of appropriate processes [97]. The major challenges which MInD addresses include:

1. A need for non-weight based manufacturing cost estimation tool
2. The balance of fidelity between design and manufacturing
3. An integrated multidisciplinary model which generates appropriate data for trades
4. Data visualization to enable multi-attribute decision making

To date, a variety of efforts have been pursued to merge design and manufacturing considerations. Design for manufacture (DFM), design for assembly (DFA), and design for manufacture and assembly (DFMA) are amongst the most notable methods. As the names suggest, DFM centers around reducing the complexity of parts for the purpose of increasing the ease with which they are manufactured. Similarly, DFA aims to reduce the complexity associated with the assembly of parts; while DFMA is an amalgamation of the two [26]. These methods are often employed via CAD plug-ins, or automated spreadsheets, which analyze the impacts of reducing part counts, minimizing assembly times, and standardizing parts [190]. While these methods have merit in certain applications, they are inadequate for complex aerospace systems, where cost is a result of the complexity of individual components where the maximum functionality is integrated into the smallest and lightest envelope [140, 190].

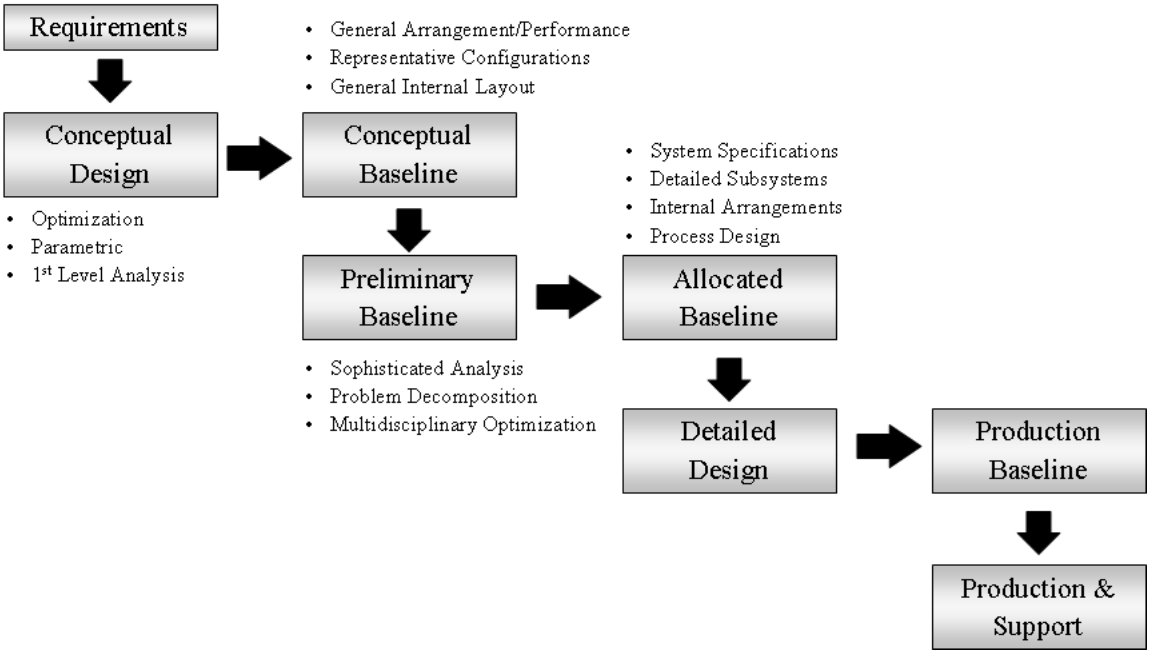


Figure 28: A Typical Aircraft Product and Process Development Flow [122]

The MInD methodology was first conceived by researchers at ASDL and applied to aircraft preliminary studies to facilitate harmonious trades between design and manufacturing [122, 35, 50]. Instead of providing a CAD plug-in or rule based part assessment tool, MInD emphasizes the need to rethink the process through which designs evolve. The traditional serial product and process development flow, shown in Figure 28, limits the system development process to the "Paradox of Sequential Design." Conceptual design is categorized by low-fidelity analysis which focuses upon performance and results in only a general representation of the system. Only in the Detailed Design phase is sophisticated analysis leveraged to define the system, subsystems and manufacturing processes at great detail [122].

The fundamental premise of this methodology is the notion that weight-based cost estimation greatly limits a decision makers ability to accurately assess the implications of design decision on manufacturing, particularly when novel manufacturing technologies — such as composite materials or immature fabrication techniques— are used. The need for a process-based approach to cost estimation is the key-factor which differentiates MInD from the Design for X design paradigms. To enable process-based cost, the MInD approach requires the infusion of sophisticated, physics-based analysis into Conceptual Design to enable a **quantitative** means of assessing manufacturing and production implications of the design decisions which comprise the baseline vehicle configuration. This infusion is predicated upon the fact that the inputs to process-based cost estimation must match the desired fidelity of the outputs of said estimation tool. Namely, if the desire is to assess the variation on number of panels which comprise a specific component, or the effects of varying fabrication techniques, then the analysis which determines the weight must be capable of differentiating between these unique concepts. Since the traditional conceptual analysis environments — described in Section 2.2.3 — do not possess this capability, higher fidelity tool must be brought forward and leveraged earlier in the design process.

Since its inception in 2011, this methodology has been expanded to include production planning considerations and demand variability for aircraft programs. The MInD production planning optimization framework (MInD PRO) leverages DES to model production flow layout and simulate the fabrication and assembly of an aircraft wing-box [203, 202]. This framework enables the quantification of geometry and factory layout impacts on performance, production, and profitability.

The MInD approach effectively rewrites the development flow and provides an alternate perspective on a program's life cycle; explicitly reducing epistemic uncertainty. The application of MInD to the launch vehicle problem is discussed in Section 3.5, and the alternative perspective which it affords is discussed in the following section.

2.6 An Alternative Perspective on the Program Life Cycle

The compartmentalization of a program into design phases is the standard approach in industry, as detailed in Section 2.2. While each organization has a different number of phases and a varying degree of periodic reviews, they all follow a general flow. First, a problem (or gap in capabilities) is defined, which warrants the creation of a new system to provide the capability to overcome the problem. The next part of the process is aimed at identifying the parts necessary to comprise the proposed system, thereafter developing them to an appropriate level of maturity. These parts are then integrated with one another to form the system, which undergoes testing prior to the start of its operation (and full scale production for high volume programs[2]). Hereafter, the system is maintained (if reusable) throughout its operational life, which culminates in the disposal of the reusable system. These general categories are enumerated below:

1. Identify the problem to be addressed
2. Design: Focus on selecting the appropriate combination of elements, with which to build a system, which provides and affordable solution to the established problem
3. Develop: Mature the necessary elements

---

[2] While the term "high-volume" is relative; in the case of a launch vehicle, in which only a handful are produced and few (if any) are identical, a quantity of more than 10 may be considered high volume

4. Integrate and test: unify the matured elements to form a complete system. Perform tests to ensure conformance to requirements
5. Operation: Maintain the system and support its operations
6. Disposal

As described in Section 2.1, the distinction between these phases is the fidelity of analysis and the availability of information (gained through decision making) at each successive phase. The notion that as much as 80% of costs are locked in by the end of Conceptual Design, suggest the need to re-evaluate the caliber of the analyses performed and the gravity of the decisions made during Conceptual Design [114, 20].

It is often necessary to delve more deeply into the space of possible designs than has yet been done [114]

The need to possess greater analysis capabilities during Conceptual Design, and thus gain insight into impacts which would not typically be available until Preliminary or Detailed Design, warrants a reclassification of the traditional life cycle phases. This shift to a physics based analysis during Conceptual Design will facilitate the ability to assess the impact of any decision on the value metrics which define the problem. Thus, the Conceptual Design phase will be reclassified as "design". This shift in analysis does not imply that Preliminary and Detailed Design will be devoid of analysis, it does facilitate the change in focus from higher fidelity analysis to activities which contribute to the maturation of the elements which comprise the vehicle. As such, Preliminary and Detailed Design will be grouped into the development" phase. This reclassification bolsters the Manufacturing Influenced Design mindset, detailed in Section 2.5, and facilitates the development of the proposed methodology. Figure 29 provides a visual depiction of the reclassification of program life cycle phases.

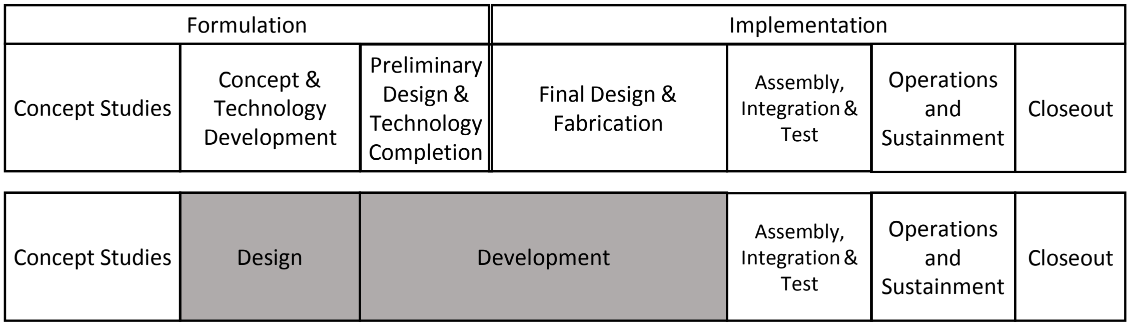


Figure 29: Recategorization of Program Life Cycle Phases

With this re-categorization, the design phase (formerly Conceptual Design) possesses more information with which to make decisions. In the context of this research, affordability has become a key factor in decision making, and its definition has evolved into the ability to assess both cost and schedule (i.e. time-phased cost) simultaneously. The logical progression through which a decision maker may proceed begins with the ability to assess whether overspending (represented by phased cost exceeding the allowable budget) occurs, and the likelihood of it occurring. Furthermore, the decision maker will have the ability to visualize when the excess expenditure is expected to occur. If this configuration is desirable, the activities may be rearranged in an attempt to mitigate excess spending. In the event that no practical arrangement of activities yields an affordable outcome, then the trade will evolve into assessing which elements benefit from manufacturing technology infusion resulting in an affordable design. Manufacturing technologies could include varying materials (metallics and composites), trading fabrication techniques to determine whether one process is more affordable than another. This progression is depicted in Figure 30, and enabling this kind of insight is the prime focus of the methodology developed in the following chapter.

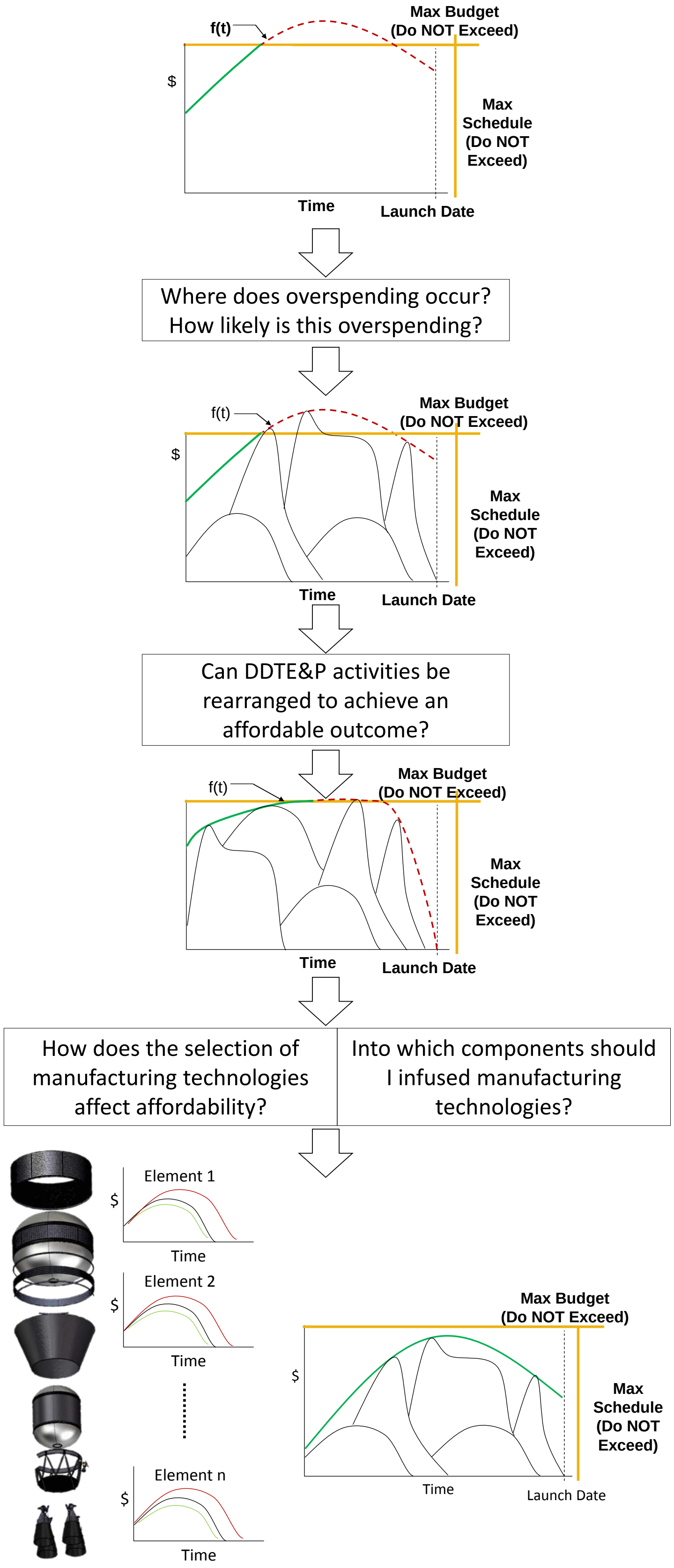


Figure 30: Trades Facilitated by Proposed Methodology

CHAPTER III

METHOD DEVELOPMENT

The development of the research objective for this thesis identifies the need to quantitatively capture the effects of manufacturing technology on system affordability during Conceptual Design. The previous section establishes the goal of the method which is to facilitate the comparison between vehicle concepts using affordability as the key objective. Technology infusion has been identified— by a number of aerospace and defense executives— as the basis for a company's competitive advantage [61]. To do so, this method aims to provide two improvements to launch system design. The first, as described in Section 2.6, is changing the design paradigm from the traditional sequential and segmented process, to an integrated product and process methodology. The second revolves around the ability to define a portfolio of manufacturing technologies (e.g. advanced materials and novel fabrication techniques) and assess its impact on the program. The methodology shall culminate with an additional decision support tool for the use of the technical team during Conceptual Design in order to refine a manufacturing technology portfolio. To begin, a brief introduction to portfolio theory is presented, followed by the description of the approach used to arrive at a methodology to assess the merits of a manufacturing technology portfolio.

3.1 Portfolio Theory

Modern portfolio theory, for financial assets, is fathered by Markowitz, who delineated the theory in 1952. He formulated the portfolio problem as a choice of the mean and variance of a portfolio of assets. One either sought to hold the variance constant and *maximize* the return or hold the expected return constant and *minimize* the variance [76]. This theory emphasized the importance of diversifying the assets of a portfolio in order to provide a balance between the value of a portfolio and the risks associated with achieving that value. In the 1970's this concept was adopted by industry and academia to address technology portfolio management, often termed new product development (NPD) [212, 92, 123]. Dubos provides five key notions which characterize the portfolio management problem [71]:

1. Portfolio management is a resource allocation problem in which a company must select and appropriately distribute scarce resource — such as funding or time— amongst a selection of projects.
2. Innovation is essential to the success of a company.
3. "...uncertainties and risk are essential motivators for a portfolio mindset..."
4. Portfolio management revolves around finding balance between value and risk, maintenance and growth, and short and long-term products.
5. The selection of portfolio products is a dynamic and iterative process in which development should be tracked and progress revisited at various stages of the development process.

A variety of methods have been proposed in literature regarding the development and management of R&D portfolios. A common theme amongst these methods is that the process is comprised of three phases [217, 6]:

Phase I: Identification, definition, and prioritization of market opportunities and company objectives and constraints.

Phase II: The "value" of individual products is established, based upon appropriate metrics which map to the objectives and constraints defined during phase I

Phase III: The individual products are compared and the final portfolio is compiled by selecting the appropriate combination of products which provide the greatest "potential to succeed".

The selection of a portfolio with the "greatest potential to succeed" is more complex than simply selecting only the products with the highest value. "The combination of individually good projects [does not] necessarily constitute the optimal portfolio" [45], which presents one challenge in portfolio management: aggregating individual product value into the final portfolio. The focus of this thesis is to expand technology portfolios beyond a product centric approach, and into an **integrated product and process** approach. To initiate the development of the design methodology, a generic set of steps shall first be established using existing decision-making processes. This will serve as the foundation for generating the method.

3.2 Solution Approach

The Risk-Informed Decision Making (RIDM) process, presented in 2.2 and summarized here for convenience, serves as a logical starting point as it relates directly to the assessment of risk and the downselection process applicable to launch vehicle programs. This process is intended as a decision support tool which focuses on providing guidance for the direction-setting key decisions that are characteristic of NASA programs and project life cycles [65]. The RIDM process consists of three major parts. Identification of Alternatives; describing the elicitation of requirements, constraints and performance measures of a program, and the enumeration of alternatives for the problem at hand. Risk Analysis of Alternatives; categorized by the selection of an analysis methodology suitable to the problem at hand, and executing the risk analysis to quantitatively establish the performance measures for each alternative. Finally, Risk-Informed Alternative Selection; which consists of the downselection to a single alternative based upon each alternatives risk-performance relative to the program measures of performance established in part 1. This process is illustrated in Figure 31.

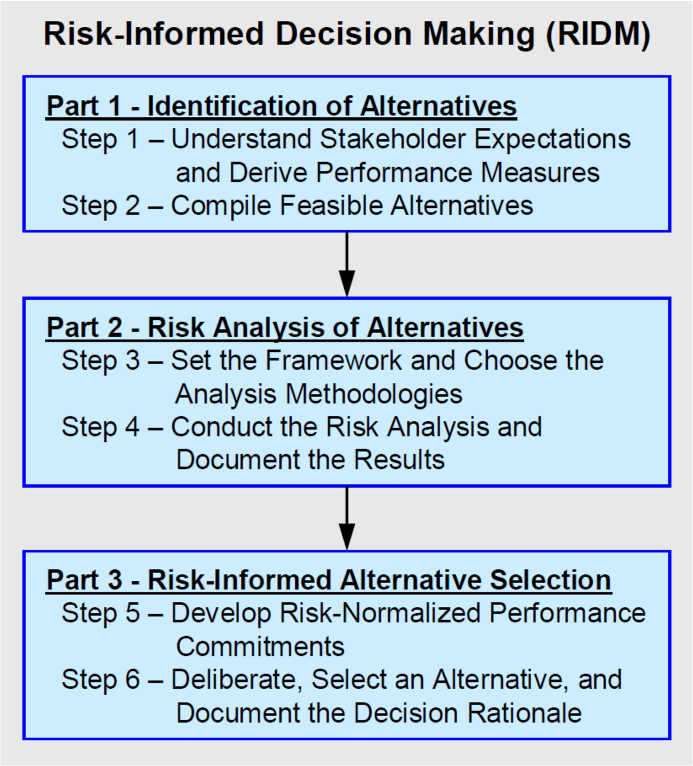


Figure 31: NASA's Risk Informed Decision Making Process [65]

Despite its application to risk assessment, the RIDM process parts are extensible to a more generic decision-making process. The Georgia Institute of Technology Integrated Product and Process Development approach (IPPD) was introduced to break down the walls between functional groups in the traditional development process. Where the traditional design process (described as the "Paradox of Sequential Design" in Section 1.3) is discipline-centric and stove-piped, the Georgia Tech IPPD method champions a top-down decision support process which combines systems engineering methods and quality engineering methods through a computer-integrated environment [197]. A visual representation of this process is shown in Figure 32, where the central column represents the top-down design decision support process.

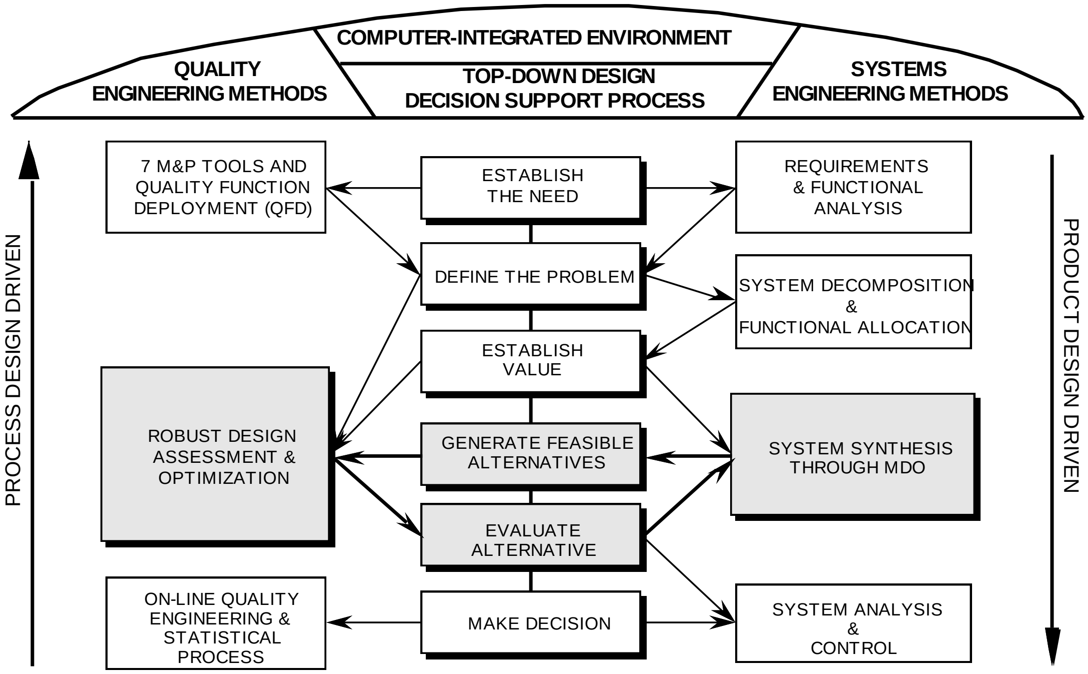


Figure 32: Georgia Institute of Technology Integrated Product and Process Development (IPPD) Methodology [197]

While both decision processes are comprised of six steps, they are not directly comparable. The Georgia Tech decision support process is more detailed in the early steps, while RIDM is more explicit for the latter steps. The first part of the RIDM process encompasses the first four steps of the Georgia Tech decision support process. Understanding the stakeholder expectations (step one of RIDM) implies that a gap is identified which establishes the need (step one of the Georgia Tech IPPD) to bridge the gap. Furthermore, deriving the performance measures (step two of RIDM) requires a complete understanding of the problem at hand, and an elicitation of the attributions required to address this problem (step two and three of the Georgia Tech decision support process). The second step of the RIDM process maps directly to the fourth step of the top down decision support process; establish a list of feasible alternatives.

The second part of RIDM is comparable to the fifth step in the IPPD decision support process. Although not explicitly stated, the evaluation of alternatives step in the IPPD process implies the selection of an appropriate analysis framework such that performance measures for each alternative may be quantified. Similarly, the final step of the IPPD decision support process implies that the downselection shall be based upon a prioritization of the performance measures developed earlier and that the selected alternative shall be documented. An aggregation of these two processes, by expanding steps five and six of the IPPD process to more explicitly capture part two and three of RIDM, would result in a nine step decision support process, as shown in Figure 33.

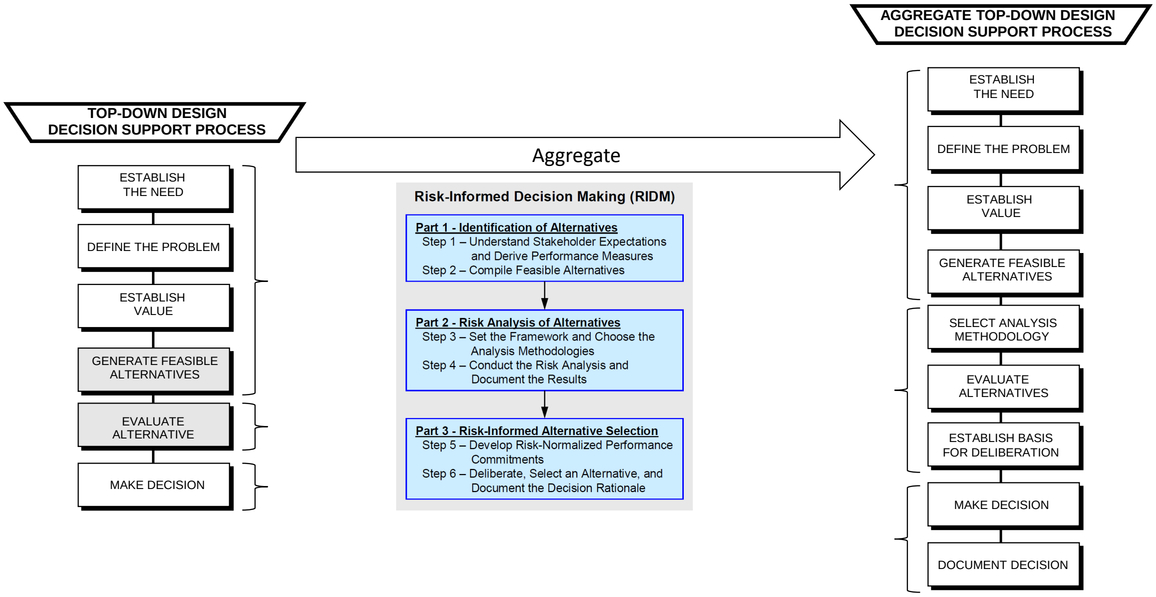


Figure 33: Aggregate Design Decision Support Process (adapted from [197, 65])

This aggregated decision support process can be recomposed into a generic process which will be used to guide the method development in the subsequent sections. The first four steps — Establish the Need, Define the Problem, Establish the Value, and Generate Feasible Alternatives — shall be combined into a single Problem Definition step. For the purpose of assessing the affordability implications resulting from the infusion of manufacturing technologies, this step will entail enumerating possible technology portfolios, and identifying the affordability measures of interest. The selection of an analysis methodology, evaluation of alternatives, and establishment of the basis for deliberation shall be combined into an Affordability Analysis step. This step will contain the relevant approach for evaluating the affordability of a given manufacturing technology portfolio. The analysis method will be selected such that it provides the capability to compare alternatives based upon the affordability measures of interest identified in the previous step. The final step in the generic process that will guide the method development is to Establish the Baseline. This step constitutes the decision making process in which a direct comparison between the alternatives is performed, and the final baseline configuration is downselected. The mapping from the RIDM and IPPD process to this three-step generic Manufacturing Technology Design Decision Support Process is shown in Figure 34

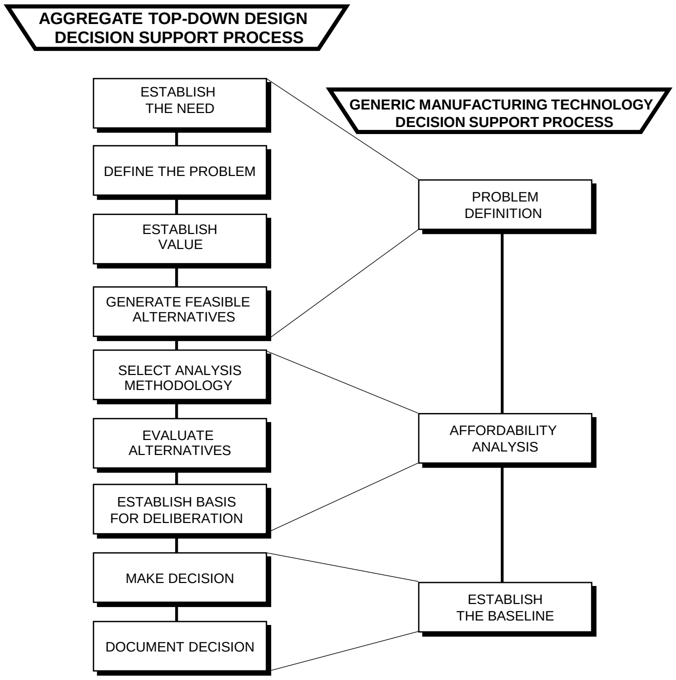


Figure 34: Generic Manufacturing Technology Design Decision Support Process

Having defined a generic decision-making process for the assessment of affordability implications of manufacturing technologies, these steps may now be used to guide the methodology development. The first research question develops naturally from the introduction of portfolio theory, NASA's RIDM process and Georgia Tech's IPPD decision support process, all of which require some value metric(s) which describe the "Goodness" of a particular alternative.

3.3 Research Question 1: How can the value of a launch vehicle manufacturing technology portfolio be assessed?

The previous section develops a generic Manufacturing Technology Decision Support Process which provides a structure with which the implications of infusing manufacturing technologies on affordability may be assessed. The first two steps have been addressed by the preceding chapters. The historical trend where programs are canceled early due to excessive cost and schedule slips establishes the need to hold affordability paramount and re-evaluate the insight available in early Conceptual Design. After delving into the methods and guidelines typically leveraged in early Conceptual Design, the problem lies in the lack of time-evolutionary insight into affordability. Namely, the analysis used during Conceptual Design does not provide sufficient information to perform the "right" trades to down-select a baseline configuration. Beyond the absence of a time-phased cost assessment, they lack the information necessary to assess the impact that design decisions have on the fabrication processes; such as the impacts on production by the selection of materials —which dictates the appropriate fabrication tasks— the weight-reducing stiffening concepts, and the implications on integration when multiple materials are used.

Proceeding through the Manufacturing Technology Decision Support Process, as shown in Figure 35, the next step is to establish the value. This value determination bridges the entire process, as it establishes the criteria which will drive the selection of a baseline. Furthermore, the selection of this value metric dictates the information that the analysis methodology must provide in order to categorize the respective value of each alternative.

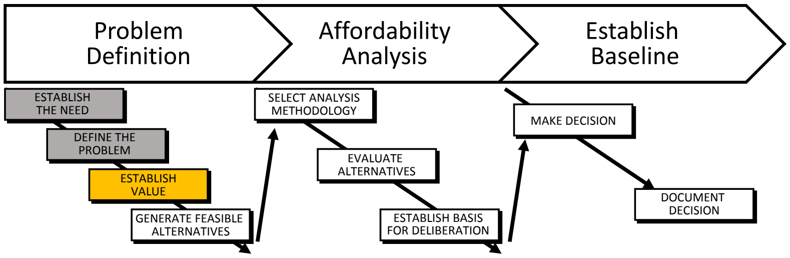


Figure 35: Generic Manufacturing Technology Design Decision Support Process

During step one, an enumeration of alternatives is compiled, and the measures of interest are gathered. The second step requires the selection of an analysis methodology capable of quantifying the measures of interest for each alternative, and the final step requires the downselection to a single configuration based upon how "well" each alternative performs with respect to the metrics of interest. These metrics of interest aggregate to define the value associated with a particular alternative. Research question 1 addresses the definition of this "value" term, which will be used to describe the worth or usefulness of a launch vehicle (and manufacturing technology portfolio). This worth, or usefulness, metric shall facilitate the comparison of alternatives on an "apples-to-apples" basis, by decision makers, in order to select the most useful configuration.

Research Question 1

What measure of value is appropriate for comparing launch vehicle manufacturing technology portfolios?

The decision making process for launch vehicles involves balancing multiple, often conflicting, requirements to arrive at a solution which meets the decision makers preference, often through quantifying the value of a concept. Establishing the value associated with a particular vehicle concept revolves around both the decision makers' priorities, and the strategic goals of the company. The priorities for NASA launch vehicles have shifted from a design for performance to a design for affordability, which is clearly shown by the weighted metrics used for SLS studies [157]:

1. Affordability — 80%[1]
2. Performance —10% [2]
3. Programmatic — 10%

These metrics clearly show that performance is becoming more of a requirement than a metric which contributes to the perceived value of an alternative. There is no longer any benefit to a system providing more performance than required, especially when cost and schedule are adversely affected. Furthermore, the shift to affordability extends beyond the plethora of canceled programs presented in Section 1.2. NASA and Congress spent more than \$192 billion (in 2010 dollars) on the Shuttle between 1971 and 2010. NASA launched a total of 131 flights during that time frame, which results in an average cost of around \$1.5 billion per launch, which is much greater than the \$450 million advertised during its operation [174, 173, 167].

Most recently, two volumes of "Lessons Learned" have been published by NASA regarding the failure of the Constellation program. These lessons learned provide a practical perspective on the approach to design, as well as the shortcomings the constellation program experienced as a result of the "Paradox of Traditional Design." Under this serial approach, design is predominantly rule-based, where every requirement is equally important. This is the approach that was initially followed on the Orion program. With this mindset, the technical team was unable to determine any feasible option that could simultaneously satisfy every requirement. The problem was over-constrained and the design mindset had to be changed in order to successfully

---

[1] This value has been adjusted from the original source to conform with the definition of affordability presented herein. The original reference lists affordability (defined as the life cycle cost) weighted at 55% and schedule at 25%

[2] This weighting represents the importance of performance improvements beyond that which is required.

identify feasible concepts. The solution was a risk-informed, "risk as a commodity" approach, wherein all but the mission critical requirements were removed. The technical team were then able to identify solutions that would satisfy the mission critical requirements and then trade the alternatives based on how well they met the requirements which had initially over constrained the problem. From this, NASA recommends that the design focus be mission success while treating other metrics as "commodities," which may be traded [179, 180].

These Lessons Learned documents justify the system-level weightings which are being applied to the design of the SLS. The fundamental premise being that **if the performance requirements are properly set, no benefit is gained by exceeding them**. Furthermore, the succession of best practices and guidelines published over the last decade suggests that **NASA is trying to break the trend of initiating unaffordable programs**. The increase in expectation of thorough risk assessment has positioned NASA as one of the most risk-aware aerospace organizations [49]. However, as established in Section 2.2, these risk practices do not provide a resolution greater than total LCC and often the technical risk is decoupled from the affordability risk. However, despite the prescribed risk-emphasized approach, design margins are still used in practice.

Section 2.4 highlights the shortcomings of current industry practices to truly assess the affordability of a vehicle concept during early Conceptual Design. Despite the evolution of the design paradigm to a risk-informed approach with affordability moving to the forefront of the decision makers' mind, the methods do not facilitate the generation of information relevant to the current definition of affordability. *The ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals* implies that the time evolution of cost and schedule are considered. Thus, neither a point estimate for cost and schedule, nor probabilistic estimates for LCC and expected completion date, are sufficient. The need to establish a time-phased affordability estimate requires that cost and schedule be estimated in a more cohesive manner, and at a greater level of detail than prescribed by best practices or facilitated by current Conceptual Design methodologies.

To summarize, NASA has exclaimed that the focus of design should be mission success, and risk should be traded as a commodity. Furthermore, point estimates for LCC and DDTE&P schedule is insufficient to ensure cost constraints are met for all points in the life cycle. As such time-phased costing, in which cost and schedule are coupled, is necessary. This discussion provides the means to develop a conjecture to research question 1:

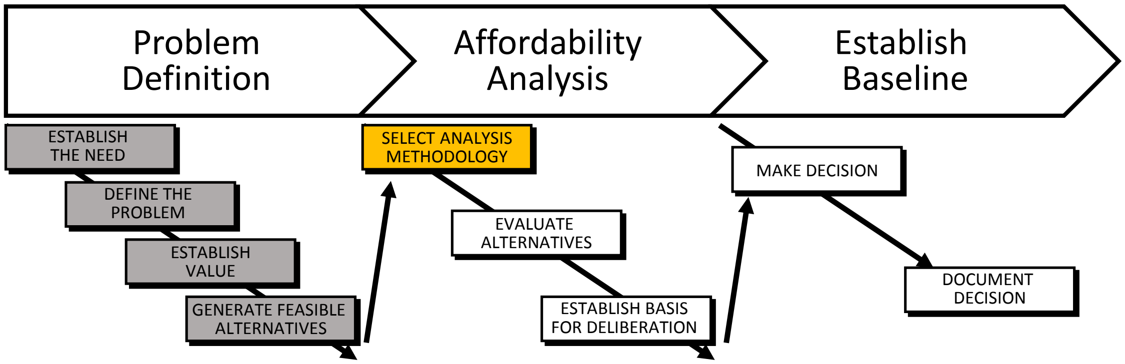
Research Question 1

What measure of value is appropriate for comparing launch vehicle manufacturing technology portfolios?

Conjecture to Research Question 1

The **risk of exceeding** a pre-established **budget** ceiling or **schedule goals—given that mission critical performance is met** — is the most desirable measure of value for launch vehicles.

This definition of value emphasizes the need to create an estimate which provides significantly more insight than the traditional coupled cost and schedule estimate that is often presented during Conceptual Design. A budget ceiling may vary from year to year, and thus this risk includes a temporal component which can only be assessed if a time-evolutionary cost is developed. Thus, this research question suggests two elements are needed to provide the decision maker with sufficient information with which to select an alternative. The generation of feasible alternatives relates to the identification and selection of manufacturing technologies to analyze, and will be discussed in more detail in 3.6. The first element is to establish the mission critical performance criteria, and the second is to establish the components which comprise risk. These two elements will be the driving factor behind the selection of the analysis methodology, as the analysis tools must provide the granularity of information necessary to define *The risk of exceeding a pre-established budget ceiling or schedule goals—given that mission critical performance is met.*



3.3.1 Research Question 1.1: Mission Critical Performance

With the design paradigm shifting from a focus on performance to a focus on affordability, there are no longer any benefits to providing more performance than required. Furthermore, based on the lessons learned from the Constellation program discussed in Section 3.3, it is recommended to take a risk-informed approach, where mission critical requirements are met and other metrics are traded as commodities. This prompts the second research question, regarding the specific metrics that adequately represent the mission critical requirements.

Research Question 1.1

What measure of performance can be used to ensure that mission critical requirements are met?

The term "mission critical," distinctly suggests that the measure of performance is directly related to the capability of a launch vehicle, as opposed to the manner in which it achieves that capability. The systems engineering guides from NASA, DoD, and INCOSE prescribe the initiation of new programs and projects through first identifying gaps in current capabilities [114, 64, 103]. This process identifies specific missions which then leads to a need to create a vehicle which fulfills this mission. The SLS, for example, has been designed to send astronauts back to the Moon and eventually on to Mars, which directly equates, from a physics perspective, to the SLS's ability to deliver certain payloads to certain orbits. This notion, of delivering certain payloads to certain orbits, warrants the introduction of physical relationships that drive the design of launch vehicles.

3.3.1.1 The Rocket Equation

A mission to place an object in a particular orbit requires that the object be accelerated such that it has sufficient orbital energy to sustain the desired orbit [118]. Thus, a launch vehicle must impart energy to the object to provide acceleration. This acceleration is also known as the change in velocity ΔV, and is mathematically modeled by the rocket equation, shown in its simplest form (representing a single propulsive burn) in Equation 11 [118, 93].

$$\Delta V_{effective} = g_0 I_{sp} ln \left(\frac{m_{initial}}{m_{final}} \right) \tag{11}$$

This equation includes propulsion characteristics ($g_0 I_{sp}$), structural characteristics ($ln(\frac{m_{initial}}{m_{final}})$), and aerodynamic parameters ($\Delta V_{effective}$). The effective ΔV is comprised of two parts; ΔV_{ideal},which represents the acceleration required if no external forces were acting on the system, and ΔV_{losses}, which represents additional acceleration required to overcome gravitational forces, aerodynamic drag, and thrust control [118]. The structural characteristics, defined by the mass ratio in Equation 11, is comprised of three distinct mass categories: Payload mass, structural mass, and propellant mass. The initial mass is the sum of all three masses, while the final mass

— defined to be the instant at which the burn ceases — assumes that all propellant has been consumed. Thus, the rocket equation may be expanded as shown in Equation 12.

$$\Delta V_{ideal} + \Delta V_{losses} = g_0 I_{sp} ln\left(\frac{m_{payload} + m_{propellant} + m_{structures}}{m_{payload} + m_{structures}}\right) \tag{12}$$

This simplified version of the governing equation of space flight, allows for the distinction between different performance attributes of a vehicle and a mission. The ideal change in velocity (ΔV_{ideal}) is determined by the desired orbit in which the payload is to be inserted, i.e. it is defined by the mission for which a vehicle is designed. The losses (ΔV_{losses}) are based upon gravity, and the aerodynamics of the vehicle itself; the shape of the vehicle and the trajectory flown to arrive in the desired orbit determines a majority of these losses. For launch vehicles, the acceleration required to overcome gravity is immense, which often limits the orbit a launch vehicle can achieve to that of low-Earth orbits (LEO) which extend from 100km to 600km in altitude [118]. The propulsion characteristics are contained within the specific impulse (I_{sp}), which is a measure of the energy content of the propellants, and how efficiently they are converted into thrust [118]. The mass of the propellant and structural mass are typically dictated by the combination of the other parameters in the rocket equation; the propellant mass is dictated by the mass of the payload and the final desired orbit, but also by how efficient the engines are and the mass of the structures which house both the propellant and the payload. While it may now be observed that the payload mass and the final desired orbit (i.e. ΔV_{ideal}) are representative of mission parameters and the others more aptly describe how the vehicle achieves that mission capability, all parameters are interrelated. Table 4 distinguishes between mission and vehicle parameters for the terms in the expanded rocket equation 12.

Table 4: Rocket equation elements distinguished as mission or vehicle parameters

Mission Parameters	Vehicle Parameters
ΔV_{ideal}	ΔV_{losses}
$m_{payload}$	$m_{structures}$
	$m_{propellant}$
	I_{sp}

A decomposition of this equation suggests that both the payload mass and the ideal velocity change are adequate, mission critical, parameters which may be used to assess the performance of a launch vehicle. However, a more common approach is to assess the payload mass that a particular vehicle can delivery to a particular orbit. This represents a rearrangement of the expanded rocket equation such that payload mass is a function of the other terms, as shown in Equation 13.

$$m_{payload} = (m_{propellant} + m_{structures}) * \left(\frac{1 - \frac{m_{structures}}{m_{propellant}+m_{structures}} * e^{\frac{\Delta V_{effective}}{g_0 I_{sp}}}}{e^{\frac{\Delta V_{effective}}{g_0 I_{sp}}} - 1} \right) \tag{13}$$

The interrelated nature of the terms in this equation necessitate a highly iterative analysis method, the logic of which follows. The designer selects a propulsion system, which immediately dictates the propellant(s) and appropriate propulsion parameters that would allow her to estimate the propellant needed to meet the required mission parameters — place a payload ($m_{payload}$ into an orbit described by ΔV_{Ideal}. The structural mass is determined predominantly by two constraints; the first being volumetric such that the vehicle has sufficient space for all the propellant needed and the payload, and secondly the vehicle must be structurally sound so that it does not break apart during ascent to orbit. The primary linkage between propellant mass and structural mass is the trajectory that the vehicle would fly to reach the desired orbit. The propellant mass is determined by the **total mass** which has to be delivered to orbit, which includes structural mass, and the particular trajectory that is flown. This trajectory will define the ΔV_{losses} which describe the effective velocity change which has to be imparted to the vehicle through chemical energy (i.e. propulsion). Similarly, the structural mass will change with the trajectory, as different loads are experienced as the trajectory changes. These loads ultimately determine the thickness of the structural elements which impacts the total structural weight, which in turn affects the required propellant mass...which in turn will adjust the volume necessary to store the propellant which again affects structures. This highly coupled relationship between structures and propulsion often requires the use of a "guess and check" method in which the designer runs a series of analyses (trajectory, propulsion, and structures) which result in a viable payload mass delivered to the desired orbit given a few high-level design parameter selections, such as the engine type, propulsion system type, and material used for large components. The resulting payload mass will then be compared to the desired payload mass, and the vehicle will be scaled until the resultant payload mass converges to the desired payload mass. Payload mass is more appropriately considered an output which results from the selection of propulsion and structural parameters. It is for this reason that payload mass has been separated to the left of Equation 13; and it is for this reason that payload mass delivered to an orbit is an appropriate physics-based performance measure. Thus a conjecture to research question 2 may be posed.

Conjecture to Research Question 1.1

From a physics perspective, the payload delivered to a low-Earth orbit is an appropriate measure of performance as it represents the system capability and is often a hard requirement defined at the onset of a program.

Using the payload mass capability of a concept addresses only part of the conjecture to research question 1; the crux of the conjecture falls on the ability to assess the risk of exceeding a pre-established budget ceiling or schedule goals.

3.3.2 Research Question 1.2: Quantifying Risk

As presented in Section 1.1, risk is often categorized by the likelihood of an event occurring, and the consequence that would arise should that event occur. More colloquially risk may be described as a set of triplets [65]:

1. The **scenario(s)** leading to degraded performance with respect to one or more performance measures
2. The **likelihood** of those scenario(s) occurring
3. The **consequence** that would arise should the scenario(s) occur

Quantifying the risk of a scenario requires two pieces of information, uncertainty of a particular attribute, and the requirement of said attribute. In the case of either cost or schedule, the traditional risk estimation described in Section 2.2 would require the generation of the uncertainty distribution on total cost or total schedule. Once established, the required total cost (or duration) would be overlaid on the figure and the integral of the undesirable area would represent the risk of exceeding the requirement. In the case of cost, and as depicted in Figure 36, the shaded blue region represent the risk of exceeding the required total cost (or schedule).

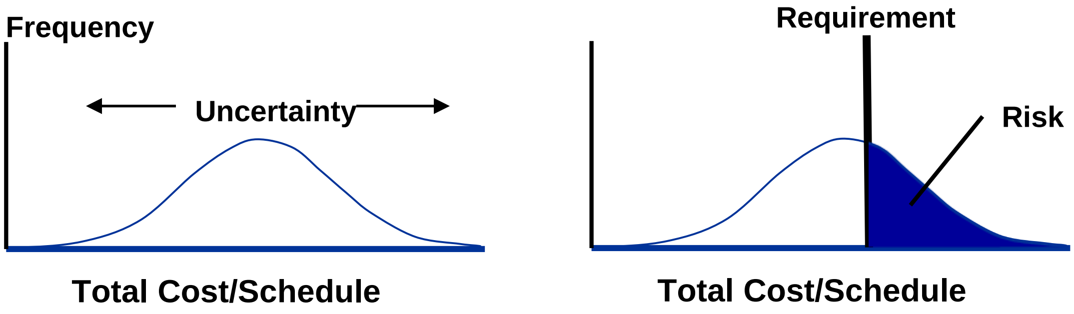


Figure 36: Uncertainty and Risk [adapted from [65]]

However, within the context of affordability it has become clear that the traditional cost and schedule representations are inadequate to ensure that a programs' *ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals.* Thus, another research question may be formulated

Research Question 1.2

How can the risk of exceeding a pre-established budget ceiling or schedule goals be quantified?

In order to understand risk, it is necessary to examine the sources of uncertainty and focus on those which pertain to launch vehicle development programs and affect a program's affordability. Beginning with uncertainty, there are two major types; epistemic and aleatory.

Uncertainty due to the inherent randomness of a physical system or the environment is termed aleatory uncertainty [96]. This type of uncertainty is also known as randomness, stochastic uncertainty, and irreducible uncertainty and examples include weather patterns and manufacturing variability [226, 62]. Epistemic uncertainty describes one's lack of knowledge of the state of a system and includes things like lack of data, analysis model assumptions, and measurement device error [171, 184, 226].

This type of uncertainty is theoretically reducible; it decreases as knowledge of the underlying system increases [62]. Robertson presents an extensive review of various uncertainty taxonomies, culminating in one which applies specifically to space and launch vehicle development programs, shown in Figure 37.

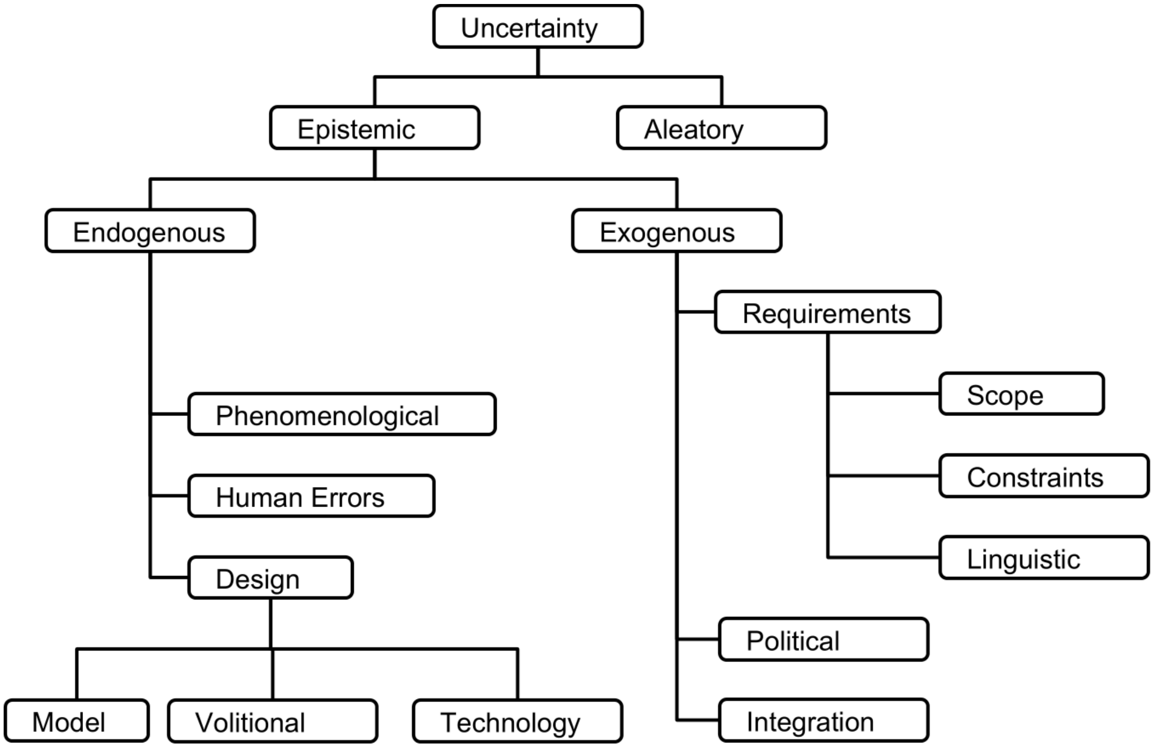


Figure 37: Taxonomy of Uncertainties in the Development of Space and Launch Vehicles [186]

This taxonomy focuses on the reducible form of uncertainty, which is further decomposed into sources traced to within the program development office, and those traced without; endogenous exogenous uncertainty, respectively. Exogenous uncertainty can be further decomposed into requirements uncertainty — further broken down into scope, constraints, and linguistic uncertainties — political uncertainty and integration uncertainty. The former defined as uncertainty of development fund instability, and the latter which stems from the notion that individual projects/subsystems — such as engines — will develop at a different rate than the system which they comprise[186].

The endogenous uncertainty comprises phenomenological uncertainty, human errors and design uncertainty. Phenomenological uncertainty relates to a lack of knowledge of phenomena, physical or otherwise, and is often dubbed the "unknown unknowns." Robertson exemplifies this uncertainty with the first U.S. satellite which began to nutate from its axis of rotation due to unimagined physical phenomena. The second source of endogenous uncertainty is human error, which — as the name suggests — is defined as faults which occur during design, manufacture, test, or operation of a system. The final subcategory is design uncertainty which relates to the lack of knowledge in the design of the system, and often forms a large part of endogenous uncertainty[186].

Design uncertainty is comprised of three parts, model uncertainty, volitional uncertainty, and technology uncertainty. Model uncertainty refers to the analysis tool fidelity as well as the fidelity level of the designers' and engineers' mental models of the system under development. Technology uncertainty stems from the incorporation of new technologies and the assumptions made about those technologies during the development of a system. The most common form of this uncertainty pertains to a misrepresentation of a technology's capability; often providing overly-optimistic performance gains or cost reductions. The final source of design uncertainty is volitional uncertainty, which is a result of the decisions of actors within the design process of the system. This is primarily in the form of future design decisions which either add detail to a low-fidelity design or fundamentally change the design of the system in question.

This uncertainty taxonomy provides a means to identify the uncertainties which exemplify the affordability problem. As stated in Section 2, the early phases of design leverage low-fidelity analysis (in comparison to that used in Detailed Design) to estimate performance and affordability metrics. These metrics are used to acquire program funding which may be ceased if the program becomes unaffordable. Within

Robertson's taxonomy of uncertainty, this highlights a connection amongst some of the uncertainties. The political uncertainty which is exogenous to the design team is somewhat connected to the design uncertainty which is endogenous. Fundamentally, the political uncertainty may become grandiose if the design uncertainty, with which funding was secured, is large. This places a burden on the designers to provide high-fidelity affordability analysis in an attempt to mitigate the portion of political uncertainty which is reducible by the program office. This places an emphasis on affordability, and the ability for the early design analysis and trades to include time-phased cost estimates for each alternative.

Time-phased cost estimation would provide time evolutionary insight into annual expenditure as a function of design decisions, and allow the decision maker(s) considerably more awareness into potential political risk that may be lurking in the future. Through this, affordability curves could be generated, as described in the thought experiment in Section 2.4, to elucidate the affordability as a function of time. These curves will facilitate informed decisions when it comes to assessing the political aspect of funding and deliverable timeline. These curves would simultaneously facilitate a time-phased risk analysis for a given concept with respect to budget and timeline scenarios. Risk, in the traditional sense, is defined at a specific point-in-time; i.e. Figure 36, which represents the traditional schedule risk analysis performed during Conceptual Design, shows a snapshot of the risk at the end of the development phase. It portrays the risk of exceeding the total/cumulative schedule for the development program, where the overlaid requirement would be an estimate of the total acceptable time to complete program. It does not, however, provide any insight into the risk experienced along the way which would identify **WHEN** schedule slips will begin.

Figure 38 portrays a notional risk assessment generated using affordability curves ,i.e. time-phased cost estimation curves. These curves represent the annual optimistic, pessimistic and expected affordability for a specific concept. The expected funding profile and desired launch date have been overlaid to represent the area in which the program remains affordable. Any deviation outside this area represents a potential for program cancellation. This perspective facilitates the visualization of the evolution of risk throughout the program. During the early phases, when little is spent but much is committed, there is a high probability of remaining affordable since all three curves are well within the constraints (i.e. there is low affordability risk). At a later time the risk becomes excessively high as the affordability curves have all exceeded the budgetary requirement. And finally, where the curves terminate on the x-axis represents the completion of tasks needed to achieve first flight forms the risk curve for the total schedule described in the previous paragraph.

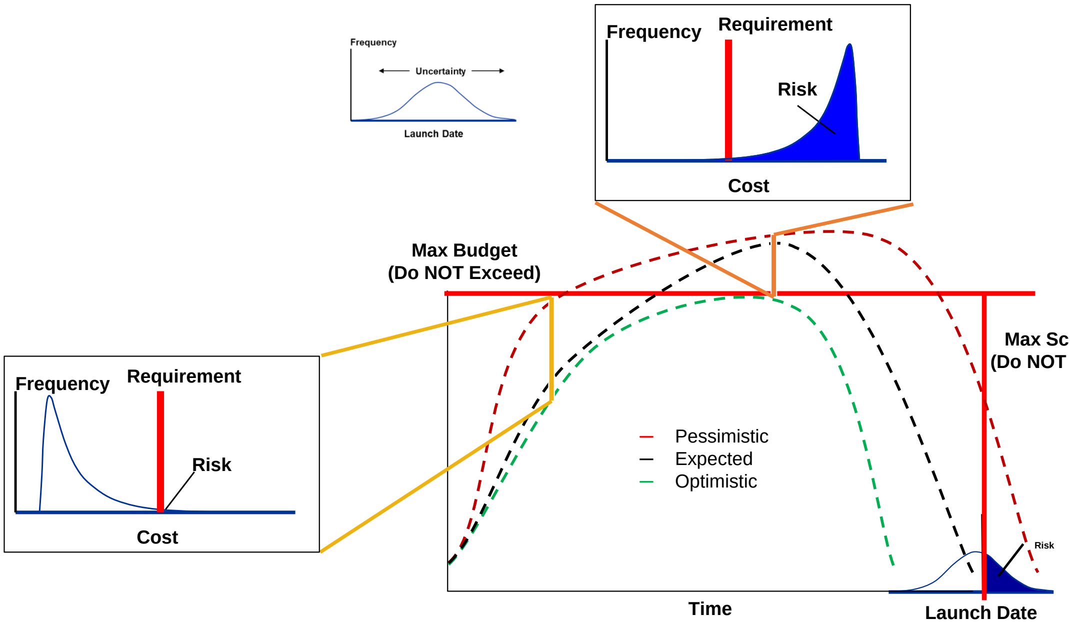


Figure 38: Notional Affordability Risk Assessment

This affordability risk assessment will be instrumental in the selection of future launch vehicle concepts as they will provide significant insight into the evolution of risk throughout the development stage of a program. This visualization forms the basis for a conjecture to research question 1.2.

Conjecture to Research Question 1.2

Establishing probabilistic affordability curves to identify the likelihood of remaining beneath budget ceiling and within schedule goals will provide a means to quantify a launch vehicle programs affordability risk

However, before probabilistic affordability curves can be generated, it is necessary to first establish a method for determining a deterministic representation of time phased cost. This deterministic cost will then be adapted into a series of curves which represent probabilistic affordability.

3.4 Research Question 2: Affordability Distributions

A mission critical performance parameter, namely payload mass delivered to LEO, has been identified as an appropriate parameter to set as a requirement while assessing various manufacturing technology portfolios. Furthermore, a desire to assess affordability risk as a function of time has been established. The need to first generate a single affordability distribution leads to Research Question 2.

Research Question 2

How can affordability distributions be developed?

The notion of time-phased cost suggests analysis which is based upon a close relationship between cost and schedule. Furthermore, the desire to perform trades on specific aspects of a vehicle concept requires that the analysis also provide detailed insight in key manufacturing aspects. The ability to distinguish between various materials (metallic and composite) as well as the resolution to discern the impacts of manufacturing processes, stiffening concepts, and the number (and therefore size) of the components which comprise it. These are the criteria which must be satisfied as an appropriate method is sought in literature.

3.4.1 Integrated Methods for Affordability Analysis

Having established that the method criteria heavily rely upon the correlated relationship between cost and schedule, it is natural to begin reviewing methods which attempt to integrate cost and schedule estimates. The desired affordability distributions will provide a cost as a function of time for a program **AND** facilitate trades between lower-than-system-level attributes, such as subsystem stiffening concepts, number of major pieces (e.g. barrel panels or dome gores), and the process by a subsystem is fabricated.

3.4.1.1 Garvey: System Cost Uncertainty Analysis

Garvey addresses cost and schedule as correlated random variables whose uncertainties may be quantified through joint probability distributions. While the focus here is on cost analysis, Garvey realizes that the uncertainty in cost estimates originates from inaccuracies in cost-schedule estimation models [83]. The foundation of this method lies in developing a detailed probabilistic WBS for a system and performing a bottom-up estimation of cost and schedule based on assumed joint probability distributions and correlations. His aim is to facilitate the ability for the decision maker to answer questions such as "What is the chance the system can be delivered within cost and schedule?" and "how likely might the point estimate cost be exceeded for a given schedule?" [85] Garvey presents a family of joint-probability (bivariate) distributions as candidate theoretical models that may be assumed by analysts [85]. The candidate models include the bivariate normal, bivariate normal-lognormal and the bivariate log-normal distributions, which possess convenient characteristics. First, the correlation between cost and schedule is captured, and secondly the marginal distributions of cost and schedule are conveniently either both normal, one normal and one log-normal, or both log-normal [84]. This method operates on total lifecycle cost, and total project duration such that project level trades may be made. Equations 14 and 15 are the mathematical relationships for the probability that cost, a, and schedule, b, constraints are met, and the probability that cost, a, is met given that schedule, b, is met, respectively [85]:

$$P(Cost <= a \,\&\, Schedule <= b) \tag{14}$$

$$P(Cost <= a|Schedule <= b) \tag{15}$$

While this method seeks to provide insight into the correlation between cost and schedule, its reliance upon a detailed WBS results in inflexibility during Conceptual Design, when vehicle component design is fluid. Furthermore, the system-level correlation does not provide the means to assess the implications of infusing new materials or leveraging novel fabrication processes (manufacturing technologies) into a single element Nor does it facilitate varying the DDTE&P activities associated with a particular program. The method also requires the correlation to be precisely known. An alternative, albeit similar approach has been taken by MackKenzie and Addison, who present a method to determine this correlation for space systems based upon historical data [128]. While their method is traceable, it focuses on piece-to-piece variation and recurring costs during production of space system components. The reliance on a large data set, and the focus on recurring costs does not lend this method extensible to launch vehicles, which are produced on extremely low-volume scales which results in non-recurring costs driving life cycle costs.

3.4.1.2 Phase Estimating Relationships

In 1997, Lee, Hogue and Gallagher developed a method to "spread" the total research and development cost over the projected years of the program [119]. The method assumes the program expenditures follow a Rayleigh function, whose probability density function (PDF) and cumulative distribution function (CDF) are represented by

Equation 16 and 17, respectively and shown in Figure 39.

$$f(t) = 2ate^{-\alpha t^2} \tag{16}$$

$$F(t) = 1 - e^{-\alpha t^2} \tag{17}$$

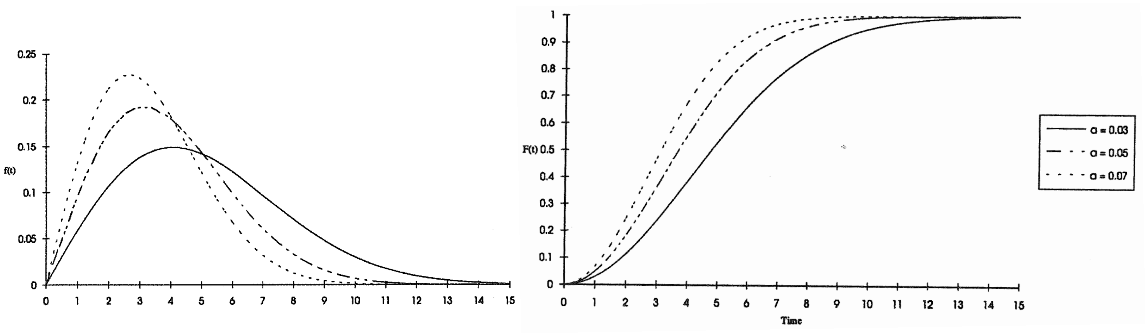


Figure 39: Rayleigh PDF (left) and CDF (right) for Various Time-Scale Parameters (α) [119]

The cumulative expenditures at time t (E*(t), in constant year dollars) for a program is determined by scaling the Rayleigh distribution by the total cost estimate (d). This representation is shown in Equation 18, where the shape parameter, α, would be determined from the expected time of peak expenditure, or the expected completion date.

$$E*(t) = d(1 - e^{-\alpha t^2}) \tag{18}$$

This analysis is predominantly based upon defense acquisition data. Further studies identify the shape limitations of the Rayleigh distribution and prescribe the use of the Weibull distribution for greater flexibility and lesser fitting error [219, 29, 176, 31]. The Weibull distribution has improved flexibility over the Rayleigh model in that additional shaping parameters allow for the representation of expenditure scenarios which cannot be modeled by the Rayleigh distribution [31]. The general form of the

Weibull CDF is shown in Equation 19, where α and β are shaping parameters, and γ is a time-delay parameter [31].

$$F(t) = 1 - e^{-\alpha(t-\gamma)^{\beta}} \tag{19}$$

Burgess develops a new expression (Equation 20) which "spreads" the given cost estimate based upon given schedule estimates and the Weibull CDF. This estimate is based upon DoD space systems, predominantly spacecraft missions, and includes consideration for the "standing army" of contractors which typically dominates spending in late years [31].

$$F(t) = d[Rt + 1 - e^{-\alpha(t-\gamma)^{\beta}}] \tag{20}$$

Here, 'R' corresponds to a constant-rate associated with the "standing army" of contractors which government agencies employ, and 'd' is the normalized cost of a program. Currently, two functional forms of regressed parameters have been developed by Burgess and Elliott; one for project-level phase estimation, and a second for spacecraft-level estimates. The values of the regressed coefficients for the above equation may be found in [74].

While this method possesses the ability to "spread" a **furnished** cost estimate based on **furnished** schedule components, this method does not contain any estimation of either cost or schedule. First and foremost, this method operates only on the high-level estimates; this inherently assumes that the estimates provided account for the infusion of manufacturing technologies or varying the order in which DDTE&P activities are performed. Secondly, this method does not consider any independent variables, the regressed shaping parameters are based solely on schedule parameters and a total program cost estimate. Finally this method does not consider uncertainty in the provided cost and schedule estimates, nor does it address the propagation of uncertainty inherent in the assumption that a new program will proceed similarly to a history of other programs — whose similarity is not established to a new program.

3.4.2 Summary of Integrated Methods for the Generation of Affordability Distribution

While Garvey's approach aims to provide insight into cost risk as a function of schedule uncertainty, the phasing relationships provide a means to "spread" a program/system level cost estimate across a provided program duration. Both methods operate on total project/system cost and total duration, which does not provide the resolution to assess the implications of varying lower-than-system-level attributes. Garvey's reliance upon a detailed WBS limits its flexibility to perform Conceptual Design trades where it is impractical to document every task, let alone all permutations of a WBS for design space exploration of large complex systems. Similarly, the phasing approach is predicated upon Department of Defense space systems, which almost exclusively limits its applicability to satellites. While this method is reasonably accurate for assessing cumulative cost, it has poor accuracy when assessing annual cost expectations [77]. Furthermore, this approach does not actually estimate the cost or schedule of a system, it is applied to furnished total cost and total schedule estimates. The approach of "spreading" an estimate, however, seems appropriate for Conceptual Design phases in which little detail is available. However, its restriction to system level application limits its ability to either rearranging DDTE&P activities or assess manufacturing technology infusion. Finally, the phase estimating relationships do not leverage independent variables which describe any aspect of the system or its components, which disallows insight into how design decisions impact the program phasing and whether technology infusion (manufacturing or otherwise) can improve them. Clearly, the desired affordability distributions will take a form similar to the phase estimating relationships, revealing Burgess' method as a reasonable starting point for generating affordability curves. However, several additional aspects will need to be considered; namely the inclusion of independent variables at a lower-than-system-level to enable planning and manufacturing technology trades. In order to assess the implications on the lower-than-system-level elements, the system must be decomposed and estimates generated for the key elements which comprise the space system. These estimates would thereafter be aggregated into a system level affordability distribution which facilitates trades in design attributes of the elements, as well as the planning of element development in achieving program level budget and schedule goals. This leads to a hypothesis to Research Question 2.

Hypothesis 2

If phase estimating relationships are used to generate affordability distributions which represent the development of individual elements, they can be aggregated into a system level affordability curve which provides insight into manufacturing technology infusion and development.

This hypothesis immediately elicits a series of questions which need be addressed. Namely the generation of phasing relationships for key elements, elucidating the elements which comprise a launch vehicle system, and the aggregation of these elements into a system level affordability distribution.

3.4.3 Research Question 2.1: Generating Phase Estimating Relationships.

The generation of phase estimating relationships requires insight into the manner in which cost is incurred as a program moves through the development phases leading up to first flight. This implies a linkage between cost estimation and schedule estimation, and provides guidelines which may be used to select an appropriate estimation method.

Research Question 2.1

How can the cost and schedule be quantified to enable the development of phase estimating relationships?

Successfully determining phase estimating relationships will require a method which meets a few key criteria

1. The method **MUST** provide cost and schedule estimates and capture their interdependencies.

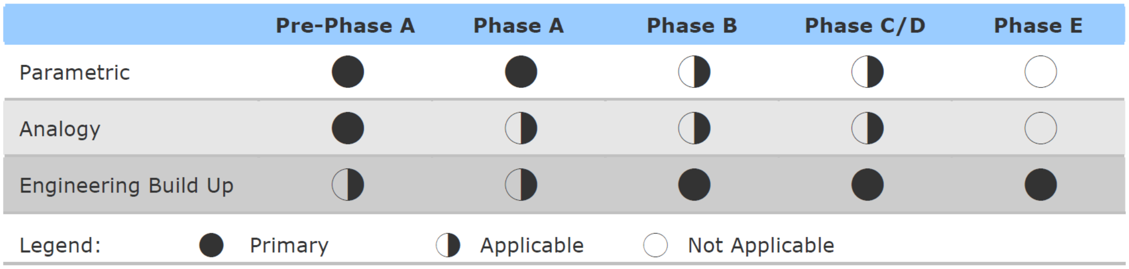
2. The method shall be capable of assessing lower-than-system-level design and manufacturing aspects.

   e.g. variation in fabrication techniques for a subsystem, or varying the number of parts which comprise that subsystem.

With these criteria in place, a review of various cost and schedule estimation methods is needed in order to identify the viable candidate(s).

3.4.4 Traditional Cost Estimating Methods

The three most distinct, and common, cost estimating methods are analogy, parametric, and engineering buildup [151]. In practice, each of these methods is used at different stages within a projects life cycle, where thorough estimates often include some combination of all three [115]. Figure 40 depicts the use and applicability of each of the three methods at different phases of a NASA project's life cycle. A detailed description of each is described below.



	Pre-Phase A	Phase A	Phase B	Phase C/D	Phase E
Parametric	●	●	◐	◐	○
Analogy	●	◐	◐	◐	○
Engineering Build Up	◐	◐	●	●	●

Legend: ● Primary ◐ Applicable ○ Not Applicable

Figure 40: Cost Estimating Methodology Selection Chart [151]

3.4.4.1 Analogy Estimates

Analogy estimates are created based upon a comparison to single, similar, past programs. Attributes of the new/proposed system are compared to the same attributes of the past system, and the cost is scaled up or down based upon differences between the two systems. This method is typically used during the earliest phases of design when little detailed information about the new system has been decided. This cost estimating method relies upon actual historical data, which yields traceable and reliable estimates if a strong analogy system may be found and minor deviations from that system are desired. Limited historical data and the reliance on a single data point limit the use of this method. Furthermore, the reliance on expert opinion to define, not only the relevant analogy system, but also to accurately enumerate the relative deviations between the two systems results in heavily subjective estimates which are often optimistic, and lead to cost and schedule overruns [19, 151]

3.4.4.2 Parametric Cost Estimates

Similar to the analogy method, parametric cost estimation is based upon historical data, and is also used during the early design phases [151]. Where the analogy method leverages one analogous system, parametric estimates leverage mathematical regressions based upon the aggregate relationship between cost and cost-driving attributes. These mathematical regressions, typically referred to as cost estimating relationships (CERs), "relate quantifiable characteristics of a system such as flight hardware weight, power, data rate, thrust, and non technical variables such as schedule, team experience, and new technology to an estimated cost" [100]. The use of such regressions implicitly assumes that the cost-driving attributes for new systems are identical to those which drove costs in previous systems. Generating parametric estimates are quick and defensible, as the reliance on expert opinion has been replaced by logical correlations and the scientific method [151]. However, this reliance on a large set of data is an impairment due to effort and time commitment required to gather relevant data. Especially in the case of space and launch vehicles, this data is sensitive in nature and guarded from free availability, often deemed proprietary, classified, or export controlled. These parametric relationships, however, are only credible within the range of data used to create them [151]. Their predictive capability is reduced when novel concepts are analyzed, particularly in the case of infusing new technologies [188]. In revisiting the types of tools which are used during Conceptual Design, presented in Section 2.1, the cost estimating tools rely heavily upon weight-based CERs. Fundamentally,empty-weight regressions no longer provide accurate estimates when one shifts to composite concepts.Furthermore, weight-based cost estimates are unable to provide insight into the implications that a design decision may have on manufacturing a system, nor does it facilitate trades between the various fabrication techniques which could be leveraged to produce major systems. Notably, however, parametric estimates are used by NASA during pre-phase A and Phase A to secure funding and establish the initial LCC estimates, detailed in Section 2.2, for a program [114, 65, 151].

3.4.4.3 Engineering Build-Up Cost Estimates

The engineering build up method, referred to as a "bottom-up" or "grass roots" approach, aggregates low-level cost estimates into a system level estimate [151]. The low-level estimates are computed from WBS elements at the lowest level of detail where work hours and bills of materials are discernible [115]. Estimates generated with this method are intuitive, credible, and defensible due to the level of detail upon which the estimate is based. Generating these estimates is costly and time consuming, often requiring the cost estimator to work in conjunction with a technical expert with knowledge in the activities. These estimates hinge upon a highly-detailed WBS, the complexity of which often results in the omission or duplication of elements, and inherently requires a new WBS for each and every scenario. “There is no such thing as a good WBS, just look for the least evil WBS [100]. The quantity and caliber of the information required for these types of estimates is typically not available in early phases, thus this method is typically only used beyond the completion of Conceptual Design, as shown in Figure 40, once the vehicles configuration has stabilized [90].

3.4.4.4 Process or Activity-based Costing

Process/Activity-based costing is designed to reveal “the links between performing particular activities and the demands those activities make on the organization’s resources [55]. Process/Activity based costing assumes that activities cause cost, and by managing the forces that cause the activities — namely the cost drivers— costs will be managed for the long term [70]. This approach was developed in the late 1980’s as a way to shift the basis of decision making from allocating resources to the unit (i.e. total product cost) to a more refined approach of separating expenses and appropriately allocating resources to the tasks which consume them [55, 69]. This method thus calculates the cost associated with individual processes (or activities) and then sums them (similar to the bottom-up approach of an engineering build-up) to arrive at the system level cost. This may be considered a hybrid between an engineering build-up and parametric approach, described above. Process-based models are typically used to provide a cost estimate at the subsystem level as opposed to the vehicle level (parametric) or the work element level (engineering build-up)

[195]. This method has the benefit of providing a higher fidelity analysis than the traditional parametric models without the need to painstakingly define a detailed WBS. Process-based cost estimating tools are both commercially available, such as SEER-MFG, and are developed in-house by various organizations, such as Process-Based Economic Analysis Tool (P-BEAT). These types of tools estimate the hours required to perform the activities necessary to bring a system into fruition. While these tools possess information which could be used to generate schedule estimates and potentially time-phased cost distributions, they are seldom used to provide anything more than point-estimate life cycle, development and/or production costs.

3.4.4.5 Other Methods

Other estimation methods include extrapolation from actual costs, learning curves, a pure solicitation of expert opinion, and process/activity-bases estimation [90]. The first two methods, learning curve and extrapolation, are intended to provide the cost estimator with insight into unit costs evolution over time. Extrapolation looks at the time history of production for the project and forecasts costs based on a moving average. This method is best suited for follow-on units of the same item where ample production data exists. The learning curve approach, which is better suited for projects where little data is available, is based on the premise that the efficiency of performing a task increases as the number of task repetitions increases. This often results in a reduction in labor hours, more efficient use of resources, employee learning, etc. One of these two methods are typically included, in the form of CERs, in the main estimating tools described previously. While expert opinion alone is typically too subjective, in the absence of data, it may prove useful. This method requires a cost estimator to interview an expert in order to elicit information upon which the estimate is based [90].

3.4.5 Traditional Scheduling Techniques

As described in Section 2.2, the industry-wide best practices recommend the generation of a schedule which sets the expected timeline leading up to project completion. The level of detail included in the schedule estimates increases as the program progresses through the lifecycle phases. The current industry-wide best practice dictates that the schedule will be generated from a WBS, and the program duration is determined by applying the Critical Path Method (CPM) [103, 64, 155].

3.4.5.1 Critical Path Method (CPM)

The Critical Path Method (CPM) was first introduced into project planning in the 1950's, and has since become one of the most well-known and widely used planning methods [75]. The critical path method requires the construction of logic networks based upon the tasks listed in the WBS. This logic network establishes functional relationships between all the tasks, identifying the predecessor and successor relationships between tasks. Using these relationships, and the fixed durations assigned by an SME, CPM organizes the tasks and ultimately results in the identification of the most lengthy, serial task progression. This progression represents the longest series of tasks which cannot be rearranged to shorten to total program duration; this is the critical path, as it is the series of events which drives project duration. A few important distinctions must be made regarding this technique:

1. A highly detailed WBS is needed to generate an accurate critical path
2. Logic network creation is extremely dependent on expert opinion
3. Task durations are deterministic

This method has become popular due to the direct, and logical, nature of its creation and the ease with which the final duration may be understood. Its reliance upon a highly detailed WBS, which cannot be easily generated, yield this method inappropriate for Conceptual Design trades. Furthermore, the deterministic nature of this method has resulted —although not explicitly stated in any best practice documents — has resulted in industries using the Program Evaluation and Review Technique in conjunction with CPM.

3.4.5.2 Program Evaluation and Review Technique (PERT)

Program Evaluation and Review Technique (PERT), developed in the late 50's, aimed to more explicitly capture the uncertainties associated with task durations [129]. This method is very similar to CPM; a complete list of activities (i.e. complete WBS) and a logic network, establishing the predecessor and successors of each task, is required. Where CPM requires fixed task durations, PERT requires that three time estimates be provided; the pessimistic, optimistic, and most likely task durations. These three estimates are used to establish an expected value and variance for the duration of each task [56]. This not only allows for one to estimate the probability of completing the program (or individual activities) within time constraints, but also determine the time duration associated with a given probability [33]. Various criticisms of this technique have appeared in literature since the early 1960's:

1. PERT only considers critical path tasks when computing probabilities and durations. It ignores other paths, and cannot account for scenarios in which a "near-critical" path becomes critical [33].

2. Method relies heavily on SME provided estimates. These are often subjective, and may not be related to statistical sampling of actual times [94, 141]

3. The method of calculating the mean and variance of activity durations are estimates of the mean and variance of the beta distribution [9]. This implies that the scheduled tasks follow a beta distribution[3]

---

[3] At the time of PERTs development, no study had been performed to assess the form of activity or project duration distributions [127]. Recent studies of space systems suggest that these distributions

While many other scheduling methods exist (Petri-nets, Markov Chains, etc.), they all possess the same shortcomings.

3.4.6 Summary of Traditional Methods

One fundamental flaw in the traditional estimating methods, reviewed above, is that the estimates are typically generated independently. The cost estimates do not explicitly consider the schedule required to complete a program, and, at best, the schedule estimates may be used to determine a total cost (multiply total number of hours by average hourly wage). The political requirement of stringently maintaining cost and schedule coupled with the desire to push the boundaries of performance and capability inherently requires analysis which not only estimates cost and schedule simultaneously, but also facilitates technology trades at a lower-than system-level view-point.

Analogy and parametric cost estimating methods are limited greatly by the data upon which they are based. These methods rely on limited, high-level design information to estimate the cost of a new system. While the estimates can be performed quickly, the lack-of-insight into the finer details of subsystems disallows trades at the lower-than system-level. A prime example of this, within the manufacturing perspective, is varying the number of panels used to fabricate a tank barrel, or changing the stiffening pattern used on those panels. The need to incorporate manufacturing insight into the Conceptual Design process leads towards a desire to use engineering build-up methods. A deterrent to this is the excruciating detail needed to define the subsystems in order to accurately estimate a system.

The scheduling methods each suffer from a need to detail every activity, its duration, and in some cases, the resources needed for each and every task. NASA scheduling handbook states that there should always be integration between funding,

---

more closely resemble normal, log-normal, or Weibull distributions [84, 72, 119] planned budget, and the associated work content to be scheduled such that the relationship between project funding and project budget may be captured, as shown in Figure 41 [155].

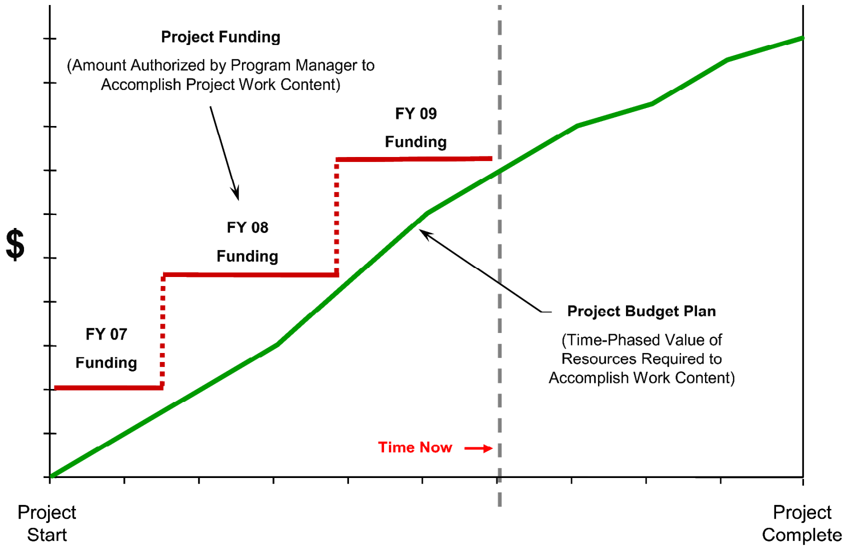


Figure 41: Relationship Between Project Funding and Project Budget [155]

While these methods provide traceability to the required tasks and attempt to capture this relationship, there is some nebulousness in assigning task durations, and required resources. Unless the new program is very similar to a previous, then significant analysis will be required to determine task durations and required resources. Furthermore, these methods typically focus on generating one schedule, with little to no consideration for optimality. By definition, determining an optimal schedule would require the creation of numerous schedule options and then assessing each based on the required duration and resources (i.e. an affordability problem within an affordability problem). The need to document every task (in an engineering build-up fashion) makes these approaches impractical for Conceptual Design studies, during which many alternatives should be generated, and the value of those alternatives weighed in order to find the "best" possible schedule for the program at-hand. While the schedule estimating methods have the potential to provide good estimates (where cost would be determined by multiplying the total hours by a \$/hr figure), the level of detail required far exceeds the information available during Conceptual Design. The notion of time-phased cost requires schedule and cost to be evaluated in a more integrated fashion, and the focus on leveraging methods during Conceptual Design requires a shift away from explicitly generating a detailed WBS.

On balance, a process-based approach becomes attractive. The additional detail required to facilitate an estimate lies between the typical parametric and engineering build-ups, and the method allows insight into many fabrication trades beyond the granularity of analogy and parametric methods. Furthermore, process-based estimates are typically generated for system elements, as opposed to complete systems. This application has two benefits, the most important of which is the added breadth of similar systems from which to draw estimates. Fundamentally, when one decomposes a system into subsystem elements one finds many more similarities with historical systems than if trying to compare vehicle to vehicle. The prime example to this is the SLS; in comparing this vehicle to historical systems, only the Saturn V has any resemblance and it would be unwise to assume that the SLS will have a similar cost or development timeline to the space shuttle, or the X-33. However, in decomposing the SLS into elements, one notices that the fuel tank, for example, is very similar to the shuttle's external tank, and lessons learned from the ET may be applied directly to the tanks of the SLS...such as the desire to use Al-2219 over Al-Li 2195 for cost savings but performance deterioration [206]. The second benefit is directly relatable to schedule; where the cost estimate is determined by generating a high-level schedule, based on the system element insight from historical programs, and assigning resources to the scheduled tasks commensurate with historical programs.

This discussion culminates in a hypothesis to research question 2.1

Hypothesis 2.1a

Utilizing a process-based cost estimation method, and extracting typically underused schedule information, will provide the capability to assess the interrelated cost and schedule of lower than system-level estimates.

Given the limited availability of cost and schedule data within the public domain, the process-based costing will serve as a truth-model from which PERs may be generated. This will provide a basis from which an adaptation of Burgess' phase-estimating methodology may be applied.

Hypothesis 2.1b

For the purpose of generating lower than system-level PERs, what elements comprise a launch vehicle and would thus be leveraged to generate a system level affordability distribution?

Having hypothesized that modifying process-based costing and extracting the typically unused high-level scheduling information will facilitate lower than system-level trades, it is necessary to discuss which aspects will be analyzed through a discussion on launch vehicle decomposition.

3.4.7 Research Question 2.2: Launch Vehicle Decomposition

Research Question 2.2

For the purpose of generating lower than system-level PERs, what elements comprise a launch vehicle and would thus be leveraged to generate a system-level affordability distribution

Previous MInD efforts conducted at Georgia Tech in relation to aircraft design have focused on a key element of a fixed wing aircraft, namely the wing-box [50, 35, 38]. In these studies, the wing-box structure is considered a key element which contributes to the performance, cost, and complexity of the overall system. SEER for manufacturing (SEER-MFG) was used to model the part fabrication and assembly costs and SEER for hardware (SEER-H) was used to estimate the development and operations costs [200]. A similar study, aimed at performing higher-fidelity sizing during early Conceptual Design, focused upon the primary body structures of a SSTO vehicle [36]. In a recent aircraft study in which a process-based cost estimate was generated for a variety of Boeing aircraft, using P-BEAT. Each aircraft was decomposed into sixteen key subsystems — plus a seventeenth estimate for integrating those subsystems [195].

Fundamentally, a launch vehicle and an upper stage have the responsibility of delivering a payload from an initial altitude to a final altitude. For a launch vehicle core stage this is typically from the launch pad to some staging altitude; for launch vehicle upper stages (or SSTO launch vehicles) the final altitude is some LEO altitude — and potentially beyond LEO. As such, the each of these vehicles must possess the following functional categories:

1. A propulsion system and propellant sufficient to insert payload into LEO (and potentially perform addition in-space maneuvers).

2. Sufficient structure to house the necessary propellant, withstand propulsive and aerodynamic loads, and support the payload.

3. A thermal control systems to maintain appropriate conditions for propellant and avionics throughout mission.

4. A reaction control system for attitude control and course correction throughout the mission.

5. An avionics system to manage communications, navigation and control, thermal and power systems.

6. A power system to ensure that all electronics maintain functionality throughout mission.

These functional categories are clearly described in one of the earlier presentations on the currently name EUS for use on upgraded SLS configurations, shown in Figure 42. Similarly, NASA fact sheets on the core stage shows a very similar exploded view of the core, shown in Figure 43. While the visualization only includes structural and propulsion elements, the accompanying description describes the inclusion of an avionics system and a flight computer which will undoubtedly contribution to the reaction control systems and require a power system.

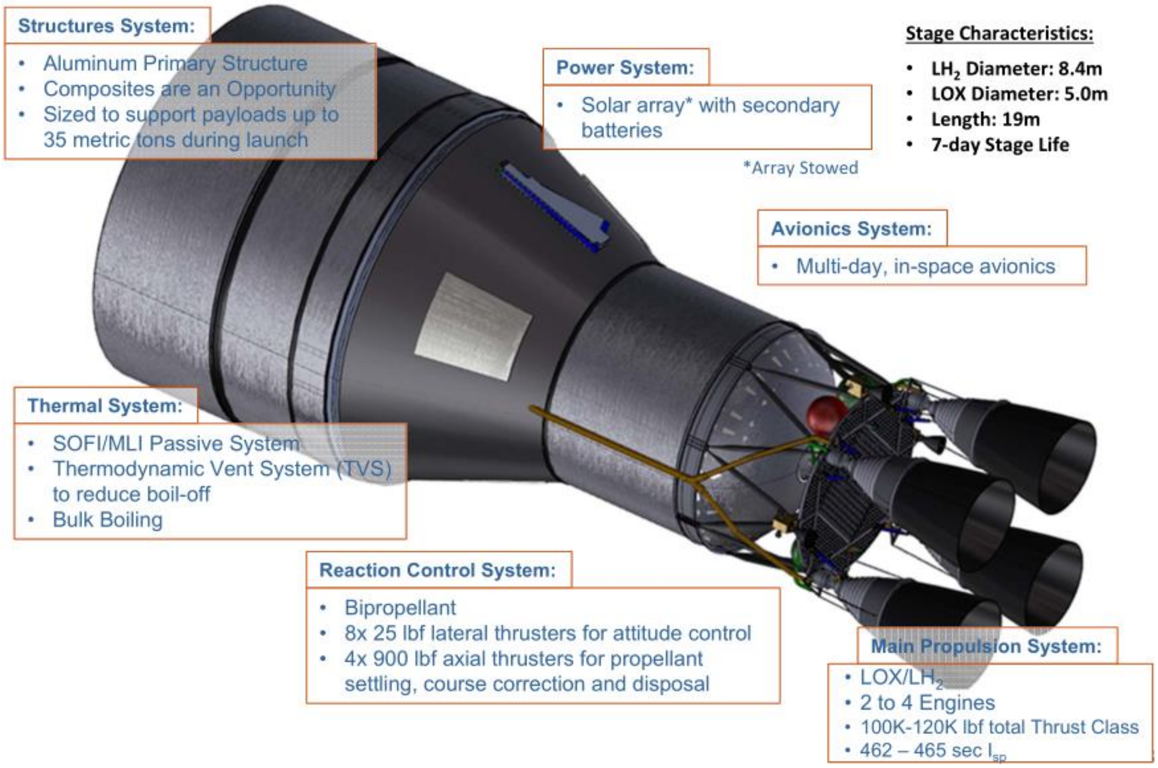


Figure 42: Overview of Exploration Upper Stage Key Subsystems [58]

From an analysis perspective, as discussed above, it is typical to decompose these functional classes further. The structures of a launch vehicle are typically divided into two categories; primary body structures and secondary structures. Primary body structures are the largest components which contribute the majority of a stage's structural mass, examples of these would be the fuel and oxidizer tanks. The secondary structures, while no less important than the primary structures, are typically much smaller and lighter, such as the small helium tanks which assist in maintaining the propellant tank pressures. These secondary structures are often estimated within one of the other functional classifications listed above.

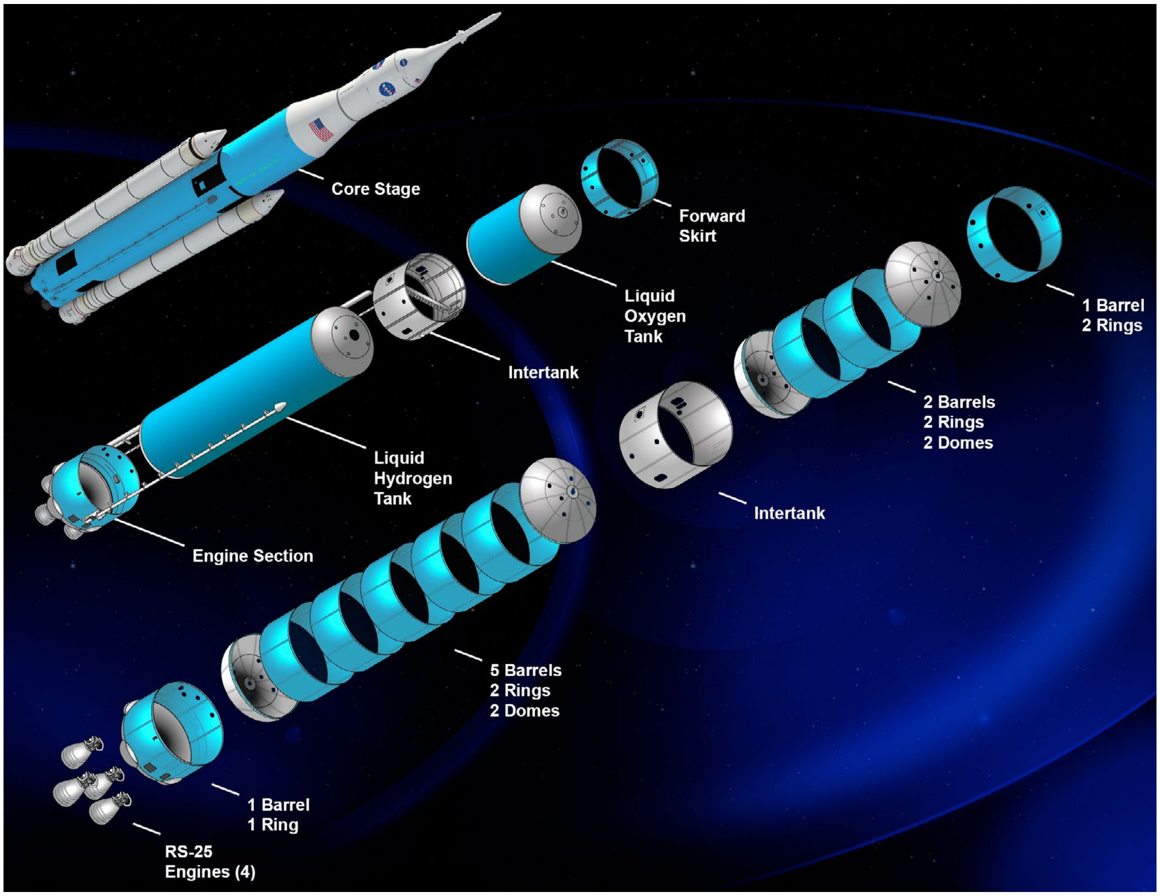


Figure 43: Overview of NASA Space Launch System Core Stage [165]

In the case of helium tanks, these would be included in the main propulsion system (MPS) which manages the flow of propellant to the engines as well as regulating helium pressurant [58]. Additionally, the thermal control system consists of two parts, one active and one passive. The passive component, often referred to as thermal protection, is insulation for the propellant tanks to reduce the effects of boil-off during the mission. In Figure 42, Multi-Layer Insulation (MLI) and Spray-On Foam Insulation (SOFI) comprise this passive system. The active system continuously monitors propellants and avionics and abates heat through heat exchangers, fluid mixing and venting systems. With these distinctions, the following 12 subsystems — plus an integration estimate — would be sufficient to generate a complete estimate for a launch vehicle core or upper stage:

1. LH_2 Forward Skirt
2. LH_2 Tank
3. LH_2 Aft Skirt
4. Intertank
5. LO_2 Tank
6. Thrust structure
7. Main Propulsion System (MPS)
8. Thermal Protection System
9. Active Thermal Conditioning
10. Power Systems
11. Avionics System
12. Reaction Control System

Conjecture 2.2

A total of twelve elements comprise a launch vehicle stage. Generating phase estimating relationships for these elements, plus a thirteenth for integration, would facilitate the generation of a system level affordability distribution?

The decomposition of a launch vehicle stage introduces the need to consider the integration of the system elements in order to adequately represent a full system estimate. Thus, the key to combining the system elements into a system-level perspective requires careful consideration of the aspects which affect the assembly and integration of elements into the full system.

3.4.8 Research Question 2.3: Aggregation of Elements into a System-Level Perspective

The notion that the whole is more than the sum of the parts suggests that simply summing individual elements would not provide a representative estimate of the affordability implications of the system as whole. After all, when considering the logical progression through which a program evolves, once the elements themselves have been developed, they must be integrated to ultimately form the completed system. Thus, a fourth research question may be posed:

Research Question 2.3

What additional metrics are required to capture the integration of system elements?

It is necessary to note that there is one additional aspect that must be discussed as it will also affect the first launch date, and that is testing. Once all elements have been assembled and integrated, the full-up vehicle will undergo extensive testing before being considered flight-ready. This testing includes the final integrated functional testing, structural tests, and flight tests. The functional testing verifies the inter-system compatibility between hardware and software, the structural test certify the vehicle's structural integrity, and the flight tests are "to separate the real from the imagined, and to make known the overlooked and unexpected problems"[113, 210]. These activities are often termed verification, validation, and testing (VVT) or qualification (Qual) testing.

While testing approaches vary from program to program, the planning of such activities is beyond the scope of this thesis, and addressed extensively in Sudol's dissertation [215]. For the purpose of this thesis, a brief look into the testing procedures for the STS will provide a reasonable assumption into the duration of these tests on the first unit. This duration will provide an estimate for the expected duration of tests which separate the end of system integration and the first launch of a new launch vehicle.

STS Challenger, initially designated a test vehicle, underwent 12 months of ground testing in Palmdale to certify the orbiters structural integrity. STS Columbia orbiter integration test, which certified inter-system compatibility, endured for 140 hours. Once all the shuttle components — orbiter, boosters, and ET — were mated, a series of flight readiness firings were conducted as a final demonstration of the mated vehicle in a near-to-launch environment. Finally, prior to the first orbital flight, launch readiness verification was conducted to ensure hardware integrity after the flight-readiness firings, and demonstrate proper flight sequencing. Once this test is completed, the launch countdown begins [113].

This insight provides general guidelines for tests through which the first launch vehicle of a new development program will be required to pass before its first launch. While durations for most of the STS tests are not listed, the descriptions of these allude to durations much shorter than the structural testing conducted in Palmdale.

Therefore, an assumption that once a launch vehicle stage is integrated, approximately one calender year will be alloted to full testing of the stage and final mated vehicle.

Having established a one year window, allotted for stage and full vehicle testing, a discussion on the integration of stage elements into a stage may now be discussed. What follows is a brief introduction to technology readiness level (TRL), and a review of relevant literature on integration and aggregation.

3.4.8.1 Technology Readiness Level

The concept of TRL was introduced by NASA in the 1980's as a measure which supports an assessment of the maturity of a specific technology, and thus facilitate the consistent comparison between technologies. Initially defined as a seven levels, the TRL scale was refined to the 9-level scale by Mankins in 1996 [189, 130]. Since then, the TRL scale has been adopted by the DoD, the European space agency, and many commercial and government entities; each of whom have perturbed the definitions to suit their products. Table 5 is the TRL scale presented by Mankins, and still forms the basis for all the variations found in nearly every systems engineering handbook across the aerospace industry.

Table 5: Technology Readiness Level Summary [130]

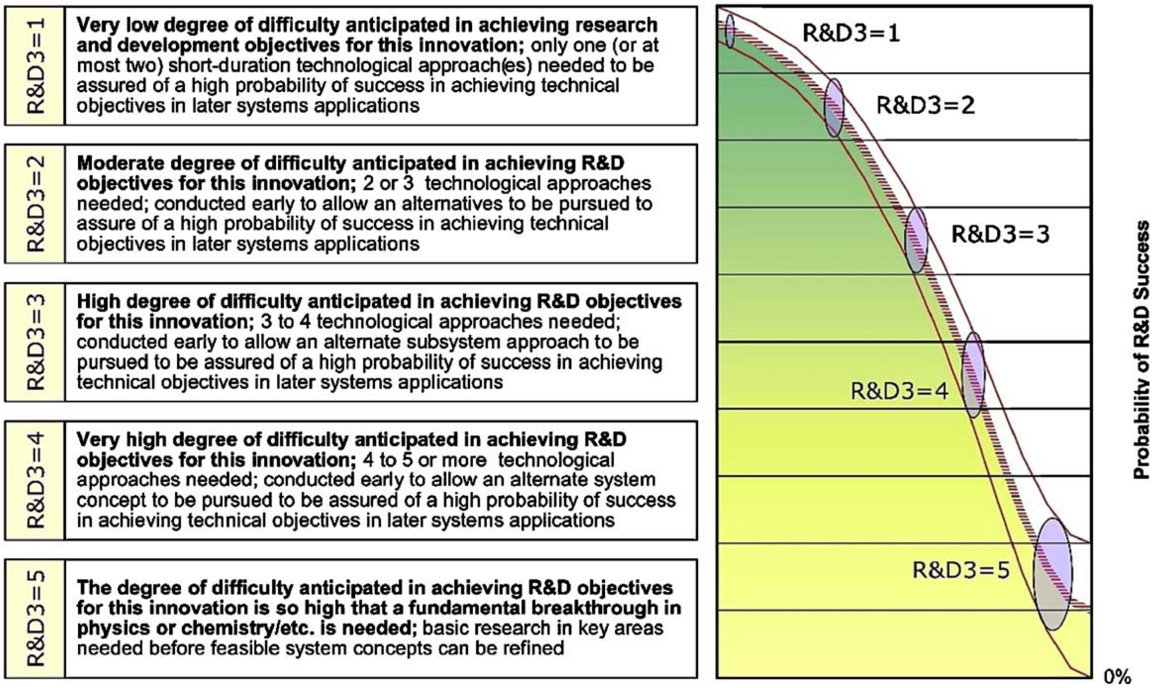
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified“ through test and demonstration (ground or space)
TRL 9	Actual system“flight proven“ through successful mission operations

TRL was not initially intended to provide an accurate technological representation of the maturity of a system. It was designed to assess a specific technology or to facilitate comparisons between two technologies. Despite this, a variety of methods have been proposed in an attempt to abstract TRL from the level of an individual technology to a system-level, which has resulted in some literary criticism [193, 208].

3.4.8.2 Integrated Technology Index

Mankins develops a body of work aimed at addressing the evaluation of the overall technological challenge associated with the development new system. He develops a methodology which aims to quantify an Integrated Technology Index (ITI) calculated using TRL, delta-TRL (Δ TRL) steps, research and development degree of difficulty

(R&D^3), and Technology Needs Values (TNVs)[132]. R&D^3 aims to measure the difficulty associated with maturing a technology from one TRL to another [131]. The R&D^3 scale is a 1 to 5 scale, where 1 denotes a technology with a low degree of difficulty and thus a high probability of successfully completing R&D [133]. Figure 43 describes each of the five levels and portrays a probability of success curve to visually represent the likelihood of successfully achieving a high TRL.



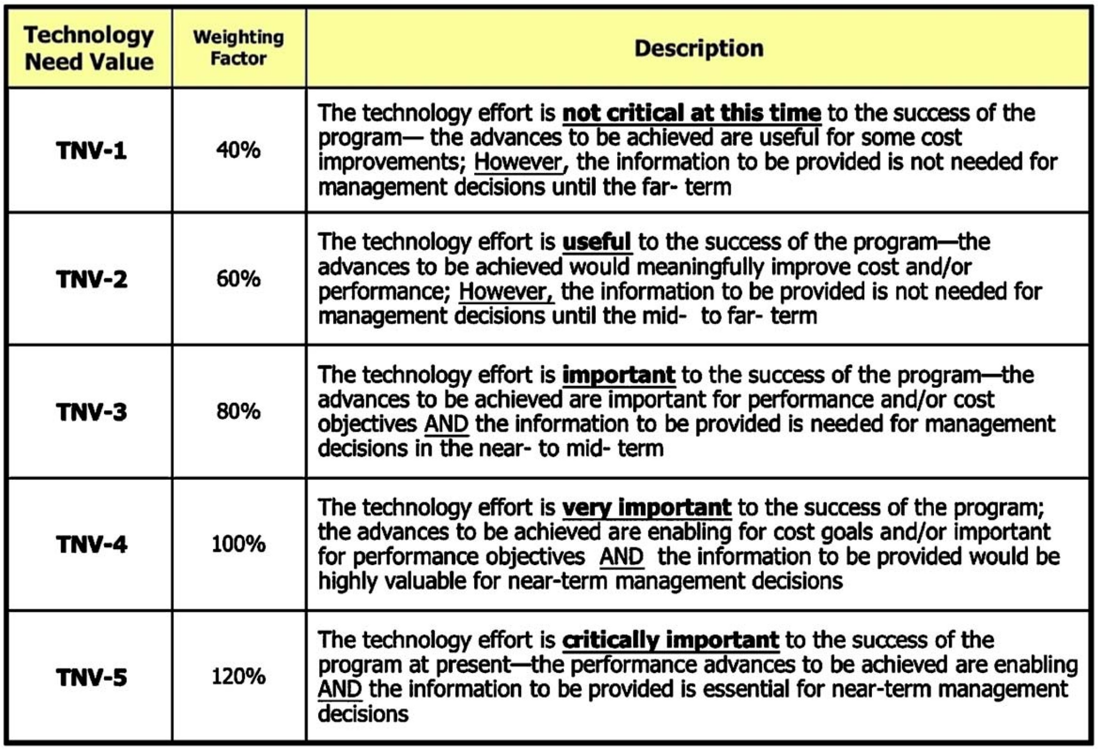
R&D3=1	**Very low degree of difficulty anticipated in achieving research and development objectives for this innovation;** only one (or at most two) short-duration technological approach(es) needed to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=2	**Moderate degree of difficulty anticipated in achieving R&D objectives for this innovation;** 2 or 3 technological approaches needed; conducted early to allow an alternatives to be pursued to assure of a high probability of success in achieving technical objectives in later systems applications
R&D3=3	**High degree of difficulty anticipated in achieving R&D objectives for this innovation;** 3 to 4 technological approaches needed; conducted early to allow an alternate subsystem approach to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=4	**Very high degree of difficulty anticipated in achieving R&D objectives for this innovation;** 4 to 5 or more technological approaches needed; conducted early to allow an alternate system concept to be pursued to be assured of a high probability of success in achieving technical objectives in later systems applications
R&D3=5	**The degree of difficulty anticipated in achieving R&D objectives for this innovation is so high that a fundamental breakthrough in physics or chemistry/etc. is needed;** basic research in key areas needed before feasible system concepts can be refined

Figure 44: Research and Development Degree of Difficulty (R&D^3) [131]

The Δ TRL is simply the difference between the desired and current TRL for a particular technology; thus representing the TRL "distance" needed to mature a technology from its current state to the desired. The Technology Need Value (TNV) — essentially a weighting factor — is a qualitative measure of the importance of a technology to the functionality of the system it comprises [131, 133]. TNV has been refined to a five level scale where: TNV = 1, represents a non-critical technology, TNV = 2, represents a useful technology, TNV = 3, represents an important technology, TNV = 4 represents a very important technology, and TNV = 5 represents a critically important technology [133]. The weightings and detailed definitions are shown in Figure 45

These three scales — Δ TRL, TNV, and R&D^3, are evaluated for each subsystem technology. This value is summed for all the technologies applied to the system and then normalized by the total number of technologies being applied. Equation 21 depicts the mathematical form of ITI.

$$ITI = \sum_{SubsystemTechnologies} \frac{\Delta TRL * R\&D^3 * TNV_{WeightingFactor}}{Total\ Number\ of\ Technologies} \tag{21}$$



Technology Need Value	Weighting Factor	Description
TNV-1	40%	The technology effort is **not critical at this time** to the success of the program— the advances to be achieved are useful for some cost improvements; However, the information to be provided is not needed for management decisions until the far- term
TNV-2	60%	The technology effort is **useful** to the success of the program—the advances to be achieved would meaningfully improve cost and/or performance; However, the information to be provided is not needed for management decisions until the mid- to far- term
TNV-3	80%	The technology effort is **important** to the success of the program—the advances to be achieved are important for performance and/or cost objectives AND the information to be provided is needed for management decisions in the near- to mid- term
TNV-4	100%	The technology effort is **very important** to the success of the program; the advances to be achieved are enabling for cost goals and/or important for performance objectives AND the information to be provided would be highly valuable for near-term management decisions
TNV-5	120%	The technology effort is **critically important** to the success of the program at present—the performance advances to be achieved are enabling AND the information to be provided is essential for near-term management decisions

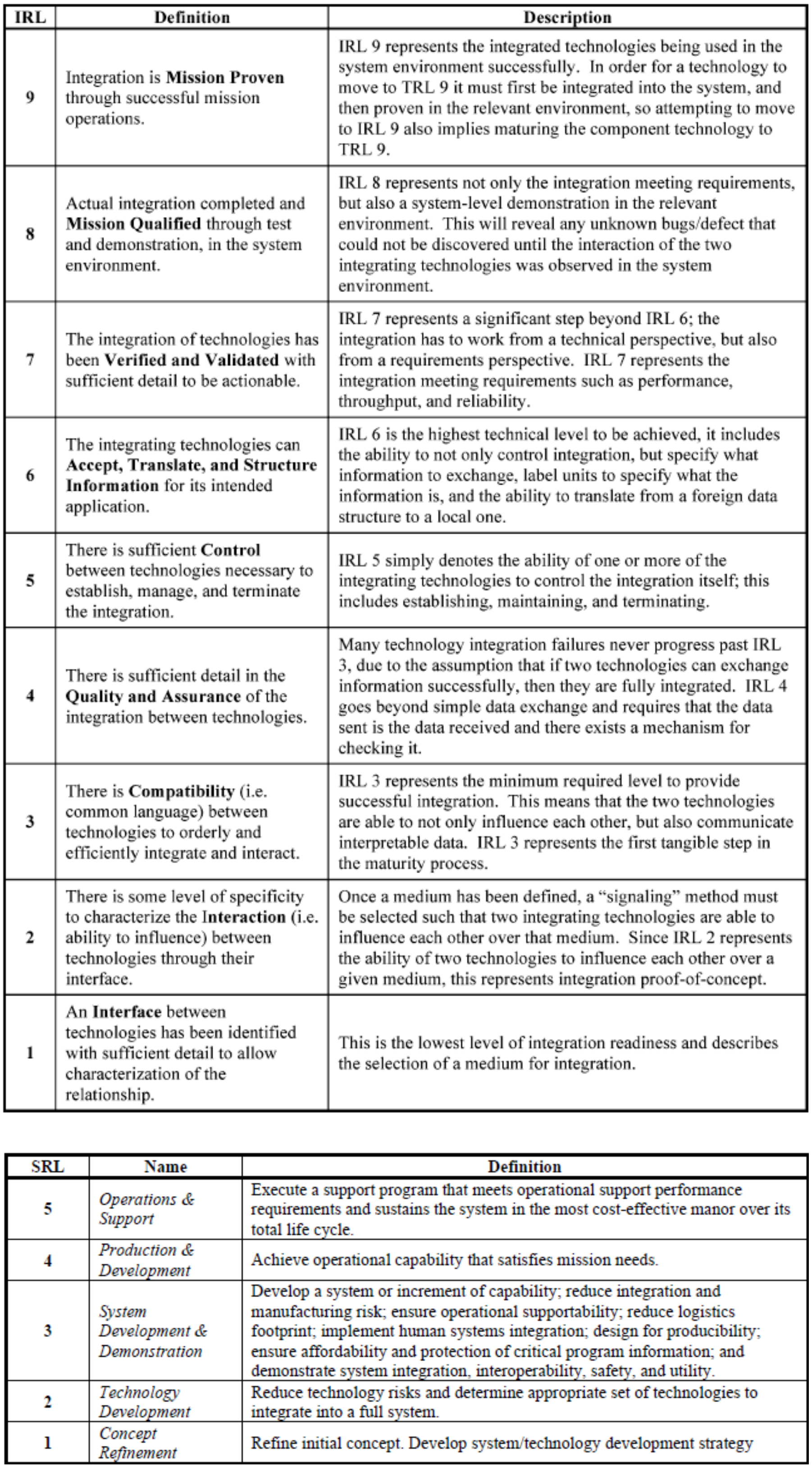
Figure 45: Technology Needs Value (TNV) Weightings and Descriptions [133]

Mankins' ITI method is a step in the right direction, attempting to capture the difficulty associated with TRL advancement as well as the relative importance of each technology within a system. However, this method does include one fundamental flaw which yields it mathematically incorrect. Each of the scales — TRL, R&D^3, and TNV are non-calibrated ordinal scales. These scales do not contain information regarding the degree of difference between levels. For instance, a technology at R&D^3 level two is not twice as difficult to advance than a technology with R&D^3 $= 1$ or half as difficult as a technology with R&D^3 $=4$. This notion is true for all three scales, even though the TNV scale has weightings associated with each value. A technology with TNV $= 3$ is not three times more important than a technology at TNV $= 1$. Over and above this, the mathematical formulation for ITI is misleading due to different directions of improvements for the three scales used.

The values that the technology index(TI),defined as the product of the three scale values for a particular technology, may assume, based on the ranges of the scales, lie on the domain of [1:54]. However, this range includes at least one impractical scenario in which a completely mature technology has extremely low probability of successfully completing R&D. Fundamentally ITI is not a monotonic function which makes it difficult to compare different portfolios of technology. Two technologies with the same TI could be extremely different; one that is almost completely mature,possessing a high probability of successfully completing R&D, and critical to system functionality (TRL $= 8$, TNV $= 5$ R&D^3 $= 1$ such that TI $= 9.6$) would possess the same TI as a technology at TRL $= 6$, TNV $= 1$ R&D^3 $= 4$ such that TI $= 9.6$.

3.4.8.3 Integration Readiness Level (IRL) and System Readiness Level (SRL)

One approach aimed at assessing the integration of system-elements is the integration readiness level (IRL) [191, 192]. IRL is "a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points (TRLs)" [193]. Initially inspired by the Open System Interconnect (OSI) standard for network systems, IRL is designed to assess the risk of integration while TRL assesses the risk associated with developing technologies [193]. Sauser et al. have extended this work by combining IRL with TRL to generate a System Readiness Level (SRL), aimed at establishing the maturity of a system and its status within a development cycle [193, 194, 177]. The scales for these two metrics are shown in Figure 46, below.



IRL	Definition	Description
9	Integration is **Mission Proven** through successful mission operations.	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system, and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.
8	Actual integration completed and **Mission Qualified** through test and demonstration, in the system environment.	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability.
6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but specify what information to exchange, label units to specify what the information is, and the ability to translate from a foreign data structure to a local one.
5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating.
4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
3	There is **Compatibility** (i.e. common language) between technologies to orderly and efficiently integrate and interact.	IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
2	There is some level of specificity to characterize the **Interaction** (i.e. ability to influence) between technologies through their interface.	Once a medium has been defined, a "signaling" method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
1	An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

SRL	Name	Definition
5	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.
4	*Production & Development*	Achieve operational capability that satisfies mission needs.
3	*System Development & Demonstration*	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
2	*Technology Development*	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
1	*Concept Refinement*	Refine initial concept. Develop system/technology development strategy

Figure 46: Integration Readiness Level [191] and System Readiness Level [193]

While this method aims to provide a more explicit approach to assessing system integration and system readiness, there are several shortcomings of this approach:

1. The IRL scale has origins in the OSI model for network systems, thus there is a large emphasis on the exchange of data/information. [71, 111]
2. The IRL scale assesses the integration of two technologies, and thus does not provide sufficient detail when multiple technologies are infused in the same element, or when the system (i.e. launch vehicle) requires the integration of several (each potentially infused with manufacturing technologies) elements.
3. "the valuation of IRL and TRL and their combination into a single SRL assessment is fundamentally flawed as it presumes that IRL and TRL are independent attributes" [111]. Jimenez & Mavris argue that integration is a fundamental aspect of technology maturation and is thus a sub attribute of the TRL metric [111].
4. Both TRL and IRL are defined based upon non-calibrated ordinal scales; they do not convey information regarding the degree of difference between measures. By extension mathematical operations are not applicable to ordinal scales, and the product of the IRL matrix with the TRL vector (mathematical definition of SRL [177]) holds no real or practical meaning [111]. The concept is elaborated upon, in Conrow [54], with a specific emphasis on averaging TRLs.

3.4.8.4 Advancement Degree of Difficulty

Bilbro develops a structured method to graphically represent a technology's TRL through form, fit and function. Furthermore, he suggests a relatively simple relationship between the integration and technology readiness: the TRL of the system is determined by the subsystem with the lowest TRL present in the system [18, 14]. Bilbro also proposes a method to capture the risk/difficulty associated with advancing

Table 6: Advancement Degree of Difficulty (AD^2) Summary [14]

Degree of Difficulty	Development Risk	Description
1	0%	Exists with no or only minor modifications being required. A single development approach is adequate.
2	10%	Exists but requires major modifications. A single development approach is adequate.
3	20%	Requires new development well within the experience base. A single development approach is adequate.
4	30%	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.
5	40%	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.
6	50%	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (Desired performance can be achieved in subsequent block upgrades with high degree of confidence).
7	60%	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.
8	80%	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursue.d
9	100%	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.

the maturity of a particular technology to a requisite level, the Advancement Degree of Difficulty (AD^2) [18]. Fundamentally AD^2 operates on each element in a WBS, assessing resource allocation in five specific areas: Design and Analysis, Manufacturing, Software Development, Test, and Operations [17]. This is a 9-level scale where, similar to $R\&D^3$ proposed by Mankins, the higher levels correspond to a greater degree of difficulty and thus a greater probability of failure. The 9-level AD^2 scale is shown in Table 6.

Bilbro does concede that establishing an AD^2 is extremely difficult, but must be approached in the same manner as establishing a TRL [18]. To ease this complexity, Bilbro modified a technology readiness calculator developed by AFRL [170, 15]. This tool has since been modified to include IRL,SRL, and several other augmentations to the TRL scale which aim to address its perceived lack of manufacturing or integration considerations [16, 225]. The final method for review is one which does not attempt to create a new assessment scale, but one which attempts to manage the consideration of multiple spacecraft technologies in a portfolio. the aim is to establish a relationship between development time and the number and maturity of technologies to be included.

3.4.8.5 Spacecraft as a Technology Portfolio

For a vehicle concept, one desires to maximize the value of a system and minimize the risk associated with achieving that value. This notion is analogous to portfolio management, discussed in Section 3.1 in which one seeks "...to reach an optimum point between risk and reward, stability and growth" [187]. Dubos and Saleh confirm this notion and classify an engineering system—specifically a spacecraft— as a value-delivery artifact, where the value-delivering elements are the "instruments" which provide scientific return. *For example, in the case of a technology demonstration* *mission, the "instrument" is the subsystem being tested (such as the attitude determination device "Compass carried on-board the Space Technology 6 (ST6) spacecraft for NASAs New Millennium Program)* [72].

The focus of the work is to assess the time to delivery of a spacecraft, which consists of the time to deliver each instrument, the time to integrate and test each instrument, and the time to ship the completed spacecraft from the production facility to the launch facility. The development time for an instrument is based upon its initial TRL, the integration and testing is a function of the number of instruments and their initial TRL, and the time to ship the integrated spacecraft is extracted from historical data. A summary of the method is shown in Figure 47

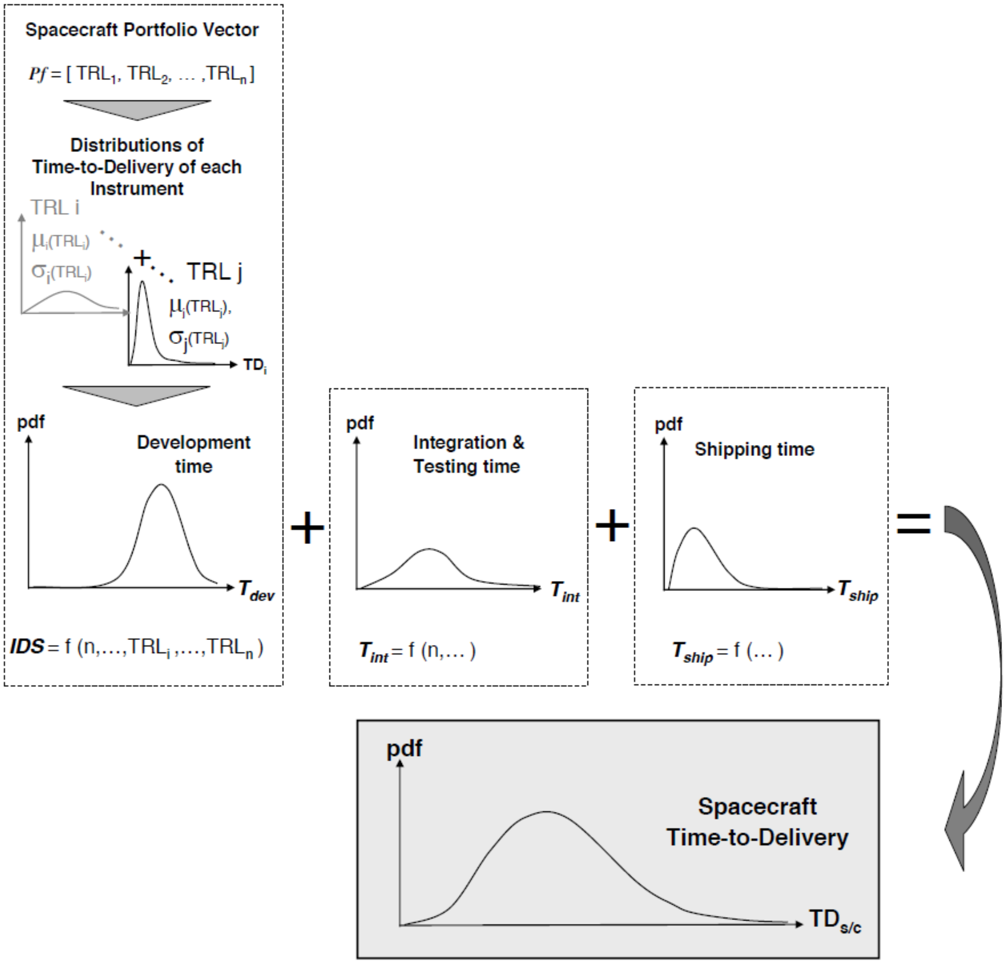


Figure 47: Summary of the Spacecraft Time to Delivery Model [71]

While Dubos draws conclusions based on regressions fit to historical data, there are several fundamental differences which prove challenging to this application to launch vehicles.

1. If a launch vehicle were to be classified as a technology portfolio, which elements would be the value-delivering artifacts? Dubos defines these artifacts as those which provide science return (i.e. payloads), which for a spacecraft/satellite makes sense. Its purpose is to perform specific tasks (to achieve science return) while on orbit. However, a launch vehicle does not directly provide science return. It provides the means to place a spacecraft into orbit, thus the equivalent of science return is the payload capacity delivered to a specific orbit, as discussed in Section 3.3. Unlike a spacecraft, where one instrument can provide a specific type of return (such as the compass example listed above) there is no one "instrument" that directly provides the capability to deliver a payload into orbit. For the spacecraft, the "portfolio is to be embedded *within* the spacecraft..." [71], while in the case of a launch vehicle, the portfolio is the elements which comprise the vehicle.

2. Since the elements of the portfolio are independent of the spacecraft, Dubos assumes that all instruments begin development simultaneously. For launch vehicles, the development of elements seldom starts simultaneously.

3. The instrument delivery schedule (IDS) is based solely upon the instrument which has the longest development time. This is analogous to the critical path method described in Section 3.4.5. While this assumption is appropriate when the development of all instruments begins simultaneously, this will not capture variations in the DDTE&P plan which causes a new path to become critical.

Dubos does explore the concept of "portfolio balance," which assesses how the uniformity (homogeneity) of TRLs of the instruments which comprise the portfolio impacts the value. While the method is not directly extensible, for the purposes of infusing manufacturing technologies into elements, there will need to be some consideration for the homogeneous nature of materials between components. This alludes to the fact that joining elements of the same material (or even material family) is relatively straight forward (e.g. welding), however, when the materials are significantly different, the integration process is considerably more difficult (e.g. welding a composite skirt onto a metallic tank is not feasible). This difficulty equates to a more lengthy (and costly) integration process which must be accounted for within the time-phasing relationship development.

3.4.8.6 Summary of Technology Readiness and Integration Abstraction

Since the formalization of TRLs, by Mankins in the 1990's, this scale has become instrumental to qualifying the maturity of designs throughout the aerospace industry. The previous section highlights the many augmentations to this scale, but is no means exhaustive. Many other scales — Capability Readiness Level [13], Manufacturing Readiness Level [2, 172], Production Readiness Level [14]— **all of which possess two fundamental flaws**; one logical and one mathematical.

The first flaw is regarding the inclusion of manufacturing and integration considerations within the TRL scale itself. Fundamentally, the TRL levels from 6 to 9 implicitly include integration considerations. Integration and manufacturing are a sub-attributes of technology readiness level. Upon inspection of the definitions, it is evident that as the TRL increases, the subject of each description escalates from a low-level to high-level, within the context of the hierarchical decomposition of a system. Component validation occurs during TRL 4 and 5, TRL 6 escalates to the system/subsystem — which implies that components have been integrated into a subsystem and/or subsystems have been integrated into a system. TRL 7 requires prototyping at the host-system level, and once a technology reaches TRL 8, it has been demonstrated as fully integrated into the host system. Jimenez and Mavris provide a detailed description of the TRL levels and the integration/manufacturing considerations commensurate with each [111].

The mathematical flaw, while at a much more detailed level than the previous, equally deters from the applicability of these methods. All the proposed scales are centered around non-calibrated ordinal scales, and thus it is mathematically incorrect to perform any operation upon them. This is to say that it is not feasible to **quantify** the numerical improvement associated with maturing a technology in any of the scales. A TRL of 4 is not twice as mature as a TRL of 2, an AD^2 of 1 does not imply half the risk of a level 2, and the average or standard deviation of TRL is not meaningful.

There are, however, useful elements presented here which, coupled with mathematical care, may be used to formulate an hypothesis to Research Question 2.3. Bilbro's use of form, fit, and function, while intended to graphically measure a technology's maturity (see Figure 4 in [14]) is important to assessing the physical act of assembling system elements. Additionally, Dubos perspective on considering the number of technologies and variation in their maturities may prove useful in assessing the variation of the composition of a system based upon the selected technologies. Finally, while not discussed at length in this thesis, Conrow, has developed the mathematics required to convert the non-calibrated, ordinal TRL scale into calibrated coefficients [54]. These useful elements facilitate the formulation of an hypothesis to Research Question 2.3.

3.4.9 Hypothesis 2.3

The preceding section has discussed various methods to explicitly capture integration, typically through the introduction of non-calibrated, ordinal scales such as AD^2 or SRL. While certain elements will be useful, these methods do, however, neglect to consider the **composition** of the system into which technology is to be infused.

From a logical standpoint, assembly and integration is the piecing together of elements into a system. At the simplest level, there are really two aspects which govern the ease with which this activity can occur; the ease with which the elements fit together, and the ease of securing them together. While Bilbro's use of form, fit, and function is limited to assessing the TRL of a specific technology, extending this consideration to the system level is necessary to capture the ease with which the elements fit together. Furthermore, Dubos' more detailed approach of accounting for the variety of technologies included (i.e. the material composition) in the system, can capture the ease of securing these elements. The latter of these two centers around material composition. If a system comprises very similar materials, say aluminum, then a welding process could be used; however, if composite materials are dominant, then a completely different set of processed would be required.

Hypothesis 2.3

The consideration of form, fit, and function of each technology, and the system composition (from a material standpoint) are required to capture the integration of system elements.

In order to substantiate Hypothesis 2, two experiments are needed to first confirm its constituents, Hypothesis 2.1 and 2.3. The first aims to verify the applicability of process-based cost estimation to generate a time-phased cost distribution for a lower than system-level element, from which a phase estimating relationship can be drawn. The second experiment aims to develop a phase estimating relationship for the integration of elements, leveraging system composition.

Before the experiments are formulated, it is necessary to present the current state of the Exploration Upper Stage Manufacturing Influenced Design Effort of ASDL at Georgia Institute of Technology. It is upon this work that experiments one and two are heavily based.

3.5 Exploration Upper Stage Manufacturing Influenced Design (EUS MInD)

As described in Section 2.5, the general MInD methodology aims to facilitate harmonious trades between design and manufacturing, ultimately through the use of a metric that each discipline can relate to: cost. Fundamentally, MInD seeks to provide the ability to quantitatively assess the cost implications that design decisions have on manufacturing, or vice versa. This approach effectively reduces epistemic uncertainty through higher-fidelity analysis and a more complex design space exploration. Process-based cost estimation is a key-enabler for this method, although a significant amount of new information was needed to generate a traceable and reliable cost estimate.

Process-based cost estimation requires a detailed description of the activities which transform raw materials into the final product. These activities, however, are determined (or at a minimum highly constrained) by the design information which describes materials and structural concepts leveraged. Furthermore, the design information is based upon a structural analysis and optimization, which in turn is driven by the loads resulting from the chosen mission and vehicle information. This conundrum requires careful consideration of all of these items, and dictates that the quality of information at each be high. A visualization of this flow of information is shown in Figure 48. Note that this figure proceeds chronologically while the description is presented in reverse-chronological order to establish the need to leverage analysis tools which provide higher quality (i.e. higher fidelity) information necessary to enable process-based cost estimation.

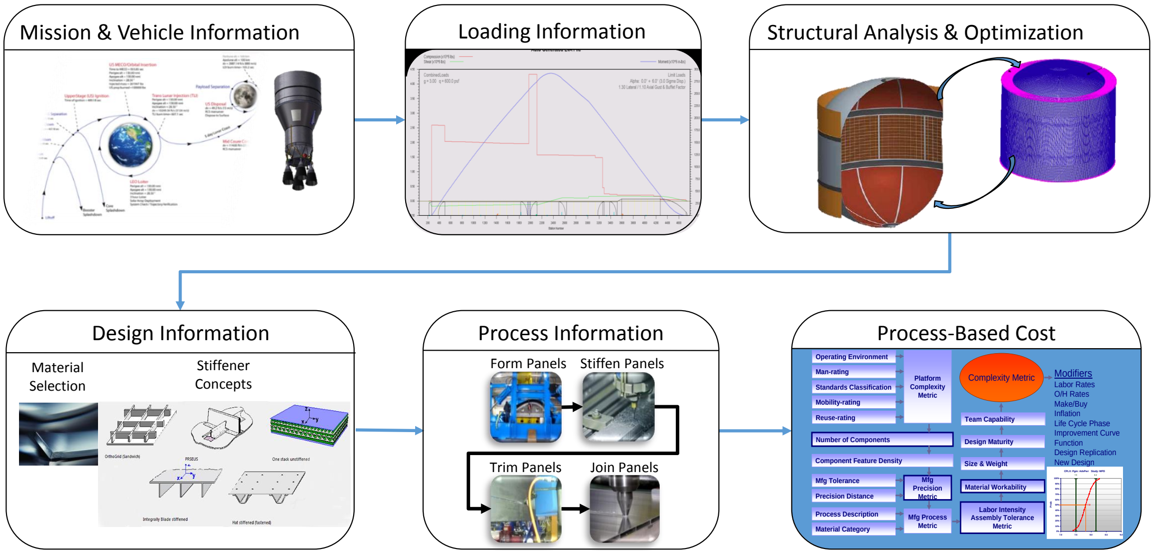


Figure 48: Overview of Information Flow for Process-Based Cost Estimation [58]

Naturally, the first step in implementing the MInD methodology for launch vehicles is to determine an appropriate process-based cost estimation tool and then back-track to determine what additional information would be required above the tools leveraged during Conceptual Design. The EUS MInD study was performed in conjunction with the Advanced Concepts Office at NASA Marshall. The analysis tools typically leveraged are LVA, INTROS, POST, and NAFCOM, as discussed in Section 2.2.3.1.

3.5.1 Process-Based Cost Tool Selection

A variety of process-based cost estimation tools exist, they fall into two distinct categories; those which are commercially available, and those developed "in-house" by industry and often dubbed proprietary. The most notable of commercially available tools is SEER-MFG developed by Galorath Incorporated. This tool is the result of the governments Composite Affordability Initiative which gathered a large breadth of current industry data from many aerospace companies [35]. SEER-MFG was selected by the previous MInD Efforts for its availability to ASDL, its applicability to aircraft, and its reconfigurability [35].

Two proprietary tools in particular stand out for their application to launch vehicle analysis; Process-based Economic Analysis Tool (P-BEAT), and a Process-based cost model developed by Science Applications International Corporation (SAIC)[115]. P-BEAT is the result of collaboration between NASA-Glenn Research Center and Boeing. The tool relies on complexity-based relationships, and implements a hybrid estimation approach which leverages parametric and analogy methods simultaneously [195]. Furthermore, P-BEAT possesses the capability to estimate both development and hardware manufacturing costs, including 50 development processes and more than 700 manufacturing processes. Discussions with the tool developer, John Reynolds, has yielded remarkable insight into the depth and breadth of manned space system relevant data upon which the complexity-driven CER's are based. P-BEAT is an Excel-based tool which also provides a great deal of transparency into the manner in which estimates are generated as well as providing the user the ability to re-configure the tool by adding new materials and processes to its database [185].

The SAIC Process-Based Cost Model, while also an excel based model, leverages a process-based model to refine weight-based parametric CER's [207]. Like P-BEAT, the SAIC tool is built with extensive process catalogs, and was developed closely with NASA Marshall [115, 207]. The origins of this estimation tool, being within the launch vehicle cost office at MSFC, make it the ideal candidate for the task at hand. However, this tool is extremely difficult to acquire as it is heavily safe-guarded.

The availability of the SAIC tool yields it a non-option, leaving P-BEAT and SEER-MFG as the two viable candidates. While both tools possess large quantities of data, P-BEAT is significantly geared towards space systems while SEER-MFG focuses on fixed wing aircraft. Furthermore, SEER-MFG has limited estimation capability for the development phases of a program, and its commercial nature results in limited traceability and high-difficulty associated with adding new materials or processes to its database. Therefore, on balance, P-BEAT is the ideal candidate for use as the process-based cost estimation tool to improve Conceptual Design studies by providing harmonious insight into the impacts that design decisions have on manufacturing. What follows is an introduction to P-BEAT with a discussion on the necessary inputs which will drive the need to augment the traditional Conceptual Design tool-set.

3.5.2 P-BEAT

P-BEAT does not leverage weight-based (or performance based) regressions; it employs complexity driven CERs and thus estimates the cost, from an activity build-up based on the complexity of the component and the particular activities needed to transform raw material into the finished product. Secondly, P-BEAT provides estimates at a lower than system-level. Cost estimates of components or subsystems are preferred, which can then be amalgamated into an estimate for a complete system. Based upon the user manual and discussions with the tool developer, the appropriate method to estimate a complete vehicle entails creating estimates for the major subsystems and one for the integration of those subsystems. This benefit results from P-BEAT's database, which contains subsystem and component data at the process level rather than information of complete systems as most other tools leverage. A third benefit of P-BEAT, is that the estimated complexity factor of a particular component/subsystem is used to estimate durations of the activities which comprise DDTE&P, which is then used to estimate cost. Thus, P-BEAT captures the fundamental relationship between the complexity of a component — which is ultimately driven by the material and process selection and certain performance parameters— and the time taken to bring the component to fruition. P-BEAT, however, does not provide estimates for tooling or infrastructure needed for the DDTE&P of any subsystem. This is not surprising considering the custom nature of the tooling and equipment needed for launch vehicle fabrication.

3.5.2.1 Scope of the Estimates

P-BEAT leverages a significant amount of data, at the process level, to generate a bottom-up estimate for the entire life cycle of a program, or any portion thereof. The life cycle is discretized into ten parts which are compared to the NASA Program Life Cycle Phase, discussed in Section 2.1, the alternative perspective on the life cycle phases, discussed in Section 2.6, in Figure 49.

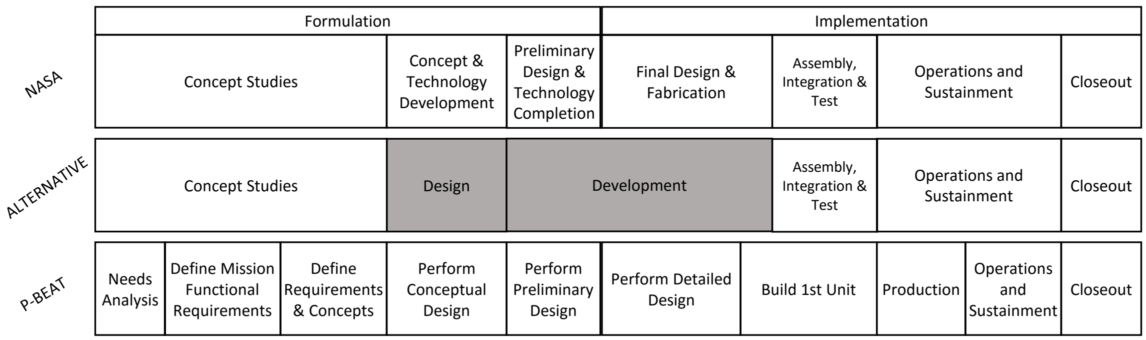


Figure 49: Comparison Between Life Cycle Phases

The program can be used in two ways, the first is a pure estimation mode, which arrives at a result exclusively based upon the statistical regressions upon which P-BEAT is built. The second approach is a hybrid analogy and parametric approach which leverages an analogy program in conjunction with the built-in regressions to arrive at a more refined estimate. The requirements — on the user — are to identify an appropriate, and real, analogy point to anchor the estimate to an actual system [195]. In each of these two implementations, the user may toggle whether to include or exclude each of the ten life cycle phases shown in Figure 49.

3.5.2.2 Inputs, Outputs and Inner-Workings

P-BEAT contains more than 50 development processes and 700 manufacturing processes [195]. Fundamentally, the user-provided inputs are used to calculate a complexity metric which is then use, in conjunction with built-in CERs, to calculate man-hours for all of the development processes and the relevant manufacturing processes. Hereafter, a series of modifiers — including labor rates, improvement curves, and make vs buy toggles — are used to calculate the total cost per phase. These estimates do **NOT** include tooling costs due to the custom nature of tooling for space-related programs. This analysis would need to be performed separately, one valid approach is presented by Heckwolf, and requires the collection of cost data for similar tooling and regression creation to interpolate based on workpiece envelope [105].

In general, the inputs fall into three categories; platform, design, and manufacturing. The platform inputs describe how the component will be used, and includes items like whether the system is to be man-rated, the environment in which the system will operate, and how stringent the standards are. The design inputs include the size, weight, and maturity of the component, as well as less tangible items such as the capability and experience of the design team. Additionally, operational aspects are included, such as the operational life of the system, and a breakdown of its functional classification.

By far, the most extensive inputs fall under the production category. Similar to the design category, process maturity and production team experience are required. Physical attributes such as material selection, and the number of components which compromise the system are also required inputs. Hereafter, the process inputs become more detailed and less tangible. The user must now proceed through the nearly 700 built-in manufacturing processes and specify the number of times a process occurs, and the expected intensity of that process. The final consideration, although not required for an estimate, is the expected duration of qualification (or VVT) testing. The premise here is that the user enumerates all the processes needed to convert raw material to a finished product.

The user interface is well laid out, and the tool has a small help window which prompts the user with appropriate definitions and guidelines pertinent to the current input area. While numerous inputs are required for any estimate (approximately 100 at a minimum), the act of defining these inputs is more cumbersome than complex, *and does require significant collaboration between designer and manufacturer.* Figure 50 shows a simple visualization describing the conversion of inputs to outputs by generation of a complexity metric and then using it with modifiers to arrive at a final estimate.

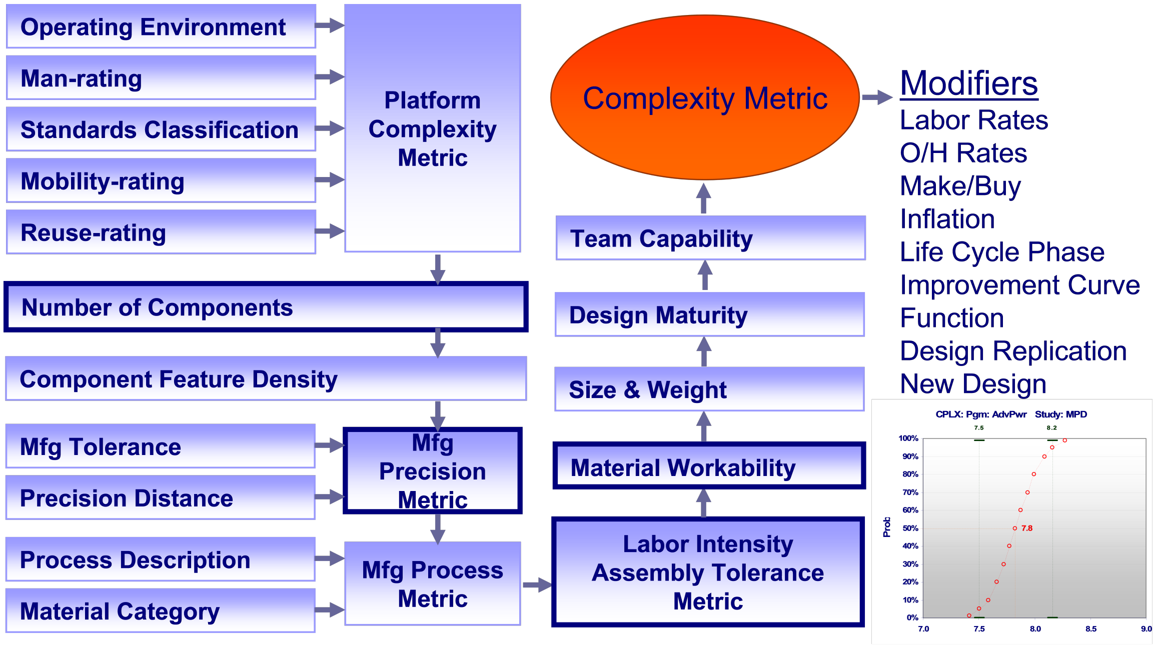


Figure 50: P-BEAT Analysis Flow

One aspect of P-BEAT which requires some elucidation, is the TRL scale with which it assesses design maturity. While P-BEAT does leverage a TRL scale from 1 to 9, it includes TRL 3.5, TRL 5.5, and TRL 8.5 as interim levels. These interim TRL levels were proposed by DARPA PM Douglas Gage, and is a commonly accepted modification to the TRL scale [91, 204]. The TRL scale and definitions used in P-BEAT are shown in Table 7, below.

Table 7: Technology Readiness Level Used in PBEAT [204]

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 3.5	Target functionality, performance & cost verified to support further technology development
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 5.5	Integration of technology into system/subsystem evaluated and validated
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified through test and demonstration (ground or space)
TRL 8.5	Production/Deployment
TRL 9	Actual system flight proven through successful miss ion operations

P-BEAT is said to generate the most accurate of estimates when in hybrid mode; when a real, and analogous, program is used to anchor the cost in reality [204]. This requires the user to include detailed information regarding the design maturity, process maturity and team capabilities of the analogous system. Nevertheless, in either hybrid or parametric mode, the above listed inputs are used to estimate man-hours for 56 development processes and the used manufacturing processes. These hours are then modified by labor and overhead rates to arrive at the final cost estimate which is broken down by life cycle phase, engineering discipline and development process. In addition, theoretical first unit (TFU) cost, average unit cost, and other learning curve considerations are available.

This insight into the inner-workings of P-BEAT has brought to light the need for sizing analyses tools which have the ability to capture the differences in design at a greater level of detail. Being able to estimate the mass of the same object with various design options is paramount; one cannot expect a process based estimate to be accurate when the inputs to that estimate are unable to capture the required intricacies. This notion has formed the foundation of work effort in the EUS MInD Sponsored Research at Georgia Tech. The following section elucidates the selection of analysis tools used to compliment the standard set of tools leverages at the Advanced Concepts Office at MSFC, described in Section 2.2.3.1.

3.5.3 Higher Fidelity Analyses Necessitated by Process-Based Cost Estimation

While process-based costing holds the potential to provide a significant amount of invaluable information, the use of this method necessitates the infusion of high-fidelity analysis tools to capture previously overlooked aspects of design. While P-BEAT does **NOT** leverage weight-based CERs, weight is still an input. The primary focus of this effort is to provide the analysis capability to differentiate — from a weight perspective — between unique but similar concepts.

As discussed in Section 2.2.3, the system models, which size the launch vehicle, are unable to discern between designs when manufacturing considerations are changed. That is to say that if an estimate for two unique tanks is desired, where the difference between them is a stiffening concept, or the number of panels which comprise the barrel section, then the weight analysis must possess the fidelity to model these subtleties. For example, these tool are often predicated on an assumption that each component is a 1-piece component, and the resultant weight is increased by a certain percentage to account for weld lands. Thus, the resultant weight for a component which consists of two pieces welded together would be identical to that of a ten-piece component. Furthermore, the inclusion of stiffening concepts is either overlooked or limited to one or two concepts at most and contain no ability to vary aspects of those concepts. Additionally, these tools — which are heavily based on aluminum-centric historical designs — lose their predictive ability when composite concepts are assessed.

In order to capture these intricacies, a set of high-fidelity tools, typically used only during Preliminary or Detailed Design phases, have been integrated to augment the capability of the ACO tool set shown in Figure 17, repeated below. Operations, reliability and safety have been excluded from this analysis; while they are not considered unimportant, the foundation of the methodology is aimed at improving the system model which sizes the vehicle and provides weight estimates for key components.

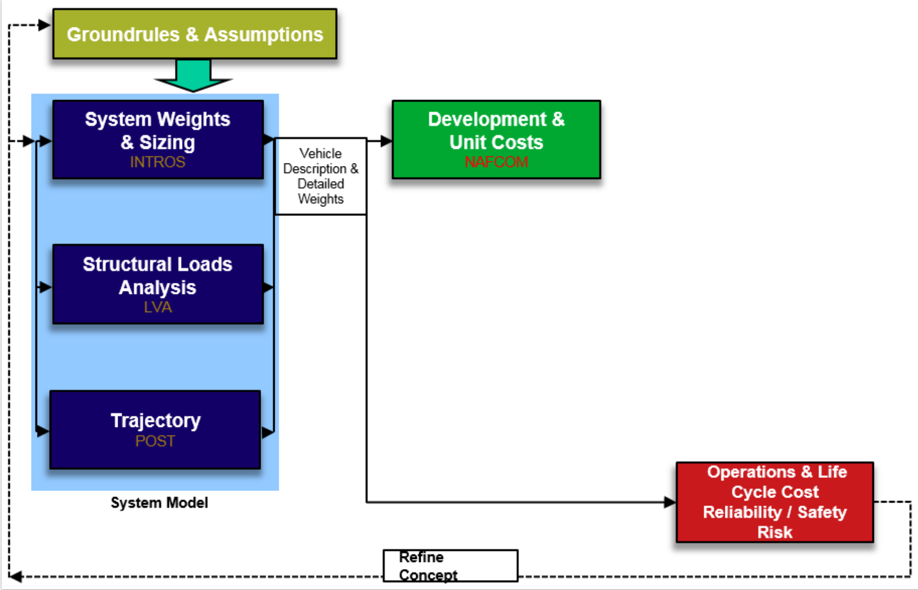


Figure 17: Launch Vehicle Conceptual Design Analysis Process Relevant to Achieving First Flight

The EUS MInD methodology involves a multidisciplinary analysis of trajectory, aerodynamic and structural loads, which aim to provide greater structural definition as a function of vehicle geometry, and fuel tank design attributes. With tankage contributing 60% of vehicle dry mass, and the fuel tank being the larger of the two tanks, the fuel tank of the EUS was selected as the only varying component [80]. The tank attributes that were traded include the material, the number of barrel panels, the stiffening concept of those panels, and the process by which the components which comprise the tank are joined.

A series of industry standard tools, which align with NASA experience, have been selected to augment the system model shown in Figure 17. The use of parametric finite element analysis, parametric structural optimization and integrated load case analysis is necessary to capture the required structural fidelity.

The original ACO system model is used to generate an initial guess at the trajectory of the sized launch vehicle (SLS Block IB). This trajectory (taken from the design reference mission presented in [58] and analyzed in POST) is run through an aerodynamic load analysis program (Cart3D) to determine the most constraining load cases the vehicle experiences from launch to LEO. These aerodynamic loads are then translated (in VLOADS) to structural loads which is then fed into the structural design and optimization loop which determines material thickness and certain stiffening concept attributes required for the EUS to withstand the input structural loads. This optimization loop includes Nastran, Patran, and HyperSizer and operates upon the EUS primary body structures only. The resulting EUS component weights are then fed into the original sizing loop (LVA and INTROS) to estimate the secondary and tertiary weights before resizing the core and comparing to the previous vehicle. This iteration will continue until the weight of the current iteration and previous are within 100 pounds. The resulting weights of the fuel tank, since only it was analyzed at the fidelity commensurate with the needs of a process-based cost model, coupled with the traded attribute values are used to estimate the process-based cost (with P-BEAT) of the tank. This process, shown in Figure 51, is repeated for the desired combinations of material, number of barrel panels, stiffening concept, and fabrications techniques.

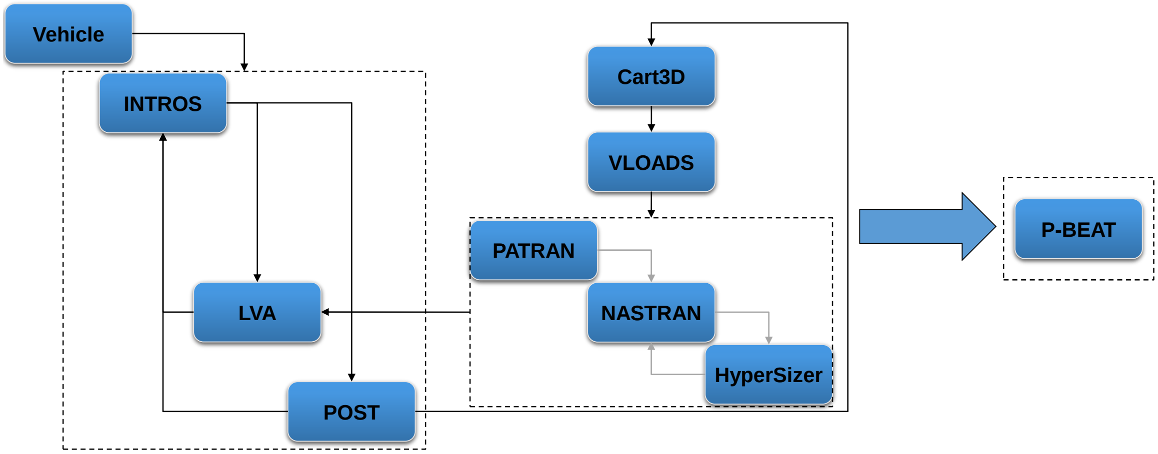


Figure 51: EUS MInD Analysis Overview

The resulting information from this analysis is used to compare various manufacturing-centric fuel tank concepts based on the associated process-based cost. Up to this point, the estimate is limited to a total life cycle cost estimate, or the costs anticipated during any of the life cycle phases shown in Figure 49. The framework developed herein adapts the MInD methodology and shifts the affordability risk perspective to capture the uncertainty associated with the budgetary environment in which NASA operates. This framework is depicted in Figure 52.

The preceding sections develop two hypotheses, Hypothesis 2.1 and 2.3. Experiment one and two aim to test these foundational assumptions and generate deterministic affordability distributions. Experiment 1 aims to verify the use of process-based costing for the generation of time-phased affordability curves and PERs for lower than system-level elements. Experiment two aims to establish an appropriate system maturity index and thereafter develop PERs for the integration of these elements.

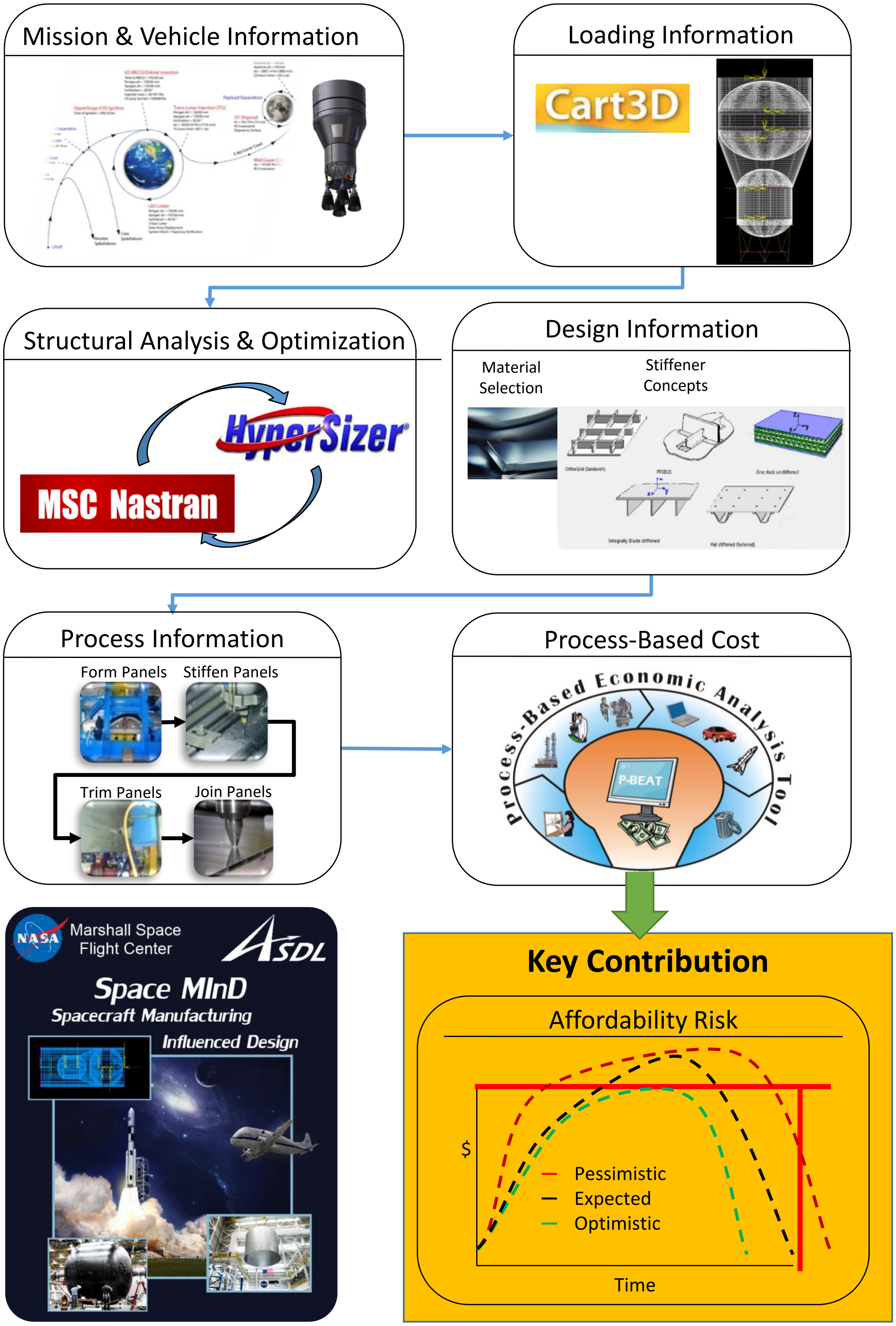


Figure 52: Final EUS MInD Framework

3.6 Experiment 1: Verifying Process-Based Cost Utilization

The previous section establishes a series of research questions and testable hypotheses. This section aims to test the foundational hypotheses of this thesis, from which the remainder of the experiments will be based.

3.6.1 Purpose

The purpose of this experiment is three-fold. Firstly, this experiment aims to test Hypothesis 2.1a, whether current process-based cost tools (namely P-BEAT) can be adapted such that interrelated cost and schedule information may be extracted and facilitate the generation of an affordability distribution for a launch vehicle element. Secondly, and dependent upon the first part, this experiment aims to test Hypothesis 2.1b; whether a probabilistic Weibull distribution can describe the behavior of the affordability distributions.

3.6.2 Approach

To begin, it is necessary to delve even further into the details of P-BEAT in order to understand and appropriately extract the man-hours it ultimately estimates. Once gathered, it will be necessary to order these activities such that an affordability distribution (i.e. cost vs time) may be generated. Once a task order has been determined, a design of experiments (DOE) shall be run for a use case. Finally, the results will then be analyzed to determine whether a smooth probability distribution, such as a Weibull curve, can provide adequate fit and which independent variables drive the variability in the response.

3.6.2.1 P-BEAT Estimation of Man-Hours and Ordering Tasks

As mentioned in Section 3.5.2, the complexity-based CERs in P-BEAT are used to estimate man-hours required to complete the development and manufacturing of the input element. These man-hours are then modified by labor rates and overhead to generate the final high-level estimates of cost per phase or per discipline. This experiment shall leverage these data novelly; by logically ordering the disciplines and assuming a fixed workforce, these hours could be used to generate a time-phased cost distribution. The 56 development processes are presented in Tables 8 and 9, categorized by discipline.

An affordability distribution hinges upon ordering these 56 development processes logically. Based upon on the historical data which P-BEAT's CERs have been formulated, these tasks will be representative of the manner in which development programs are managed, and thus provide an appropriate expenditure trend for space programs. Since this method is intended for use during Conceptual Design, and intended to provide affordability insight up to first flight, only three P-BEAT life cycle phases shall be discussed. Namely, Preliminary Design, Detailed Design, and First Build.

Preliminary and Detailed Design phases are predominantly analysis based, with the fabrication of development hardware beginning sometime during Detailed Design. As such, the order of activities in these two phases is identical. Each phase begins with the analysis of systems requirements; interpreting these and flowing these down to discipline-specific requirements. The decomposed requirements would then initiate the start of the mechanical design tasks. The mechanical design of a system is iterative, linked by the system layout design and analysis process. The structural, aerodynamics, and mechanical design (both subsystem and detailed) should occur simultaneously. This is justified by the analysis environments presented in Sections 2.2.3, and 3.5 where a closed vehicle is only achieved once structures, mechanical, and aerodynamics considerations align. Thus, the development processes which fall under the mechanical design discipline would be performed in parallel order.

Specialty engineering tasks are part and parcel of the mechanical design tasks. The mechanical, structural, and aerodynamic design of a system require the consideration of human factors, system safety, and the survivability and vulnerability of

Table 8: P-BEAT Engineering Disciplines and Development Processes [204]

Engineering Discipline	Development Process
Systems Engineering	System Requirements Analysis
	System Verification
	System Integration
Mechanical Design	System Layout, Design and Analysis
	Aerodynamics System/Subsystem Design
	Structural System/Subsystem Design
	Mechanical/Electrical System/Subsystem Design
	Structural Component Detailed Design
	Mechanical/Electrical Component Detailed Design
Electrical Design	Electrical Subsystem Design
	Electrical Detail Design
Software Engineering	Software Planning and Requirements Analysis
	Software Configuration Management
	Software Development Tools
	CSCI Implementation
Specialty Engineering	Survivability and Vulnerability
	Mass Properties
	Parts, Materials, and Processes
	Electromagnetics
	System Safety
	Human Factors Engineering
	Affordability
Test and Evaluation Engineering	System Level Test and Verification Processes
	Development Test
	End Item Qual Test
	Integration Qual Test
	TSE/STE Requirements
	Installation, Assembly, and Checkout
	Test Facilities
	Test Platform/Support Facility Maintenance
	TSE/STE Detail Design
	Functional Checkout and Acceptance Test
Operations Engineering	Configuration Change Management
	Data Management/Change Management
	Foreign Disclosure
	Engineering Operations Summary

Table 9: P-BEAT Engineering Disciplines and Development Processes continued

Engineering Discipline	Development Process
Logistics Engineering	ILS Management
	Logistics Support Analysis Summary
	Support Equipment Analysis
	Reliability, Maintainability, and Testability
	Site Activation
	Contractor Support
	Provisioning Spares
	Training System Requirements
	Develop Training Materials
	Conduct Training Course
	Training Systems - Operate & Maintain
	Training Equipment Design and Analysis
	Technical Publications
	Integrated Electronic Technical Manual
Subcontract Management	Subcontract Management
Factory Support	First Article Fabrication and Kit Installation
	Production and Deployment Support
Modifications	Mod-Receival, Checkout and Maintenance
	Mod-Over & Above
	Mod-Site Engineering
Program Management	Program Management

a system. Furthermore, the mechanical design analyses would yield mass properties and provide insight into parts and their materials. These specialty engineering tasks would be performed in parallel with the mechanical design tasks. The system verification and integration tasks,under the systems engineering, would occur during the final iteration of mechanical design. The converged system layout/design from the mechanical design tasks would be analyzed to verify that system-level requirements have been met and the layout is amenable for integration.

For the purposes of Preliminary and Detailed Design, the Test and Evaluation Engineering pertains to the analysis and design of the tests required for the 1st article build. These tests, however, cannot be designed until the mechanical design of the systems is reasonably well defined. As a result, the tasks dedicated to testing can only be performed once mechanical design is complete. The second set of tasks contained within Test & Evaluation Engineering pertain to the test facilities themselves, which cannot be adequately designed until the required tests have been determined. Thus these tasks can only be performed after test considerations are complete. Similarly, the Logistics Engineering tasks — which predominantly deal with items which support the manufacturing and test of the elements/system — requires the test facility design to be complete. The training tasks, which also comprise Logistics, are all serial in nature. The training requirements must be set before course materials may be developed, which must be completed before the training course can begin.

Operations Engineering tasks consists of configuration and data change management. These tasks would only commence once a configuration has been decided upon; and thus may only begin once the mechanical design is complete. During this time, engineering operations would be analyzed and subcontractor considerations would arise. Finally, towards the end of each of the two design phases — once mechanical design, test and evaluation aspects, and training has been completed — factory support shall begin.

Program Management is assumed to be a non-driving task. Instead, the management of a program is thought to supplement all the other processes, documenting common goals, identifying interdisciplinary risks, and develop and maintain a"Big Picture" perspective of the solution. As such, program management shall begin and end in conjunction with the first and final tasks, respectively. While additional program management duration is expected at the end of each phase, in order to prepare for design reviews and key decision points, these durations are not considered here for simplicity.

The preceding paragraphs elucidate the assumptions and logical ordering of the key development processes whose durations are estimated in P-BEAT. The resulting

Gantt chart with the appropriate dependencies, is shown in Figure 53, where the task durations are purely notional. This logical elucidation of the development processes for which P-BEAT estimates labor hours, shall be used to develop affordability distributions. Given the extensive, and highly detailed, database upon which P-BEAT's CERs are based, the resulting distributions are assumed to be truth models.

Figure 53: Gantt Chart Depicting P-BEAT Development Process Order and Dependencies with Notional Task Durations

The development of these truth models requires a use-case upon which to base inputs necessary to generate an estimate. The following section outlines an appropriate baseline configuration and a set of alternative materials and processes (i.e. manufacturing technologies) which shall be analyzed in the form of a design of experiments (DOE).

3.6.2.2 Use Case and Design of Experiments

The application presented herein is focused on launch vehicle affordability; as such the use case ought to be representative. With the SLS under development, poised to facilitate manned exploration of Mars, a natural selection is the key enabler to this end. As described in section 1.3 the first block upgrade consists of supplanting the Interim Cryogenic Propulsion Stage with an advanced upper stage, currently dubbed the EUS, to provide greater in-space propulsion. Furthermore, the LH_2 tank has been marked as a key element for the infusion of new materials [169, 44]. The use case shall thus establish the baseline metallic concept, and identify additional metallic materials from which the tank could be fabricated.

The LH_2 tank measure 8.4 meters in diameter and must be size, in conjunction with the LO_2 tank, to operate at the operating mixture ratio of 5.88 [58]. The baseline material shall be Al-Li 2195, the same material used on the super light-weight STS ET and the Ares I upper stage tank design [206, 13]. The tank consists of a barrel and two dome sections, joined together by Y-rings — also used to join the tank to its skirts [58]. Both the dome and barrel sections are further divided as follows.

Each dome consists of gores, a cap, and an access hole cover or sump for the forward and aft domes, respectively. The number of gores is restricted by the maximum sheet stock size available, and — due to their shape — are unstiffened [112]. The domes are assumed to consist of 10 dome gores, similar to that of the Ares I, and fabricated through stretch forming. The dome caps will be spin-formed as a single piece, and friction stir welded (FSW) to the gores, which in turn will be joined with FSW [13]. Fabrication of the sump and manhole cover are assumed superfluous when compared to the other tank components.

The tank barrel panels are assumed to be bump (manual brake) formed, similar to the Ares I tank design [112], and orthogrid stiffened as described in [58]. The number of tank barrel panels is also determined by the sheet size available, and is assumed to be six for the 8.4m baseline configuration tank. The Y-rings shall be roll forged as a single piece, and all components shall be fabricated from the same material, Al-Li 2195. Per the processes outlined for the Ares I tank fabrication, the dome and barrel shall be assembled separately before being joined, with the Y-ring, to form the final tank assembly. Each piece (gore, cap, barrel panel) shall be mechanically trimmed, once formed, for weld fit-up. All pieces shall be joined via FSW [112]. Figure 54 shows the basic decomposition of the fuel tank, and Table 10 enumerates the baseline configuration from a producibility standpoint.

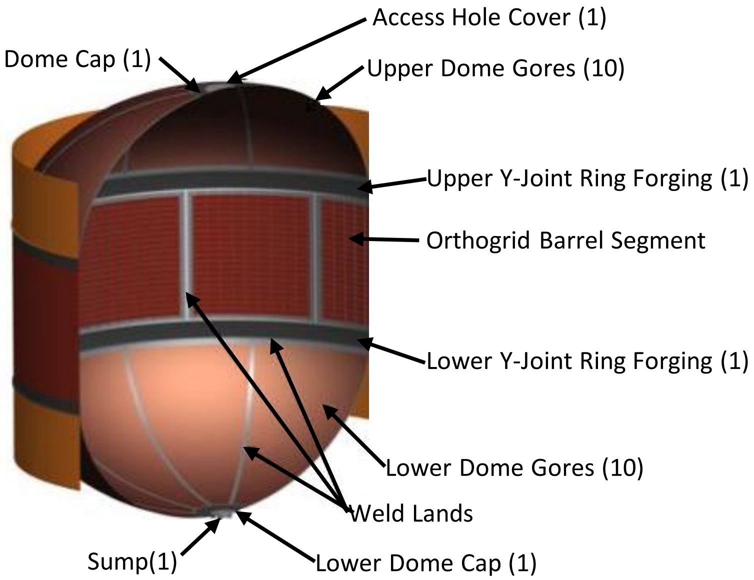


Figure 54: NASA Metallic Tank Design Concept [112]

Table 10: Baseline Tank Attributes for Use Case

Attribute	Value/Concept
Material	Al-Li 2195
Diameter	8.4m
Number of Dome Gores	10
Dome Stiffening Concept	None
Number of Barrel Panels	6
Barrel Panel Stiffening Concept	Orthogrid
Dome Cap Fabrication	Spin Formed
Dome Gore Fabrication	Shot Peen
Y-Ring Fabrication	Roll Forged
Barrel Panel Fabrication	Bump Formed
Stiffening Concept Fabrication	Machined
Weld Fit-up Trimming	Mechanical
Joining	Friction Stir Weld (FSW)

Having established a baseline configuration, it is necessary to elucidate the attributes which shall be varied, and enumerate the alternative concepts for those attributes. The SLS upgrades are based upon an in-line EUS concept, where the EUS Fuel tank is a load bearing portion of the outer mold line. This design selection is an architecture decision which would require significant design changes to the SLS Block IB and Block II; as such, the tank diameter will be assumed fixed. Additionally, the geometry of the tank — dome eccentricity and barrel height — shall be fixed along with the geometry of all primary body structures which comprise the EUS. The purpose of this study is to assess the affect of manufacturing trades on affordability and mission critical performance, which justifies a fixed-geometry analysis.

A thorough literature search, and elicitation from NASA Marshall Materials and Process Lab, has been performed to identify the appropriate alternatives for the manufacturing variables of interest. Materials were selected based on heritage data (AL 2219, Al-Li 2195, and Ti-6Al-4V were used on the Shuttle program, Ares I, and now SLS while titanium was used on Saturn V tanks) and identification by SME of two other viable candidates[120, 206, 183]. The number of dome and barrel panels were limited by the CAD/FEA model furnished by NASA, and the stiffening concepts were selected (from those available in Hypersizer) based on heritage tank concepts and SME suggestion. The fabrication techniques were extracted from literature [13, 112, 220, 98]. The matrices of alternatives for the DOE is shown in Tables 11 and 11.

Table 11: Metallic Tank Design Attributes Matrix of Alternatives for DOE

Attribute	Alternatives				
Material	Al-Li 2195	Al-Li 2090	Al 2219	Al 2024	Ti-6Al-4V
Number of Dome Gores	10	1			
Number of Barrel Panels	6	3	2	1	
Barrel Panel Stiffening Concept	Orthogrid	Integral-Blade (IBS)	Unstiffened		

Table 12: Metallic Tank Process Attributes Matrix of Alternatives for DOE

Attribute	Alternatives		
Dome Cap Fabrication	Spin Formed		
Dome Gore Fabrication	Shot Peen	Stretch Form	Spin Form (1-piece dome)
Y-Ring Fabrication	Roll Forged		
Barrel Panel Fabrication	Bump Formed	Stretch Formed	Shot Peen
Stiffening Concept Fabrication	Machined		
Weld Fit-up Trimming	Mechanical	Chemical	
Joining	Friction Stir Weld (FSW)	Plasma Arc (Titanium Only)	

This matrix includes two interwoven trade spaces; design alternatives, and production alternatives. The design alternatives are those which affect inputs into the EUS MInD analysis presented in section 3.5. This includes the material, the number of dome gores and barrel panels, and the stiffening concept used for those barrel panels. These metrics will directly affect the CAD/FEA models and result in different tank wall thicknesses and stiffening attributes as calculated through the structural optimization programs. A total of 47 design combinations were analyzed. Each of these design alternatives is then analyzed at the process level, trading fabrication and joining techniques for the various components which comprise the tank. A total of 18 process variations for each design have been analyzed, resulting in 846 unique tank candidates. It is necessary to point out that the FEA/CAD model currently available does not account for some higher-fidelity aspects such as weld land structural integrity as a function of joining alternative. While this would affect the results from the structural optimization, it is expected to be small and shall be addressed in a future work.

The matrix of alternatives (MoA) requires a brief discussion on compatibility and technology readiness to clarify assumptions. It is assumed that all components of the tank shall be fabricated from the same material, and that no more than one fabrication process would be used for the components which comprise the barrel or dome assemblies. The dome bears some exception to this since the dome cap is assumed to always be spun formed and joined to the gores (which would all be fabricated using the same process; however, if spin forming is selected for the dome, the gores and cap will be fabricated from a single sheet and thus eliminate one welding process. The single-piece spin-formed dome is also assumed to bear a technology maturity reduction (in the form of a lower TRL) due to the limitations on sheet size. Johnson presents a brief discussion on the TRL reduction, however, — since successful completion of an 18ft one-piece dome — the reduction is currently thought to be less drastic for an 8.4m (28ft) dome [158].

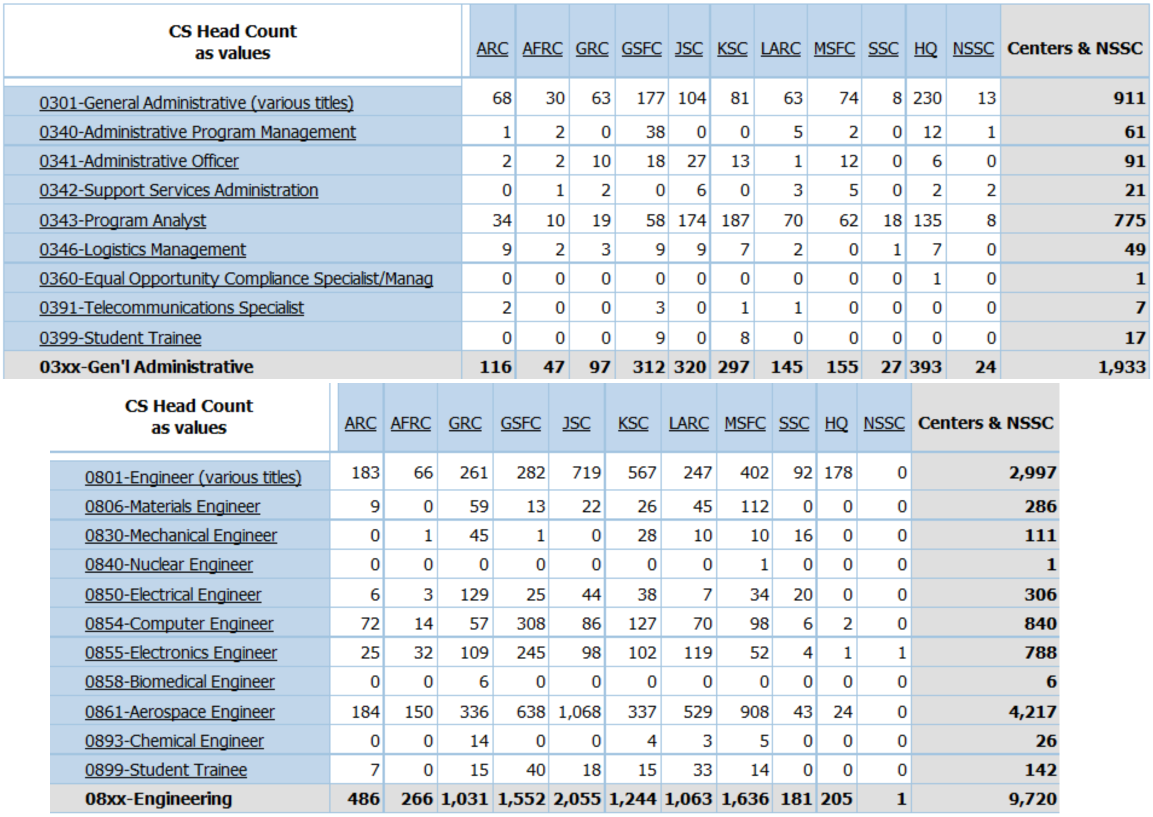
The TRL designation is predominantly based on the material and its heritage in cryogenic tank design, as well as extensive discussion with SMEs. Al 2219 and Al

2024 possessed the highest TRL, at 7, with the two Al-Li materials receiving a TRL of 5.5 and the titanium concept a 4. These TRL's were reduced to a TRL 3 and 3.5 for one-piece spin formed domes for titanium and aluminum concepts, respectively. All other inputs required for P-BEAT were determined via SME solicitation.

The physics based analysis was performed using the analysis shown in Figure 51 where a typical lunar surface DRM (described in [58]) was used with a payload mass delivered to Trans-Lunar Injection (TLI) orbit of approximately 40 tonnes. The final consideration is determining the labor force. As mentioned in Section 3.5.2, P-BEAT provides an estimate for the labor hours for development processes and the selected manufacturing processes; to convert these to an annual expenditure, some assumptions on labor force is required.

Initial analysis of P-BEAT outputs yielded the mechanical design processes to be the most labor intensive, thus justifying a large labor force relative to the other development processes. Furthermore, the NASA Systems Engineering Handbook and Program and Project Management NPRs suggest a desire to have KDP's every two years [147, 114]. Therefore the labor force will be fixed for all studies such that the baseline configuration shall achieve reviews every two years. This equates to spending two years in Preliminary Design, two years in Detailed Design, and two years in 1st Build (which includes fabrication and qual testing). While no specific data on workforce allotment to the SLS program is available, some constraints may be established. A majority of the SLS design work is being supported by NASA MSFC. Fabrication is being performed at Machoud Assembly Facility (MAF), which is managed by MSFC, and testing is distributed between NASA Stennis Space Center and MSFC. High-level labor statistics are available online, and shown for the start of FY2016 in Figure 55, and may be used as a sanity check to ensure that the labor for each P-BEAT development process and the manufacturing tasks is reasonable. Additionally, this analysis assumed a single shift of workers who work Monday to

Friday and also receive 10 public holidays per calendar year.



CS Head Count as values	ARC	AFRC	GRC	GSFC	JSC	KSC	LARC	MSFC	SSC	HQ	NSSC	Centers & NSSC
0301-General Administrative (various titles)	68	30	63	177	104	81	63	74	8	230	13	**911**
0340-Administrative Program Management	1	2	0	38	0	0	5	2	0	12	1	**61**
0341-Administrative Officer	2	2	10	18	27	13	1	12	0	6	0	**91**
0342-Support Services Administration	0	1	2	0	6	0	3	5	0	2	2	**21**
0343-Program Analyst	34	10	19	58	174	187	70	62	18	135	8	**775**
0346-Logistics Management	9	2	3	9	9	7	2	0	1	7	0	**49**
0360-Equal Opportunity Compliance Specialist/Manag	0	0	0	0	0	0	0	0	0	1	0	**1**
0391-Telecommunications Specialist	2	0	0	3	0	1	1	0	0	0	0	**7**
0399-Student Trainee	0	0	0	9	0	8	0	0	0	0	0	**17**
03xx-Gen'l Administrative	**116**	**47**	**97**	**312**	**320**	**297**	**145**	**155**	**27**	**393**	**24**	**1,933**

CS Head Count as values	ARC	AFRC	GRC	GSFC	JSC	KSC	LARC	MSFC	SSC	HQ	NSSC	Centers & NSSC
0801-Engineer (various titles)	183	66	261	282	719	567	247	402	92	178	0	**2,997**
0806-Materials Engineer	9	0	59	13	22	26	45	112	0	0	0	**286**
0830-Mechanical Engineer	0	1	45	1	0	28	10	10	16	0	0	**111**
0840-Nuclear Engineer	0	0	0	0	0	0	0	1	0	0	0	**1**
0850-Electrical Engineer	6	3	129	25	44	38	7	34	20	0	0	**306**
0854-Computer Engineer	72	14	57	308	86	127	70	98	6	2	0	**840**
0855-Electronics Engineer	25	32	109	245	98	102	119	52	4	1	1	**788**
0858-Biomedical Engineer	0	0	6	0	0	0	0	0	0	0	0	**6**
0861-Aerospace Engineer	184	150	336	638	1,068	337	529	908	43	24	0	**4,217**
0893-Chemical Engineer	0	0	14	0	0	4	3	5	0	0	0	**26**
0899-Student Trainee	7	0	15	40	18	15	33	14	0	0	0	**142**
08xx-Engineering	**486**	**266**	**1,031**	**1,552**	**2,055**	**1,244**	**1,063**	**1,636**	**181**	**205**	**1**	**9,720**

Figure 55: Select Tables from NASA Workforce Profile for Start of FY2016 [4]

Fixing the labor force will eliminate any variability resulting from labor fluctuations; while a Program manager would have specific labor information at her disposal and the ability to adjust the workforce as necessary, these considerations are beyond the scope of this work. Having established a baseline tank configuration, enumerated manufacturing alternatives for key tank attributes, and elucidated ground-rules and assumptions, the results of experiment one may be presented.

3.6.3 Results

First and foremost, the analysis which results from manipulating previously underutilized intermediate outputs in P-BEAT yields a plethora of data, from which two affordability distributions may be created. The first is a highly-coveted annual expenditure curve, which forecasts the expected cost incurred per year. The second, provides a higher-level view of the expenditure per phase, depicting the cost and duration of each phase. These two distributions for the baseline Al-Li 2195 LH_2 tank, described by Table 10, are shown in Figures 56 and 57, respectively.

Figure 56 shows the normalized annual expenditure required to complete the development of the baseline LH_2 tank from the current TRL of 5.5. This figure depicts a six fiscal year development cycle for which funding would be approved in the previous fiscal year. As expected, a majority of the expenditure occurs during Detailed Design, with the peak expenditure occurring during the first year — when development hardware is typically built.

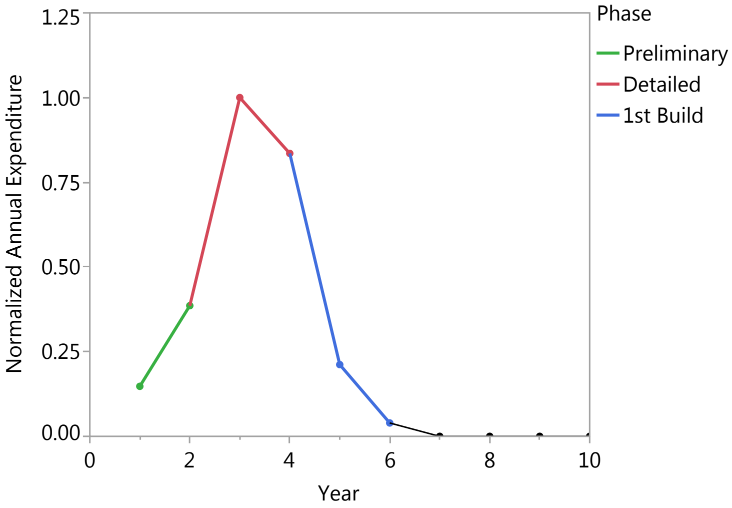


Figure 56: Normalized Annual Expenditure for Al-Li 2195 Baseline LH_2 Tank Configuration

Figure 57 shows a different perspective of the data. It depicts the distribution of expenditure across the three phases of interest, and show the years (in fractions) required to complete each phase. This provides insight into the expenditure and duration required to mature this element for each of the program review milestones.

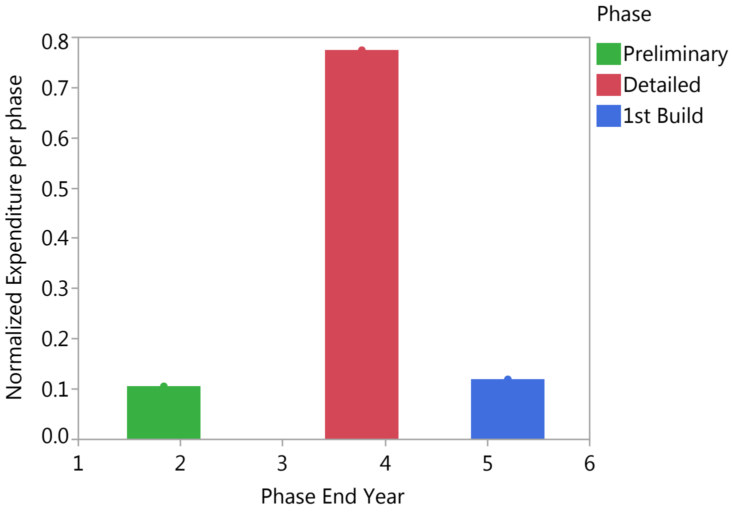


Figure 57: Normalized Expenditure and Timeline per Phase for Al-Li 2195 Baseline LH_2 Tank Configuration

In extending the analysis beyond the baseline configuration, to the complete DOE of 846 alternatives, the distributions become considerably more varied. Firstly, however, it is necessary to present the mission critical performance aspect, developed in Section 3.3. As described by the Conjecture to Research Question 1.1, the mission critical performance is measured by the payload capability delivered to a desired LEO. The mission, established in [58], includes a 130nmi LEO insertion, followed by a trans-Lunar injection maneuver where the final goal is to deliver a payload to a low-Lunar circular-orbit of 100km. The payload mass captured by the MInD analysis environment, described in Section 3.5, provides the payload mass which would be placed into this low-Lunar Orbit (LLO).

The implementation of this environment has been performed based upon a conversion of burnout mass reduction to payload mass increase and vice versa. The assumption of fixed geometry requires this approach; as a result performance benefits from a technology will materialize as payload mass increases while detriments will reduce the payload mass capability. The alternative implementation, which fixes the payload mass and resized **all** vehicle components would require significant changes to the current capability of the analysis environment described in Section 3.5. The necessary changes are described in Section 6.3.

The resulting payload mass for each of the 47 design alternatives is shown in Figure 58, normalized by the payload mass achieved by the baseline configuration described in Table 10, and represented by the large green diamond located at 1.00. Note that there is no x-axis in this figure; the points have been spread to better distinguish between them.

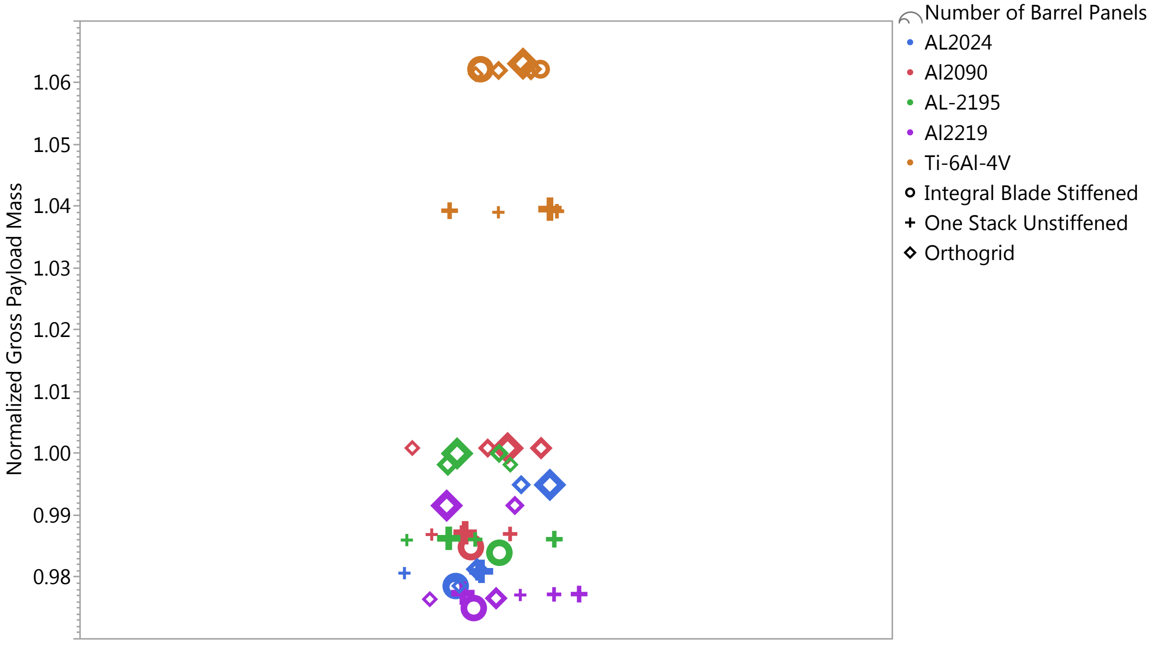


Figure 58: Normalized Payload Mass for All LH_2 Tank Design Configurations

The direction of goodness in this figure is upwards, suggesting that if decision making was performed in one-dimension —based on payload mass alone — all fuel tanks would be built from Ti-6Al-4V. This Equation also shows that the Al 2219 tanks provide one percent less payload capability than the Al-Li 2195 counterparts. This trend matches the payload capability reduction that resulted from selecting Al 2219 for the SLS core tanks [206]. The trends also suggest that the concepts which include stiffened barrel panels generally outperform the unstiffened concepts. However, the decision making process is not a one-dimensional problem. Instead, the affordability of a program is paramount, and a concept should not be selected without as much insight into the dynamic nature of cost, upon which this thesis is based.

The annual expenditure distributions range in duration from five to 20 years and the peak expenditure differs by more than 30%. Furthermore, the annual distribution for many of the concepts is bimodal — with one peak occurring early in Detailed Design, and the second just before the start of First Build. The full range of distributions is shown in Figure 59, where the costs have been normalized by the maximum cost incurred in a year across all alternatives. Upon comparing the first peak, this figure shows that some alternatives achieve their peak cost (and by extension, begin Detailed Design) sooner than the baseline configuration. This figure shows the expenditure diversity amongst the concepts analyzed.

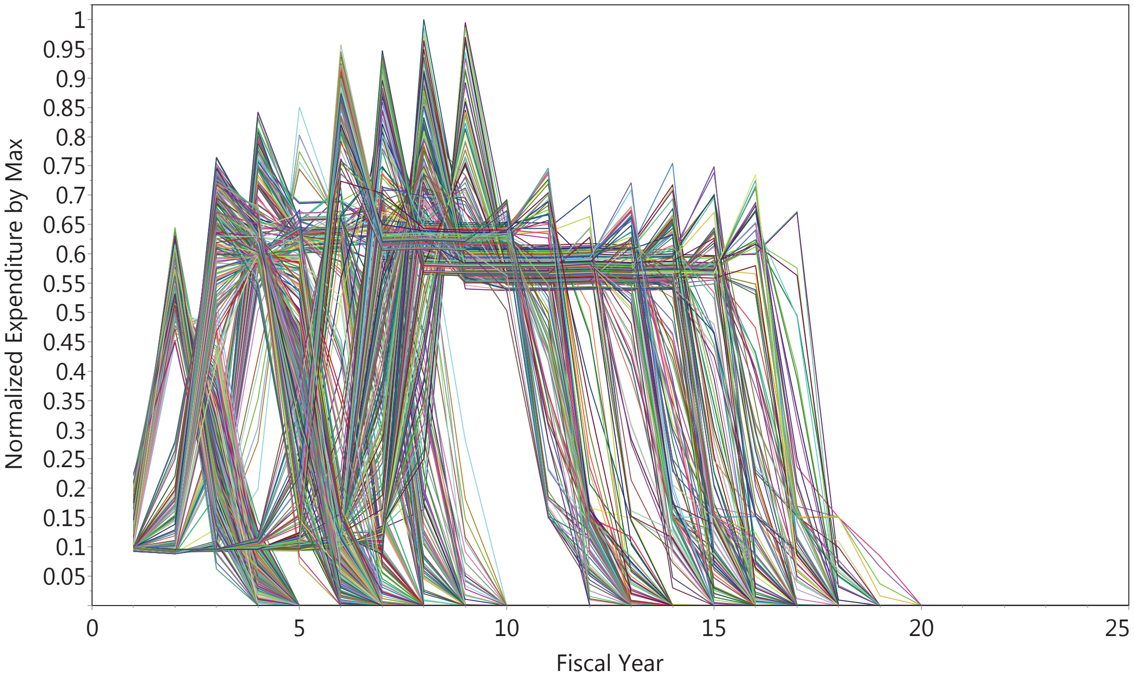
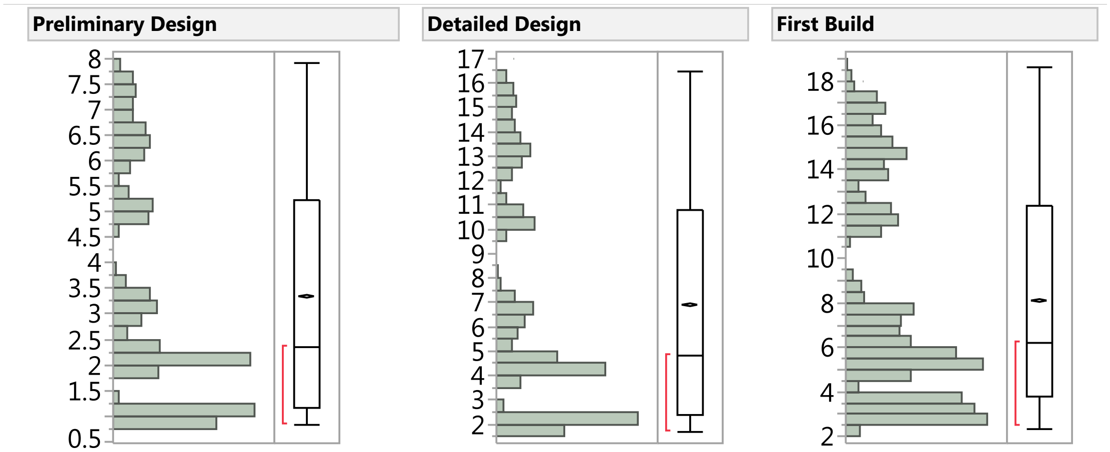


Figure 59: Normalized Expenditure and Timeline per Phase for All LH_2 Tank Configurations

In assessing the timeline and total cost breakdown per phase, similar to the baseline visualization shown in Figure 57, it is desirable to view the variation of both duration in each phase, and the relative percent of the total cost incurred during each phase.

The distribution of phase end has been generated for the alternatives whose annual expenditure is shown in Figure 59. On average Preliminary Design ends during the fourth fiscal year, Detailed Design ends in the seventh, and 1st build is completed during the ninth. There is significant variation on these durations, depicted by standard deviations of 2.2 years, 4.6 years, and 4.8 years, respectively. The summary statistics are shown in Figure 60. The shortest half of the data (indicated by the red brackets in Figure 60) shows that the densest part of the region is below the median for each phase. Approximately half of the alternatives reach the end of First Build within six years and three months, spending nearly two and a half years in Preliminary and Detailed Design, and one and a half years building and testing the first flight-unit. While this figure does not provide much insight into which candidates, it does establish a breadth of information regarding the spread of key programmatic considerations which will prove useful in generating system level affordability curves.



Quantiles		
100.0%	maximum	7.91
99.5%		7.8
97.5%		7.51
90.0%		6.74
75.0%	quartile	5.23
50.0%	median	2.35
25.0%	quartile	1.17
10.0%		0.98
2.5%		0.91
0.5%		0.86
0.0%	minimum	0.83

Summary Statistics	
Mean	3.3360051
Std Dev	2.1942887
Std Err Mean	0.0117819
Upper 95% Mean	3.359098
Lower 95% Mean	3.3129121

Quantiles		
100.0%	maximum	16.5
99.5%		16.2
97.5%		15.6
90.0%		14
75.0%	quartile	10.8
50.0%	median	4.83
25.0%	quartile	2.4
10.0%		2.01
2.5%		1.85
0.5%		1.76
0.0%	minimum	1.69

Summary Statistics	
Mean	6.9
Std Dev	4.57
Std Err Mean	0.02
Upper 95% Mean	6.94
Lower 95% Mean	6.85

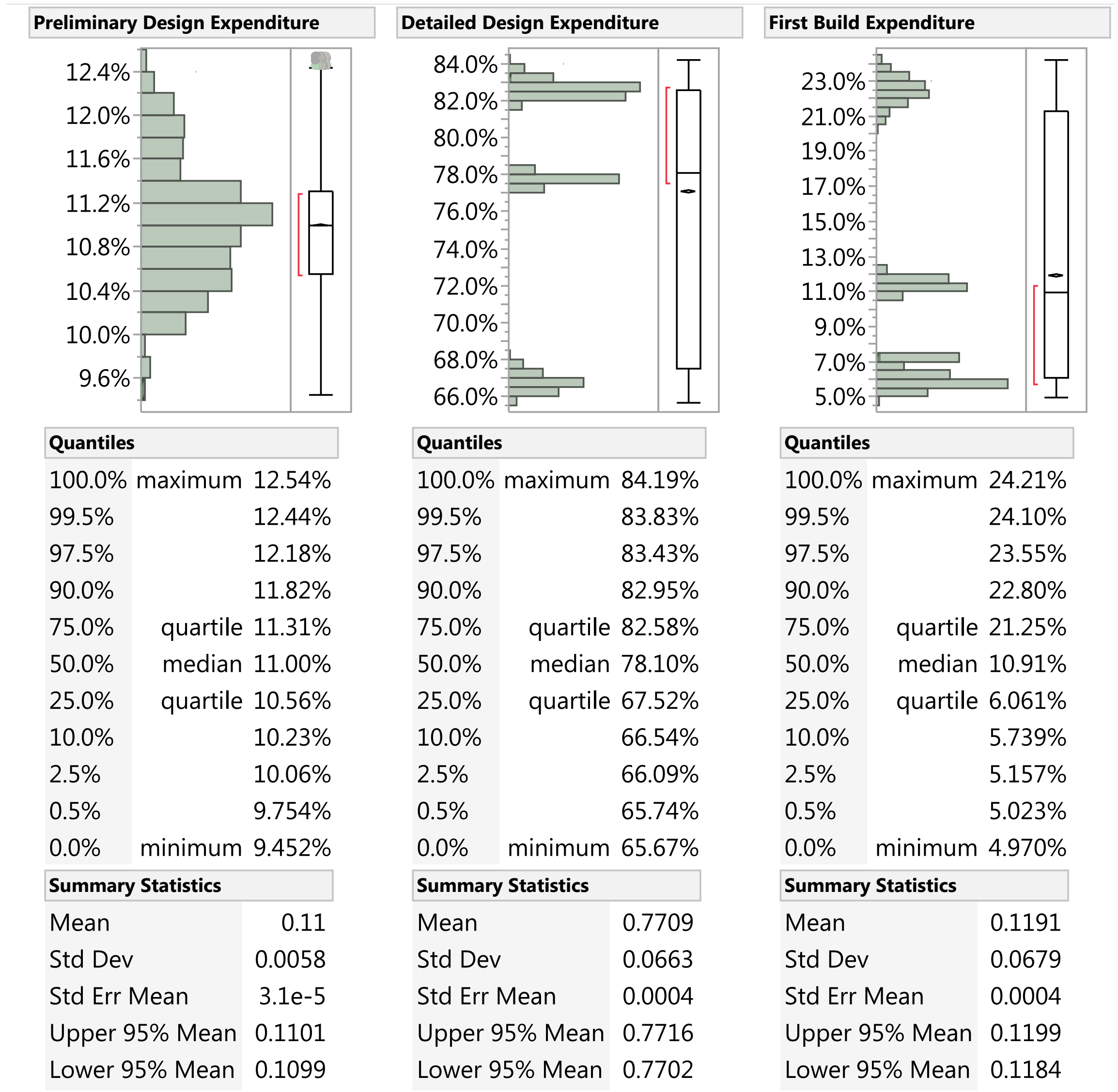
Quantiles		
100.0%	maximum	18.6
99.5%		17.8
97.5%		17.2
90.0%		15.4
75.0%	quartile	12.3
50.0%	median	6.21
25.0%	quartile	3.81
10.0%		2.96
2.5%		2.6
0.5%		2.43
0.0%	minimum	2.32

Summary Statistics	
Mean	8.1
Std Dev	4.76
Std Err Mean	0.03
Upper 95% Mean	8.15
Lower 95% Mean	8.05

Figure 60: Distribution of Phase End for All LH_2 Tank Configurations

Figure 57 also describes the proportion of cost incurred in each of the three phases. Evaluating the same information for all the alternatives described by the MOA, results in the distributions for each phase, shown in Figure 61. Right away, it is evident that P-BEAT does **NOT** use a fixed percentage to describe the cost incurred during each phase, rather the contributions depend heavily on the selected inputs — particularly for Detailed Design and First Build. On average the percent of cost incurred per phase is 11%, 77.1%, and 11.9% for Preliminary Design, Detailed Design, and First

Build, respectively. The standard deviation is 0.6%, 6.6%, and 6.8%, respectively.



Quantiles

		Preliminary Design Expenditure	Detailed Design Expenditure	First Build Expenditure
100.0%	maximum	12.54%	84.19%	24.21%
99.5%		12.44%	83.83%	24.10%
97.5%		12.18%	83.43%	23.55%
90.0%		11.82%	82.95%	22.80%
75.0%	quartile	11.31%	82.58%	21.25%
50.0%	median	11.00%	78.10%	10.91%
25.0%	quartile	10.56%	67.52%	6.061%
10.0%		10.23%	66.54%	5.739%
2.5%		10.06%	66.09%	5.157%
0.5%		9.754%	65.74%	5.023%
0.0%	minimum	9.452%	65.67%	4.970%

Summary Statistics

	Preliminary Design Expenditure	Detailed Design Expenditure	First Build Expenditure
Mean	0.11	0.7709	0.1191
Std Dev	0.0058	0.0663	0.0679
Std Err Mean	3.1e-5	0.0004	0.0004
Upper 95% Mean	0.1101	0.7716	0.1199
Lower 95% Mean	0.1099	0.7702	0.1184

Figure 61: Distribution of Percent Expenditure per Phase for All LH_2 Tank Configurations

While these figures provide insight into the overall design space in which these alternatives reside, it is necessary to delve further into detail in order to determine the independent variables which drive the variability of affordability distributions for the tanks alternatives.

3.6.3.1 Assessment of Independent Variable Impact on Response

To begin this assessment it is necessary to achieve a high-level understanding of the trends before delving into lower-level (i.e. more detail). Figure 62 shows a scatterplot matrix of the Normalized total cost and duration (to complete First Build) required to develop each tank alternative, as a function of the TRL, number of barrel panels, and various fabrication options. To reduce the matrix, the material variations are indicated by the color of the points, where red is Al 2024, blue is Al 2219, green is Al-Li 2090, purple is Al-Li 2195 and black is Ti-6Al-4V.

This matrix shows a few distinct trends which bolster the topic upon which this thesis revolves: **materials and processes matter!** The first, and perhaps most evident trend, is the large difference in total development cost, and duration when comparing a 1-piece spun formed dome with a spun form dome cap and either stretch formed or shot peened gores. In evaluating the points for the alternatives which use the latter two processes, clear stratification is evident. Al 2024 and Al 2219, represented by the red and blue points, respectively, comprise the layer which is the quickest and least expensive to develop. Al-Li 2195 and Al-Li 2090 (purple and green points, respectively) form the middle layer, and the titanium concepts form the top-most layer, being the most expensive and lengthy development cycle. This trend is expected, as titanium is the least mature concept, while the Al 2219 and Al 2024 materials represent the most mature alternatives, shown in the TRL scatter. However, in interpreting the scatter of points for the 1-piece spun form dome concepts, the absence of a trend is important. The variation of cost and duration for these concepts is less dependent on the material and more dependent on the process. Fundamentally this suggests that the maturation of the process is a greater cost driver than the maturation of material application for cryogenic tanks. This trend is repeated when considering the number of barrel panels or the stiffening concept applied to those panels; the maturation of spin forming a one-piece dome is a greater cost driver than varying any of the other design/process alternative.

Adjusting the perspective to ascertain the trends within a single maturity band will provide insight into the implications of the various process alternatives. Figure 63 bears all the alternatives whose TRL is 5.5, thus encompassing both Al-Li material alternatives, but excludes any single-piece dome concepts.

The most evident trend is based upon the selection of dividing the barrel into panels. Available sheet-stock size (listed as 246 inches long, and 130 inches wide for AL-Li 2195 in 2013 [112]) limits the lower bound to two panels for the 8.4m diameter tank, assuming no improvements on the material supplier side. Despite this limitation, the time spent and cost incurred in each phase decreases as the number of panels increases. This suggests that increasing the part count decreases the cost and time required to develop and fabricate the first flight-ready tank. This observation, while intuitive, goes against a long-held industry notion that traditional DFM/DFMA methods champion: a decrease in part count decreases cost [140, 26, 190].

Regarding the variation in stiffening concepts, while fewer IBS cases were analyzed than orthogrid or unstiffened barrel panels, Figure 63 suggests that the unstiffened concepts are slightly more costly than the stiffened counterparts. Furthermore, orthogrid stiffened concepts tend to be less costly, and quicker to complete each design phase, than the IBS counterparts. Barrel panel fabrication techniques have relatively similar variation in both cost and development time, with stretch forming tending to include the greatest spread, while bump forming possesses more clumped alternatives.

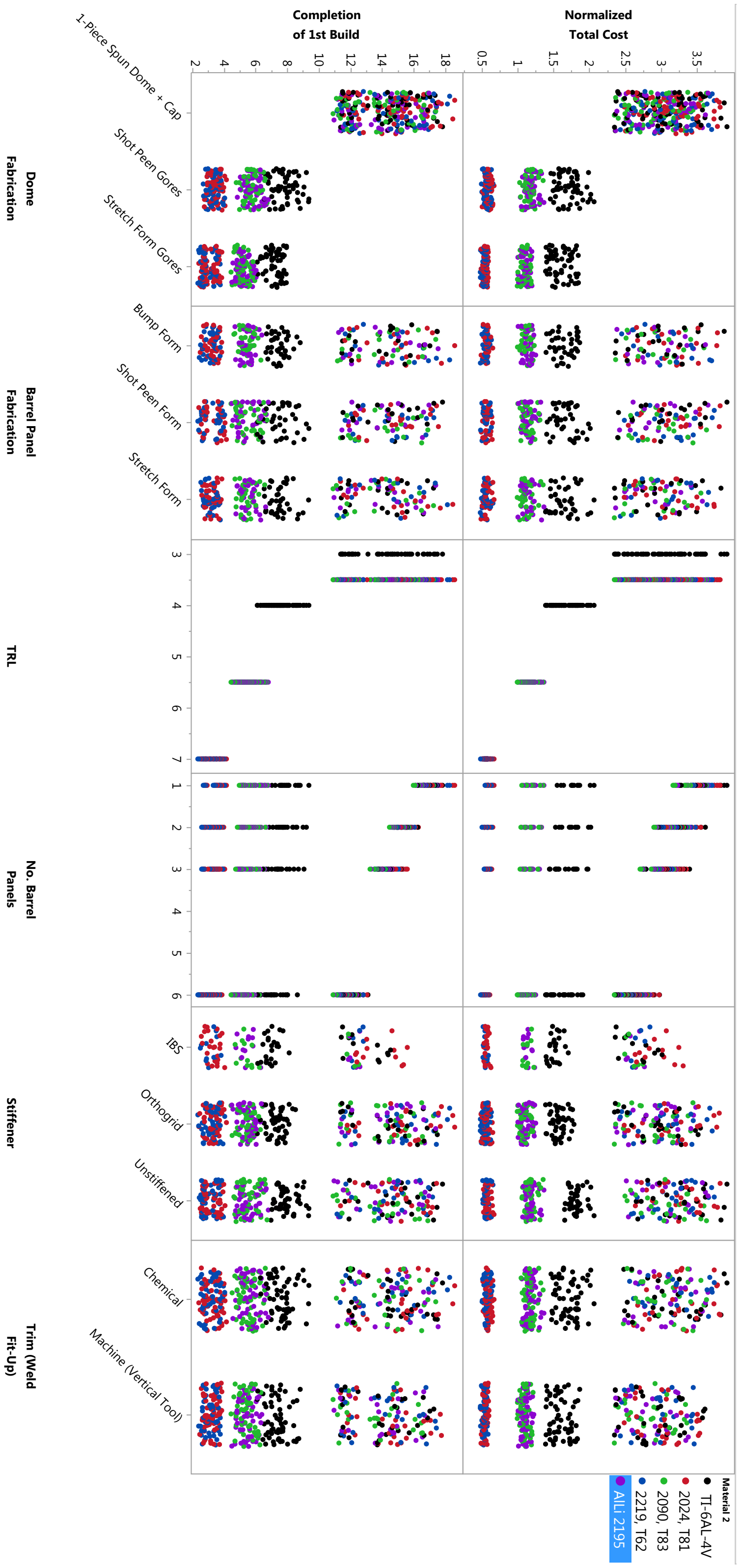


Figure 62: Scatterplot Matrix Depicting Total Cost and Total Duration Variations as a function of Independent Design Manufacturing Variables

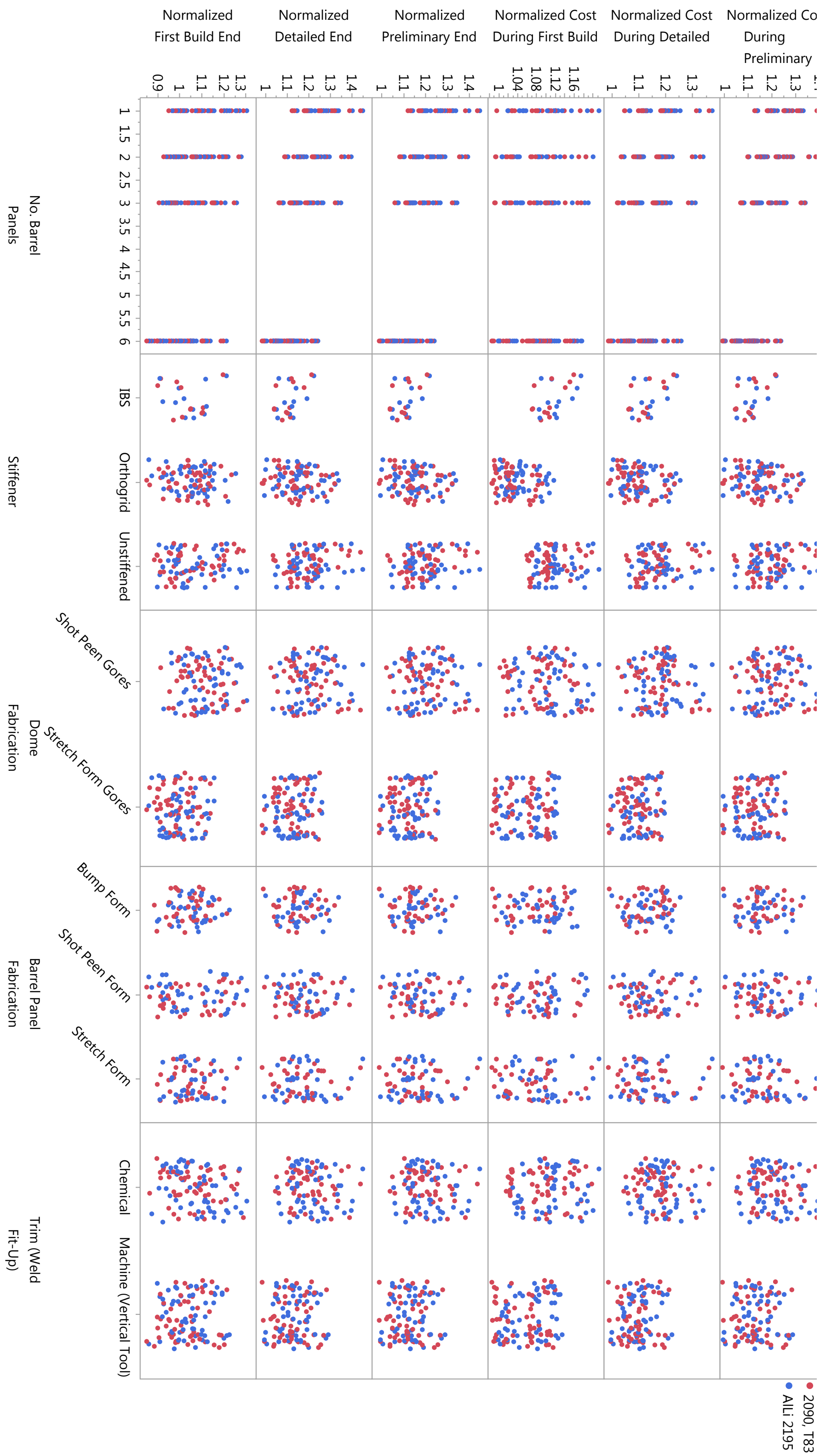


Figure 63: Scatterplot Matrix Depicting Phase-Specific Affordability Variations as a Function of Independent Design Manufacturing Variables

Stretch forming the dome gores bears lower cost and duration for each phase, as well as more clumped points, suggesting lower sensitivity to material selection. Shot peening the gores is generally more costly and a slower fabrication process for a 10 gore Al-Li dome. Once all pieces have been formed, mechanical trimming is generally the more cost effective option per phase with less variation in both development time and cost for each phase. Having established a high-level picture of total cost and development duration, it is necessary to delve deeper to understand the temporal behavior of cost and the effects of concept variations. First, the annual expenditure for barrel gore fabrication will be presented, followed by the two barrel panel variations and concluding with a comparison between concept maturity.

As is evident in the scatterplot matrix, the one-piece spun formed dome represented a significant increase in the overall cost and development duration of the tank. This is primarily due to massive limitations in acquiring raw material sheets in the appropriate size, and the proportional size constraints for spin-form tooling capabilities. As a result of these limitations, the maturity (TRL) for these concepts is considered much lower than the shot peen and stretch forming processes. Figure 64 shows the average annual expenditure — as a percent of the largest expenditure in any one year by any program, which happens to be a one-piece spun form dome concept. The curves are colored to represent the three different phases, where intermediate colors represent the variation in duration spent in each phase. The temporal behavior forecast for the three dome fabrication processes shows the low maturity spin form process bears significantly greater costs and longer development time to reach flight-ready maturity, while shot peen and stretch form processes bear little difference. Between shot peen and stretch formed dome gores, the expenditure peaks occur in the fourth fiscal year and are approximately the same magnitude. Expenditure tapers off more quickly for stretch formed domes which results in development completion by the end of the eighth fiscal year, while shot peening has slight expenditure during the ninth.

The total expenditure, represented by the area under the curve, suggests that stretch forming the domes would — on average — be the most affordable option.

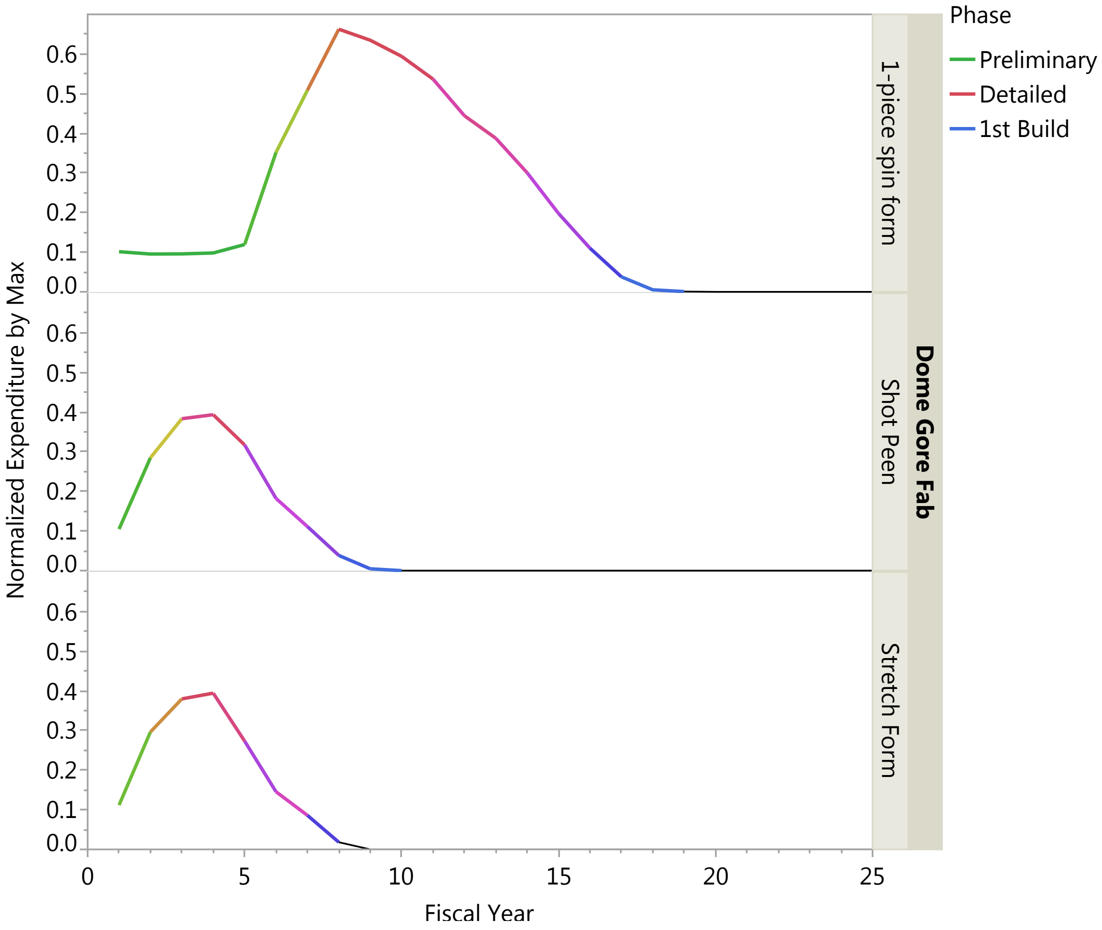


Figure 64: Mean Annual Expenditure as a Function of Dome Fabrication

Transitioning to the barrel panel fabrication process, the trends are very similar to the mature processes used for the dome. There is not much between the three processes, all three peak around the start of the fourth fiscal year, and the stretch form expenditure in the previous year is more flat than the other two processes. All three exhibit a second peak at the start of the eight fiscal year, where the shot peen peak is more pronounced than the other due to a lower "saddle" in the previous year. The area under the curves is approximately equal for these three concepts and, on a whole, there is little to encourage the selection of one process over the other. In this instance, an additional assessment of tooling costs — previously discussed as beyond the scope of this thesis — would be necessary to inform a decision.

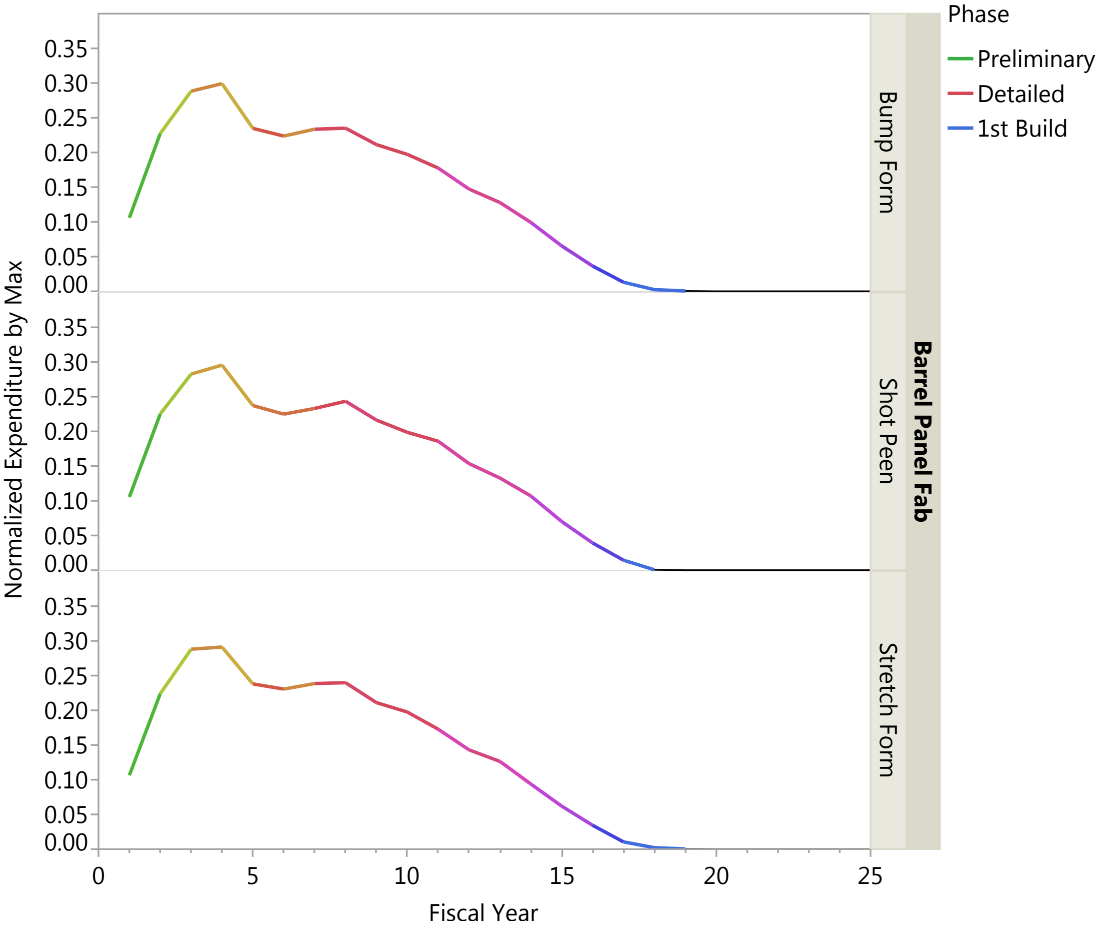


Figure 65: Mean Annual Expenditure as a Function of the Barrel Panel Fabrication

The second design variable is the division of the barrel into panels. The scatterplot matrix in Figure 62 showed that the total cost decreases as the number of barrel panels increases. The temporal behavior of cost for one, two, three, and six barrel panels is shown in Figure 66, where all curves are bimodal. The first peak, occurring at the start of the fourth fiscal year, is approximately the same for the four variations, it is the second peak which is most striking. This peak becomes more pronounced as the number of barrel panels increases, which somewhat contradicts the decrease in total cost shown in Figure 62. This may be a result of the additional care needed when dividing the barrel section into a greater number of pieces. The orientation and location of these pieces will matter, and some additional designations will need to be considered to ensure the panels are joined correctly. Counter to this point, however, is the plateau which occurs after the second peak, which is significantly shorter for a greater number of barrel panels. If additional care is needed for a greater number of barrel panels, then one would expect the plateau to follow the same trend as the peak. Ultimately, while a greater number of panels does increase the initial expenditure during Detailed Design, it also reduces the length of both Preliminary and Detailed Design phases. On a whole, the area under these curves shows that the total cost decreases as a function of increased division of the barrel section.

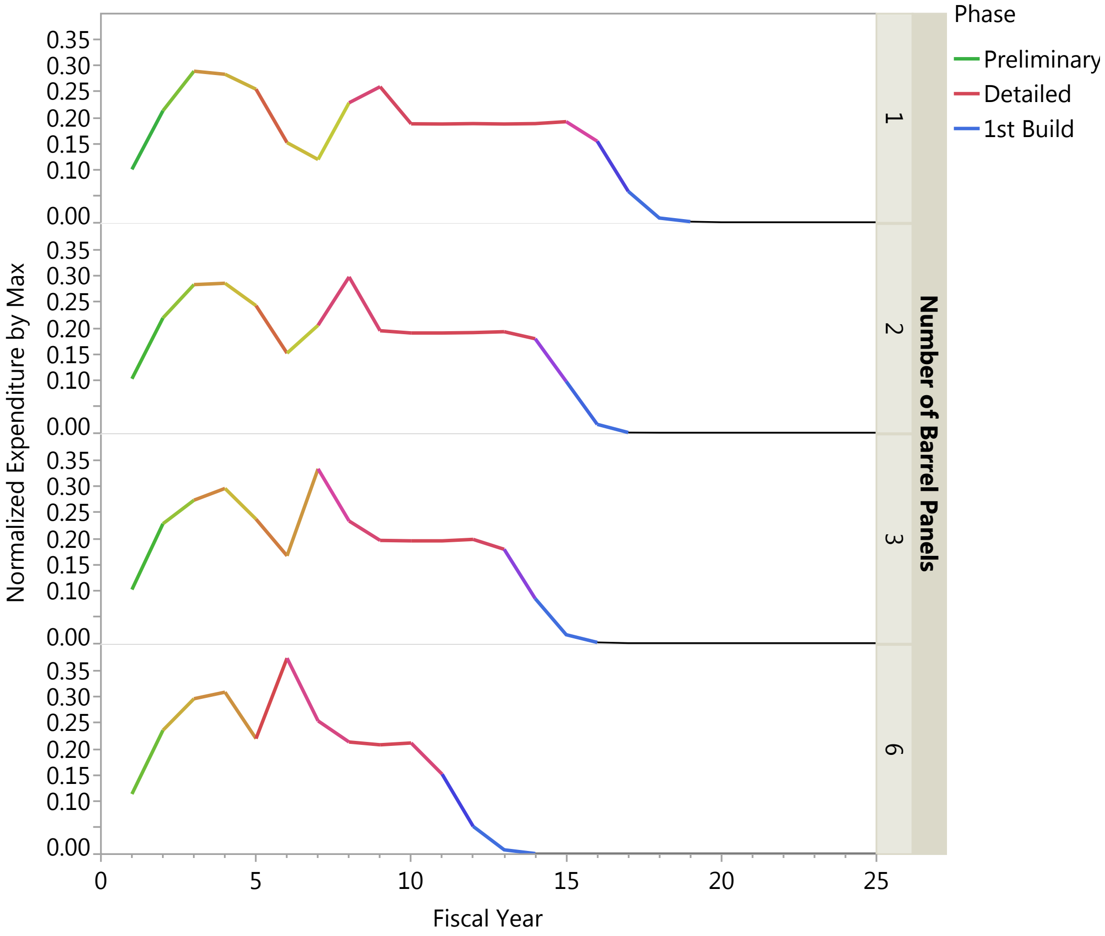


Figure 66: Mean Annual Expenditure as a Function of the Number of Barrel Panels

The final figure of interest is the annual expenditure as a function of TRL, shown in Figure 67. The trends shown herein are precisely as would be expected; the more mature concepts have shorter development cycles and peak sooner and less severely than the lower TRL counterparts. From an affordability only standpoint, one would select the most mature designs. That said, decision making is a multifaceted problem which, in this case, requires a balance of gross payload mass and affordability considerations.

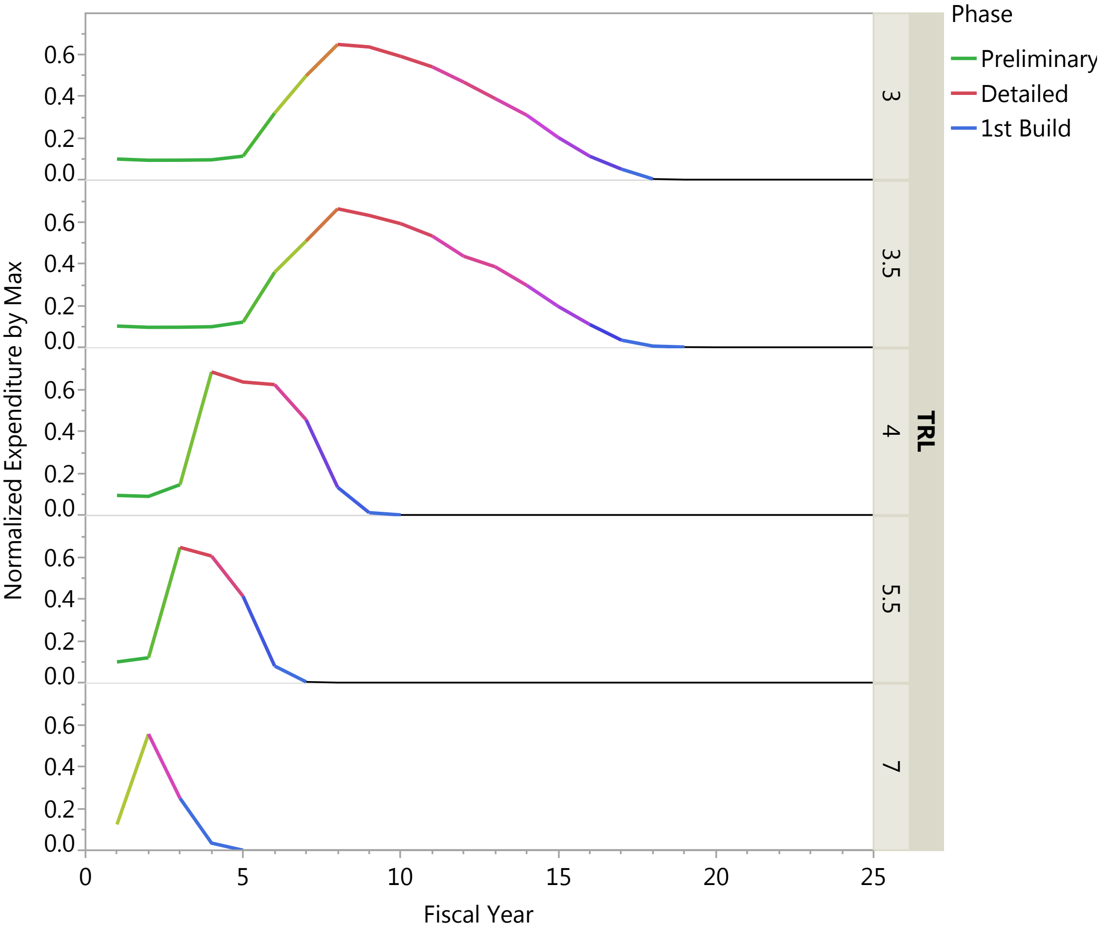
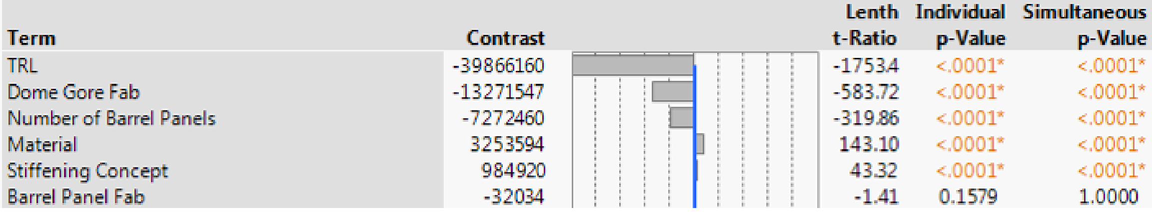


Figure 67: Mean Annual Expenditure as a Function of TRL

This in-depth analysis on tank affordability as a function of both design and manufacturing process culminates in relative importance of independent variables. The impact each attribute has on the variability of the response (in this case cost per phase and phase duration) is captured in the tornado plot shown in Figure 68.

The contrast depicts the estimate for each factor, where the sign represents the proportionality. The Length t-Ratio is the contrast normalized to remove the effects of insignificant variables, while the p-Value columns identify (by small values) the variables which have significant effects. This figure shows that TRL has the most significant effect on the response; followed by dome gore fabrication, number of barrel panels, material, stiffening concept, and barrel panel fabrication. Based upon the Length t-ratio and p-values, barrel panel fabrication is insignificant when compared to the other variables.



Term	Contrast	Lenth t-Ratio	Individual p-Value	Simultaneous p-Value
TRL	-39866160	-17534	<.0001*	<.0001*
Dome Gore Fab	-13271547	-583.72	<.0001*	<.0001*
Number of Barrel Panels	-7272460	-319.86	<.0001*	<.0001*
Material	3253594	143.10	<.0001*	<.0001*
Stiffening Concept	984920	43.32	<.0001*	<.0001*
Barrel Panel Fab	-32034	-1.41	0.1579	1.0000

Figure 68: Tornado Plot of Independent Variable Impact on Variability of Affordability

This concludes the first part of experiment 1; the aim of which is to determine whether a process-based cost tool (P-BEAT) can be adapted to provide affordability distributions (Research Question 1.1). The analysis presented shows that it indeed can provide temporal insight into cost expenditure, and that the overall trends match those presented in literature.

3.6.3.2 *Weibull Distribution Fit Analysis*

The second part of the experiment aims to establish a fit to the data using Weibull distribution curves, which have been established as more appropriate than Beta, and more flexible than Rayleigh [77]. The usefulness of such curves, if a regression is a good fit, is that any trustworthy cost estimate could be used to construct an annual expenditure curve and provide insight into the temporal nature of cost. The Weibull PDF and CDF are presented in Equations 22 and 23, respectively; where α and β dictate the shape of the distribution, and are restricted to positive values.

$$f(x) = \begin{cases} \alpha\beta x^{\beta-1}e^{-\alpha x^{\beta}}, & x > 0 \\ 0, & \text{elsewhere} \end{cases} \tag{22}$$

$$F(x) = \begin{cases} 1 - e^{-\alpha t^{\beta}}, & x > 0 \\ 0, & \text{elsewhere} \end{cases} \tag{23}$$

The procedure to determine a fit follows the multi-stage regression procedure presented by Burgess, and shown in Figure 69 [31]. A single stage regression approach, which Burgess discusses as an alternative, is not feasible in this case due to the existence of discrete input variables which drive the response. Furthermore, Burgess assumes a linear combination of variables to comprise the shape and scale parameters (α and β), this assumption would greatly constrain the search.

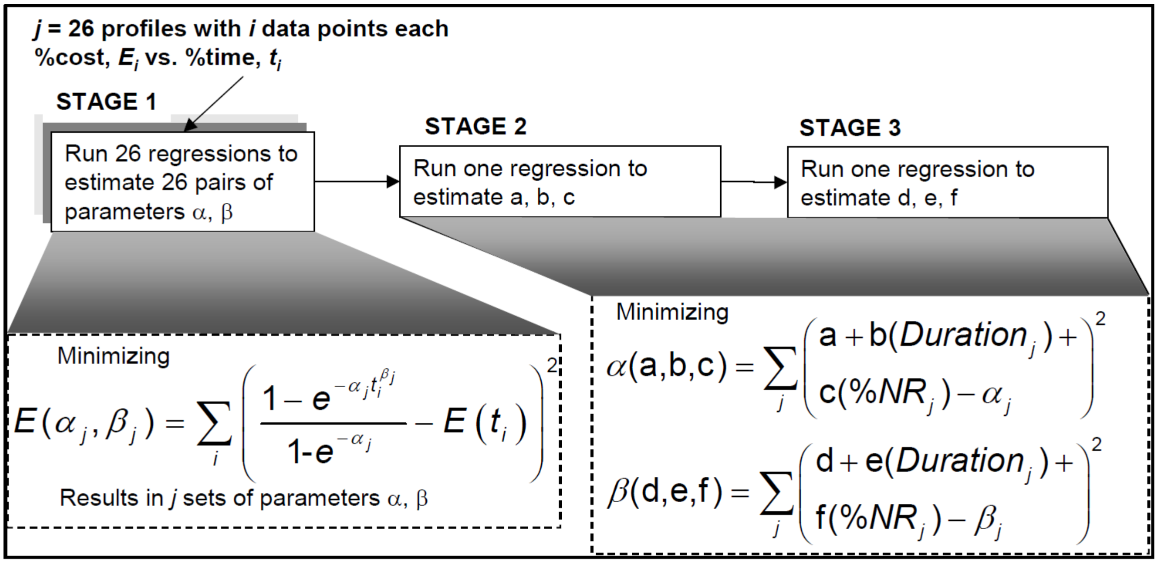


Figure 69: Multi-Stage Regression Procedure for a Candidate Weibull Distribution and Data for 26 Programs [31]

Fitting a Weibull model takes one of four forms. One could fit to either the CDF or PDF of annual expenditure, or the CDF or PDF of the expenditure per phase. Ideally the fit for annual expenditure and expenditure per phase would be a good for both the CDF and PDF. These four options are shown in Figure 70, for a random case selected from the 846 candidates used previously. This case will be propagated through this portion of the experiment to illustrate the general behavior experienced while attempting to fit various forms of Weibull distributions to the data.

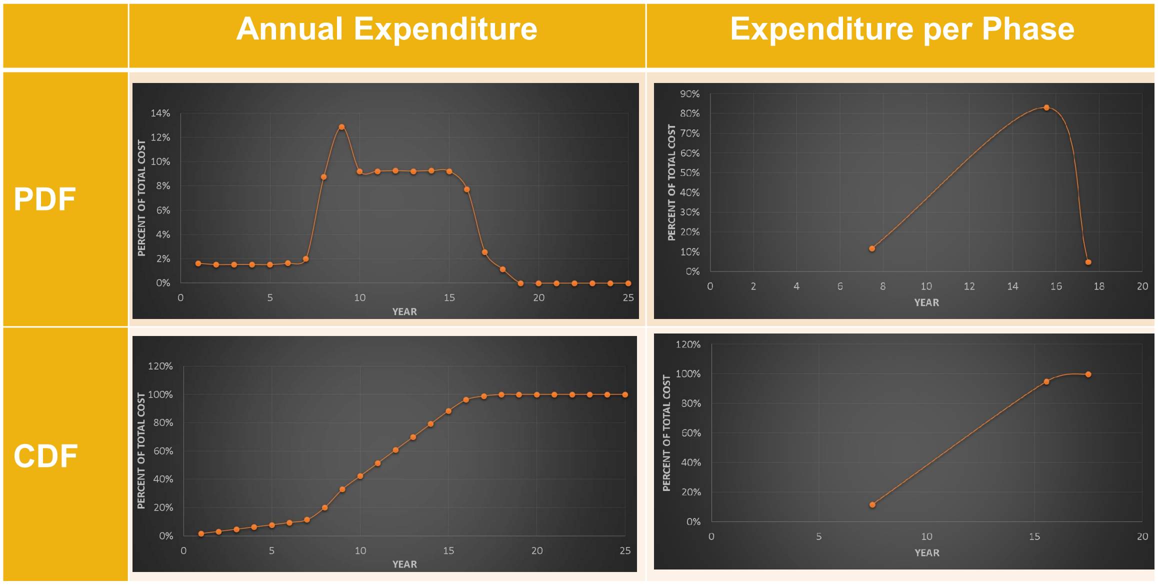


Figure 70: Options for Fitting Weibull Distributions

The annual expenditure for each case, as shown in Figure 59 shall be considered the Actual PDF for the purposes of distribution fitting, and the Actual CDF is achieved by summing the expenditure for subsequent years. Several approaches are attempted to find a unique set of α and β which adequately fit the data. First, an attempt to minimize the fit error of both the PDF and CDF was performed, followed by attempts to fit CDF and PDF separately. The actual distributions, best-in-class fits, and fit errors for the PDF and CDF are shown in Figures 71 and 72, respectively.

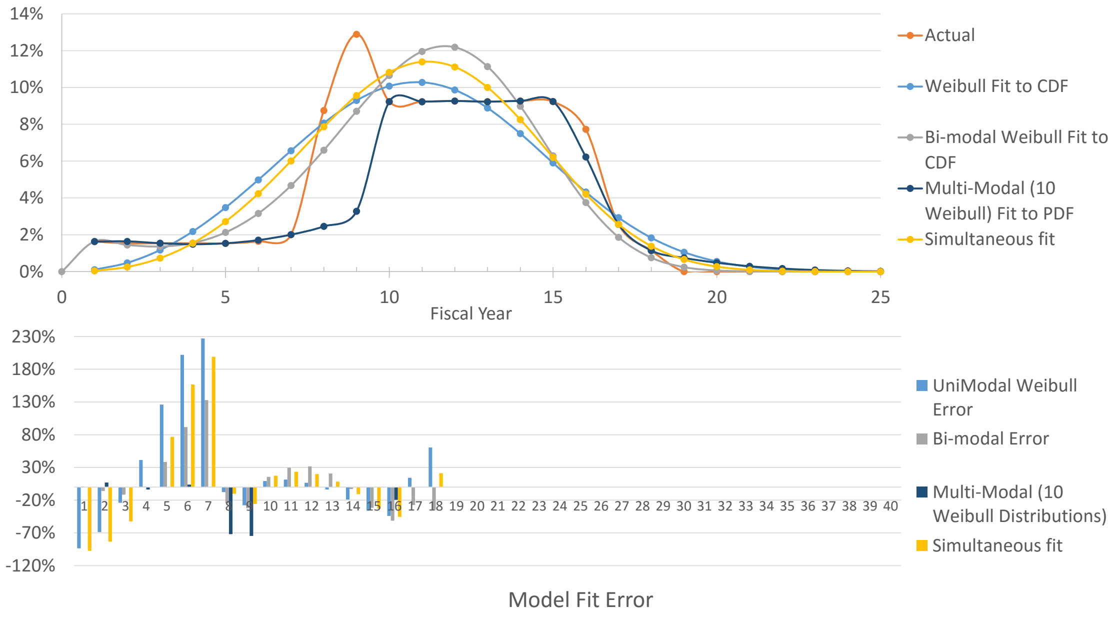


Figure 71: Attempted Weibull Distribution Fits to PDF

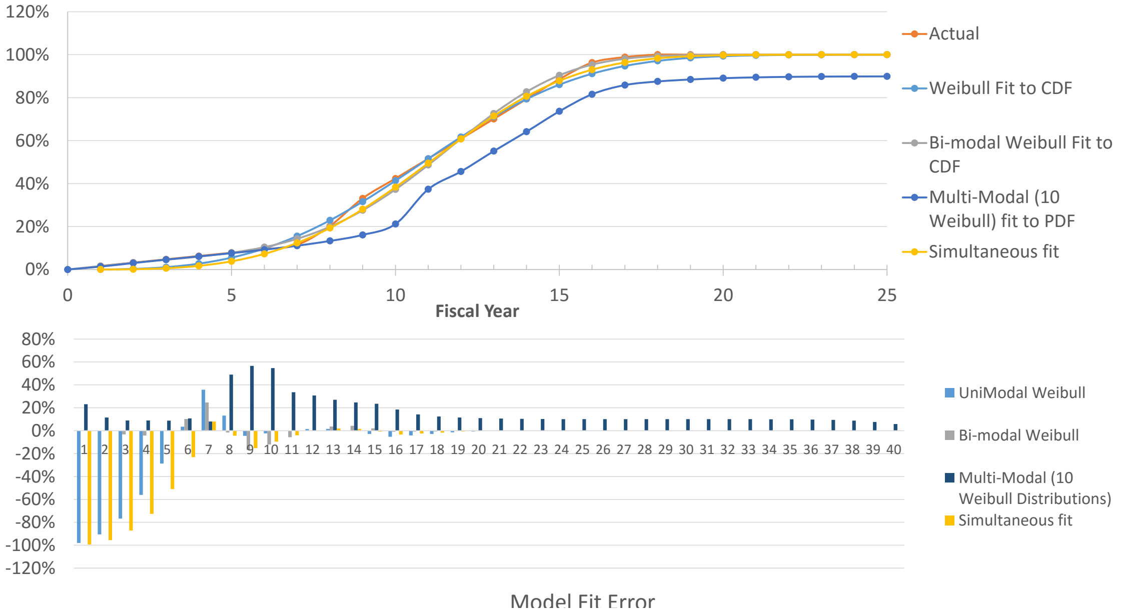


Figure 72: Attempted Weibull Distribution Fits to CDF

The fits, which aim to minimize error for Weibull PDF and CDF distributions simultaneously, performed poorly across the entire spectrum of fiscal years for both PDF and CDF. This trend is evident for all 846 cases, although some of the higher

TRL concepts achieve lower, but still unacceptable, error due to their unimodality. After exhausting the simultaneous fit option, focus turned to fitting uni-modal and bimodal Weibull distributions to the CDF only. The unimodal fits are as unsuccessful as the simultaneous fits; the error is still too large, albeit slightly better for the CDF.

A two-Weibull mixed distribution is used to perform a bimodal fit. Fundamentally, mixing distributions is simply adding unique weighted distributions together, where the weightings must sum to 1. While this provides additional flexibility, the number of parameters which must be estimated increases significantly. For the two-Weibull case the number of parameters jumps to six; an α and β for each distribution, as well as a weighting parameter for each. The mathematical representation of a mixed Weibull PDF is shown in Equation 24, where P_i represents the weighting parameter and f_i represents the PDF —described by α_i and β_i, respectively. The bimodal fits provide a significant error reduction for the CDF distribution, but achieve only a marginal improvement in describing the behavior of the actual PDF.

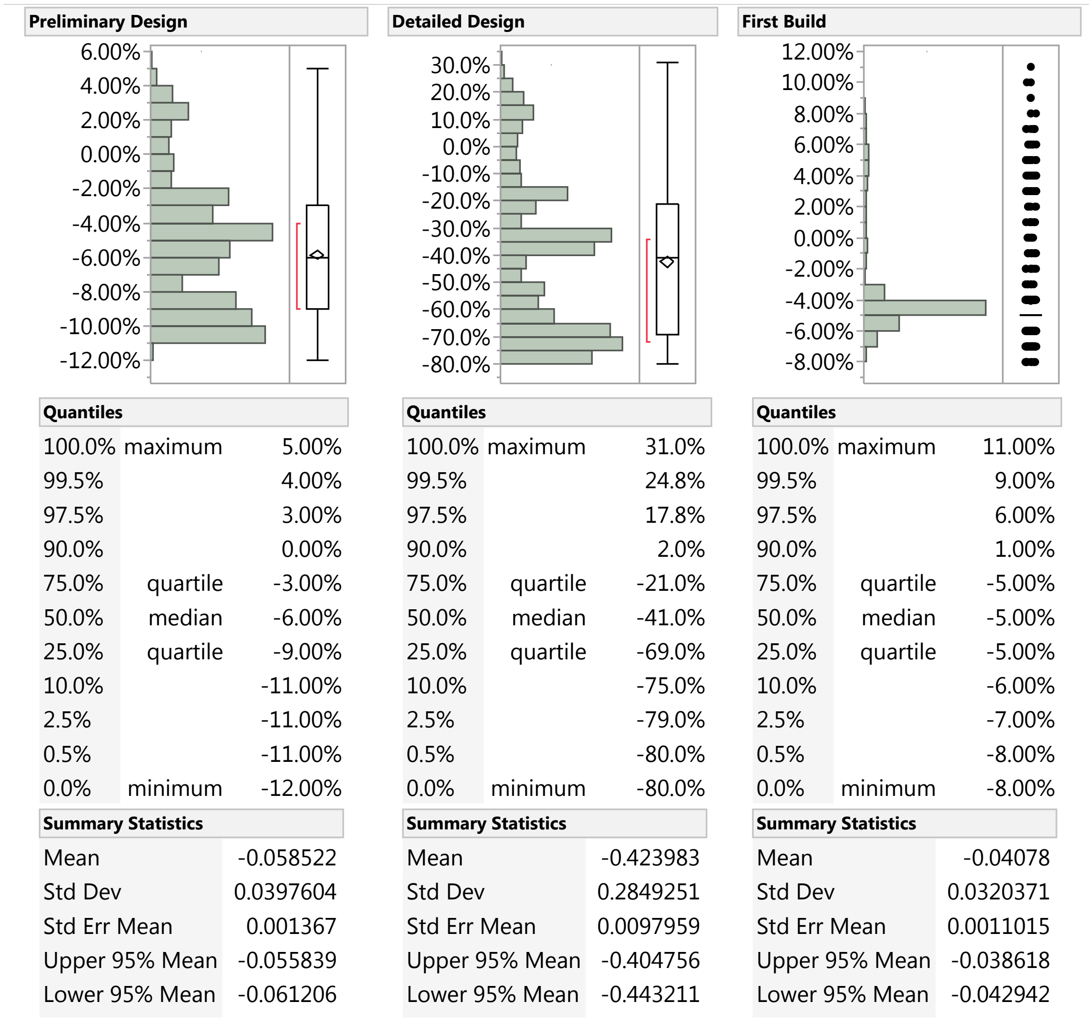
$$W(x, \alpha_1, \beta_1, P_1, \alpha_2, \beta_2, P_2, ...) = P_1 f_1 + P_2 f_2 + ..., where \sum_{i=1}^{N} P_i = 1 \tag{24}$$

In an attempt to significantly reduce the error in fitting to the PDF, and capturing the actual behavior, an extreme multimodal fit was attempted. A combination of ten Weibull distributions are mixed —such that each describes only a small portion of the horizontal axis. The reduction in error in the PDF is significant and captures a significant portion of the behavior. However, this reduction is still insufficient to capture the full fiscal behavior of cost.

At this point, expanding the mixed Weibull beyond 10 unique distributions is counterproductive due to the growth in parameters which must be regressed. For the ten distribution case a total number of 30 parameters (α's and β's and P's) must be estimated, this exceeds the number of independent variables (6) significantly. Clearly it is not feasible to achieve an adequate fit to the actual expenditure behavior with a reasonable number of mixed distributions. Thus the analysis shall shift to the phase expenditure and milestone regressions.

For assessing the phase attributes the points in Figure 57 are those to which a fit will be attempted. The curve which comprises this PDF (and CDF) is comprised of just three points, each described by a time and percent expenditure — where the CDF is the cumulative sum of the PDF points up to each time increment. While the exercise in fitting the annual expenditure sought to provide the program manager insight into expenditure behavior, it did not explicitly facilitate determining the approximate duration and expenditure incurred during each phase. This insight is beneficial for planning the periodic reviews and decision points described in Section 2.2. The CDF, within this analysis, is not particularly meaningful and thus this exercise focuses on fitting to the PDF, which provides the year in which each phase is completed, and the percent of the total expenditure incurred during each phase.

Initial attempts at fitting a Weibull distribution (described by Equation 22) provided less than acceptable error, particularly for the Detailed Design phase. The Weibull distribution under-predicted across the board; with an average error -5.8%, -42.3%, and -4.1% for Preliminary Design, Detailed Design, and First Build, respectively. The standard deviation of these errors is also particularly high; at ±4%, ±28%, and ±2%, respectively. The summary statistics for the error of the best-in-class Weibull fits is shown in Figure 73. These best-in-class fits are a result of several Excel Solver attempts to minimize these errors. A single case, the same as that presented in the previous portion of this experiment, is shown in Figure 74, along with its best-in-class fit.



Preliminary Design

Quantiles

100.0%	maximum	5.00%
99.5%		4.00%
97.5%		3.00%
90.0%		0.00%
75.0%	quartile	-3.00%
50.0%	median	-6.00%
25.0%	quartile	-9.00%
10.0%		-11.00%
2.5%		-11.00%
0.5%		-11.00%
0.0%	minimum	-12.00%

Summary Statistics

Mean	-0.058522
Std Dev	0.0397604
Std Err Mean	0.001367
Upper 95% Mean	-0.055839
Lower 95% Mean	-0.061206

Detailed Design

Quantiles

100.0%	maximum	31.0%
99.5%		24.8%
97.5%		17.8%
90.0%		2.0%
75.0%	quartile	-21.0%
50.0%	median	-41.0%
25.0%	quartile	-69.0%
10.0%		-75.0%
2.5%		-79.0%
0.5%		-80.0%
0.0%	minimum	-80.0%

Summary Statistics

Mean	-0.423983
Std Dev	0.2849251
Std Err Mean	0.0097959
Upper 95% Mean	-0.404756
Lower 95% Mean	-0.443211

First Build

Quantiles

100.0%	maximum	11.00%
99.5%		9.00%
97.5%		6.00%
90.0%		1.00%
75.0%	quartile	-5.00%
50.0%	median	-5.00%
25.0%	quartile	-5.00%
10.0%		-6.00%
2.5%		-7.00%
0.5%		-8.00%
0.0%	minimum	-8.00%

Summary Statistics

Mean	-0.04078
Std Dev	0.0320371
Std Err Mean	0.0011015
Upper 95% Mean	-0.038618
Lower 95% Mean	-0.042942

Figure 73: Fitting Error for Weibull Distribution for Each Design Phase

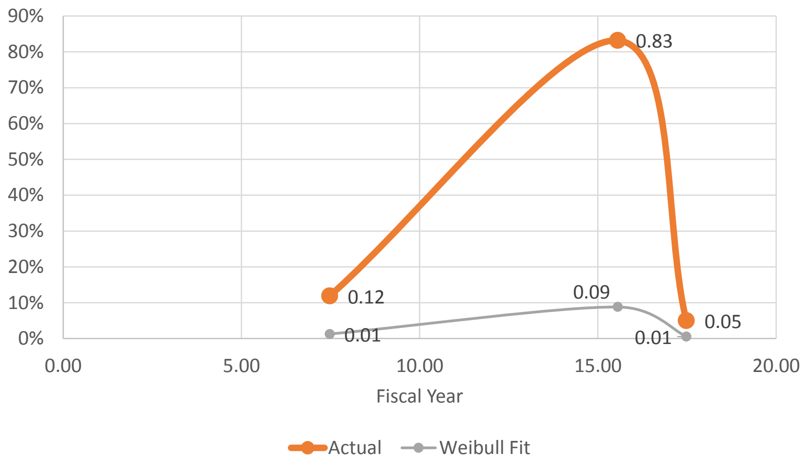


Figure 74: Weibull Distribution Fit to Phase Milestones and Expenditure PDF

Upon inspection of the visual representation of the Weibull distributions, shown above, it is clear that the extreme increase in percent expenditure incurred from Preliminary Design to Detailed Design is the main failing of fitting a single Weibull distribution. Furthermore, the number of points available with which to fit, greatly limits the ability to leverage mixed distributions — for fear of over-fitting the data. A beta distribution was also used, alas the error was considerably worse than the Weibull. Surprisingly, however, normalizing the Weibull distribution values by the sum of the sum of the discrete values yielded rather interesting results.

The same Weibull distributions, a single case is shown in Figure 74, was leveraged in a discrete fashion which yields interesting results. Since only 3-points are being used to describe the behavior, the problem lies more in the discrete realm than the continuous —in which the Weibull distribution is based. If one takes each of the discrete values and normalizes those by their sum, the values are adjusted significantly. For the Weibull distribution, this adjustment results in a massive reduction of fitting error; for the Beta distribution this simply shifts the error between points, with no significant fitting improvement. The PDF for these four distributions (actual, Weibull, Adjusted Weibull and Adjusted Beta) is shown in Figure 75, and the CDFs — simply a cumulative sum of the discrete PDF points — is shown in Figure 76

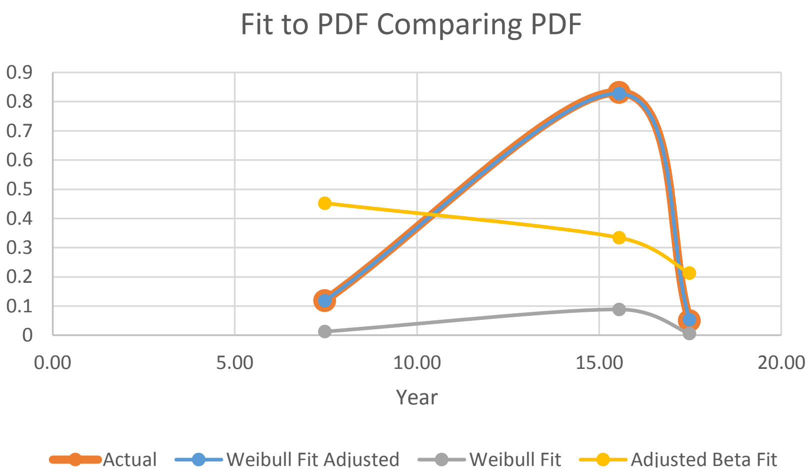


Figure 75: Options for Fitting Weibull Distributions to Phase Milestones and Expenditure PDF

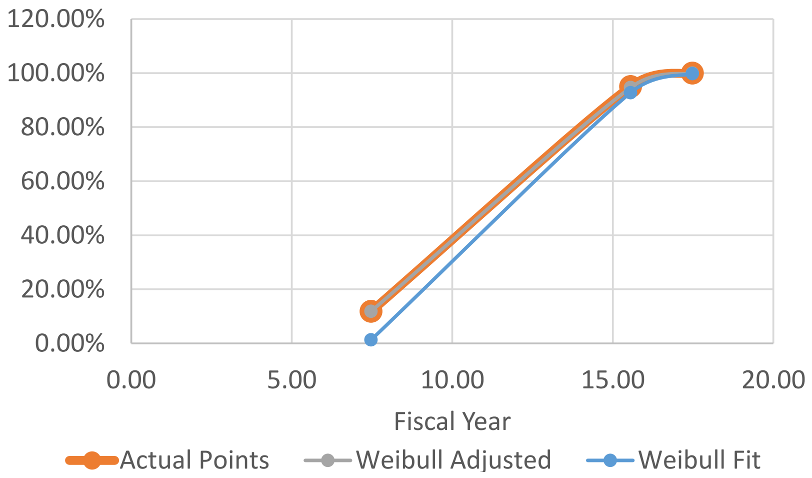
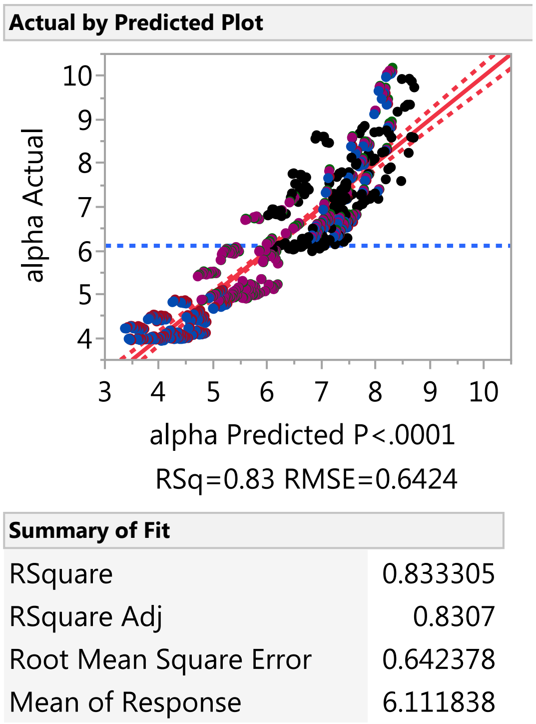


Figure 76: Options for Fitting Weibull Distributions to Phase Milestones and Expenditure CDF

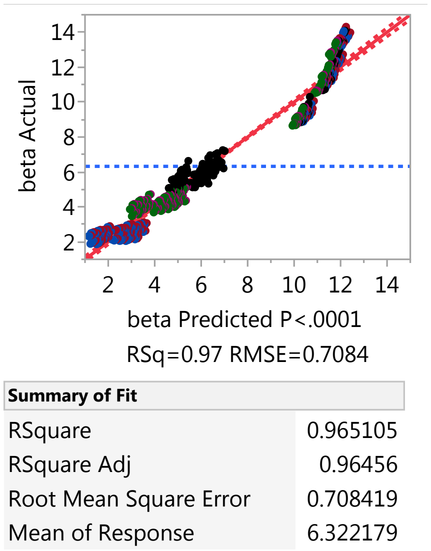
Establishing that a normalized Weibull distribution sufficiently fits the data, a regression analysis for the Weibull shaping parameters is necessary. An initial linear regression of the independent variables was used to test Burgess' assumption of a linear relationship. Figure 77 and 77 show the actual by predicted plots and summary statistics for this linear fit attempt. The R^2 values for α and β are 0.83 and 0.96, respectively; which is unacceptably low. The actual by predicted plots shows very poor prediction capability with a significant number of points deviate from the 45 degree line.



Summary of Fit

RSquare	0.833305
RSquare Adj	0.8307
Root Mean Square Error	0.642378
Mean of Response	6.111838

Figure 77: Actual by Predicted Plot and Summary Statistics for Linear Fit to α



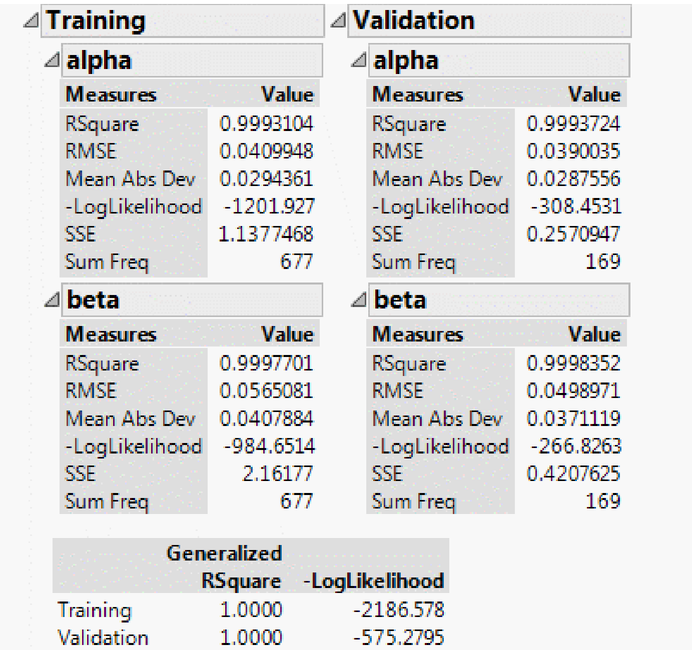
Summary of Fit

RSquare	0.965105
RSquare Adj	0.96456
Root Mean Square Error	0.708419
Mean of Response	6.322179

Figure 78: Actual by Predicted Plot and Summary Statistics for Linear Fit to β

A second order polynomial fit was then attempted, which improved the R^2 value for both significantly but failed to improve the prediction capability. Hereafter a neural network fit was performed which was successfully able to capture predict the trends. The fit was performed using a k-fold method with five folds. The method randomly bins the data (in this case 846 cases into five bins) and performs a series of network training and validation analyses. For each of these, four folds are used to train the network and the fifth is used to validate the trained network. This process is performed k-times where a different set is excluded from training and used for validation each time. The resultant fit is selected based upon the validation R^2 value, where constraints are used to prevent over-fitting

The resulting Neural Network summary statistics, actual by predicted plot, and residual by predicted plot are shown in Figures 79, 80, and 81, respectively. The R^2 values are acceptable with three 9's, which suggests the 99.9% of the response variation is captured by this fit. The actual by predicted plot depicts points which very closely follow a 45 degree line, suggesting that the predictive ability is very good. The residual by predicted plot shows the dispersion of the magnitude of the residuals for all 846 cases. From this plot, the maximum error can be extracted by locating the extreme point(s) and computing the ratio of y-to-x values. The desire here is for the y-axis to be at least one order of magnitude lower than the x-axis. Figure 81 shows that the maximum error for is approximately $-0.2/8.5\ -2\%$ and $-0.25/5.75\ -4\%$ α and β, respectively. It is necessary to point out that data clumping does exist within these plots, which is attributable to the presence of several discrete variables as opposed to the presence of a single dominant variable.



Training

alpha

Measures	Value
RSquare	0.9993104
RMSE	0.0409948
Mean Abs Dev	0.0294361
-LogLikelihood	-1201.927
SSE	1.1377468
Sum Freq	677

beta

Measures	Value
RSquare	0.9997701
RMSE	0.0565081
Mean Abs Dev	0.0407884
-LogLikelihood	-984.6514
SSE	2.16177
Sum Freq	677

Validation

alpha

Measures	Value
RSquare	0.9993724
RMSE	0.0390035
Mean Abs Dev	0.0287556
-LogLikelihood	-308.4531
SSE	0.2570947
Sum Freq	169

beta

Measures	Value
RSquare	0.9998352
RMSE	0.0498971
Mean Abs Dev	0.0371119
-LogLikelihood	-266.8263
SSE	0.4207625
Sum Freq	169

	Generalized RSquare	-LogLikelihood
Training	1.0000	-2186.578
Validation	1.0000	-575.2795

Figure 79: Summary Statistics for Neural Network Fit to α and β

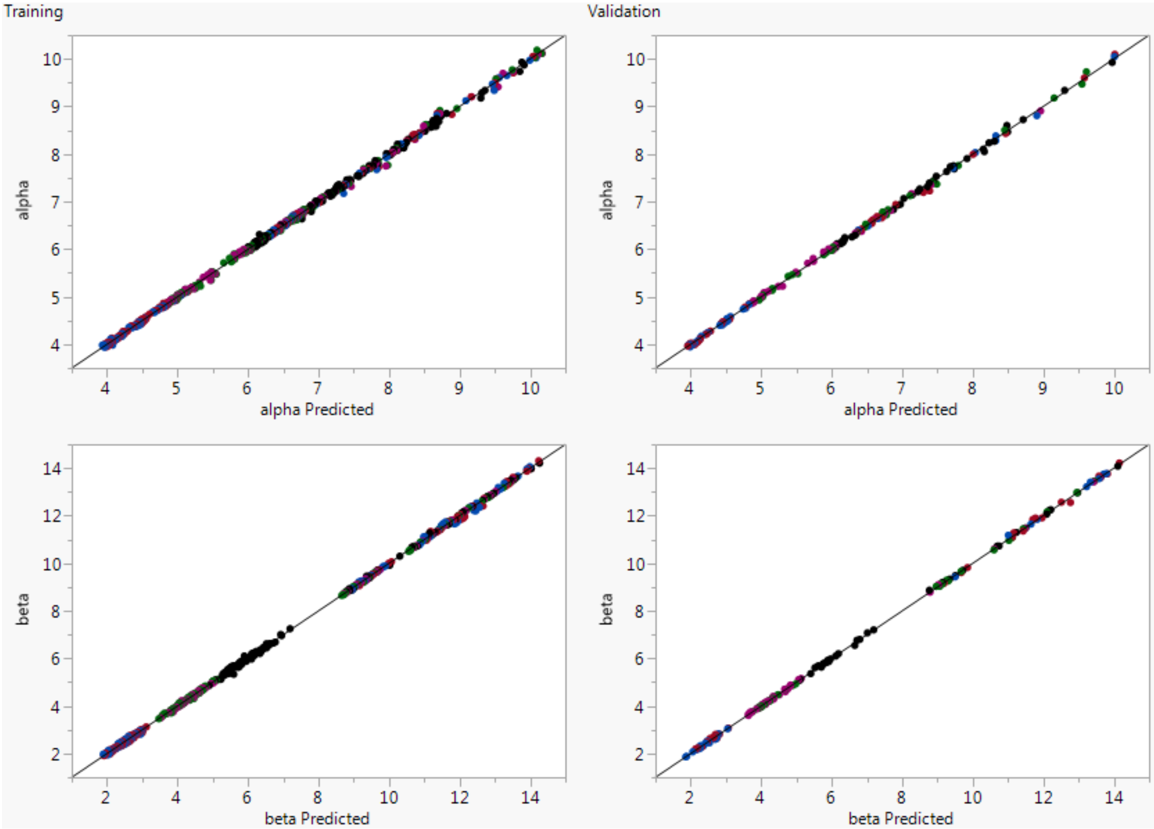


Figure 80: Actual by Predicted Plot for Neural Network Fit to α and β

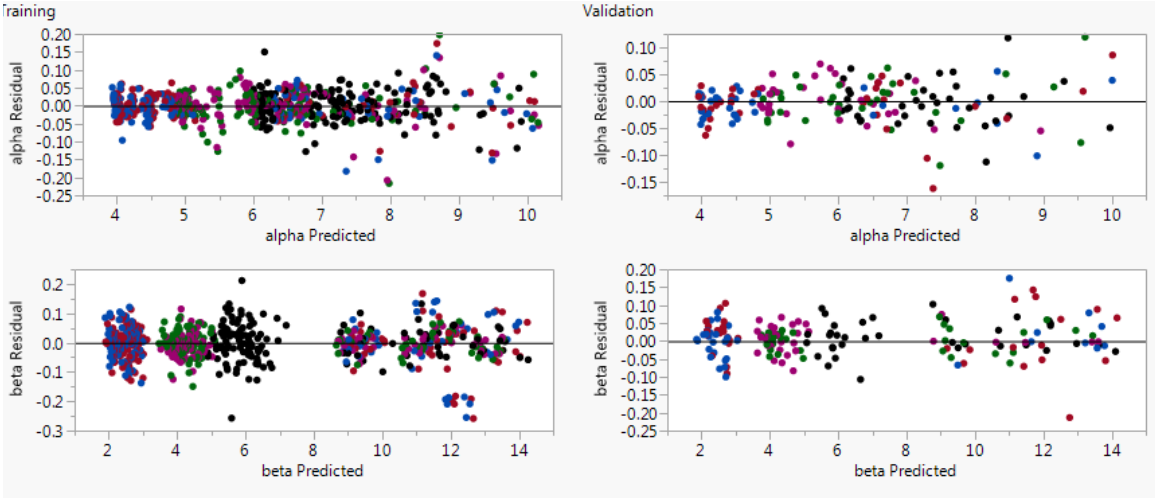
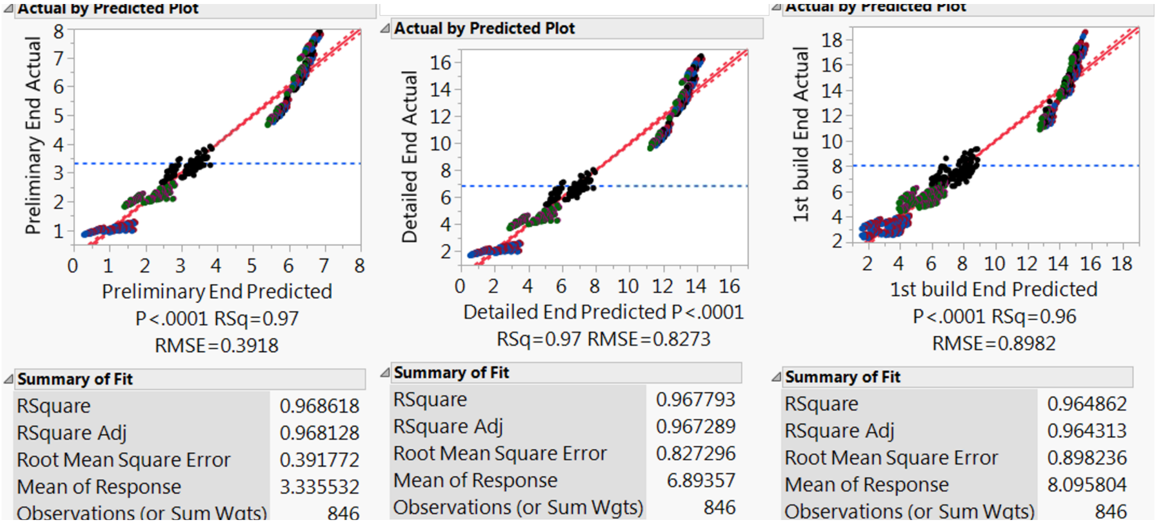


Figure 81: Residual by Predicted Plot for Neural Network Fit to α and β

The neural network equations — found in Appendix B — may be used to generate the Weibull curve, which when normalized by the appropriate discrete values, provides a forecast of the expenditure incurred during each phase. The focus of this analysis now turns to the estimation of the time values (i.e. the end of the three phases) which is needed to estimate the cost incurred during each phase. Once again the analysis began with an attempt to determine an appropriate linear fit to the fiscal year in which Preliminary Design, Detailed Design, and First Build phases end.

The best-in-class linear fit was able to capture approximately 97% of the variability of the response (determined from R^2 values) but exhibited large deviations in the actual by predicted plot. The summary statistics and actual by predicted plot for the linear case is shown in Figure 82. As a result, a linear fit has been deemed inappropriate, and a second-order polynomial fit was attempted.



Summary of Fit

RSquare	0.968618
RSquare Adj	0.968128
Root Mean Square Error	0.391772
Mean of Response	3.335532
Observations (or Sum Wgts)	846

Summary of Fit

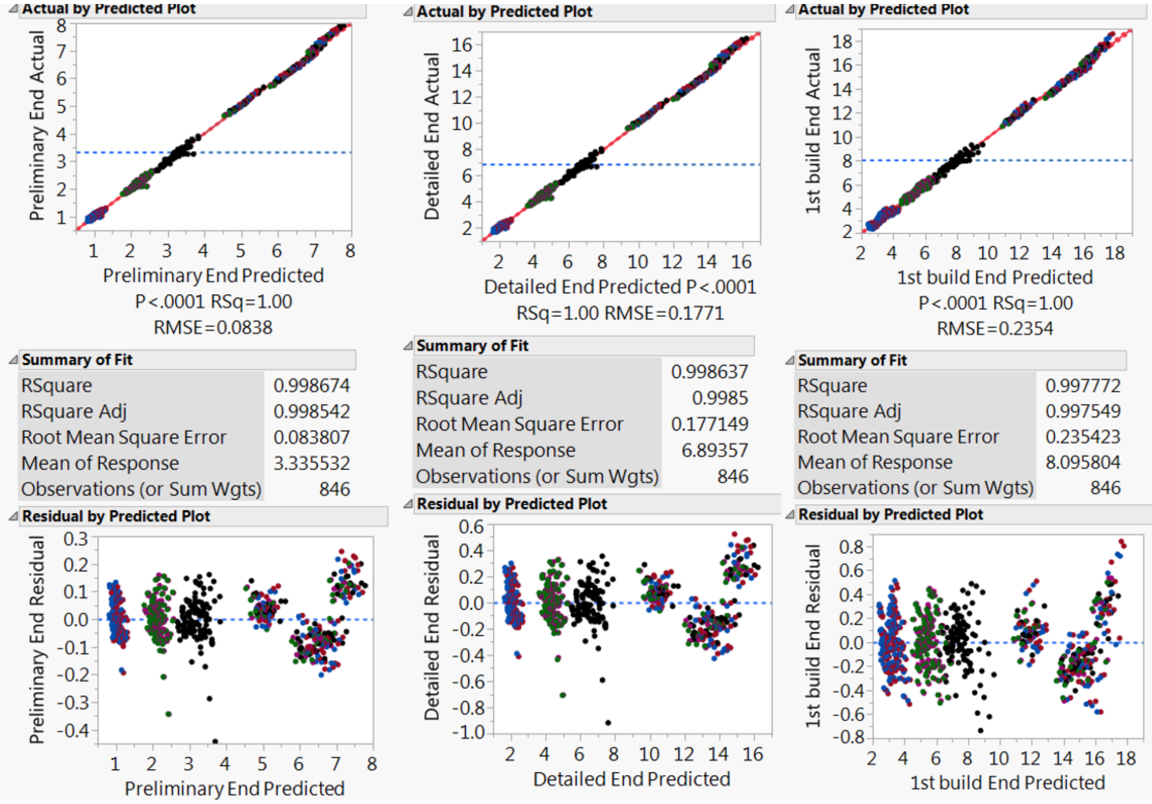
RSquare	0.967793
RSquare Adj	0.967289
Root Mean Square Error	0.827296
Mean of Response	6.89357
Observations (or Sum Wgts)	846

Summary of Fit

RSquare	0.964862
RSquare Adj	0.964313
Root Mean Square Error	0.898236
Mean of Response	8.095804
Observations (or Sum Wgts)	846

Figure 82: Actual by Predicted Plot and Summary Statistics for Linear fits to End of Preliminary Design, Detailed Design, and First Build Phases

The second order polynomial fit results were surprisingly accurate, with R^2 values of 0.998. The prediction behavior for these fits very closely follows the 45-degree line in the actual by predicted plot, and the residuals are relatively low, shown in Figure 83. The residual plots are, once again, clumped; the three leftmost clumps are the material variations for stretch and peen formed domes and very neatly show the material groups that are also present in the previously presented scatterplot matrices. The rightmost groups are all one-piece dome configurations where the left clump represents 6-piece barrel panels, the upper right clump represents a one-piece barrel panel, and the lower right represents two and three piece barrels. These clumpings — a different perspective on the results presented in Figure 66 — show that 6-piece barrels tend to complete each design phase one to two years sooner than the fewer panel configurations. The maximum residual for Preliminary and Detailed Design, is an outlier titanium concept whose dome is not a single piece. For the end of First Build, however, several 2024 and 2219 one-piece spun form dome concepts exceed the titanium outlier.



Summary of Fit

RSquare	0.998674
RSquare Adj	0.998542
Root Mean Square Error	0.083807
Mean of Response	3.335532
Observations (or Sum Wgts)	846

Summary of Fit

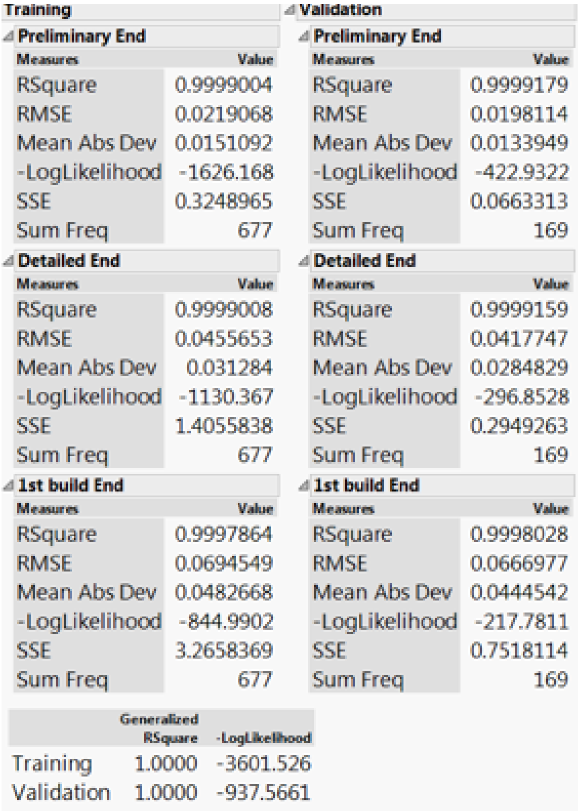
RSquare	0.998637
RSquare Adj	0.9985
Root Mean Square Error	0.177149
Mean of Response	6.89357
Observations (or Sum Wgts)	846

Summary of Fit

RSquare	0.997772
RSquare Adj	0.997549
Root Mean Square Error	0.235423
Mean of Response	8.095804
Observations (or Sum Wgts)	846

Figure 83: Actual by Predicted Plot, Summary Statistics, and Residual by Predicted for Second Order Polynomial fits to End of Preliminary Design, Detailed Design, and First Build Phases

While the second order fit may be deemed adequate, the extreme points in the residual by predicted points are borderline excessive. In an attempt to reduce these, a series of Neural Network fits have been attempted and the best-in-class shall be presented. The generation of this Neural network also leverages the k-fold cross-validation method used previously, the summary statistics, actual by predicted plots, and residual by predicted plots are shown in Figures 84, 85, and 86, respectively.



Training

Preliminary End

Measures	Value
RSquare	0.9999004
RMSE	0.0219068
Mean Abs Dev	0.0151092
-LogLikelihood	-1626.168
SSE	0.3248965
Sum Freq	677

Detailed End

Measures	Value
RSquare	0.9999008
RMSE	0.0455653
Mean Abs Dev	0.031284
-LogLikelihood	-1130.367
SSE	1.4055838
Sum Freq	677

1st build End

Measures	Value
RSquare	0.9997864
RMSE	0.0694549
Mean Abs Dev	0.0482668
-LogLikelihood	-844.9902
SSE	3.2658369
Sum Freq	677

Validation

Preliminary End

Measures	Value
RSquare	0.9999179
RMSE	0.0198114
Mean Abs Dev	0.0133949
-LogLikelihood	-422.9322
SSE	0.0663313
Sum Freq	169

Detailed End

Measures	Value
RSquare	0.9999159
RMSE	0.0417747
Mean Abs Dev	0.0284829
-LogLikelihood	-296.8528
SSE	0.2949263
Sum Freq	169

1st build End

Measures	Value
RSquare	0.9998028
RMSE	0.0666977
Mean Abs Dev	0.0444542
-LogLikelihood	-217.7811
SSE	0.7518114
Sum Freq	169

	Generalized RSquare	-LogLikelihood
Training	1.0000	-3601.526
Validation	1.0000	-937.5661

Figure 84: Summary Statistics for Neural Network Fit to End of Preliminary Design, Detailed Design, and First Build Phases

The R^2 value for the neural network is improved slightly, capturing an additional 0.99% of the variation of the response. The root mean square of the error (RMSE) is also significantly better, suggesting that fitting error has been reduced. Inspection of the actual by predicted and residual plots will provide more insight into the impact on the error.

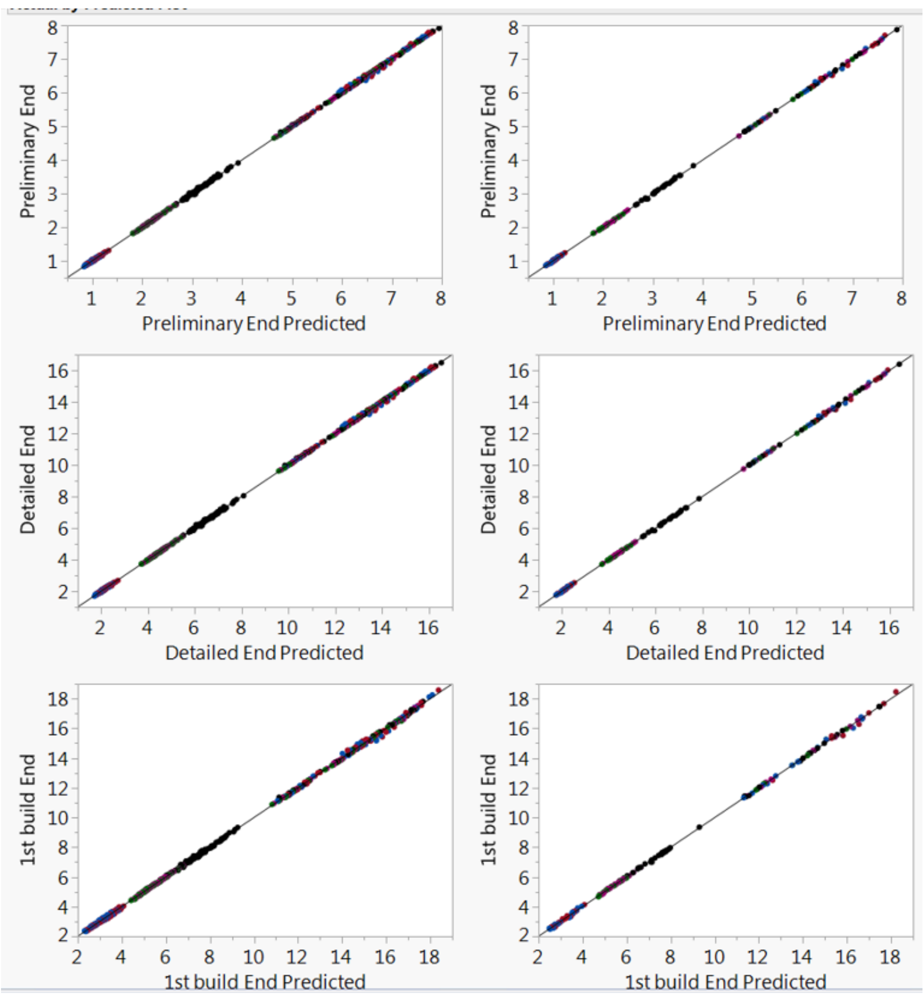


Figure 85: Actual by Predicted Plot for Neural Network Fit to End of Preliminary Design, Detailed Design, and First Build Phases

In comparing the actual by predicted plots for the neural network and polynomial fits — Figures 85 and 80, respectively — it is evident that fewer points deviate from the 45-degree line. Similarly, comparing the residual by predicted plots the maximum error for the Neural Network is approximately 5% as compared to 20% for the polynomial fit (aluminum concept, Preliminary Design end for both fits). The Neural Network fit has reigned in the error on many of the non one-piece dome concepts, with fewer outliers when compared to the polynomial fit. The Neural Network is, statistically speaking, the better of the two fits.

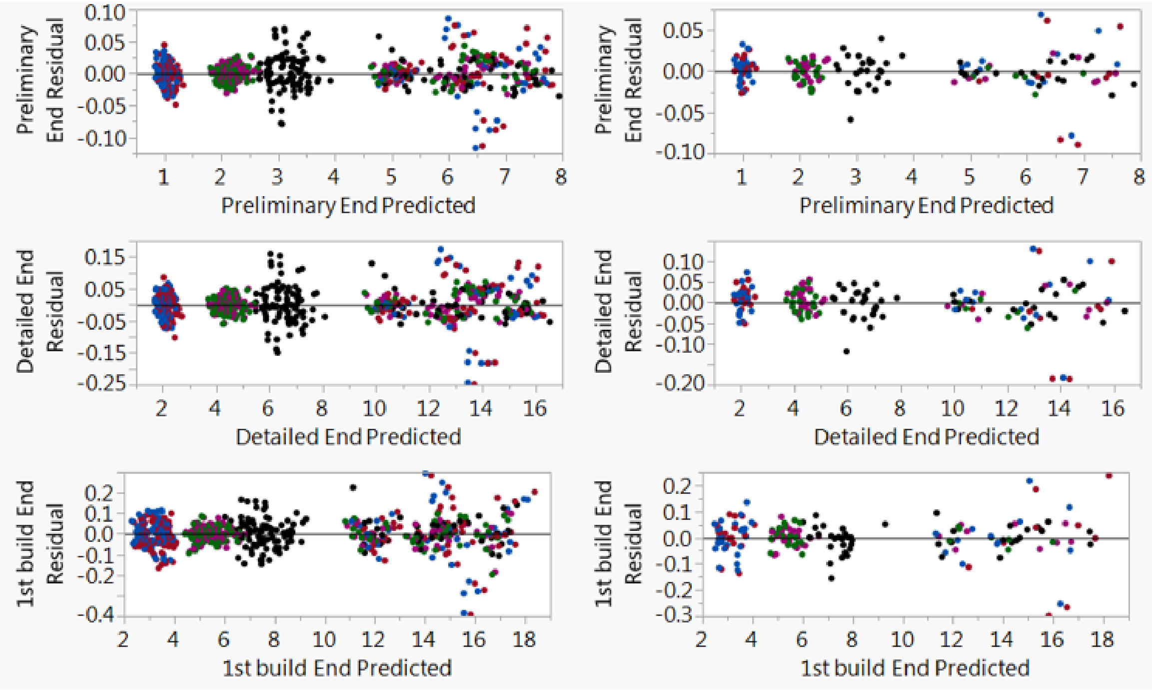


Figure 86: Residual by Predicted Plot for Neural Network Fit to End of Preliminary Design, Detailed Design, and First Build Phases

The end of phase fits would be used in conjunction with the α and β fits used to generate a Weibull distribution which describes spending per phase.

3.6.3.3 Experiment 1 Summary

Experiment 1 tested the adaptation of process-based cost estimation to generating affordability distributions for the key elements which comprise a launch vehicle stage. P-BEAT — selected for its accessibility and applicability to launch vehicles — has been adapted to generate affordability distributions for an element. **Hypothesis 2.1a may be accepted** on account that the desired affordability distributions may be generated when additional information is extracted from within a process-based cost estimating tool. Furthermore, a sensitivity analysis has been performed, which has resulted in a few interesting observations. Design TRL variations bear the greatest impact on the variability of the affordability curves when mature processes are leveraged. However, if an immature process is used — as in the case of fabricating a single-piece spun formed dome— the process becomes the largest contributor to expansion of the affordability curve. While comparisons between matured processes do not yield affordability driving characteristics, **distinct differences in distributions are evident.** Additionally, increasing the number of panels which comprise the barrel section greatly impacts the shape of the affordability distribution; where increasing the number decreases total cost and duration, as well as decreasing phase duration.

Hypothesis 2.1b, on the other hand, must be rejected. The experimentation herein includes the consideration of both single and mixed Weibull distributions in an attempt to capture the multi-modality of low TRL concepts. None of the fits attempted are capable of capturing the annual expenditure behavior (PDF) with acceptably low error. Furthermore, the mixed Weibull distributions require 3n parameters (and α, β, and P) to describe the shape of the distribution. With only 7 independent variables considered, leveraging more than 2 Weibull distributions may be considered an under-constrained problem. As such a surrogate model, leveraging a Weibull distribution or a mixture of up to ten Weibull distributions, is unattainable.

3.7 Experiment 2: Integration Phase Estimating Relationships

3.7.1 Purpose

The purpose of experiment 2 is to test Hypothesis 2.3 by determining the appropriate method of estimating element integration in P-BEAT and assessing whether an appropriate Weibull PER may be used to describe the distributions behavior as a function of time.

3.7.2 Approach

To begin, it is necessary to include a brief discussion on testing and rework. As mentioned in Section 3.4.8, once integrated the first article will undergo a significant amount of testing. A duration of one year has been assumed based upon testing performed on the STS program. This assumption is mapped to a "Qualification Test Duration" input in P-BEAT. Rework comes in two forms, planned and unplanned. A literature review of rework, performed by Sudol[215], yields three primary drivers:

1. Project/system complexity
2. Early communication between design teams
3. Resource Constraints

While various methods exist to categorize and capture rework, both planned and unplanned, P-BEAT actually includes consideration for both types of rework partially in the consideration of design iterations. In general, P-BEAT assesses the technical readiness, design maturity, and overall complexity of a system or element. The greater the design challenge the more design iterations should be expected. P-BEAT provides the ability for the user to input a specific number of design iterations, in the absence of user input a built in calculation is used to capture rework. For the case of a cryogenic tank, the number of design iterations calculated by P-BEAT is between two and three. The provided estimate for first article fabrication includes the consideration of rework and repair dispositions. Thus P-BEAT captures an appropriate amount of rework via the consideration of the complexity of the system/element being estimated and includes this in the estimate for labor hours and cost. The MInD methodology embodies early communication not only between design teams, but also between the designers and fabricators. The premise of this thesis is to bring in the consideration of resource constraints on the affordability of a system.

The fundamental discussion around which this experiment revolves requires a revisitation of the notion of TRL presented in Section 3.4.8. P-BEAT requires the use of a technology readiness level to estimate the maturity of the system/element being estimated. As such, it is necessary to determine the appropriate TRL which describes the system. The review on TRL applicability to a system culminated either using Bilbro's stance — where the the system TRL is equal to the TRL of its least mature constituent — or creating a new, calibrated scale based on established TRL scales.

Hypothesis 2.3 states the desire to consider the form, fit, and function of the each element, and the need to capture material composition. Form and fit is captured explicitly through the use of parametric CAD/FEA in the EUS MInD methodology. The structural optimization and aerodynamics analysis loops provide the function of the system and the elements which comprise it. Material composition would need be defined within P-BEAT, where the analogous system was defaulted to the integration of a new aircraft system, which is included in the P-BEAT program database[4].

At the start of integration, it is assumed that the elements (tanks, dry structure, etc.) are complete and ready to be assembled and integrated into the final vehicle. Furthermore, this analysis excludes consideration for manufacturing variability and assumes all elements are as-designed. For the purposes of P-BEAT's labor considerations, the number of workers performing integration design work is equal to the sum of the workers used for each element. Alluding to the notion that integration is a flowed down requirement and that all teams must communicate and consider cohesion between adjacent elements and the system as a whole. Additionally, the degrees of freedom available with which to regress are further limited, from those listed in Tables 11 and 12, and include material, number of barrel panels and panel stiffening concepts only. This reduction in the space is a result of several assumptions made which disallow any differentiation in mass of each element. Thus the number of distinct concepts is reduced from 846 to 49, this includes two composite concepts

---

[4] While the author concedes that aircraft assembly and launch vehicle assembly are quite different, lack of sufficient data to compile a reasonable launch vehicle assembly analogy point necessitates the use of the aircraft model.

fabricated from IM7/977-2 [112]. One unstiffened, and one with a honeycomb sandwich concept; where both are assumed fabricated from Automated Fiber Placement (AFP) and cured in an autoclave[5]. Additionally, the material selection for the other eleven elements has been established — in conjunction with SME input — such that the composition is approximately 0% Aluminium, 50% Composite, 40% Aluminium-Lithium, and 10 % Titanium. These percentages are based upon element count and not volume or percent mass.

3.7.3 Results

The first portion of these results is a presentation of expected integration affordability distributions if the TRL of the system is assumed — per Bilbro [14] — to be the TRL of the lowest component. The second part is a discovery exercise aimed at discerning a system-level TRL from the existing scales.

3.7.3.1 System TRL represented by least mature element

As previously mentioned, the degrees of freedom available at the onset of system integration reduces the number of distinct cases to 49. While each of these 49 cases represent a distinct design weight, resulting from variations in number of panels and stiffening concept, the number of distinct TRLs is dependent on the materials and whether the dome is formed as a single spun-formed piece. Table 13 lists the fuel tank TRL's, which shall be used to represent the system. For this study, the fuel tank is assumed to be the least mature of the twelve elements, enumerated in Section 3.4.7.

---

[5] While this required autoclave would be vast in both size and cost, these are not beyond the reach of todays capability. Boeing recently added a 28ft diameter, by 120 feet long autoclave to their Everett facility to cure 777x wings [25, 24]. An autoclave for an for upper stage tanks would need to be greater in diameter, but could be significantly shorter.

Table 13: System-Level TRL's for Various Concepts Based Upon the Minimum TRL Present in the System

Design	System TRL Value
Ti-6Al-4V Fuel Tanks spin formed dome	3
All Other Metallic Fuel Tank Spin Formed Dome	3.5
Ti-6Al-4V Fuel Tanks	4
IM7/977-2 Fuel Tanks	5
Al-Li 2195 & Al-Li 2090 Fuel Tanks	5.5
Al 2024 & Al 2219 Fuel Tanks	7

The burnout mass, as calculated by the EUS MInD environment described in Section 3.5 as well as generalized FSW, fastening, and bonding processes are used in conjunction with these TRLs and material composition to generate an estimate using P-BEAT. Figures 87 to 92 show the resulting affordability distributions.

The first, and most obvious, observation extracted from these results is the large affect TRL has on the shape of the distribution. As expected, and shown in Experiment 1, TRL is the greatest cost driver when mature processes are leveraged. The figures presented below, particularly for the immature one-piece dome concepts, portray massive expenditures and extremely lengthy development cycles. For reference, the peak expenditures here are approximately ten times those presented in Figure 59 suggesting that integration would be as or more expensive than all twelve elements combined, which seems unlikely. Furthermore, it is illogical that a fabrication process by which an element is constructed would have any effect on the integration. For instance, comparing the results in Figure 87 these results suggest that integrating an Al 2219 tank would be approximately five time more expensive and require 12 additional years to develop if the fuel tank domes are fabricated from a single piece as opposed to gores. This is extremely unlikely when the dimensions, material, stiffening concept, and even mass would be as near as makes no difference.

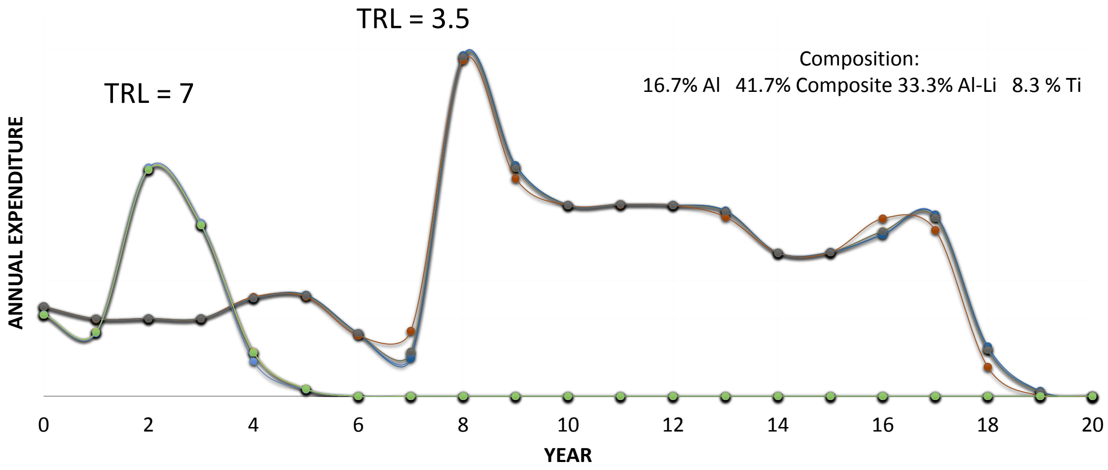


Figure 87: Annual Expenditure for Integration of Al 2219 Tanks for Various Design Concepts When System TRL = Minimum TRL

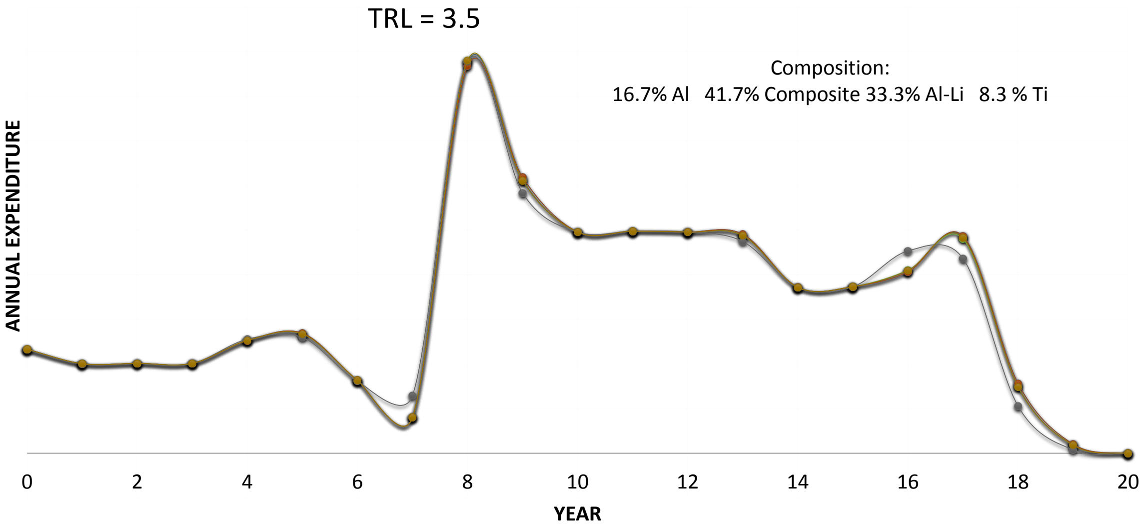


Figure 88: Annual Expenditure for Integration of Al 2024 Tanks for Various Design Concepts When System TRL = Minimum TRL

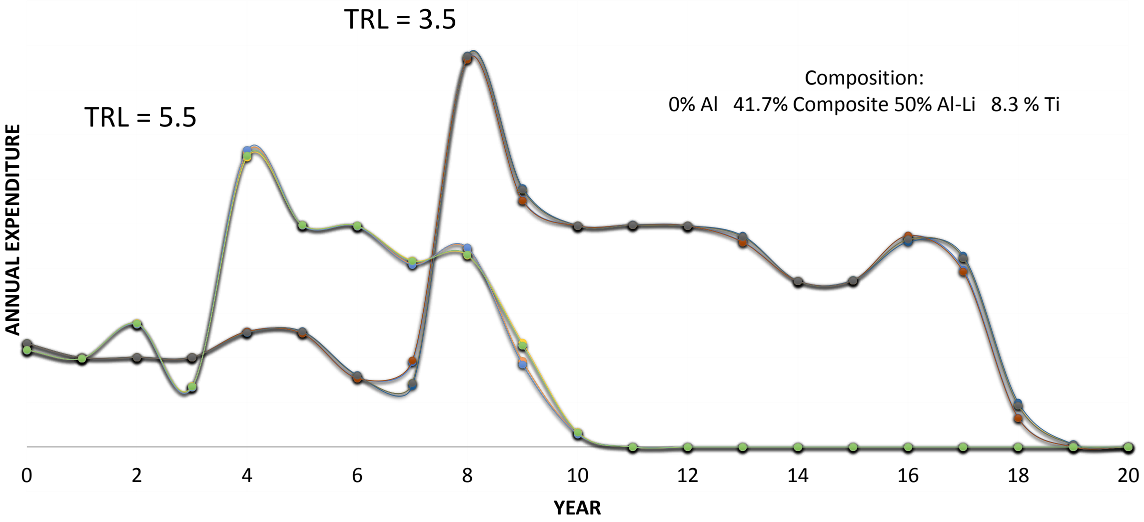


Figure 89: Annual Expenditure for Integration of Al-Li 2195 Tanks for Various Design Concepts When System TRL = Minimum TRL

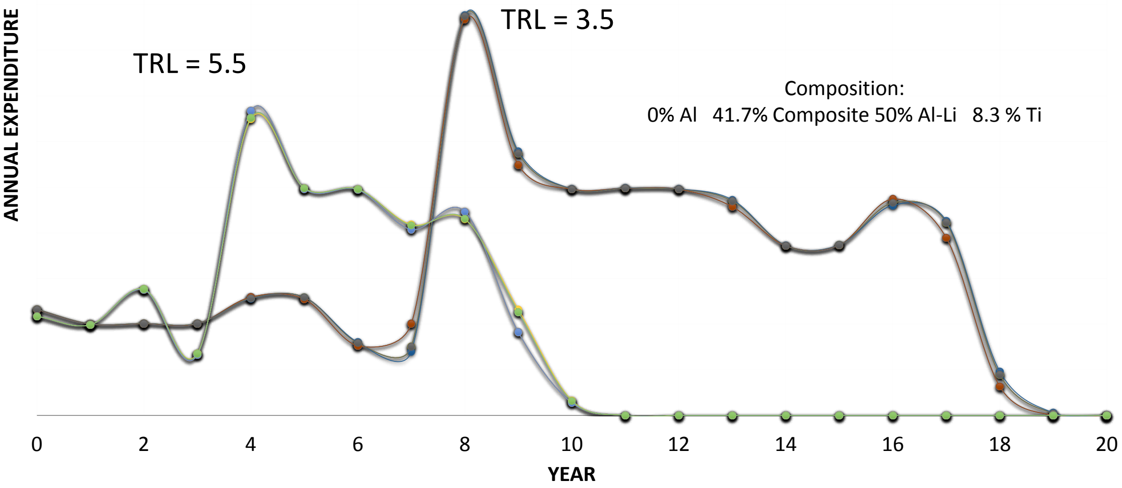


Figure 90: Annual Expenditure for Integration of Al-Li 2090 Tanks for Various Design Concepts When System TRL = Minimum TRL

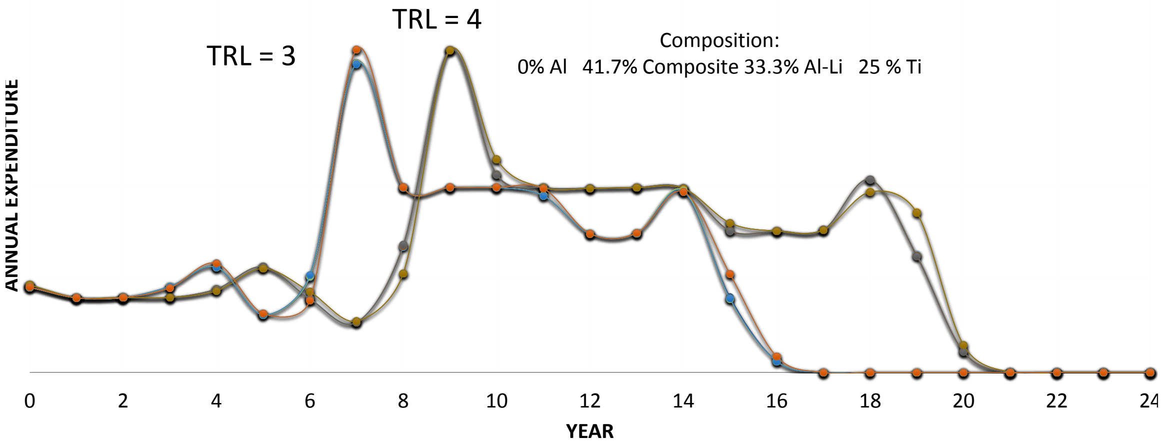


Figure 91: Annual Expenditure for Integration of Ti-6Al-4V Tanks for Various Design Concepts When System TRL = Minimum TRL

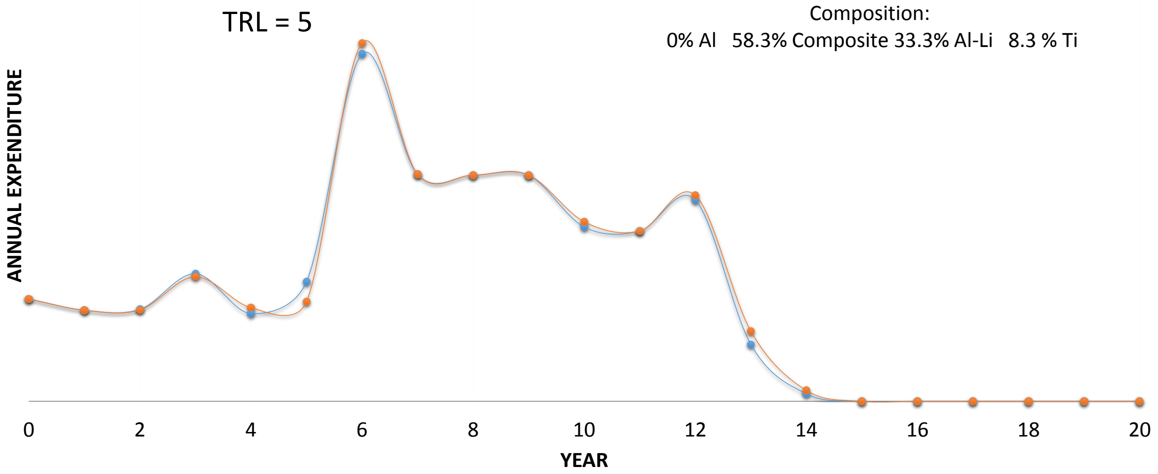


Figure 92: Annual Expenditure for Integration of IM7/977-2 Tanks for Various Design Concepts When System TRL = Minimum TRL

While Bilbro's inference that a systems TRL should be penalized by the inclusion of immature technologies is sound, the notion that it should equal that of the lowest system is far too conservative. This approach provides too large a penalization for a system which employs an immature technology, as well as leverages information which is superfluous to the task of system integration. Case-in-point being dome fabrication processes causing such a massive affordability decrease. Thus, on balance, leveraging the lowest element TRL is not an appropriate method to estimate the system-level TRL associated with integration. As such, it is necessary to revisit the maturity scale definitions presented in Section 3.4.8 to derive a TRL representation which captures composition variations without excessive affordability exaggerations.

3.7.3.2 Standardized TRL

The culminating observations of Section 3.4.8 state two major flaws; the first being the lack of mathematical soundness used in all new scale calculations, and the second being the assumption that many of the new scales are **independent** of the original TRL scale developed by Mankins (Table 5).

Upon inspecting the TRL scale more closely, it becomes clear that the terminology used is specific, and that technology maturation is commensurate with abstracting from a component level up to a system level perspective. Reexamination of this scale brings one key observation to light: **Technologies mature INDEPENDENTLY until they are integrated into the system.** Thus, the focus of this section is to determine when the technology maturation ceases to be independent of the system maturation. This will provide two results; the TRL at which each element ceases to mature independently, and the system-level TRL at the start of integration/assembly. Table 14 enumerates some higher TRL levels, and provides a characterization of integration described through the use of form, fit, and function of a technology relative to the host system.

Table 14: Characterization of Integration for Technology Readiness Levels

TRL	Definition	Characterization of Integration [111]
TRL 5	Component and/or breadboard validation in relevant environment	Almost all functionality, some form and fit attributes, are comparable to expected final technology.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	**Demonstrator** is fully functional AND full scale, comparable to form attributes. Fit into host system may not yet be fully worked out
TRL 7	System prototype demonstration in a space environment	Technology prototype is near or at planned operational system form, fit, and function. Constructed from flight articles. **Not necessarily demonstrated on host system**
TRL 8	Actual system completed and "flight qualified.. through test and demonstration (ground or space)	Technology is in final form fit, and function and is demonstrated as **fully integrated** in host system
TRL 9	Actual system"flight proven" through successful mission operations	Successful mission completed

This characterization of integration for each of the TRL-levels suggests that the elements which comprise a system mature independently up to a TRL of 7. At this TRL the form, fit, and function of the element (into which the technology is infused) is at or near the planned operational attributes. Furthermore, a prototype of the element has completed testing in a space environment, not necessarily on the host system. Revising the start TRL for the integration process, such that *every* case begins at TRL = 7, much more reasonable affordability distributions result. Figure 93 shows the affordability distributions for all 49 cases, where expenditure is recorded at the end of each year.

The annual expenditure has been normalized by the same annual expenditure which normalizes Figures 59 to provide context. These results show several trends which are expected. Firstly, the fact that all metallics follow a very similar curve reflects the similarity in assembly operations and joining during the final integration stages. The composite cases have a significantly lower peak expenditure, during Detailed Design, but maintain higher annual expenditures for all the out-years beyond the peak. Spending for composites ramps down at a much lower rate than metallics, reflecting the additional challenges associated with assembling and integrating systems comprised of a significant portion of composites. While the metallic concepts all bear the same overall shape, it is still possible to distinguish between them.

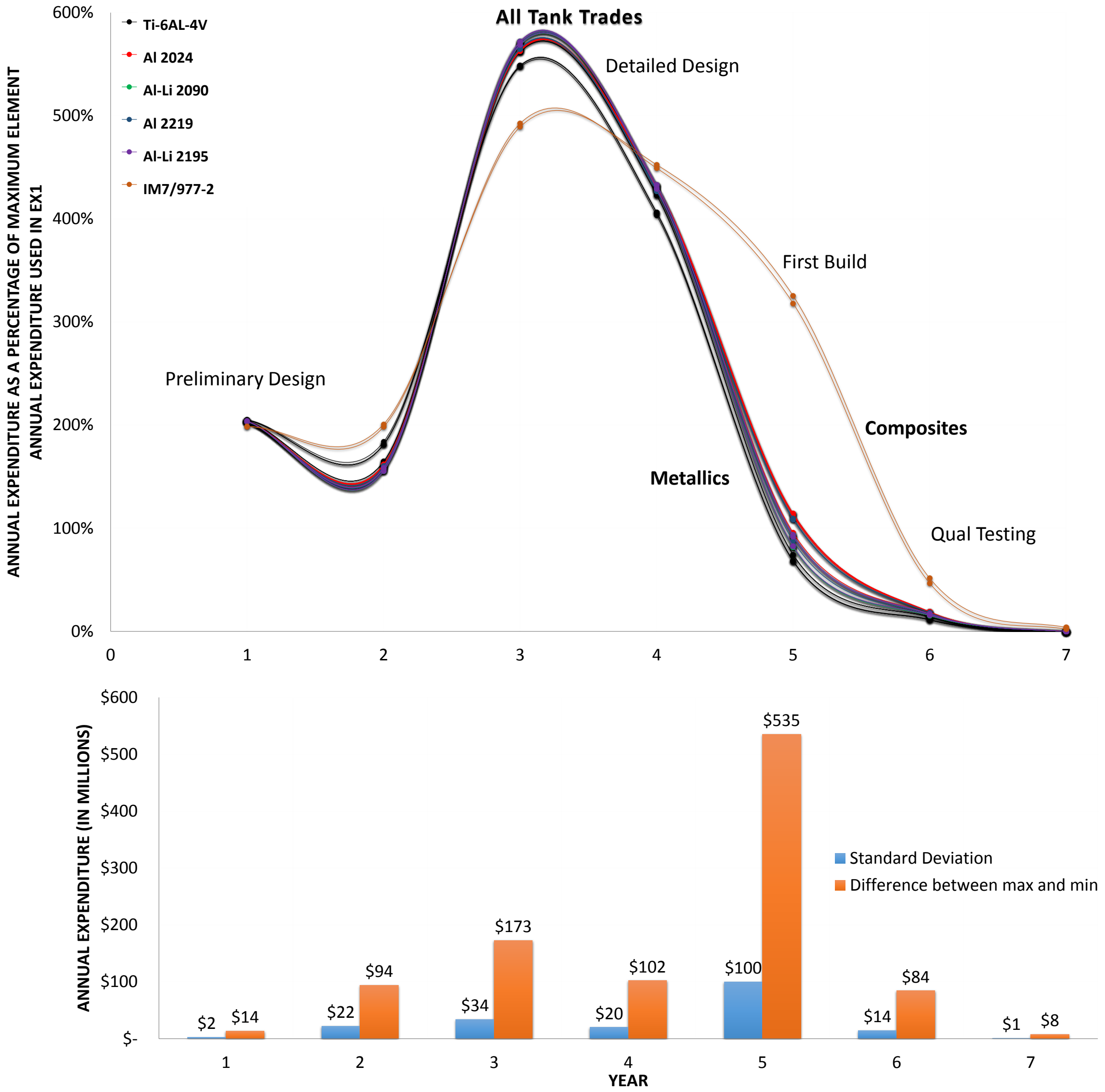


Figure 93: Annual Expenditure (*top*), Standard Deviation, and Range (*bottom*) for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7

These differences are better visualized in a scatterplot matrix, as shown in Figure 94. While the variation in number of barrel panels has no visible effect on any of the expenditures, the material and stiffening concept selection do. The selection of any stiffening concept reduces the per-phase expenditure slightly over the concepts which include unstiffened barrel panels. This is most likely attributable to weight reduction, as is the case with material selection. However, the weight reduction for composites is not sufficient to outweigh the complexity associated with integration of non-similar materials.

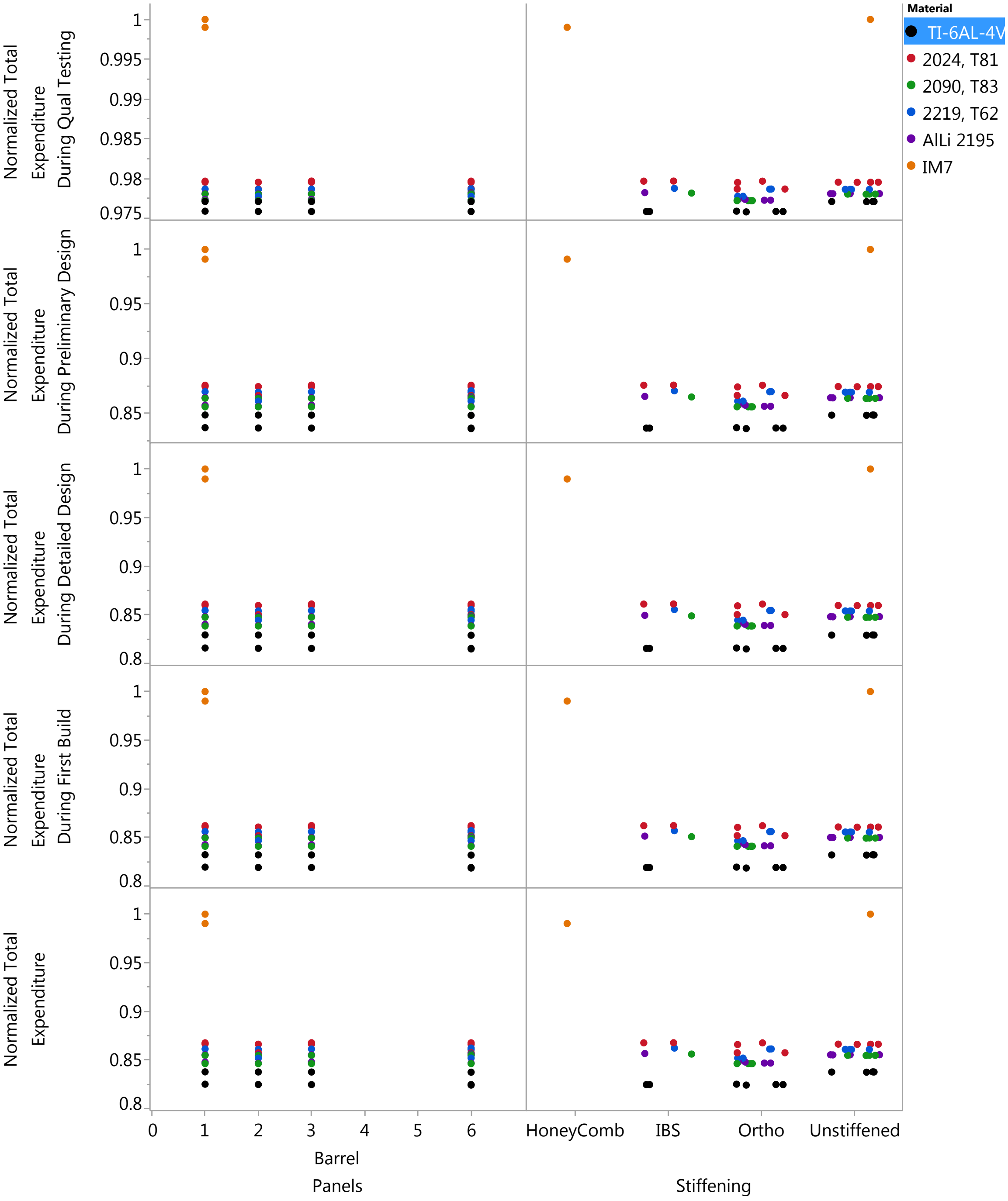
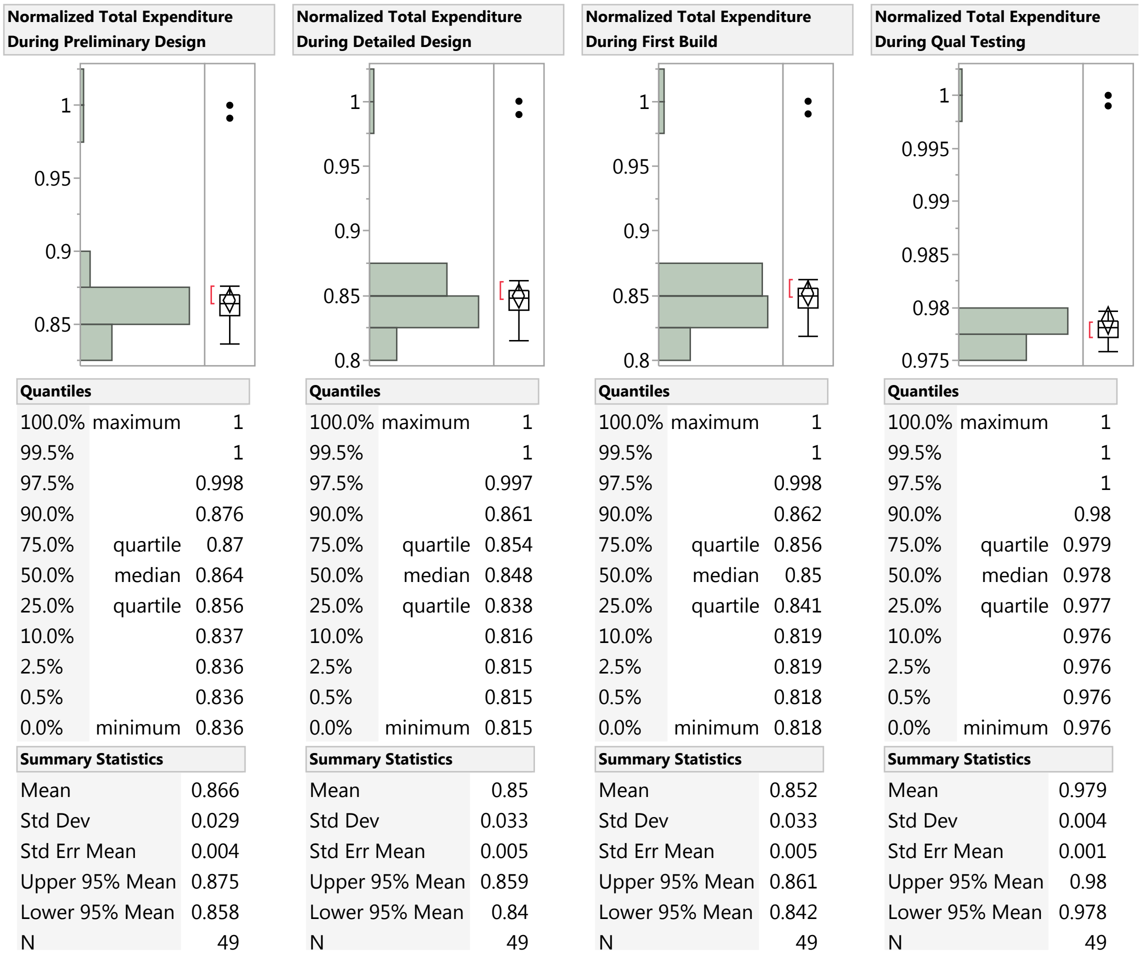


Figure 94: Scatterplot Matrix of Normalized Expenditure for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7

The total expenditure per phase, normalized by the maximum expenditure per phase, is shown in Figure 95. The metallic concepts are grouped together towards the bottom of each distribution, and the composite cases are represented as the outliers with approximately 15% greater expenditure per phase.



Quantiles

		Normalized Total Expenditure During Preliminary Design	Normalized Total Expenditure During Detailed Design	Normalized Total Expenditure During First Build	Normalized Total Expenditure During Qual Testing
100.0%	maximum	1	1	1	1
99.5%		1	1	1	1
97.5%		0.998	0.997	0.998	1
90.0%		0.876	0.861	0.862	0.98
75.0%	quartile	0.87	0.854	0.856	0.979
50.0%	median	0.864	0.848	0.85	0.978
25.0%	quartile	0.856	0.838	0.841	0.977
10.0%		0.837	0.816	0.819	0.976
2.5%		0.836	0.815	0.819	0.976
0.5%		0.836	0.815	0.818	0.976
0.0%	minimum	0.836	0.815	0.818	0.976

Summary Statistics

	Normalized Total Expenditure During Preliminary Design	Normalized Total Expenditure During Detailed Design	Normalized Total Expenditure During First Build	Normalized Total Expenditure During Qual Testing
Mean	0.866	0.85	0.852	0.979
Std Dev	0.029	0.033	0.033	0.004
Std Err Mean	0.004	0.005	0.005	0.001
Upper 95% Mean	0.875	0.859	0.861	0.98
Lower 95% Mean	0.858	0.84	0.842	0.978
N	49	49	49	49

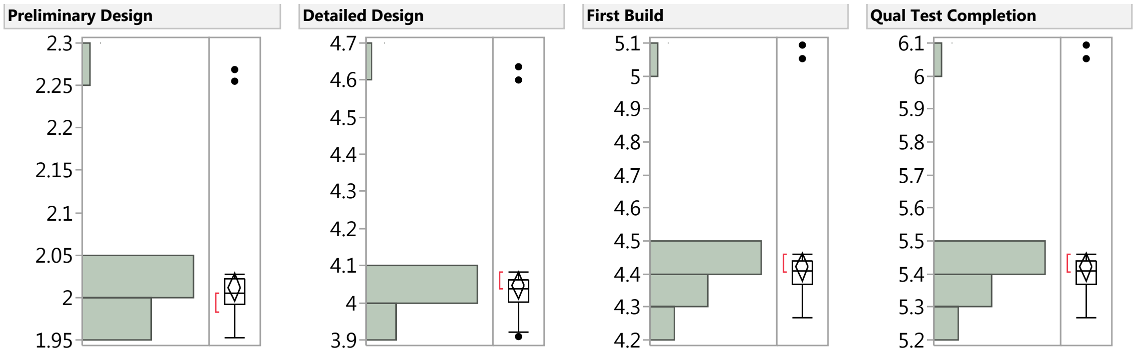
Figure 95: Distribution of Normalized Phase Expenditure for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7

Figure 96 shows the distribution phase end for system integration of all twelve system elements for various fuel tank concepts[6]. This distribution is, fundamentally, a projection of Figure 93 onto the time axis; showing a more duration-centric view. The metallic concepts are all grouped around the bottom of each of the distributions, with the composite concepts represented as outliers. On average, the composites require approximately 12.5%, 19%, and 25% more time to complete Preliminary Design,

---

[6] As mentioned previously, the Qual Test phase is assumed to endure for one full year. This explains the precise incrementation of distribution statistics from First Build to Qual Test Completion

Detailed Design, and First Build phases, respectively. Appendix C includes additional statistics regarding the phase durations as a function of material selection.



Quantiles

		Preliminary Design	Detailed Design	First Build	Qual Test Completion
100.0%	maximum	2.268	4.636	5.093	6.093
99.5%		2.268	4.636	5.093	6.093
97.5%		2.265	4.627	5.083	6.083
90.0%		2.027	4.082	4.46	5.46
75.0%	quartile	2.022	4.063	4.441	5.441
50.0%	median	2.005	4.038	4.408	5.408
25.0%	quartile	1.992	4.003	4.37	5.37
10.0%		1.962	3.921	4.274	5.274
2.5%		1.955	3.912	4.27	5.27
0.5%		1.953	3.91	4.268	5.268
0.0%	minimum	1.953	3.91	4.268	5.268

Summary Statistics

	Preliminary Design	Detailed Design	First Build	Qual Test Completion
Mean	2.012	4.047	4.421	5.421
Std Dev	0.056	0.129	0.147	0.147
Std Err Mean	0.008	0.018	0.021	0.021
Upper 95% Mean	2.028	4.084	4.463	5.463
Lower 95% Mean	1.996	4.01	4.379	5.379
N	49	49	49	49

Figure 96: Distribution of Phase End for Integration of Fuel Tanks for Various Design Concepts When System TRL = 7

These results establish that the elements of a system mature independently up until TRL of 7. The system-level TRL is not equal to that of the least mature element. Despite the inability to fit a Weibull distribution to the annual expenditure of the elements, a brief look at fitting integration shall conclude this experiment.

In a similar process to that of Experiment 1, a series Weibull distribution fits have been attempted. Experiment 1 revealed that tuned Weibull parameters which attempts to simultaneously reduce CDF and PDF error perform poorly in both areas.

Only when parameters are tuned to reduce error in one dimension (either the PDF, or the CDF) does the fit become more acceptable. Since the focus of this research is to describe the annual expenditure, the PDF is the more natural dimension in which a fit is desired. For integration, the number of independent variables is reduced to three, as such the unimodal Weibull, and a 2-Weibull mixture distributions have been selected as viable candidates. Figure 97 and 98 show example fits for the same case carried through Experiment 1, and the average model fit error for the PDF and CDF, respectively.

As before, the unimodal fit to the PDF of the annual expenditure has excessive error. This error is reduced by using a 2-Weibull mixed distribution, but not sufficiently to justify the fit. A final 2-Weibull mixed distribution fit to the CDF of annual expenditure for integration was performed, with surprisingly accurate results. The error, depicted in Figure 98 is nearly eradicated. A small 4% error,on average, occurs in the fourth year. Despite the accurate fit to the α and β parameters — described by Equation 24— a regression between these parameters and the three independent variables has failed. Several linear, quadratic, cubic and neural network fits have been attempted, with the best-in-class documented in Appendix C.

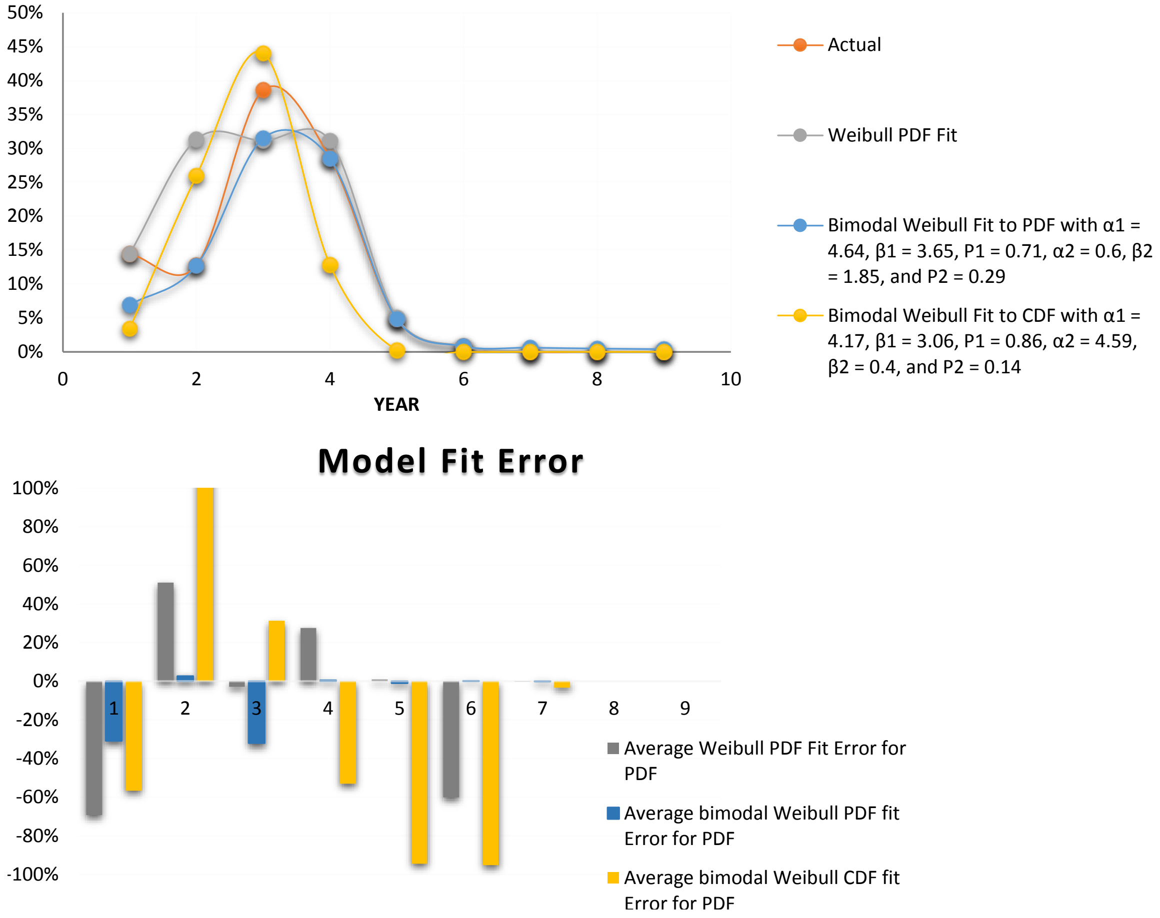


Figure 97: PDFs and Average Fitting Error

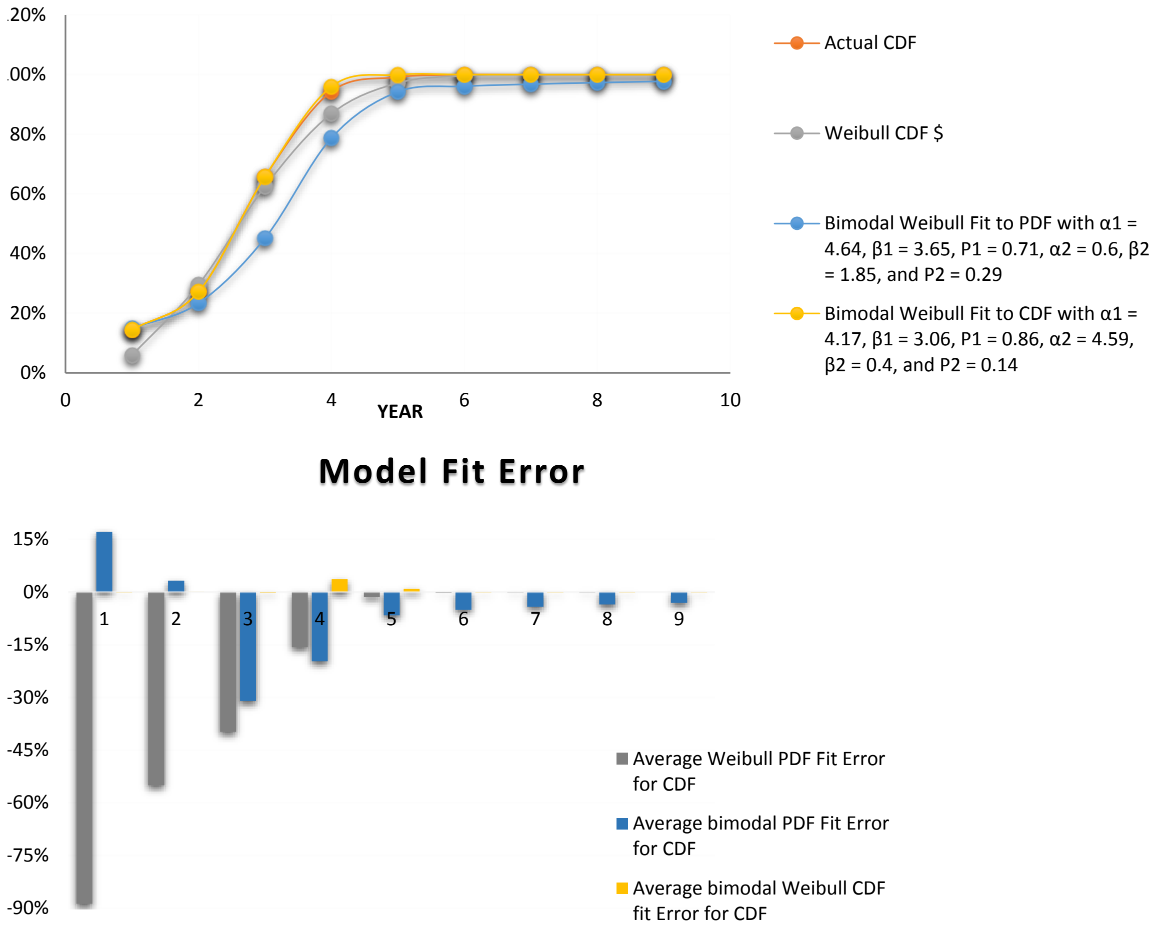


Figure 98: CDFs and Average Fitting Error

3.7.4 Experiment 2 Summary

Experiment 2 aimed to resolve Research Question 2.3 with the hypothesis that an appropriate measure of system maturity and considerations for material composition is sufficient. This experiment began with a system-level maturity measure — extracted from literature— where the system TRL is equivalent to that of its least mature element. The results proved overly conservative, with a significant amount of annual expenditure as a result of the under-prediction of the system maturity. Inspection of the original TRL-scale definitions reveals that **Technologies mature independent from the system up to a TRL of 7**. Using this as a starting point, a process-based tool (P-BEAT) was leveraged to capture the implications that material composition has on integration expenditures. The results proved logical, allowing Hypothesis 2.3 to be accepted.

3.8 Research Question 3: Probabilistic Affordability Distributions

The preceding sections and experiments have focused upon the foundation of this methodology; deterministic affordability distributions and their creation from adapting process-based models. However, Section 2.2 elucidates the fact that decisions are made leveraging probabilistic information. Conjecture to Research Question 1.2 embodies the aim of this thesis, to generate probabilistic affordability distributions which describe the temporal behavior of a program's cost. As such, the next logical segue is to delve into the conversion from the deterministic distributions — presented in experiments 1 and 2 — to a probabilistic representation of affordability. Research question 3 is thus a natural extension of the work performed up until this point:

Research Question 3

How can probabilistic affordability distributions be generated?

This question consists of several elements which are the focus of this section. In order to arrive at a probabilistic affordability distribution, uncertain attributes must be identified and their uncertainty quantified. Thereafter, this uncertainty must be propagated to arrive at the probabilistic representation of an affordability distribution. Thus, the first portion of this chapter —captured in Research Question 3.1 — is to determine precisely which attributes are uncertain.

3.8.1 Research Question 3.1: Determining Uncertain Attributes

Research Question 3.1

What is uncertain?

The generation of the affordability distributions hinges upon two components. The first is the estimation of labor hours for the engineering and manufacturing development processes listed in Tables 8 and 9. The second component is ordering these processes to develop an annual expenditure curve.

3.8.1.1 Uncertainty in Engineering and Manufacturing Development Process Labor

The uncertainty in labor for the various processes is a direct manifestation of uncertainty in the attributes which describe the system element for which an estimate is generated. This directly maps to an uncertainty in the inputs used in P-BEAT to generate an estimate. This is not to say that *every* input is uncertain; for instance there is no uncertainty associated with which material shall be used, or the process by which the element will be fabricated. These attributes are fixed. However, the properties of the material may vary slightly (affecting the weight of the element which results from a need for variations in tank wall thickness, for example) or the assumed capability of the design or production team — which affects the alacrity with which design or fabrication is completed. Table 15 enumerates the attribute groups — relevant to P-BEAT inputs — in which uncertainty is present, and where this uncertainty manifests.

Table 15: Characterization of Uncertain Attributes in P-BEAT

Uncertain Attribute	Manifestation of Uncertainty
Design Team Capability Design Maturity	Design Process Duration
Production Team Capability Production Maturity Production Intensity	Fabrication Process Duration
Material Properties	Design Weight

The team capability attributes reflect on the experience that the design and production teams posses, while the maturity describes how similar the system is to heritage systems. These maturity attributes are defined separately from TRL. Which brings up the issue of whether TRL is an uncertain attribute. Within the context of this thesis, the thorough dissection of the TRL scale denotes the simplicity and straight-forwardness with which each level is described. **As such, the identification of the TRL level for an system element bears no uncertainty.** While material property is listed as manifesting in the form of design weight variation, this input into P-BEAT affects both design and process durations.

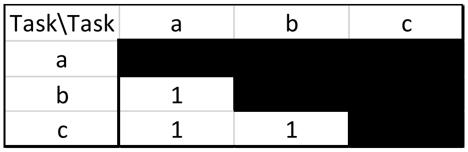
3.8.1.2 Uncertainty in the Order of Activities

The uncertainty in the order of activities centers around the planning fallacy — which refers to a *readily observable phenomenon: the conviction that a current project will go as well as planned even though most projects from a relevant comparison set have failed to fulfill their planned outcomes* [30]. The order of activities, compiled from a logical program decomposition and present in Section 3.6.2.1, states the expected or ideal order in which development will progress. However, variations on this order are entirely possible, and must be considered during the planning phase. After all, it is optimism in the early design phases which often leads to cost overruns and schedule delays [19].

The challenge associated with quantifying this type of uncertainty is the discrete nature of the problem. The activity order is governed by compatibility, which tasks can occur in parallel, and predecessor relations, which tasks must occur before others. To elucidate the magnitude of this problem, a short example shall be presented in which the number of possible schedule permutations is determined.

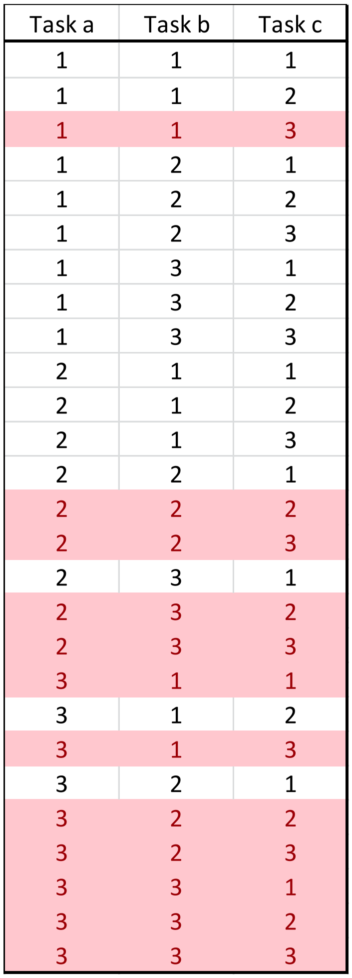
Assume that a program comprises three tasks — task a, b, and, c. If the tasks are compatible with each other, as portrayed in Figure 99, then they can be performed in parallel. If all possible permutations of the three tasks are enumerated, there exist 27 variations in which these three tasks can be completed. Figure 100 enumerates the 27 permutations, from completing all three tasks in parallel in time slot 1, to completing them in series across 3 time slots. These 27 permutations, however, include several options which are illogical. For instance, performing two tasks in time slot 1, nothing in time slot 2 and the third task in time slot 3 is not a logical permutation. A time slot would not be left vacant such that work ceases before project end, these non logical permutations are highlighted in red in Figure 100. This reduces the number of logical permutations from 27 down to 13. The next step in pruning down the number of permutations would be to consider feasibility, described by the compatibility between tasks. In this case, no additional permutations may be excluded since all three tasks may be performed in parallel.

If the compatibility between tasks were changed such that none of them could be performed in parallel, represented by Figure101, then the total number of *feasible and logical* permutations would decrease to 6. These, the result of eliminating the permutations in which tasks share a time slot, is shown in Figure 102.



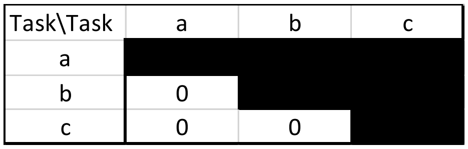
Task\Task	a	b	c
a			
b	1		
c	1	1	

Figure 99: Activity Permutation Example: Compatibility Matrix for Three Compatible Tasks



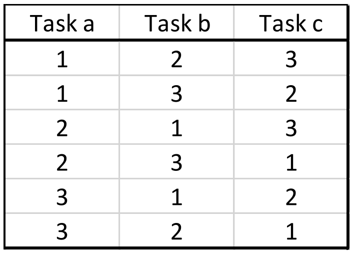
Task a	Task b	Task c
1	1	1
1	1	2
1	1	3
1	2	1
1	2	2
1	2	3
1	3	1
1	3	2
1	3	3
2	1	1
2	1	2
2	1	3
2	2	1
2	2	2
2	2	3
2	3	1
2	3	2
2	3	3
3	1	1
3	1	2
3	1	3
3	2	1
3	2	2
3	2	3
3	3	1
3	3	2
3	3	3

Figure 100: Time Slot Allocations for Tasks With Full Compatibility



Task\Task	a	b	c
a			
b	0		
c	0	0	

Figure 101: Three Fully Compatible Tasks for Activity Permutation Example



Task a	Task b	Task c
1	2	3
1	3	2
2	1	3
2	3	1
3	1	2
3	2	1

Figure 102: Time Slot Allocations for Tasks With No Compatibility

Figure 102 elicits one question regarding further reduction of the number of permutations: “Since those permutations are just variations on performing the tasks in series, aren’t they redundant?” While, from a schedule-only standpoint these permutations are equivalent, when the cost dimension is considered they are not. Fundamentally, labor considerations equate to “buying down”I task duration by increasing labor. For example, task a and c require the same duration to complete, but task b requires ten time that duration (i.e. intensity), variations in labor will affect the cost distribution which is not portrayed in these permutation tables. The intensity associated with task b dictates the peak expenditure of the program. If task a and c leverage one person to complete the work but the duration of task b is such that — in order to meet schedule goals — more than one person is required to complete it. In this case, if task b occurs in the first time slot, then program expenditure starts high and ramps down as task b completes and a and c commence. Conversely, if task b is performed in the third time slot, program expenditure will begin low and ramp up as task b begins. As such, these permutations are distinct and cannot be further reduced.

Repeating this process for up to 8 tasks, several mathematical relationships can be developed to describe the design space and bounds. Enumerating every possible permutation (irrespective of feasibility or logic), is described by the statistical relationship for permutations with repetition, shown in Equation 25. The total number of permutations with FULL compatibility is described by a regression to data shown in Equation 26, and Equation 27 describes the number of task permutations with no parallel compatibility. Figure 103 portrays the trends of these equations as the number of tasks is increased, with the actual permutations displayed above each point. While the regression diverges as n increases, it may still be used to provide a conservative estimate of the upper bound of the constrained design space.

$$P = n^n \tag{25}$$

$$P = 1.567 + 0.0609 * e^{1.695n} + 0.0008 * e^{2.526n} \tag{26}$$

$$P = n! \tag{27}$$

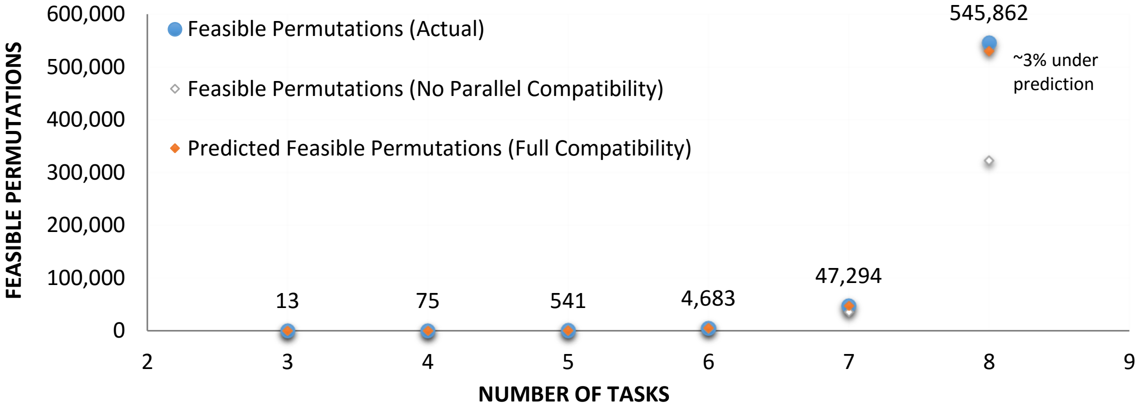


Figure 103: Time Slot Allocations for Tasks With Full Compatibility

Up until this point, the notion of task precedence has been ignored. This is primarily due to the general nature of the 56 activities for which P-BEAT generates labor estimates. The generality of these tasks allows only for a small reduction in permutations, by simply removing some tasks from the bound calculations. For instance, the program management activity can be removed since it represents the management of all other task. It would ultimately start at the beginning of the program, and endure regardless of the order of tasks. Furthermore, System Requirements analysis could be a predecessor for *all* the other tasks. The removal of these activities does not reduce the number of feasible permutations to a manageable set for which estimates can be generated. Extending this analysis such that each activity has one predecessor and removing the two previously described activities, there exist more than $1E60$ ways in which the tasks may be ordered. As such a selection of task order will be used commensurate with the appropriate distribution used to describe this uncertainty. This neatly flows into Research Question 3.2: the need to consider the appropriate selection of uncertainty distributions used for both the attributes and task order permutations.

3.8.2 Research Question 3.2: Assessing Appropriate Forms Uncertainty Distributions

A large variety of uncertainty distributions exist to describe the form of uncertainty across different attributes. The purpose of this section is to elucidate advantages and disadvantages of each, culminating in a resolution to Research Question 3.2.

Research Question 3.2

What form can be used to represent the uncertainty in attributes?

The estimates (particularly for cost and schedule) generated during initial concept design are often optimistic due to competitive pressures [19]. This results in overruns and schedule slippages, which implies that cost and schedule are more likely to exceed their expected values. The distributions often selected to describe these tend to possess a right hand skew [54, 85, 71]. Furthermore, this optimism translates into an underestimation of technical specifications, similarly suggesting that the distributions which describe the technical parameters possess a right handed skewness as well.

Commonly used distributions for cost and schedule include the Beta, Weibull, Log-Normal, and triangular distributions. [72, 84, 7]. A review of these distributions is presented in the following sections.

3.8.2.1 Beta Distribution

The Beta probability density function is defined by the following equation where α and β are parameters which define the skewness and variance of the distribution [222]. This distribution is shown in Equation 28, where $B(\alpha, \beta)$ is the Beta function shown in Equation 29.

$$f(x,\alpha,\beta) = \begin{cases} \frac{1}{B(\alpha,\beta)} x^{\alpha-1}(1-x)^{\beta-1}, & x \geq 0 \\ 0, & \text{elsewhere} \end{cases} \tag{28}$$

$$B(\alpha,\beta) = \int\limits_{0}^{1} x^{\alpha-1}(1-x)^{\beta-1} dx \tag{29}$$

3.8.2.2 Log-Normal Distribution

The log-normal distribution is represented by Equation 30 where μ and σ dictate the skewness and variance of the distribution. Figure 104 shows the log-normal distribution for various values of μ and σ.

$$f(x,\mu,\sigma) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma x} e^{-\frac{1}{2\sigma^2}[\ln x - \mu]^2}, & x \geq 0 \\ 0, & \text{elsewhere} \end{cases} \tag{30}$$

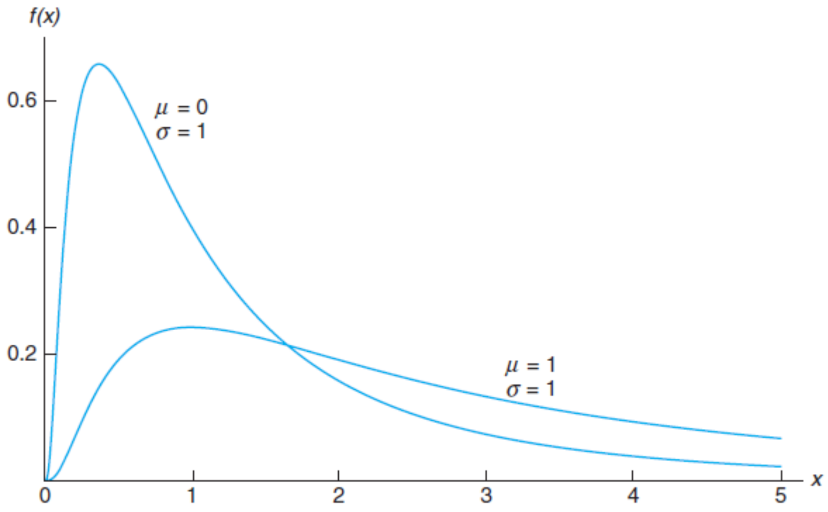


Figure 104: Lognormal Probability Density Function [222]

3.8.2.3 Weibull Distribution

The Weibull distribution is another two-parameter distribution, discussed in Section 3.6.3.2 and shown in Equation 22, repeated below.

$$f(x) = \begin{cases} \alpha\beta x^{\beta-1} e^{-\alpha x^{\beta}}, & x > 0 \\ 0, & \text{elsewhere} \end{cases} \tag{22}$$

3.8.2.4 Triangular Distribution

The triangular distribution is considerably less complicated than the distributions represented thus far. The PDF for this distribution is shown below, where c represents the most likely value, a represents the minimum, and b the maximum. Figure 105 shows several examples of this type of distribution

$$f(x,a,b,c) = \begin{cases} 0 & x < a, x > b \\ \frac{2(x-a)}{(b-a)(c-a)} & a \leq x < c, \\ \frac{2}{b-a} & x = c, \\ \frac{2(b-x)}{(b-a)(b-c)} & c < x \leq b \end{cases} \tag{31}$$

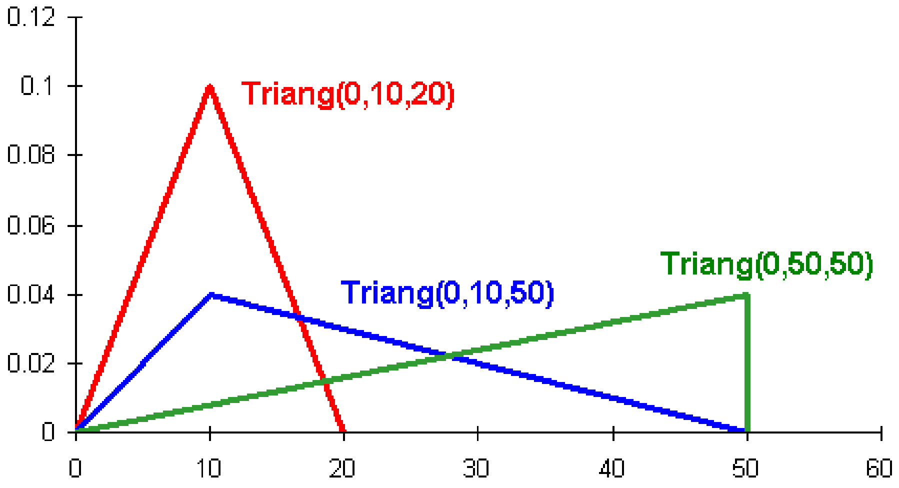


Figure 105: Triangular Probability Density Function

The Beta, Log-normal, and Weibull distributions all require two parameters to define their shape. This attribute provides significant flexibility in defining a wide variety of shapes. However, for application in Conceptual Design, these additional variables lead to a lack of traceability due to the nebulous nature of their definitions — not representing any physical quantity. The simplicity of the triangular distribution reduces ambiguity with which parameter uncertainties are characterized; providing better traceability in assumptions. Parameter definition is simply selecting the minimum, maximum and most likely value. The final aspect associated with generating probabilistic affordability distributions is the method used to propagate uncertainty in attributes to uncertainty in affordability.

3.8.3 Research Question 3.3: Propagating Uncertainty

Research Question 3.3

How can the uncertainty in attributes be propagated into affordability distributions?

Various methods exist regarding uncertainty propagation, and can generally be classified into two categories: deterministic and probabilistic. Deterministic techniques rely on a point estimate (or group of point estimates) from which uncertainty is evaluated, either through the use of expert opinion or historical data [7]. While these are relatively simple in implementation, their reliance upon extensive historical data limits applicability. Probabilistic methods present more applicable traits, and a selection of these shall be reviewed. The most applicable of these include propagation of errors, and two simulation techniques; Monte Carlo Simulation (MCS) and discrete event simulation (DES).

Propagation of errors is an analytical adaptation of a sensitivity analysis. The error is determined by the sum of individual errors weighted by the partial derivative of the functions with respect to the individual variables. This method is fairly well-known and accepted in fields closely tied to acquisition, and does not require simulation. However, in complex cost estimation problems, the absence of closed-form analytical equations would result in extreme complexity associated with computing partial derivatives[7]. Within the context of affordability distributions, a closed form Weibull equation for element distributions has proven elusive.

A MCS consists of a random draw from each of the input variable distributions, which are then used to determine the final value through the appropriate operation(s). Within the context of this thesis, a MCS would equate to a random draw from the triangular distributions on the P-BEAT input variables and task order which would then be used to calculate task duration and generate the deterministic affordability distribution, respectively. This process would be repeated thousands of times and culminate in a sample of the final probabilistic distribution. MCS is a widely used, well studied technique with a significant body of literature. Advances in computer hardware has reduced the computational expense associated with using this method, resulting in acceptable run times even for tens of thousands of cases. The primary disadvantage of this method is its reliance on the use of *independent* inputs. In the absence of independence, the correlation between input variables must be captured, which complicates the analysis significantly. The high cost of one element may impact the cost of another as a result of shared technology, manufacturing or otherwise [7].

The final method of interest is DES, which models the time based behavior of a physical system represented in the form of mathematical and/or logical relationships. These relationships allow the simulation of state changes at specific points in time — i.e. a virtual representation of performing activities or operations. While this approach would allow the detailed simulation of tasks and task order, the complexity associated with defining these integrated relationships is inhibitive. Particularly within the context of exploring various processes and materials, highly detailed models for each process variation must be created to adequately represent the physical system. While DES may prove useful for future states of this methodology —described further in Section 6.3— the resources required to appropriately represent ALL variations on the system is inhibitive.

Thus, on balance, MCS is the most appropriate of the three methods for uncertainty propagation within this context. The built-in functionality in P-BEAT lends itself well to applying uncertainty distributions to the inputs and performing random draws many thousands of times. The use of triangular distributions on these inputs will provide traceability regarding the physical meaning of the bounds of each variable. Thus an hypothesis to Research Question 3 may be posed.

Hypothesis 3

- If triangular distributions are used to represent the uncertainty of input variables and task order, the assumptions which define the shape will be more traceable than Weibull, Log-normal or Beta distributions.
- The propagation of this uncertainty through Monte Carlo simulation will provide the ability to compare manufacturing technology portfolios and their DDTE&P strategies

This hypothesis, however, does lend itself to test primarily through the consideration of applying a triangular distribution to a selection of task order variations. As described in Section 3.8.1.2, it is not feasible to enumerate every permutation of task order, let alone analyze them. While the triangular distribution is the most traceable, it poses one challenge for the application to discrete task order problems. That is, at the extremes (where $x = b$ or $x = a$) the probability of occurrence is precisely zero. Experiment 3 assesses the applicability of Hypothesis 3 to the discrete task order problem.

3.9 Experiment 3: Generation of Probabilistic Affordability Distributions

3.9.1 Purpose

The purpose of this experiment is to generate a probabilistic affordability distribution for an element, while leveraging a triangular uncertainty distribution on the inputs, and Monte Carlo simulation to propagate that uncertainty. The one variation on this, is assessing the uncertainty distribution on the task order.

3.9.2 Approach

The approach required to generate the probabilistic distribution for an element is tiered. The first step requires the propagation of uncertainty through P-BEAT to establish the probabilistic task durations. The second step requires the propagation of the uncertain task durations through the uncertain task order permutations, which poses the greater challenge.

For the purposes of task order permutations, the order described in Section 3.6.2.1 shall serve as the expected/planned order. The propagation of uncertainty here, requires some care, and shall be evaluated using both a triangular distribution and a uniform distribution. First, however, it is necessary to discuss the generation of optimistic and pessimistic orders to form the bounds of both distributions. The foundation assumption for generating the bounds lies in assessing parallelism compatibility for the development processes listed in Tables 8 and 9. The optimistic task order would include a more parallel order of tasks, while the pessimistic will be serial in nature.

Relative to the logic used to develop the expected order, shown in Figure 53, it is feasible to begin the consideration of system and element tests during the last iteration of mechanical design. This assumption shortens the total program duration since Test and Evaluation Engineering can begin in parallel with the latter portion of mechanical design. Furthermore, it is conceivable that logistical considerations may commence before the completion of the test and evaluation activities, and even as the final mechanical design iterations draw to a close. By this point, the required tests and appropriate facilities may be sufficiently defined to begin site activation and allow support equipment tasks to commence. Additionally, training aspects could be determined in conjunction with the Test & Evaluation Engineering tasks. This optimistic schedule is depicted in Figure 106 and is a notional representation of a very parallel task order.

Pessimistically, it is feasible that development processes could all occur in series. Resulting in a very lengthy and inefficient program duration. The exception to this, however, are the mechanical design tasks which would still possess some parallelism. This is a result of the highly-coupled nature of the analyses where outputs of one domain are inputs to another. For instance, the aerodynamics analysis will require a description of the outer mold-line and some mass and propulsive properties. These result from iterative analysis/trades performed between determining the structures required, which in turn dictates the mechanical systems needed to propel said structures, which in turn have electrical requirements. Not to mention that the electrical requirements dictate the size and weight of the power systems and wiring which must then be reconsidered in the mechanical and structural calculations. This very iterative process disallows independence betweenthe tasks which comprise Mechanical Design. That being said, Figure 107 represents an extremely serial task order.

Figure 106: Gantt Chart Depicting Optimistic (Parallel) P-BEAT Development Process Order and Dependencies with Notional Task Durations

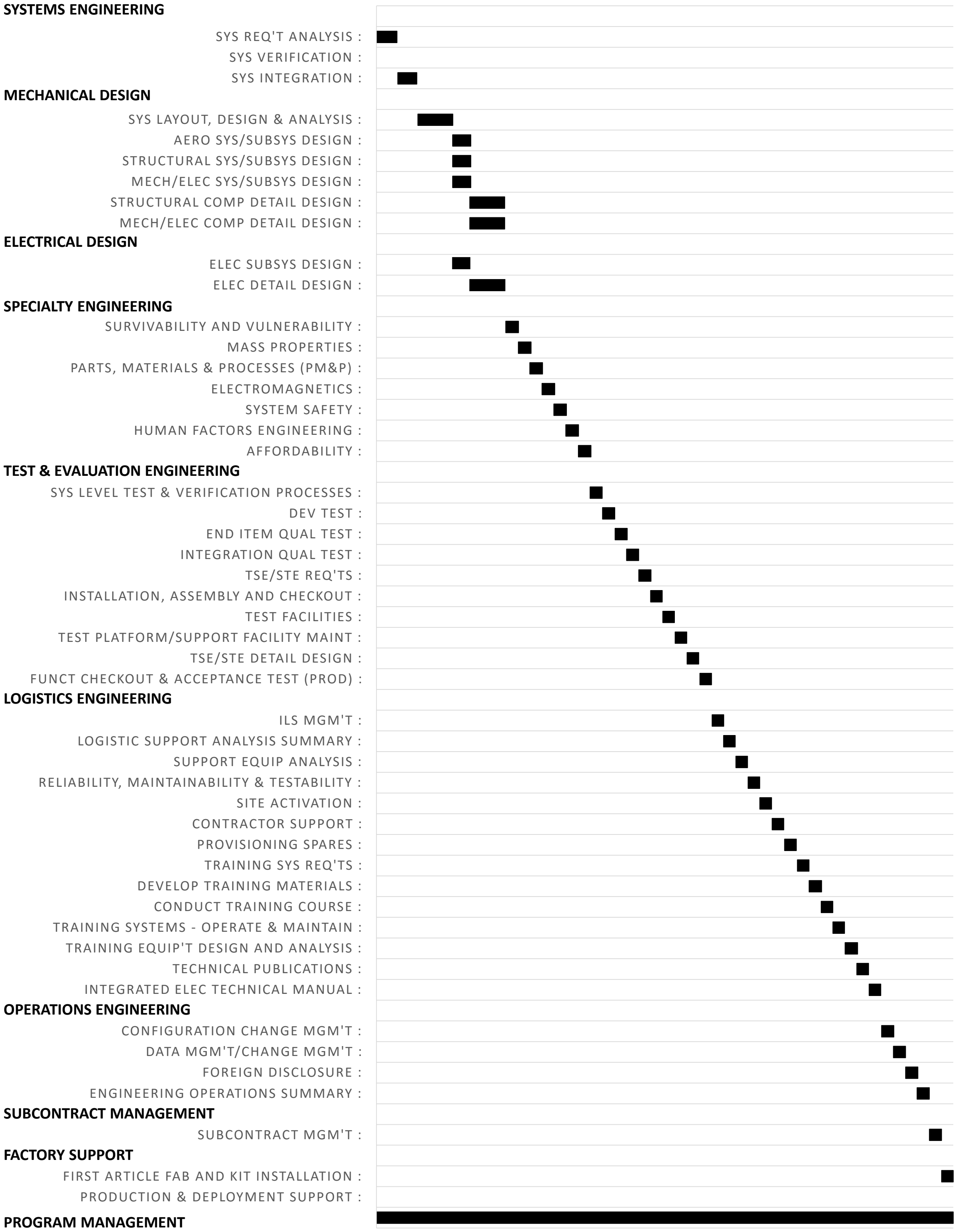


Figure 107: Gantt Chart Depicting Pessimistic (Serial) P-BEAT Development Process Order and Dependencies with Notional Task Durations

As mentioned previously, P-BEAT lends itself well to applying uncertainty distributions to its input variables. It has several built-in functions; allowing the definition of optimistic, pessimistic, and expected input values to define the uncertainty distribution, as well as the ability to run Monte Carlo simulations. To this end, SME input has been used to appropriately define the bounds of triangular uncertainty distributions on the various inputs — categorized in Table 15 — and the built in functions were used to perform 10,000 MCS runs to sample the space. The resulting uncertain total cost is shown in Figure 108, below, for one of the 846 tank concepts discussed in Section 3.6. Figure 109 shows the distributions of Preliminary Design, Detailed Design, and First Build durations for each of the three task order permutations discussed.

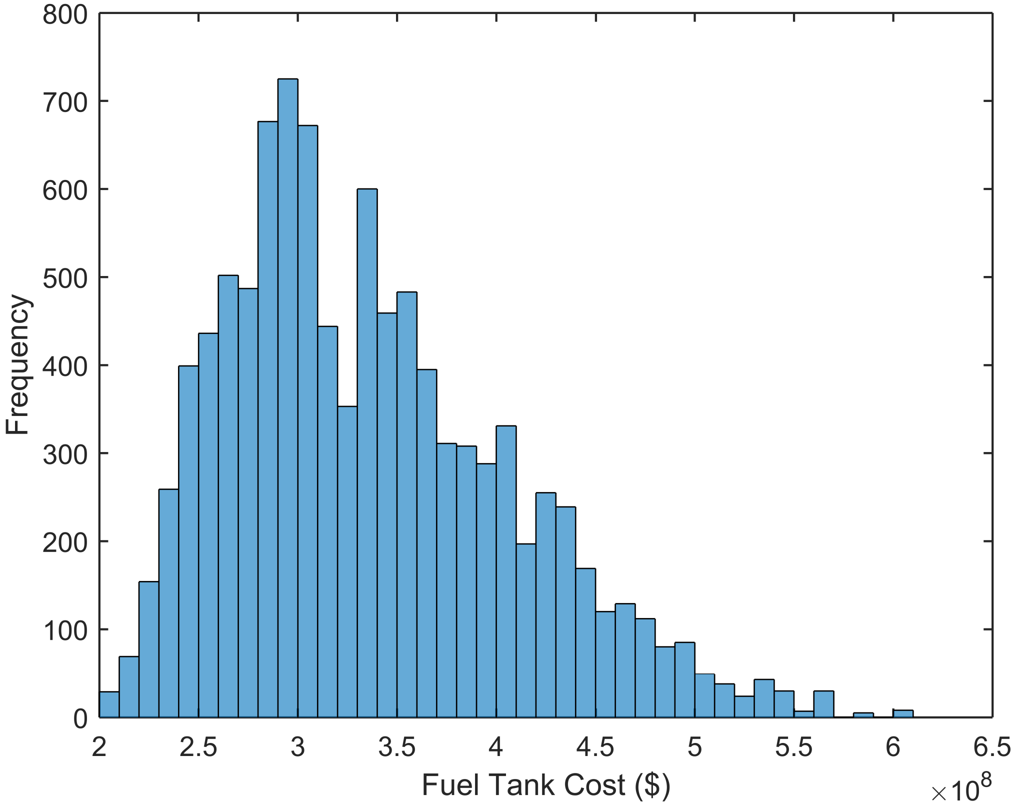


Figure 108: Uncertainty in Total Cost (2011 USD)

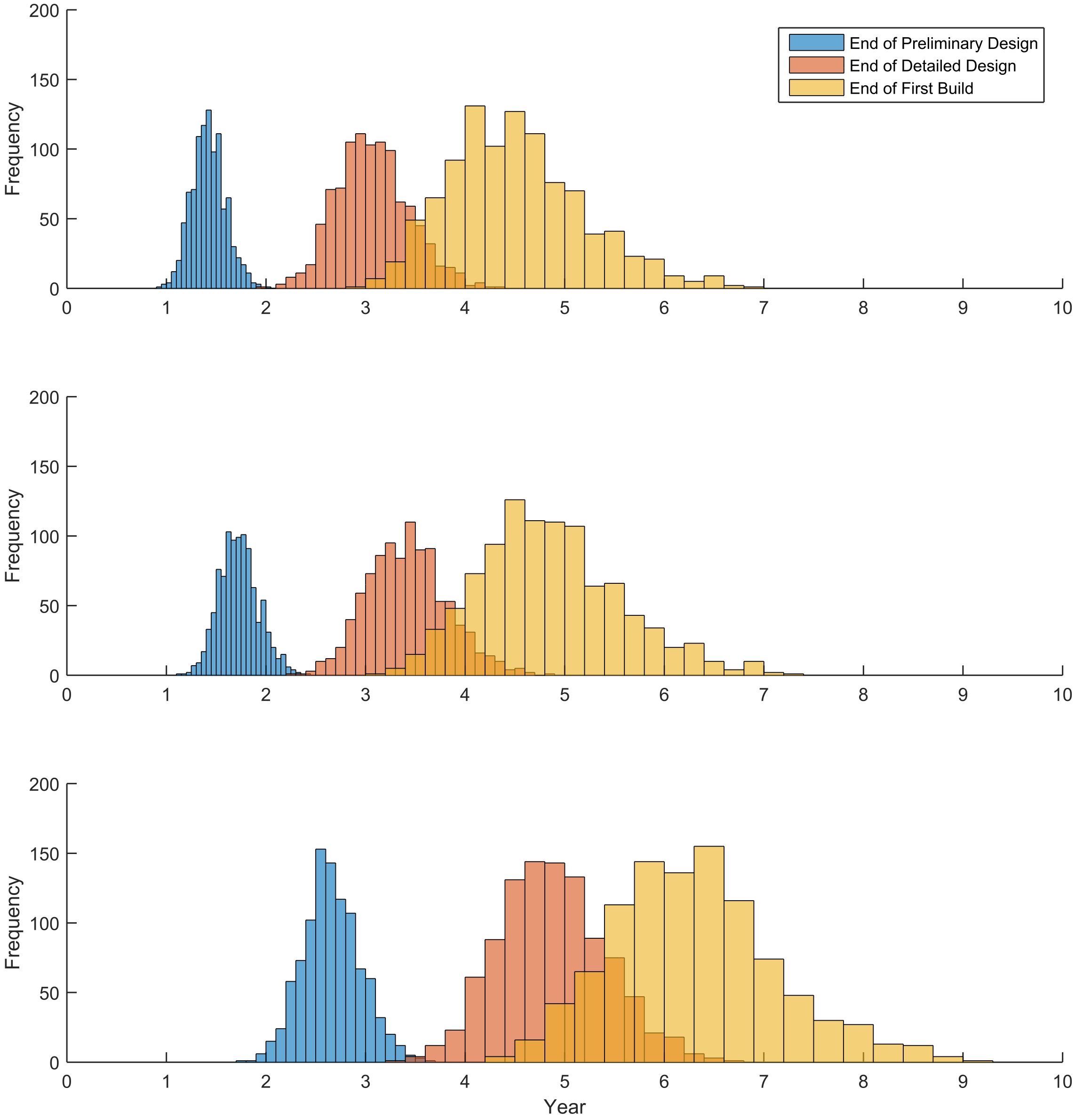


Figure 109: Phase Durations for Optimistic (*top*), Pessimistic (*bottom*), and Expected (*middle*) Task Order Permutations

The assumptions presented herein dictate that this total expenditure will be the same for all three task order permutations described by Figures 53, 107, and 106. However, the phase durations, and thus total program duration varies as expected, as shown in Figure 109. The optimistic task order phase completion approximately six-months sooner than the expected, while the pessimistic order shows additional time required to complete each phase. The following results section describes the variation for each of the three schedule options, and compares a uniform and two triangular distribution options for representing discrete schedule uncertainty. Implementation of this uncertainty propagation shall employ bootstrapping — a computational "resampling," with replacement, from the existing population rather than by making parametric assumptions about the estimator [142].

3.9.3 Results

Hypothesis 3 establishes the desire to use triangular distributions to represent the uncertainty — in both attributes and task order — due to its traceability. However, this poses a distinct challenge in task order where three discrete cases are selected to represent the optimistic, pessimistic, and expected value. By definition — Equation 3.8.2.4 — the likelihood of $x = b$ or $x = a$ is precisely zero. If random draws from the three distributions would be defined by the pure triangular distribution, then only the expected value cases would be propagated. This leaves two options, the first would be simply to leverage a uniform distribution, while the second involves dividing the triangular distribution into three bins, one for each permutation.

The uniform distribution dictates equal likelihood for all values between the optimistic and pessimistic value, as described by Equation 32. For this discrete case, this would equate to 33.33% likelihood for any of the three task permutations to occur. Figure 110 shows the resulting phase durations. With an equal representation of the three task order permutations, the resulting distributions are as expected, a clear amalgamation of viable task order candidates. Both Preliminary Design and Detailed Design exhibit two peaks; the first results from the similarity between expected values for the optimistic and expected task orders, while the second peak represents the pessimistic case. Unsurprisingly, this is also evident when comparing the magnitudes of the frequencies for these peaks. Particularly for the Preliminary Design distribution, the first peak is almost precisely double of the second.

$$P(x,a,b) = \begin{cases} \frac{1}{b-a} & a \geq x \geq b, \\ 0 & \text{elsewhere} \end{cases} \tag{32}$$

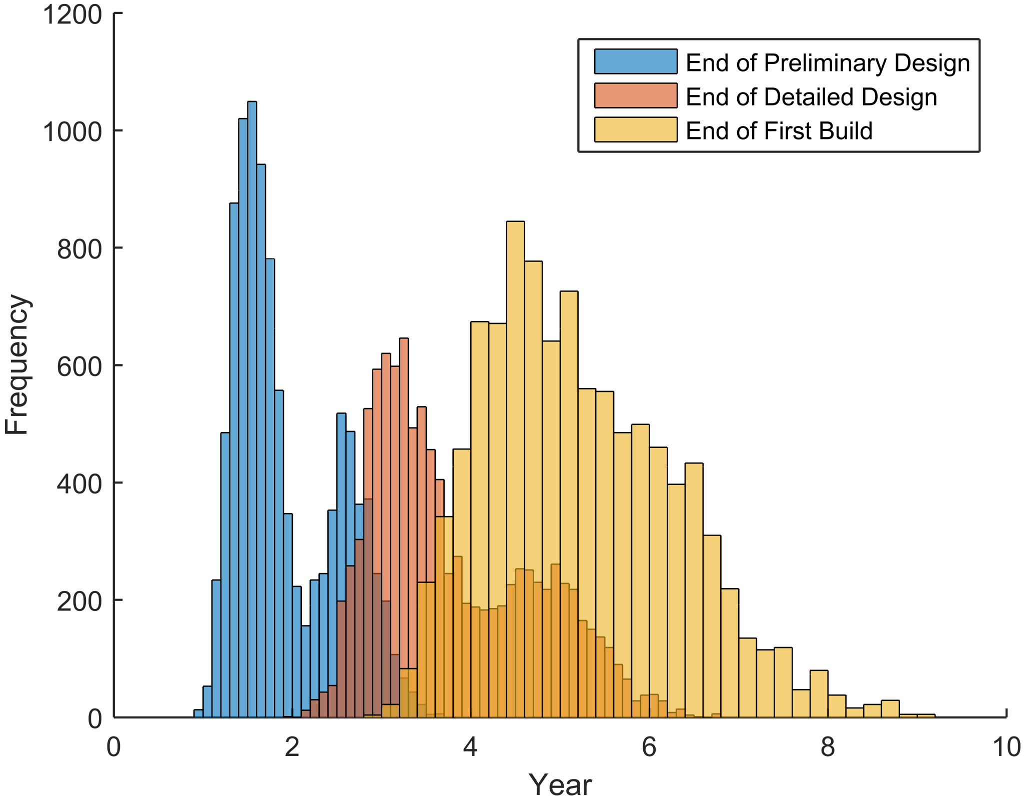


Figure 110: Phase Durations Resulting from Uniform Distribution

However, the likelihood of the optimistic and pessimistic task permutations occurring is expected to be less than the expected task permutation. Thus warranting a discussion on creating a binned triangular distribution. The division of the triangular distribution has one major requirement which could potentially diminish the traceability of a triangular distribution. *How should the bins be created?* This is directly related to the allotment of likelihood to each of the three orders. The first, and perhaps most arbitrary method, is to select a small percentage based on SME or historical insight. The second option, useful when SME or historical data is absent but perhaps more arbitrary, would be to use a statistical measure such as standard deviation.

In exploring the first option — selecting a percentage of the tails of the triangular distribution based on SME or historical data — implies that the likelihood of the pessimistic or optimistic cases is precisely known. If they are assumed equal, based upon sampling from a triangular distribution, a transformation is needed. In performing the random sampling, one would specify the x-axis location which bounds the bins. However, the likelihood percentage refers to the *area* enclosed in the bins, and not their bounds. If the likelihood of the extremes occurring is 5%, and the triangular distribution is defined such that $a = 0$ and $b = 1$, then the x-bounds of the bins are 0.15 and 0.85 for the pessimistic and optimistic permutations, respectively. Figure 111 portrays this scenario; where the pessimistic or optimistic distributions are only sampled, if the sample drawn from the triangular distribution is less than or equal to 0.15 or greater than or equal to 0.85, respectively. In this figure, the frequency of 0, 0.5, and 1 represent the frequency of the optimistic, expected, and pessimistic distributions, respectively.

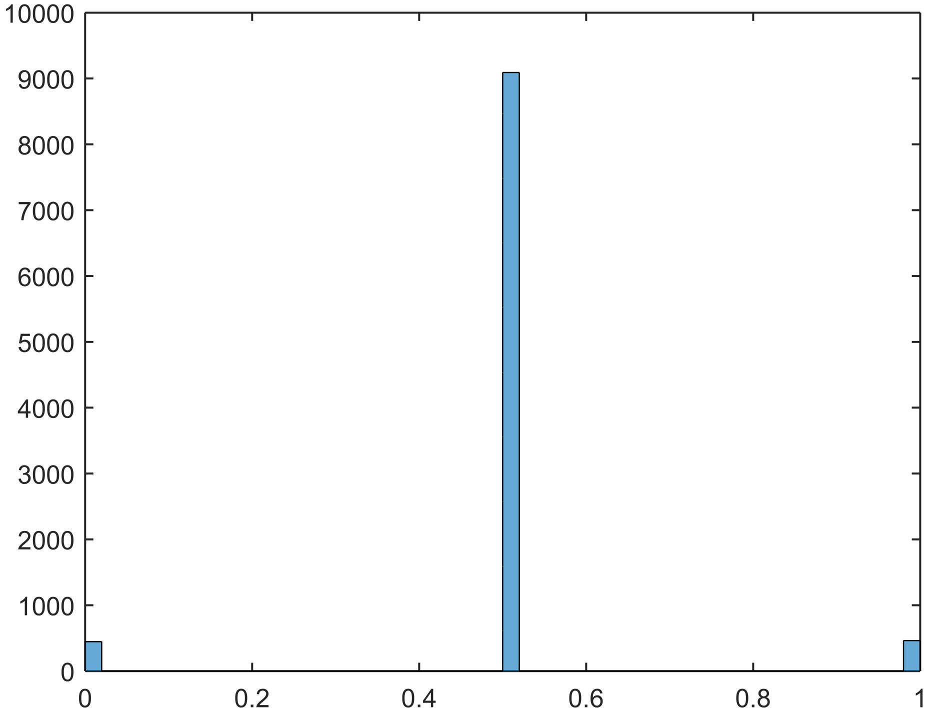


Figure 111: Likelihood of Sampling Pessimistic ($x = 0$), Expected($x = 0.5$), and Optimistic($x = 1$) Distributions for x-bounds of 0.15

In the absence of SME input or historical data, the standard deviation could be used as a means to specify the binning. This approach is based off the amount of variation present in the assumed uncertainty distribution. For the case of a triangular distribution $\sigma \approxeq 0.2041$, which dictates that the x-bounds for the extremes are 0.2959 and 0.7041. This equates to likelihoods of approximately 17.5%, 65%, and 17.5% for pessimistic, expected, and optimistic permutations, respectively. The resulting phase end distributions from these two cases are shown in Figures 112 and 113, respectively. The relationship between the likelihood and bin bounds is described by Equation 33.

$$x = \sqrt{\frac{Likelihood}{2}} \tag{33}$$

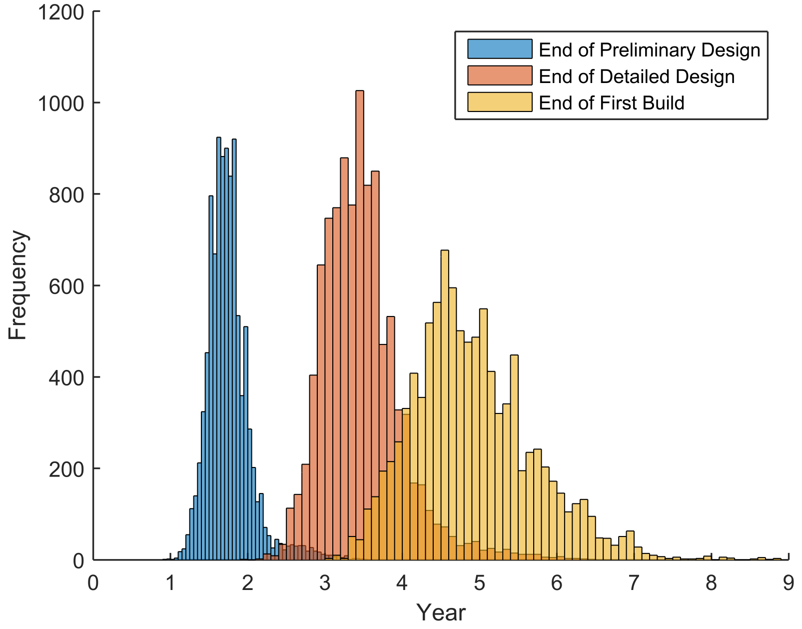


Figure 112: Phase Durations Resulting From Triangular Distribution With Likelihoods Determined From Notional SME Input

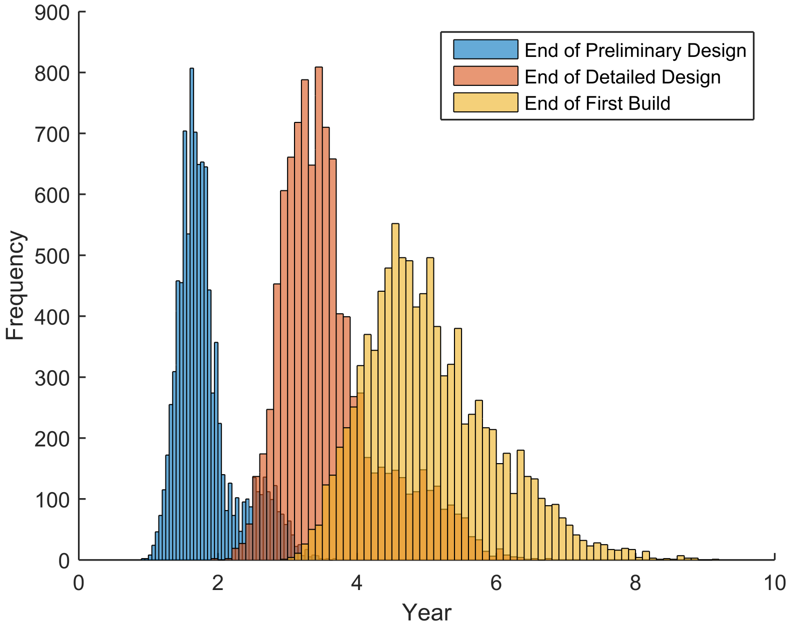


Figure 113: Phase Durations Resulting From Triangular Distribution With Likelihoods Determined From Standard Deviation

Comparisons between these two figures reveals the expected trend that as more of the extreme cases are included (i.e. probability of sampling these distributions increases) the closer the distribution gets to the uniform distribution case. In the absence of historical data and SME input into the likelihood of various schedule permutations occurring, it is prudent to utilize the uniform distribution. These results were presented devoid of the affordability distributions due to the inability to distinguish trends between them within the perspective of total duration and phase end. However, the culmination of this experiment is to show that the assumptions developed thus far facilitate the creation of probabilistic affordability distributions for the elements which comprise a launch vehicle.

Figure 114 portrays the probabilistic affordability distribution which results from using the uniform distribution to propagate the schedule uncertainty. While it is difficult to discern any trends from the range which describes the probabilistic distribution, a few cases are highlighted. These cases are extracted from the information that typically forms the basis for cost analysis at the Conceptual Design phase; the minimum, maximum, median, and mean total program costs. While the expected distribution approximately divides the range in half, **the minimum and maximum total costs do NOT form the lower and upper bounds of the range, respectively.** As alluded to earlier, the total cost only represents area under the affordability distribution. The importance of this observation cannot be overstated and bolsters the utility of the framework developed in this thesis. The clear depiction of the need to consider more than just a total cost or total schedule is embodied herein. Interestingly, the maximum total cost distribution does represent the longest development duration.

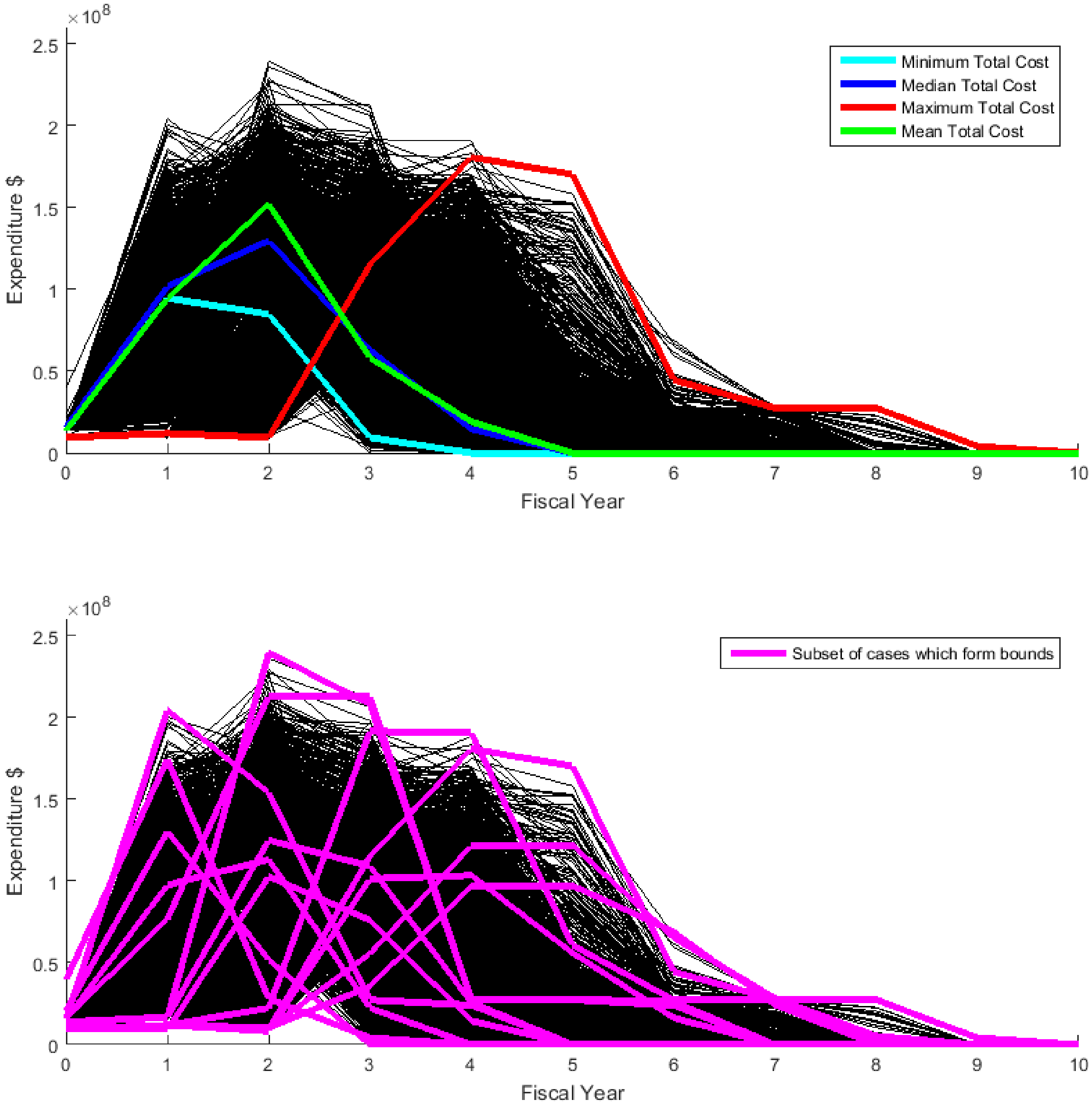


Figure 114: Probabilistic Affordability Distribution for One Fuel Tank Concept With Highlighted Total Cost Statistics (*top*), and Highlighted Cases Which Form Bounds (*bottom*)

The second subplot in Figure 114 highlights all the cases which have at least one point that bounds the range of affordability distributions. The most notable feature of these distributions, is that some grouping is occurring with respect to the initial ramp-up of expenditure.

3.9.4 Summary

The aim of this experiment is to test Hypothesis 3, the applicability of leveraging triangular distributions to represent uncertainty in inputs, particularly for discrete task-order permutations. Furthermore, this experiment aimed to demonstrate the generation of a probabilistic affordability distribution — for an element — and assess any trends which arise.

While triangular uncertainty distributions prove traceable for inputs to P-BEAT, this traceability is lost when attempting to abstract this distribution to discrete task permutations in the absence of detailed historical data. The definition of the bounds of the triangular distribution for P-BEAT inputs are tangible, as many of them are continuous or have been mapped to discrete bins through historical data and SME input upon which the tool is based. In bounding the potential time duration by defining optimistic, pessimistic and expected task permutations, a significant amount of ambiguity is introduced when attempting to quantify the likelihood of each permutation occurring.

Therefore it is only possible to accept Hypothesis 3 with the caveat that a uniform distribution is more traceable for task order permutations. While this caveat has only been tested for applicability to the three-permutation example presented herein, this issue will most likely be extensible to the scenario in which every feasible task order is established and analyzed. Despite the fact that SME input, or historical data, could be used to rank the likelihood for each scenario, each will have a distinct flaw. The former would be prone to bias and/or optimism resultant from the planning fallacy and/or pressure to reduce cost [107]. The latter, for the purpose of launch vehicle programs would most likely include too few sample schedule from which to draw any meaningful likelihoods. Thus, on balance, it would be prudent to assume uniform uncertainty across the task order permutation domain.

The final section, and subsequent experiment, aim to amalgamate the concepts generated thus far and generate a system-level probabilistic affordability distribution. This includes the utilization of probabilistic affordability distributions for the system elements and integration but is not yet free of challenges.

3.10 Research Question 4: System Level Probabilistic Affordability Curves

The culmination of this chapter seeks to establish a means to inform decision making. Have established a means to generate probabilistic distributions, these now need to be combined to form a system-level curve over which constraints can be laid and a probability of success metric be generated to compare various concepts. The final research question will close the loop on Research Question 1.2: the quantification of risk associated with exceeding a pre-established budget ceiling or schedule goals.

Research Question 4

How can the development activities be arranged to generate a system-level estimate with which to compare the affordability impact of manufacturing technology infusion?

The underlying premise here is that since each portfolio of manufacturing technologies has its own distinct set of development activities, there is a need to organize those activities in a manner which provides a suitable basis to perform comparisons between different combinations of manufacturing technologies. This is to say that each combination should be compared based upon the "best" possible plan to develop, and integrate the system-elements into the complete system, thus achieving first flight. Furthermore, there is a desire to include the implications of risk. These final consideration shall be elucidated through a final experiment.

3.11 Experiment 4: Generation of System-Level Probabilistic Affordability Distributions and Their Use in Decision Making

3.11.1 Purpose

Experiment 4 is not so much intended to test any hypothesis as such, but more to explore the compilation of results provided thus far. This experiment also serves as a means to assess whether an optimization method is necessary when determining probability of success (POS).

3.11.2 Approach

Experiment 3, provided the method for generating an affordability distribution for each of the system elements, and integration. Generating an estimate is commensurate with establishing a DDTE&P plan which dictates the order in which elements should be developed to achieve the greatest POS. This is analogous to the affordability risk — the likelihood of remaining under the mandated funding curve and within schedule goals.

First, it is necessary to address the addition of elements and the various permutations associated with the DDTE&P plan. Fundamentally, an element can begin development at any time during a program. However, there are some logical limitations that can be placed upon the plan right away. Reviewing the two most recent launch vehicle programs — the ongoing SLS program, and the canceled Constellation program — a constraint on the duration of Preliminary Design may be established. The Ares I launch vehicle reached Preliminary Design in approximately two years [41][7] and the SLS — which includes aspects carried over from the Constellation program — completed Preliminary Design in one year [42]. It is no inconceivable to extend this

---

[7] There is some ambiguity on where Formulation Start falls within the program life cycle portrayed in 9. In this context it is assumed to refer to the start of Conceptual Design, which dictates that Ares I crew vehicle completed Conceptual Design and Preliminary Design in three years.

observation to state that a program could potentially spend 3 years in Preliminary Design phase alone.

This affords some freedom to the decision maker to delay the beginning of development for some vehicle elements in an attempt to prevent all elements reaching peak expenditure in the same year. If Preliminary Design must be completed within three years, then the development of certain elements may be delayed for one fiscal year. This equates to a combinatorial space in which elements can all start together in year one, some can be shifted to start in year two, all the way to all elements beginning in year two. This equates to a total number of $2^{12} = 4096$ variations on the start vector which describes the year in which the development of each element begins. Depending on the complexity and run-time of analysis, this many combinations may warrant the use of an optimization method.

Experiment 1, 2, and 3 describe the process required to generate a probabilistic affordability distribution for an element of a system. The use case used throughout has been a metallic fuel tank — the largest structure for a launch vehicle stage. For brevity and simplicity, the affordability distributions for the other eleven elements and integration shall be developed by photographically scaling the expenditure distribution. This scaling is also applied to the phase durations except in the case of integration.

Since the fuel tank is the largest component, many of the other components are expected to be less costly to develop, except the main propulsion system and integration. The MPS is expected to be more costly, and the integration curve is available, Figure93, from Experiment two results and has been selected based upon the metallic LH_2 tank used herein. Table 16 lists the factors selected for the elements.

Table 16: List of Scaling Factors Used to Generate Probabilistic Distributions for Launch Vehicle Elements by Scaling Fuel Tank Outcome

Element	Scaling Factor
LH_2 Forward Skirt	0.5
LH_2 Aft Skirt	0.5
Intertank	0.7
LO_2 Tank	0.8
Thrust structure	0.4
Main Propulsion System (MPS)	1.5
Thermal Protection System	0.5
Active Thermal Conditioning	0.5
Power Systems	0.5
Avionics System	0.5
Reaction Control System	0.5

With the distributions for each element, and integration, defined; the final step in generating the system-level affordability distribution is adding these distributions. The summation of the twelve elements would be based off a "Start" vector, which specifies the start year for each of the twelve elements. However, the addition process is more complex than simply stacking probabilistic distributions on top of one another. This approach would assume that the sum of affordability curves is done with respect to the likelihood value. Instead, bootstrapping each distribution and adding one sample from each, many times over is a more appropriate method to propagate uncertainty to the system level. Ten thousand samples should be sufficient considering the element distributions are comprised of 10,000 MCS runs.

The final consideration for adding the distributions is to determine the appropriate inclusion of integration. While the integration distribution does include a Preliminary and Detailed Design phase, assigning a start date in the "Start" vector implies that integration is independent of the elements. Instead, there are two options to consider when assessing the appropriate time to start integration efforts. The first is to leverage SME input or historical data to determine the number of elements (or which elements in particular) that must complete their First Build phase in order to commence the First Build phase of Integration. While this method would be more representative of the practical aspect of the problem; ambiguity, bias, or may be introduced. The second, and far more conservative option is to assume that all twelve elements must complete their First Build before their integration commences. This assumes that all twelve elements have completed their First Build and have reached a TRL of 7 — each is flight-ready hardware and form, fit, and function are near or at planned level. While this might be considered an overly conservative approach, it is also the most transparent. Therefore, on balance, the latter method shall be used for the development of this thesis.

This approach will generate a system-level probabilistic affordability distribution which, when overlaying constraints, will provide a POS value. POS forms the complement to risk, which is defined as the likelihood of an adverse outcome. This notion is portrayed in 36, repeated below where POS would represent the non-shaded area. In this case, however, the affordability distribution is visualized in a realm which contains two constraints, one for schedule and one for expenditure.

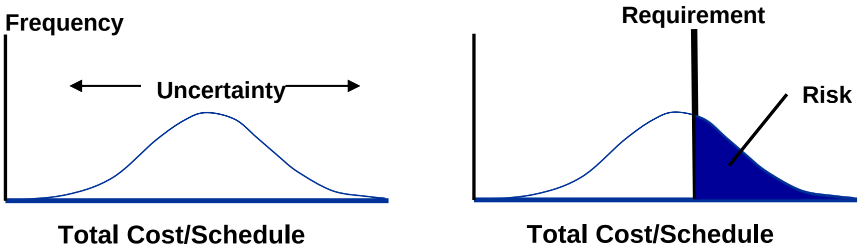


Figure 36: Uncertainty and Risk [adapted from [65]]

A vertical line, representing the desired launch date forms the schedule constraint, while a horizontal line — or step — represent the budget ceiling that would be appropriated by congress. The budgetary ceiling could take on a variety of shapes, as is shown in Figure 115 with notional a depiction of flat funding, increasing and decreasing funding. While an increasing funding profile is typical, both the constellation program and SLS have experienced flat funding profiles.

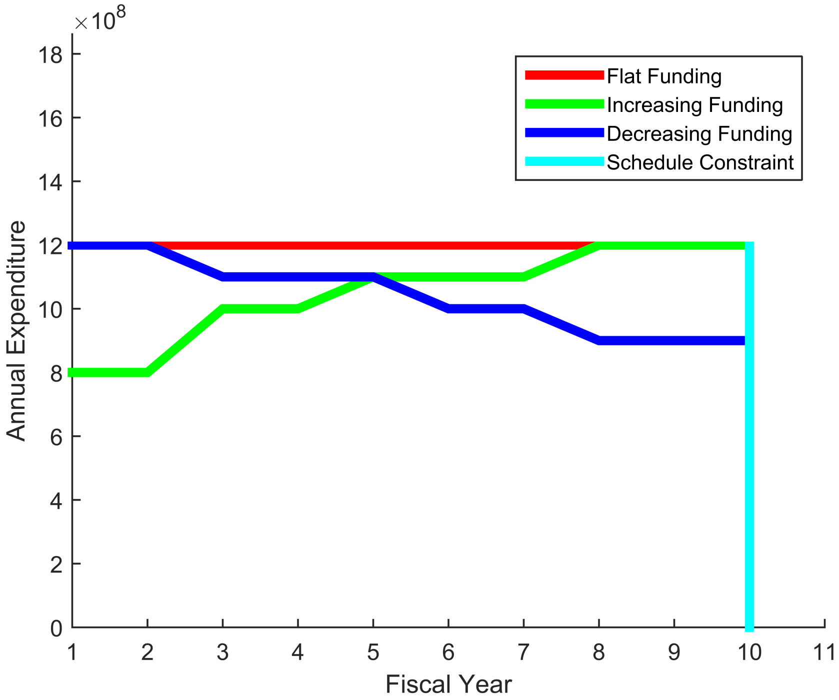


Figure 115: Notional Constraint Diagram

In comparing this constraint diagram to that shown in Figure 36, shading the area of distribution is not meaningful. Instead, any distribution which fails to remain beneath the defined budget ceiling, and within the scheduled launch goal should be eliminated. In this context, risk is not proportional to the area described by the excess of a distribution, but whether a distribution exceeds a constraint. Thus, risk can be quantified as the percent of the distributions which exceed the constraints; and the POS, its complement.

3.11.3 Results

The result generated from the approach described previously is, fundamentally, a constraint diagram which would be used for decision support. The full probability distribution would be visualized, over which the constraints are superimposed. All cases which meet the constraint — remain under the budget ceiling AND within schedule goals — could be highlighted. Figure 116 shows a representation of such a decision making tool.

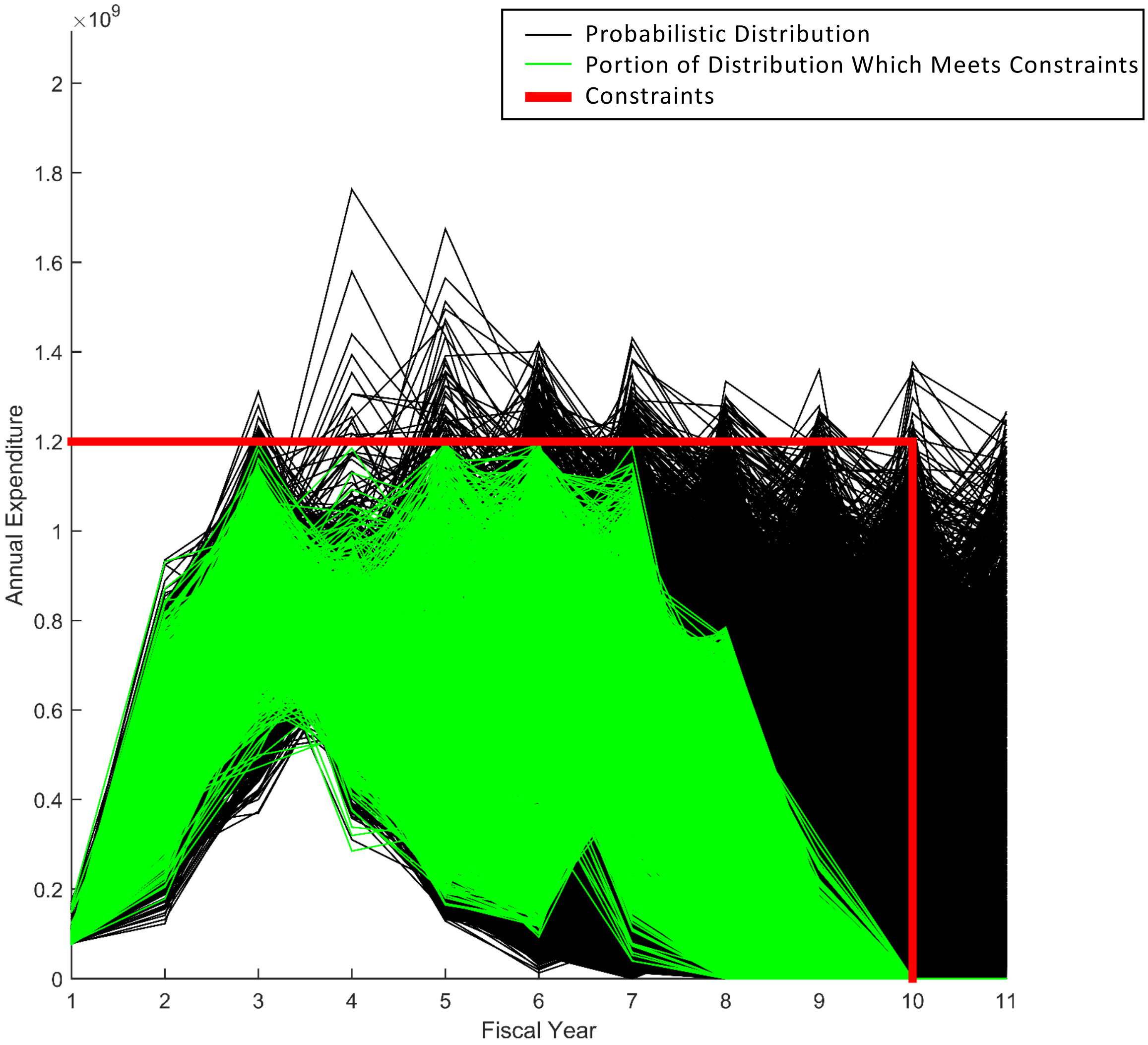


Figure 116: Affordability Constraint Diagram

The probabilistic distribution consists of every combination of "Start" vector for a specific system design; thus representing a full-factorial analysis of delaying element development. The Matlab code, contained in Appendix D, has been written to leverage logical program as much as possible. While there may be some room for improvement (primarily further improving speed by removal of a 'parfor' loop) the run time of this program for the full factorial analysis is approximately 2-3 minutes. This runtime was assessed on two desktop computers, where the more powerful of the two exhibited runtime closer to two minutes regardless of the form of the cost constraint[8]. The premise of this code is to add the probabilistic distributions for the elements and integration — as described above — to for a system distribution. User-defined Start vector and cost constraint matrix are leveraged in a full factorial exploration to determine the POS of each of the 4096 variations on the development start year for each element. The code concludes by providing visualizations of the "best" candidate start vector, where "best" is defined as the case which is robust to variations in the cost constraint, as shown in Figure 117. These variations represent the high-level uncertainty in funding on a year to year basis; an ideal candidate would possess a 100% POS.

---

[8] More powerful machine: Dell XPS 8700 with Intel i7 4890 with 24GB of RAM
Less powerful machine: Dell Optiplex with Intel i7-2600 and 16GB RAM

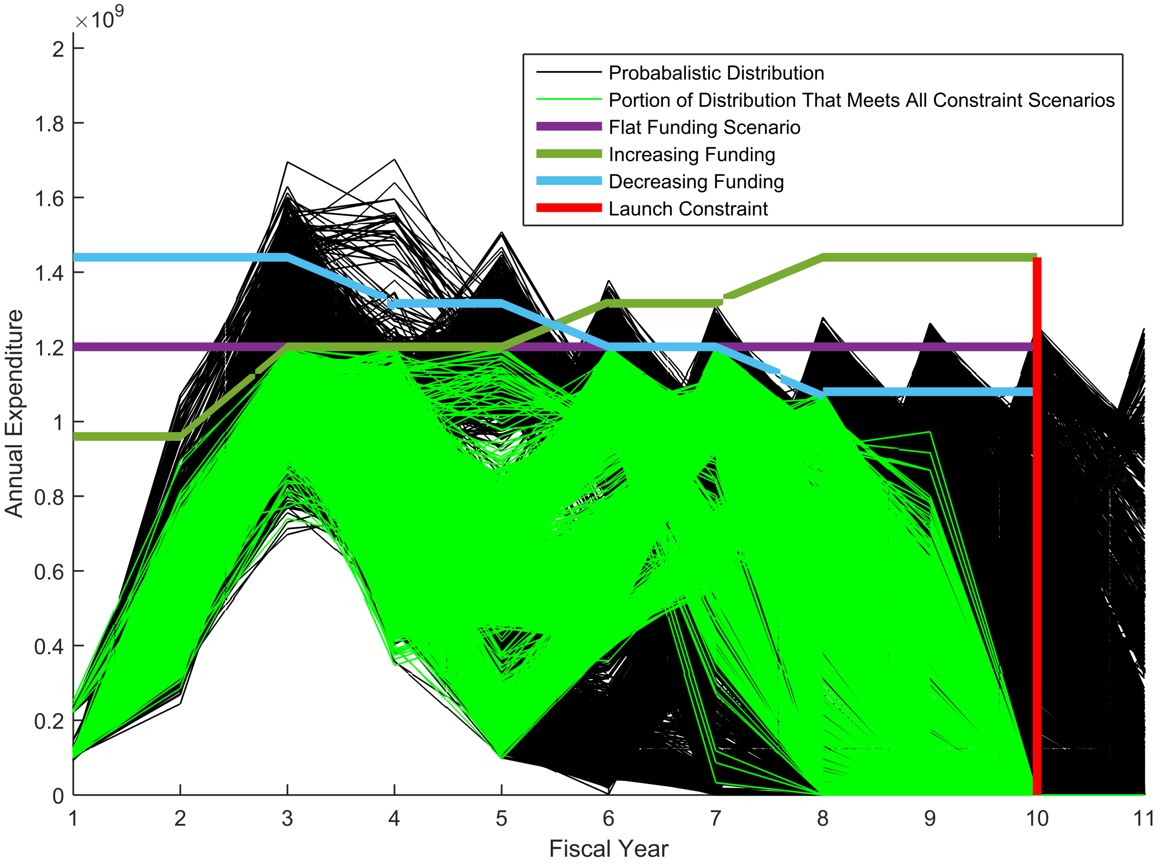


Figure 117: Robust Affordability Constraint Diagram

With the generation of the probabilistic affordability distribution, it is necessary to convert this back into the more traditional method for assessing cost and schedule risk to determine any major differences. Figures 118 and 127 show the total cost and schedule milestones for the entire probabilistic population and those which meet the constraints for one start vector permutation. First and foremost, the ability to generate an uncertainty distribution of the end of the phases is an improvement of the traditional approach highlighted in Section 2.2. Secondly, the form of the constraints represented in these figures is **NOT** a vertical line commensurate with traditional risk assessment procedures. Instead, the subset of distributions which meet the constraints seem to be bounded by a curve. Upon inspection, no direct relationship to the parent (i.e. complete set) distribution is evident.

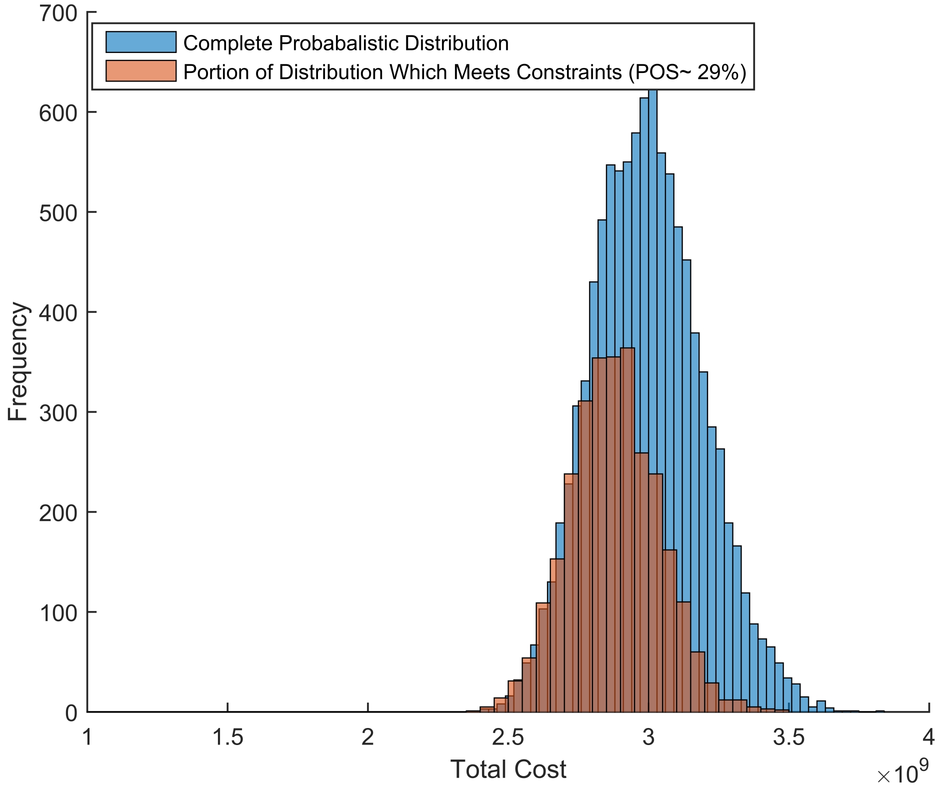


Figure 118: Comparison of Total Cost Distributions for One Constraint Scenario

3.11.4 Correlation Analysis

One additional aspect of this experiment that may hold significant observations is the correlation between cost and schedule. More specifically, two questions may be posed in order to elicit observations with respect to the correlation between cost and schedule:

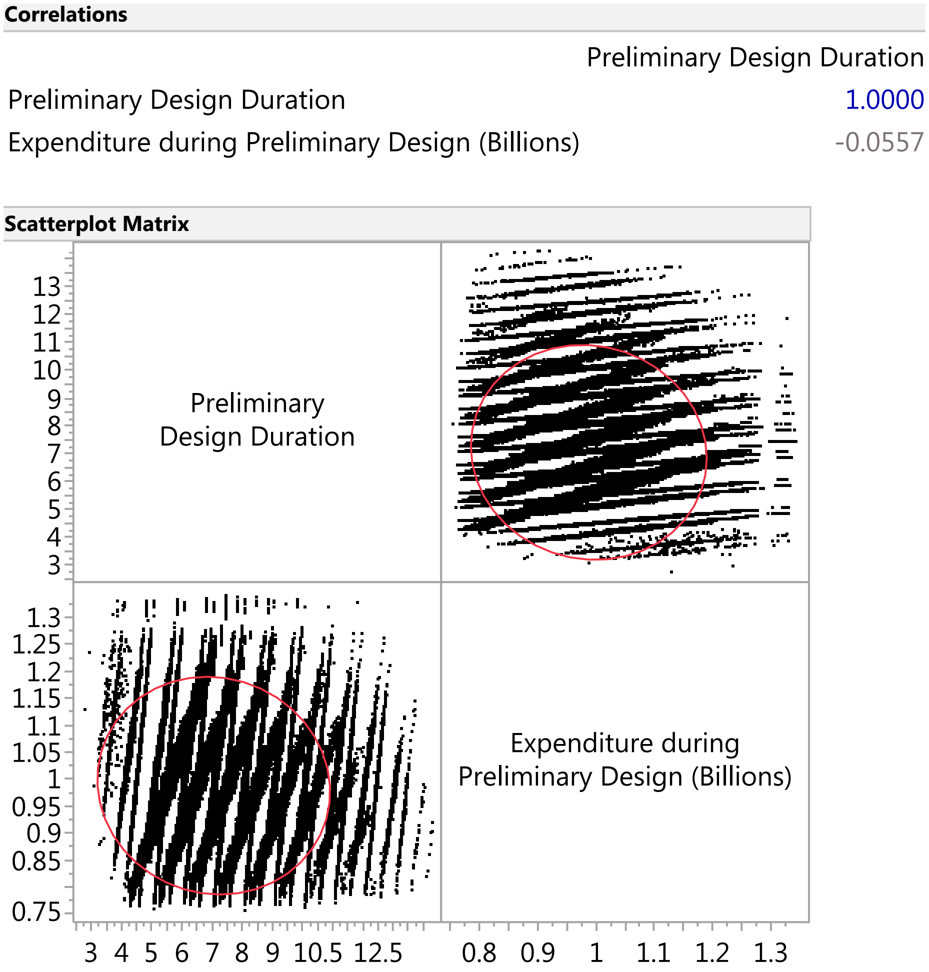
1. Does the correlation vary with time?

2. Does the correlation vary with DDTE&P plan?

To address the first question, there are two perspectives which must be assessed; the cumulative behavior, and the non-cumulative. More specifically, assessing the expenditure in each of the three design phases, as well as the cumulative expenditure through these phases are of interest. The proceeding analysis has been performed using the baseline Al-Li 2195 fuel tank described in Table 10. Due to computational limitations, the full set of 4096 start vectors could not be leveraged for this analysis. Instead, a subset of 52 distinct start vectors were selected; the two cases which bound the space, and 50 vectors randomly sampled between them.

3.11.4.1 Non-Cumulative Behavior

Beginning with the Preliminary Design phase, Figure 119 shows the correlation and scatterplot visualization between the expenditure and phase duration for the 52 sample DDTE&P plans. The correlation across all plans is depicted as weakly negative, with striations appearing in the scatterplot matrix. Since the scatterplot represents one design concept with uncertain inputs, many of which are discrete, the striations are depictions of variations in these variables. Specifically, these bands depict the expected positive correlation between cost and schedule, which results from varying inputs from completely optimistic to pessimistic.

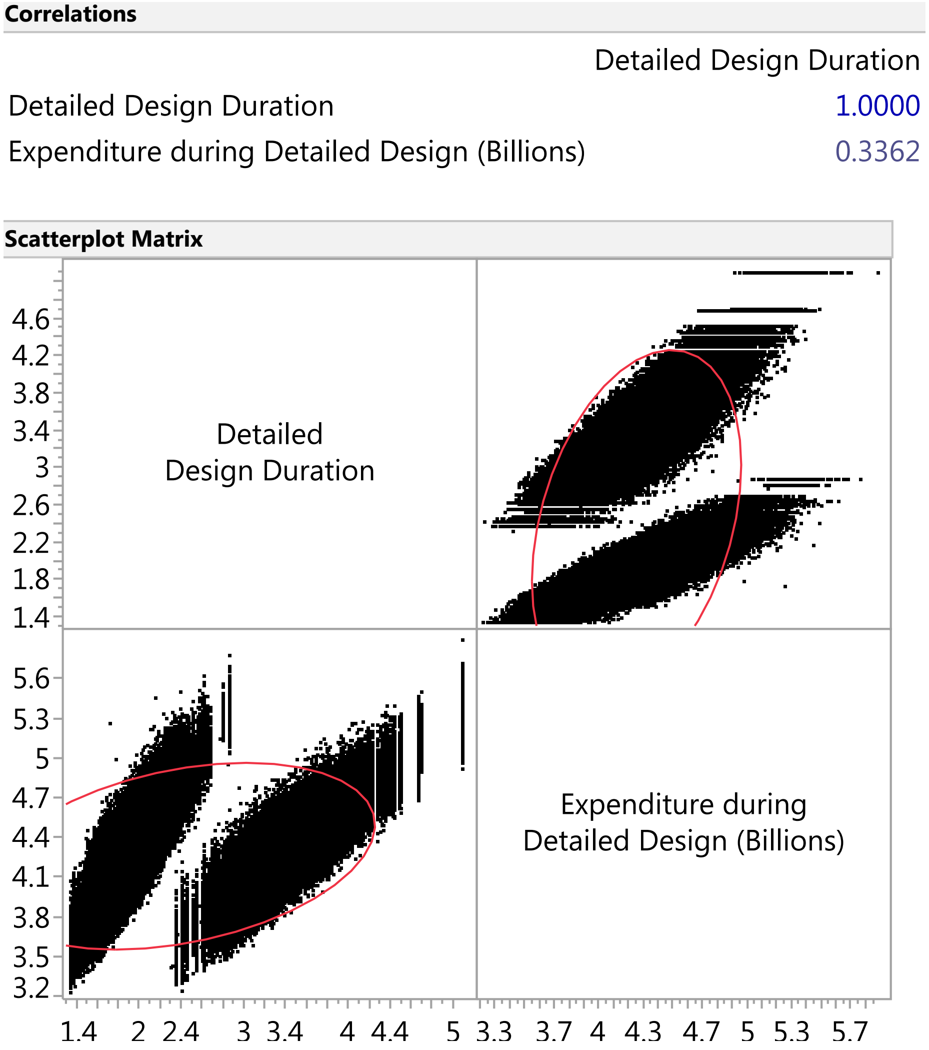


Correlations

	Preliminary Design Duration
Preliminary Design Duration	1.0000
Expenditure during Preliminary Design (Billions)	-0.0557

Figure 119: Correlation for Expenditure During Preliminary Design

Moving onto the expenditure and duration of Detailed Design, a positive correlation and distinct grouping is present. The scatterplot matrix, shown in Figure 120, shows two distinct groupings of points, each with a positive correlation. Upon inspection of these two distinct groupings, the separation is a result of the task order permutations used in the uncertainty analysis described in Section 3.9. Of the three task order permutations used in this analysis, the optimistic and expected permutations are more similar than the pessimistic permutation. Figure 121 shows the adjusted correlations when these two groupings are separated. Both groupings have a strongly positive correlation, with the pessimistic task order permutation exhibiting a slighter stronger correlation due to the parallel nature of task order. These two representations due explicitly prove that the correlation between cost and schedule is sensitive to variations in the schedule by which a systems elements are developed.

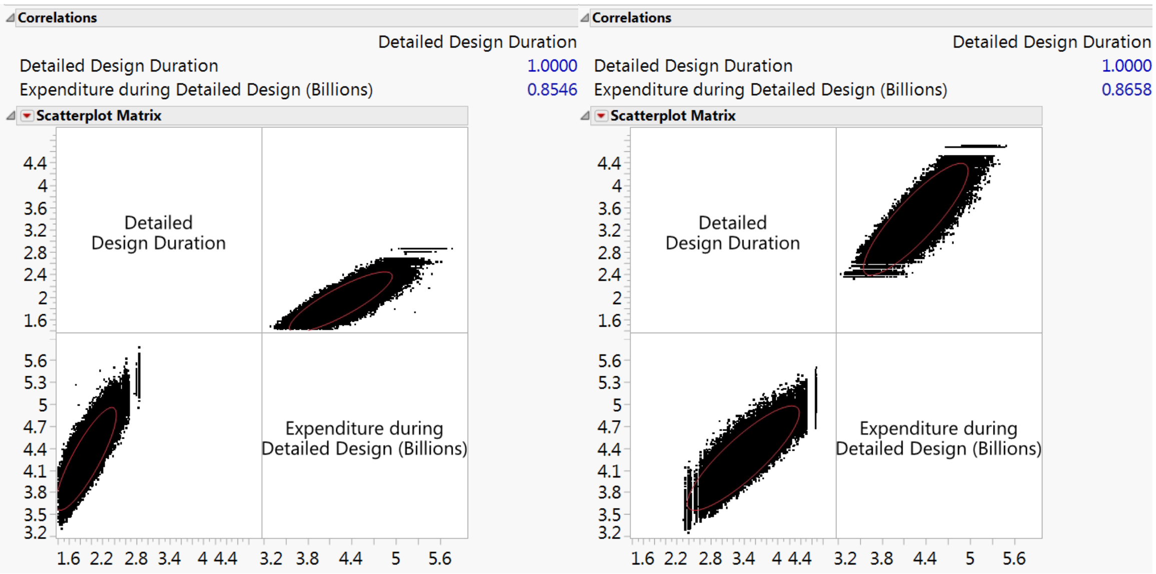


Correlations

	Detailed Design Duration
Detailed Design Duration	1.0000
Expenditure during Detailed Design (Billions)	0.3362

Scatterplot Matrix

Figure 120: Correlation for Expenditure During Preliminary Design



Correlations

	Detailed Design Duration
Detailed Design Duration	1.0000
Expenditure during Detailed Design (Billions)	0.8546

Correlations

	Detailed Design Duration
Detailed Design Duration	1.0000
Expenditure during Detailed Design (Billions)	0.8658

Figure 121: Differentiation Between Correlations for Optimistic and Expected (left) and Pessimistic (right) Task Order Permutations

In assessing the correlation during the First Build design phase, a slightly positive correlation is present. While two distinct bands of points are shown in the scatterplot matrix, their cause is unclear. These bands are not a result of task order permutations or DDTE&P plan variations. The rightmost band (relative to the scatterplot matrix in the lower left quadrant of Figure 122) consists of just 0.17% of the total number of points, and the band just to its left consists of an additional 0.27% of the 520,000 points analyzed (10,000 MC points for each of the 52 DDTE&P plan variations). Additional analysis is needed to determine the causation of these strata.

Correlations

	First Build Duration	Expenditure
First Build Duration	1.0000	
Expenditure during First Build (Billions)	0.0928	

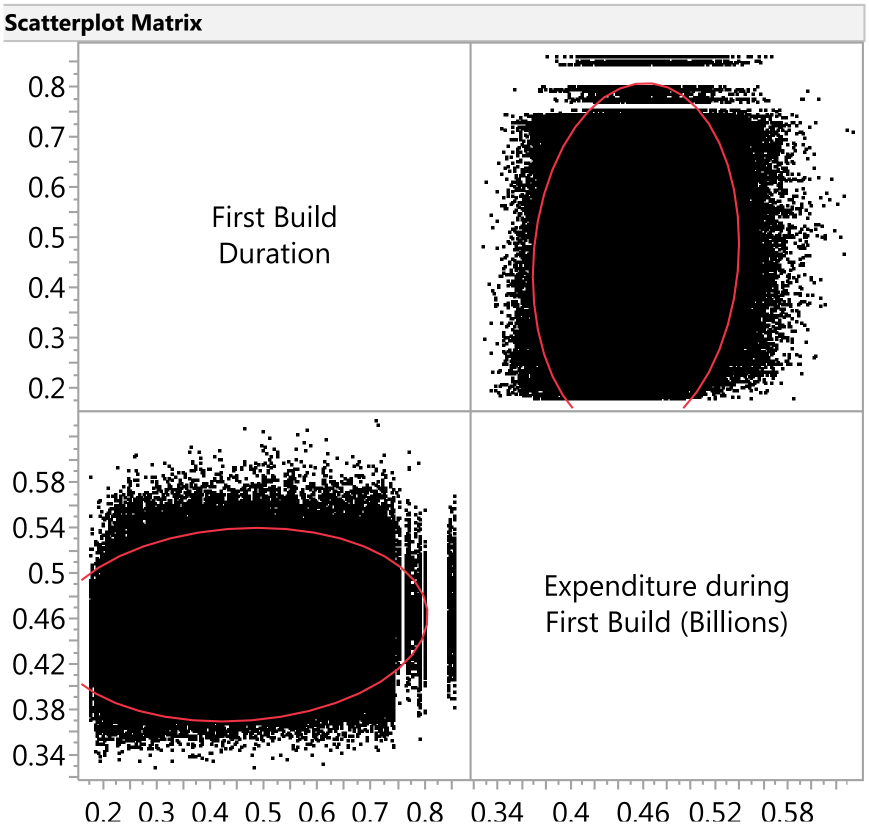


Figure 122: Correlation for Expenditure During Preliminary Design

Finally, regarding the non-cumulative behavior, an assessment of how these correlations vary from one DDTE&P plan to another has been performed. A selection of four DDTE&P plans is shown in Figure 123, where each digit the Start Vector represents the year in which each of the twelve launch vehicle elements begins development. Included in the visualization are two extreme DDTE&P plans and two plans which fall in between them. While these results do show that the correlation strengths do vary with DDTE&P plan, there is no evidence that the correlation increases or decreases proportionally to the increase of elements whose development is delayed.

Multivariate Start_Vector=111111111111

Correlations

	Preliminary Design Duration	Expenditure during Preliminary Design (Billions)	Detailed Design Duration	Expenditure during Detailed Design (Billions)	First Build Duration	Expenditure during First Build (Billions)
Preliminary Design Duration	1.0000	-0.0237	-0.1897	0.1317	-0.0720	0.2708
Expenditure during Preliminary Design (Billions)	-0.0237	1.0000	0.3889	0.8793	0.0442	0.3869
Detailed Design Duration	-0.1897	0.3889	1.0000	0.3413	-0.0876	0.1486
Expenditure during Detailed Design (Billions)	0.1317	0.8793	0.3413	1.0000	0.0543	0.7675
First Build Duration	-0.0720	0.0442	-0.0876	0.0543	1.0000	0.1050
Expenditure during First Build (Billions)	0.2708	0.3869	0.1486	0.7675	0.1050	1.0000

Multivariate Start_Vector=122222111212

Correlations

	Preliminary Design Duration	Expenditure during Preliminary Design (Billions)	Detailed Design Duration	Expenditure during Detailed Design (Billions)	First Build Duration	Expenditure during First Build (Billions)
Preliminary Design Duration	1.0000	-0.0501	-0.1956	0.1181	-0.0377	0.2764
Expenditure during Preliminary Design (Billions)	-0.0501	1.0000	0.3691	0.8749	0.0637	0.3736
Detailed Design Duration	-0.1956	0.3691	1.0000	0.3220	-0.0941	0.1335
Expenditure during Detailed Design (Billions)	0.1181	0.8749	0.3220	1.0000	0.0590	0.7642
First Build Duration	-0.0377	0.0637	-0.0941	0.0590	1.0000	0.0885
Expenditure during First Build (Billions)	0.2764	0.3736	0.1335	0.7642	0.0885	1.0000

Multivariate Start_Vector=211212111211

Correlations

	Preliminary Design Duration	Expenditure during Preliminary Design (Billions)	Detailed Design Duration	Expenditure during Detailed Design (Billions)	First Build Duration	Expenditure during First Build (Billions)
Preliminary Design Duration	1.0000	-0.0483	-0.2250	0.1118	-0.0647	0.2682
Expenditure during Preliminary Design (Billions)	-0.0483	1.0000	0.3910	0.8829	0.0452	0.3982
Detailed Design Duration	-0.2250	0.3910	1.0000	0.3392	-0.0767	0.1434
Expenditure during Detailed Design (Billions)	0.1118	0.8829	0.3392	1.0000	0.0493	0.7705
First Build Duration	-0.0647	0.0452	-0.0767	0.0493	1.0000	0.0971
Expenditure during First Build (Billions)	0.2682	0.3982	0.1434	0.7705	0.0971	1.0000

Multivariate Start_Vector=222222222222

Correlations

	Preliminary Design Duration	Expenditure during Preliminary Design (Billions)	Detailed Design Duration	Expenditure during Detailed Design (Billions)	First Build Duration	Expenditure during First Build (Billions)
Preliminary Design Duration	1.0000	-0.0884	-0.3245	0.0705	-0.0535	0.2416
Expenditure during Preliminary Design (Billions)	-0.0884	1.0000	0.3971	0.8813	0.0318	0.3864
Detailed Design Duration	-0.3245	0.3971	1.0000	0.3455	-0.0682	0.1400
Expenditure during Detailed Design (Billions)	0.0705	0.8813	0.3455	1.0000	0.0313	0.7646
First Build Duration	-0.0535	0.0318	-0.0682	0.0313	1.0000	0.0755
Expenditure during First Build (Billions)	0.2416	0.3864	0.1400	0.7646	0.0755	1.0000

Figure 123: Correlation for Non-Cumulative Expenditure and Phase Duration for a Selection of DDTE&P Plans

3.11.4.2 Cumulative Behavior

The final portion of the correlation analysis is to assess the cumulative development behavior. The Preliminary Design behavior is excluded in the proceeding analysis as it remains unchanged from the previously presented non-cumulative case. The cumulative behavior is described by the expenditure up until the end of the life cycle phase, and the total development time required to reach the phase end — this includes both expenditure and duration of all previous phases.

The expenditure and total development time required to reach the end of Detailed Design are positively correlated, as is the total development duration and expenditure. Figures 124 and 125 show the correlation at the end of Detailed Design and First Build phases, respectively. As is the case in the non-cumulative analysis, the correlation strengthens with time. Figure 126 shows the correlation variation for four DDTE&P plans. Similar to the non-cumulative case, while these results do show that the correlation strengths do vary with DDTE&P plan, there is no evidence that the correlation increases or decreases proportionally to the increase of elements whose development is delayed.

Correlations

	End of Detailed Design
End of Detailed Design	1.0000
Expenditure up to End of Detailed Design (Billions)	0.2436

Scatterplot Matrix

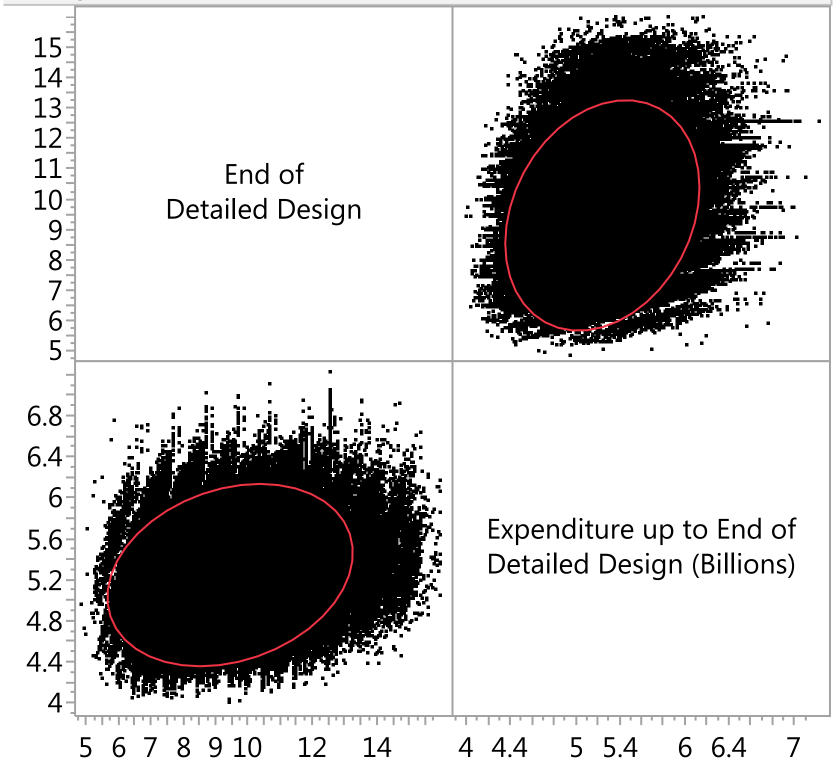
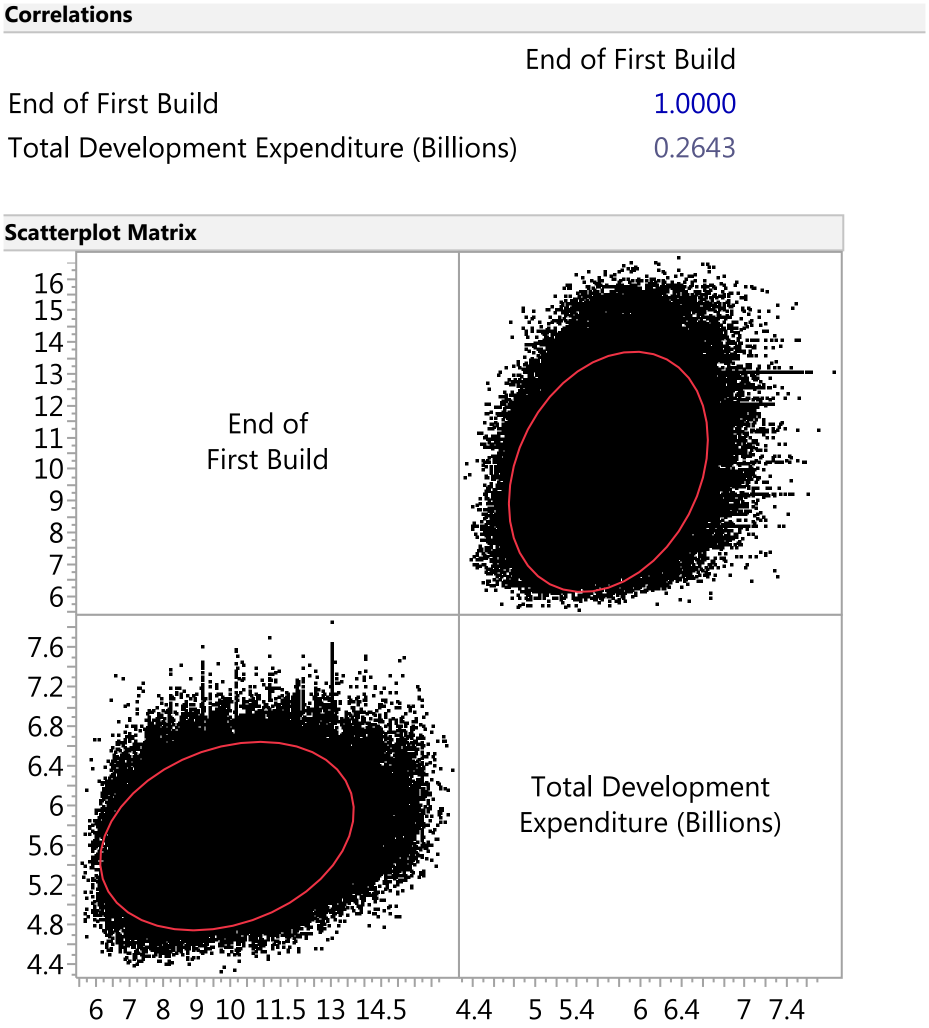


Figure 124: Correlation for Cumulative Expenditure Up to the End of Detailed Design



Correlations

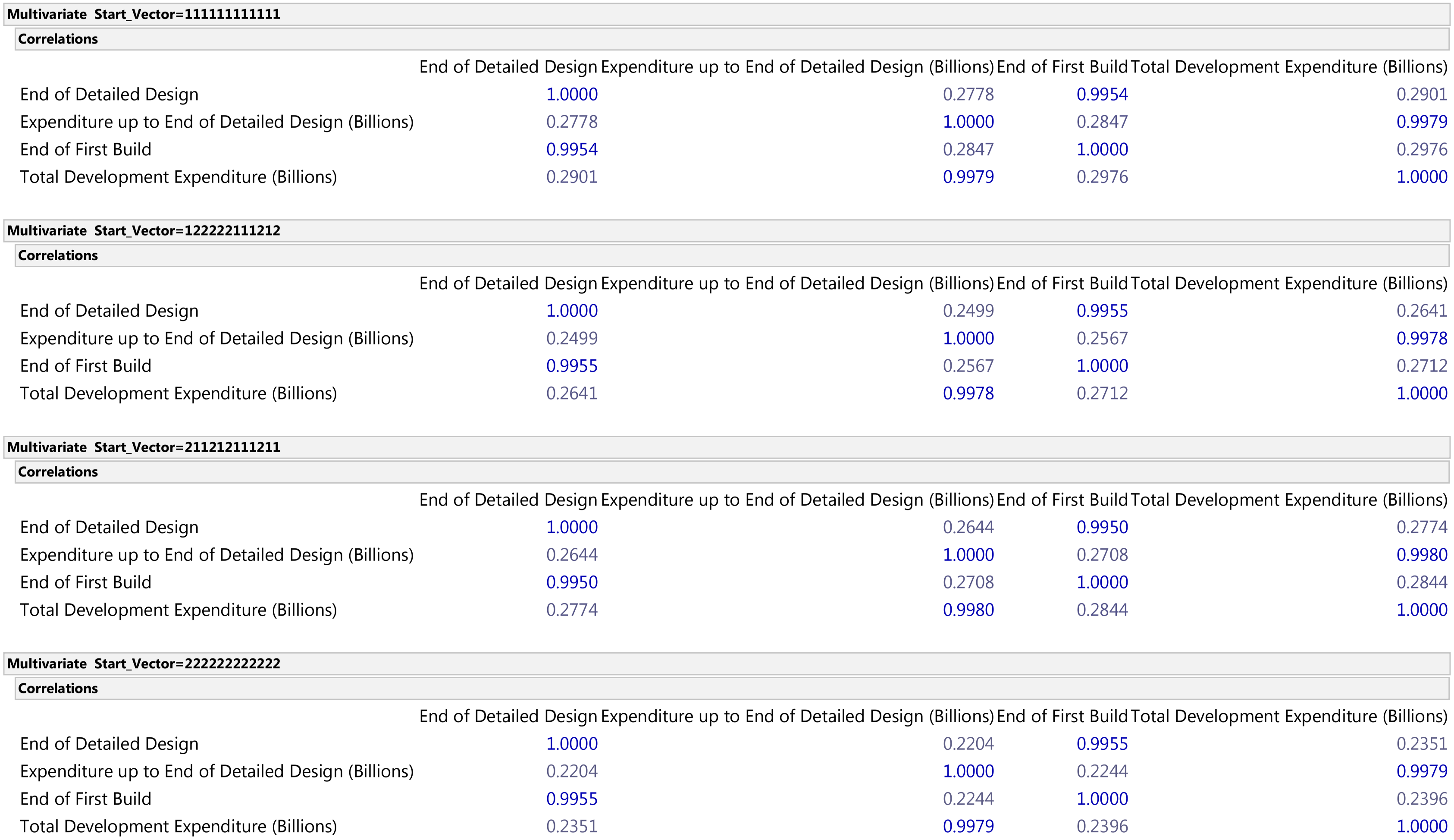
	End of First Build
End of First Build	1.0000
Total Development Expenditure (Billions)	0.2643

Scatterplot Matrix

Figure 125: Correlation for Cumulative Expenditure Up to the End of First Build

The correlation analysis sought to establish observations revolving around the temporal evolution of cost and schedule correlation and the effect of DDTE&P variation. Both the cumulative and non-cumulative analyses depict an increase in the magnitude of correlation strength as development progresses over time. This strengthening of these correlations over time suggests that the cost and schedule implications become more severe as time progresses. Ultimately alluding to the notion that cost overruns and schedule slippages are most severe when issues arise late in the design process, i.e. during manufacturing.

The schedule variations — from element task order permutations and DDTE&P



Multivariate Start_Vector=111111111111

Correlations

	End of Detailed Design	Expenditure up to End of Detailed Design (Billions)	End of First Build	Total Development Expenditure (Billions)
End of Detailed Design	1.0000	0.2778	0.9954	0.2901
Expenditure up to End of Detailed Design (Billions)	0.2778	1.0000	0.2847	0.9979
End of First Build	0.9954	0.2847	1.0000	0.2976
Total Development Expenditure (Billions)	0.2901	0.9979	0.2976	1.0000

Multivariate Start_Vector=122222111212

Correlations

	End of Detailed Design	Expenditure up to End of Detailed Design (Billions)	End of First Build	Total Development Expenditure (Billions)
End of Detailed Design	1.0000	0.2499	0.9955	0.2641
Expenditure up to End of Detailed Design (Billions)	0.2499	1.0000	0.2567	0.9978
End of First Build	0.9955	0.2567	1.0000	0.2712
Total Development Expenditure (Billions)	0.2641	0.9978	0.2712	1.0000

Multivariate Start_Vector=211212111211

Correlations

	End of Detailed Design	Expenditure up to End of Detailed Design (Billions)	End of First Build	Total Development Expenditure (Billions)
End of Detailed Design	1.0000	0.2644	0.9950	0.2774
Expenditure up to End of Detailed Design (Billions)	0.2644	1.0000	0.2708	0.9980
End of First Build	0.9950	0.2708	1.0000	0.2844
Total Development Expenditure (Billions)	0.2774	0.9980	0.2844	1.0000

Multivariate Start_Vector=222222222222

Correlations

	End of Detailed Design	Expenditure up to End of Detailed Design (Billions)	End of First Build	Total Development Expenditure (Billions)
End of Detailed Design	1.0000	0.2204	0.9955	0.2351
Expenditure up to End of Detailed Design (Billions)	0.2204	1.0000	0.2244	0.9979
End of First Build	0.9955	0.2244	1.0000	0.2396
Total Development Expenditure (Billions)	0.2351	0.9979	0.2396	1.0000

Figure 126: Correlation for Cumulative Expenditure and Phase End for a Selection of DDTE&P Plans

plan variations — precludes the ability to determine a closed-form joint-probability distribution to describe the cost and schedule behavior. Perhaps the most significant observation from this analysis is the necessity to consider both schedule variation degrees of freedom to truly capture the affordability risk associated with development planning. Thus, the use of the methodology developed herein is paramount to truly capturing the affordability risk perspective in which government-funded programs operate, and assessing the correlated cost-schedule implications of development planning.

3.11.5 Summary

With respectable runtime for the full factorial problem defined herein, the use of an optimization method is unnecessary[9]. The results show that the method can indeed provided significant new insights and a powerful decision support tool. This tool could be used to evaluate the robustness of a specific design alternative (with distinct manufacturing technologies) to fluctuations or uncertainty in the available funding. Furthermore, new insights into the manner in which the correlated cost-schedule constraint propagates in the traditional uncertainty domain. The constraint seems to be formed by a curve — for both total cost and the schedule milestone distributions — instead of a vertical line which is typically assumed. The importance of this discovery provides justification for how a program, which would meet the risk criteria under the traditional analysis, could still achieve significant cost and schedule overruns.

---

[9] A brief analysis was also performed on expanding the start vector by allowing one additional year postponement of development activities. While this increased the full factorial space to $3^{12} = 531441$ cases, the required runtime was increased to 8-10 hours. This runtime would allow overnight analysis, but would ultimately warrant the use of an optimization technique.

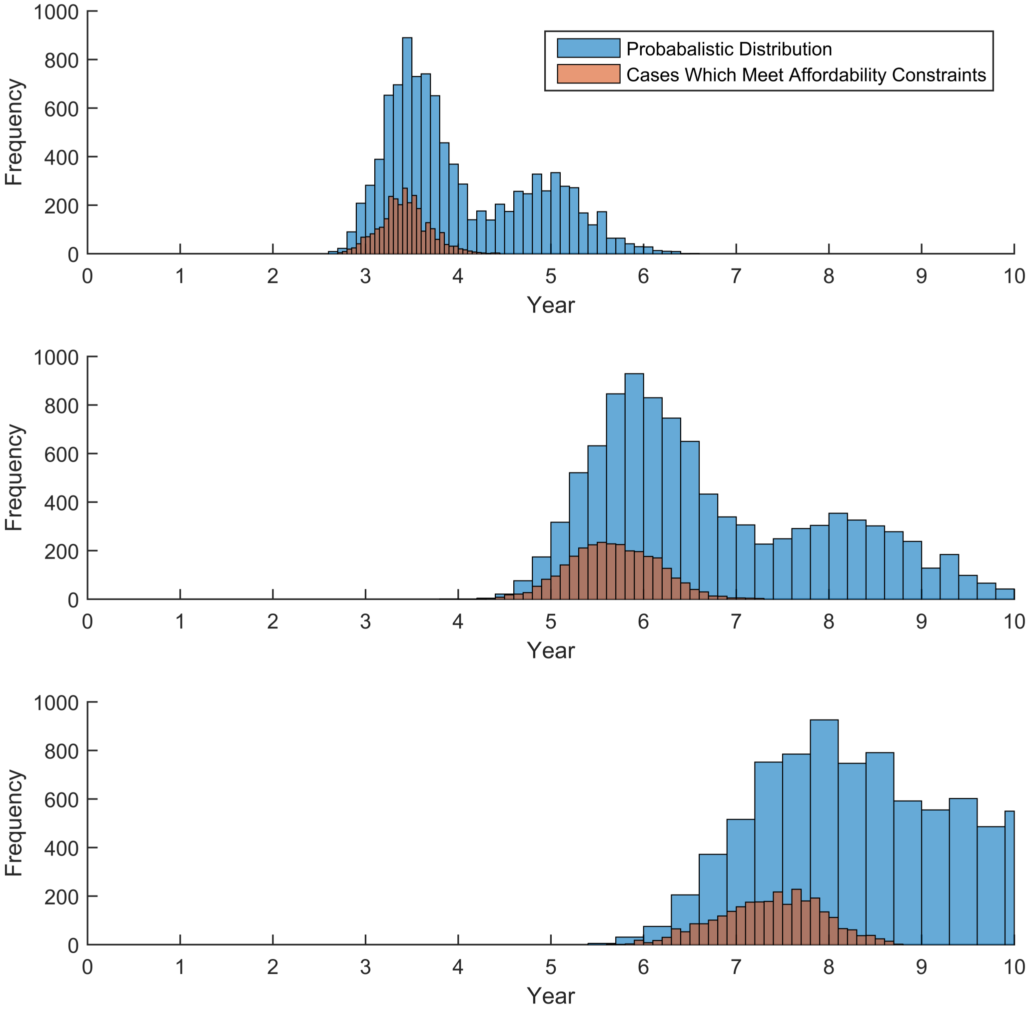
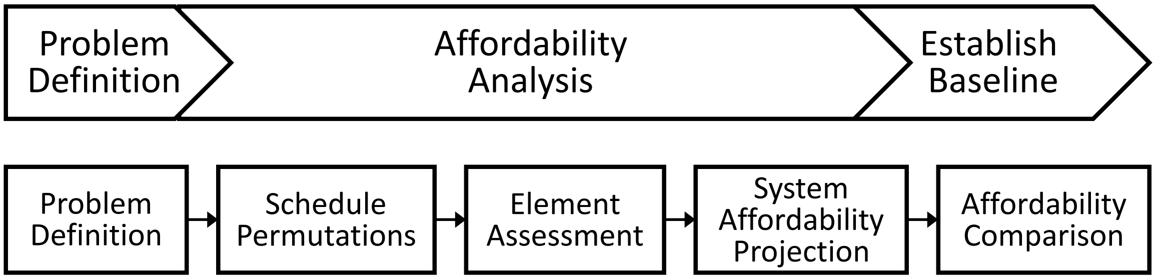


Figure 127: Comparison of Schedule Milestone Distributions for One Constraint Scenario

CHAPTER IV

METHODOLOGY OVERVIEW

Chapter 3 presented four experiments which, in conjunction with literature review — define the specific steps which comprise this methodology. Section 3.2 describes a generic process outline from which the method has been built, resulting in a five step process. First, Problem Definition represents the identification and enumeration of alternatives and constraints for a mission of interest. Hereafter, an assessment on viable schedule permutations is necessary. The third block entails the generation of probabilistic element affordability distributions through MInD analysis and uncertainty propagation. After producing these the fourth block, System Affordability Projection, establishes a system-level probabilistic affordability distribution. Finally, the Affordability Comparison block represents the evaluation of a robust Probability of Success (POS) with respect to the political constraints on the development program. Each of these shall be summarized in the following sections.



4.1 Problem Definition

The intent of this methodology is to inform decision makers during Conceptual Design, while a baseline vehicle configuration is sought. As such, the methodology is founded on the completion of pre-Conceptual Design; the mission requirements have been set and vehicle architecture candidates selected. The method begins with the decomposition of the vehicle architecture(s) into its primary elements, followed by an exploration of design and manufacturing alternatives and technologies, culminating in a complete set of alternatives.

The vehicle decomposition process culminates in the identification of the elements for which affordability assessment and uncertainty propagation shall be assessed. While this thesis performed a single level decomposition to the element level, further decomposition to subsystems, assemblies or even all the way down to the part could be performed (See [114] for hierarchy of decomposition). However, two major issues arise when further decomposition is desired; the fidelity requirements on FEA/CAD analysis become computationally driving, and the number of affordability distributions required increases significantly. The FEA/CAD must possess sufficient fidelity to capture the desired level of decomposition. Once the level of decomposition has been determined, then the identification of alternatives shall ensue.

This portion of the problem definition is exploratory in nature, and can be as vast as deemed appropriate. The primary concern here is to enumerate all the degrees of freedom whose affects on both performance and affordability are sought. The most important aspect of this is to ensure that sufficient information is available to adequately define each within the context of required inputs to the analysis suite selected.

The selection of the analysis suite centers around the desire to assess **process-based cost**. As such — and as established in the MInD methodology description in Section 3.5 — the fidelity of the performance analysis portion must be commensurate with the required inputs of the process-based tool. In the case of P-Beat, and most other process-based cost models, this fidelity is beyond the scope of typical Conceptual Design tools, such as CONSIZ or INTROS alone, and requires the use of tools typically used in Preliminary or Detailed Design to augment capabilities. Including high fidelity aerodynamics and parametric structural optimization, such as Cart3D and Nastran/Hypersizer/Patran.

4.2 Schedule Permutation Enumeration

The activities which define the development schedule are a function of the selection of a process-based cost tool. The benefit of P-BEAT is two-fold; the first is the large database upon which CERs are based, and the second is the general processes for which labor hours are estimated. This second step involves a thorough review of the tasks and development of at least three task order permutations and appropriate uncertainty distribution binning.

The enumeration of task order permutations can be performed in a variety of ways. As described herein, elucidated a clear logical flow of tasks can provide a likely permutation, and further logical discussion yields an optimistic and pessimist version as well. A second method, and perhaps one founded more in reality, is to review the manner in which activities played out in recent programs whilst developing permutations. This method would reveal certain expected behavior amongst the various historical programs and can thus be used to generate a worst case, best case, and many combinations in between.

It is necessary to note that despite the ability to leverage historical schedules to generate various task order permutations, the use of a uniform uncertainty distribution is recommended. While this thesis explores the use of triangular distributions for uncertainty propagation, the need to discretize this for each of the task order permutations considered introduces traceability concerns. Fundamentally, these concerns revolve around the planning fallacy — which dictates significant optimism in estimating schedule components despite significant historical examples pointing to failure in achieving these estimates— and the inability to predict the future. Thus there is little traceability in stating that one task order is more likely to occur than another.

4.3 High-Fidelity Analysis to Enable Element Deterministic Affordability Curve Generation

This portion of the method encompasses the performance analysis of each alternative and its ability to achieve the mission requirements. Within the context of affordability in this thesis, this step aims to determine whether or not a particular alternative is capable of fulfilling the mission critical requirements. For a launch vehicle concept: "can the alternative deliver a payload of mass X to a low-Earth Orbit of Y?" While mission criticality varies significantly — and can include safety, reliability, and logistic requirements — for demonstration purposes within this thesis this requirement has been reduced to a fundamental performance requirement. It is assumed that the analysis environment leveraged is capable of capturing the metrics which describe all applicable critical requirements.

This analysis can be performed in one of two ways, depending on the scope of alternatives included. If the analysis is limited to a single stage of a launch vehicle, the fluidity of the design of the remaining concepts will affect the scope — and thus required fidelity of the analysis environment. If the entire vehicle is fluid, then the analysis would include a consistent resizing such that the mission critical requirements are precisely met by the entire vehicle. In an analogy to a notional SLS program, if the design of the core stage were fluid, assessing variations in material of the upper stage elements would require resizing of the core stage as well[1]. The second option would result when part of the vehicle design is fixed.

This is the case with the SLS program in which the core stage (i.e. Block I) is fixed, and the design of the EUS upgrade is still fluid. Here, mass reduction in the EUS would not affect the core stage at all, and would instead be realized by adding payload mass capability as structural mass is reduced, or the opposite[2]. The former scenario would require the analysis environment to include extensive parametric scaling values to assess the ripple-effect on all the core systems as well, while the latter scenario would only require subtle changes to the EUS. Once the analysis is complete, there is sufficient detail to provide the inputs needed to generate the element affordability distributions.

4.4 System-Level Probabilistic Affordability Distribution Generation through Monte Carlo Simulation

The first step in this portion of the methodology is to propagate the uncertainty in inputs to the that of the outputs for each of the twelve elements and integration. This propagation has two parts, one to quantify the uncertainty in task durations, and another the uncertainty in task order. This is achieved through Monte Carlo Simulation (MCS) and random sampling/bootstrapping.

The uncertainty in task durations (i.e. direct output of process-based cost model) is a result of uncertainty in the attributes which define each element, from both a design and manufacturing standpoint. The design attribute uncertainty is an input to the analysis environment — described in the previous section — and includes potential

---

[1] This embodies the highly coupled nature of launch vehicle design; where the propellant required must be sufficient to lift the payload, structure and itself to the desired orbit. Reduction in structural mass (resulting from a lighter structure) would reduce the amount of propellant required, and the reduction in propellant mass would result in a further reduction in structural mass (less propellant translates to smaller tanks) which in turn would further reduce propellant requirements.

[2] This assumes that the SLS core stage flies as designed instead of reducing propellant mass by only partially filling tanks. Furthermore, the author realizes that the conversion of structural mass to payload mass is not precisely a 1:1 gear ratio.

variation in dimensions and material properties[3]. For the purposes of traceability, a triangular uncertainty distribution has been selected to represent the uncertainty in these attributes. While the analysis is arduous, the only output that is used by the process-based cost tool is element weight[4].

With the uncertainty of weight determined, the other process-based cost input parameters may be assigned, also based upon a triangular distribution. Documenting the assumptions used to define each variable is paramount. Once these are defined, a MCS would be performed through the costing tool, either at random or using one of the many sampling techniques available in literature. Sample sizes in the thousands and millions are not uncommon, with error typically reducing as the number of iterations increases [68, 49].

The second portion of the propagation of uncertainty is to account for the uncertainty in task order. At this juncture, the uncertain distributions on the task order are available and now need to be re-sampled based on a task order binning. For the purpose of a discrete set of task order permutations, assuming that each permutation is equally likely (bootstrapping from a uniform distribution across the permutations) has been shown to be more traceable than a triangular distribution. This ensures that no bias is introduced and that each permutation is equally likely. Quite simply, dividing a uniform distribution into regions and assigning each region to specific permutation has been performed herein. A random number sampled from the uniform distribution will fall into one of the bins and thus dictate which permutation is to be sampled. This sampling, called bootstrapping, is performed thousands of times, and

---

[3] The propagation of uncertainty through this environment could be significantly complex due to the extent of the analysis. This thesis excludes consideration for variations in atmospheric conditions, which would vary the trajectory and thus change the loading information, as well as the inclusion of manufacturing variability or material inclusions and so on.

[4] The fidelity of the analysis environment must match that of the desired level of decomposition of the system. If the aim is to provide insight into varying barrel panels or stiffening concepts, for example, then the analysis environment MUST be able to differentiate between these concepts. Simply using a low fidelity tool, incapable of distinguishing between similar but unique concepts, would not be useful and may provide erroneous results.

will culminate in a probabilistic affordability distribution for an element which could follow any one of the task order permutations. Appendix A includes a screen shot of the Excel translator that has been used to determine the affordability distributions for each of the task order permutations presented in Chapter 3. Bootstrapping is to be performed for each of the twelve elements, plus integration, to arrive at the distributions which will comprise the system.

The addition of the element distributions is subject to a schedule variable that a program manager will have control over: when the development of each element should start. This is represented as a vector — whose elements correspond to the system elements — which is constrained by a logical development progression. For instance, one can argue that the Preliminary Design phase should not endure for more than 4 years and that each system element should complete Preliminary Design within this time frame. This example states that an element with a two-year Preliminary Design duration should not be started later than year 2. This scoping allows for the enumeration of all the possible permutations of the start vector which would be assessed. The number of permutations is described by 34, where L is the maximum delay in years (integer), N is the number of elements which can start development in year L, and k represents the number of distinct start years.

$$Permutations = \prod_{i=1}^{k} L_i^{N_i} \tag{34}$$

Thus, if all elements could start in either year one or two then $L = 2, N = 12 and k = 1$ such that $Perm = 2^{12} = 4096$. Similarly if 5 elements had to start in year one, three could start in year one or two and the remaining 4 could start in year one, two or three, then $k = 3, L_1 = 1, L_2 = 2, L_3 = 3, N_1 = 5, N_2 = 3$,and $N_3 = 4$ such that $Perm = 1^5 * 2^3 * 3^4 = 648$. Once all the permutations have been established, the probabilistic affordability distributions for the elements can be added to form the system affordability distribution for each of the start vector permutations.

4.5 Evaluation and Selection

The evaluation and section of an alternative is based around the concept of robustness in the presence of funding uncertainty. The underlying principle is that the selected system should be resilient to future variations in the potential budget ceiling — appropriated by congress on a year-to-year basis — such that decreases in funding in future years do not cause the program to immediately cease being affordable and thus risk cancellation.

This is achieved by overlaying constraint scenarios over the system-level probabilistic affordability distribution and assessing the probability of success(POS). This is described, in Equation 35, as the ratio of samples which fall within the constrained space, and the total number of samples which comprise the probabilistic distribution.

$$POS = \frac{Number\ of\ samples\ which\ meet\ constraints}{Total\ number\ of\ samples} \tag{35}$$

The POS would be evaluated for every permutation of start vector — describing the year in which each element begins development — and every permutation of cost and schedule constraint pairs. The robust solution is considered the start vector candidate which results in the greatest POS, on average, for all permutations of cost and schedule constraint pairs. As such, it may not be the best for each and every constraint pair, but will be the most resilient to variations in future funding and thus circumvent excessive risk of cancellation in development out years. This candidate, which meets the critical mission requirements and bears the greatest POS, would be considered the baseline candidate, and moved forward into Preliminary Design (i.e. program implementation).

While a desired POS value has not been set, the ideal solution will be 100% and various entities may have (or develop) guidelines on a threshold minimum POS value. For NASA programs, as described in Section 2.2, a program may not proceed into the implementation phase without establishing that it has a 70% likelihood of achieving first flight on time and on budget (JCL). This requirement represents the basis for the development of the DDTE&P plan based on the arrangement of development and integration 70% time-phase curves. From a decision making standpoint, a concept should achieve a 70% POS with respect to affordability risk.

While 70% is a reasonable POS, its applicability to probabilistic affordability distributions has yet to be determined. This threshold has been generated based on a traditional WBS approach in which a single, highly detailed WBS (also known as Integrated Master Schedule (IMS)) has resources “hung” onto it to facilitate the generation of a JCL value [99]. The JCL is still founded on the total cost and total schedule insight with an attempt to capture their correlation [154].

CHAPTER V

APPLICATION & RESULTS

Chapter 3 and 4 present the development of this methodology through observations drawn from literature review and experimentation. The purpose of the experiments were to assess the appropriateness of the associated hypotheses and provide context with which to accept or reject them. One final experiment is needed to demonstrate the methodology within the context of a real world problem, and test the overall research objective, repeated below.

Research Objective

Support the development of affordable launch vehicles by quantitatively capturing the effects of manufacturing technology selection during Conceptual Design

---

To meet this overarching research objective, the following series of requirements have been derived:

Develop a methodology which has the following characteristics:

1. Quantitative means to select an affordable portfolio of manufacturing technologies
2. Produce a quantitative forecast of both cost AND schedule risks associated with a development plan.
3. Flexible and scalable to apply to complex systems such as launch vehicles.
4. Robust to uncertainty in inputs.

To test the completion of this research objective, this methodology is applied to a real world system and alternative manufacturing technologies are compared to determine the impact on affordability and DDTE&P planning. This experiment will be based upon an actual launch vehicle stage, and assess actual manufacturing alternatives being considered. The NASA SLS program plan includes a family of 3 variants. The first variant, designated as the "Block I," is expected to achieve its first launch in 2018, followed by a second launch in the 2020's [164, 145, 108]. The first launch will be unmanned and serve as a system readiness test, while the second flight will be manned and undoubtedly incorporate design changes identified from the test launch. To date, only these two missions have been approved [164]. An additional 5 missions have been proposed, which provides insight into the expected evolution of the SLS. The third launch, which is expected no sooner than 2023, is shall be the first launch of the second SLS variant, the "Block IB" [12]. This variant will include the Exploration Upper Stage (EUS), which will increase both the launch performance and the in-space capability, and is considered an intermediate step towards the final SLS variant. The EUS has been identified as a prime opportunity for the infusion of composite materials, and recent studies show that the cryogenic tanks are prime candidates [58, 80]. Figure 42, repeated below, shows an overview of the EUS and its subsystems.

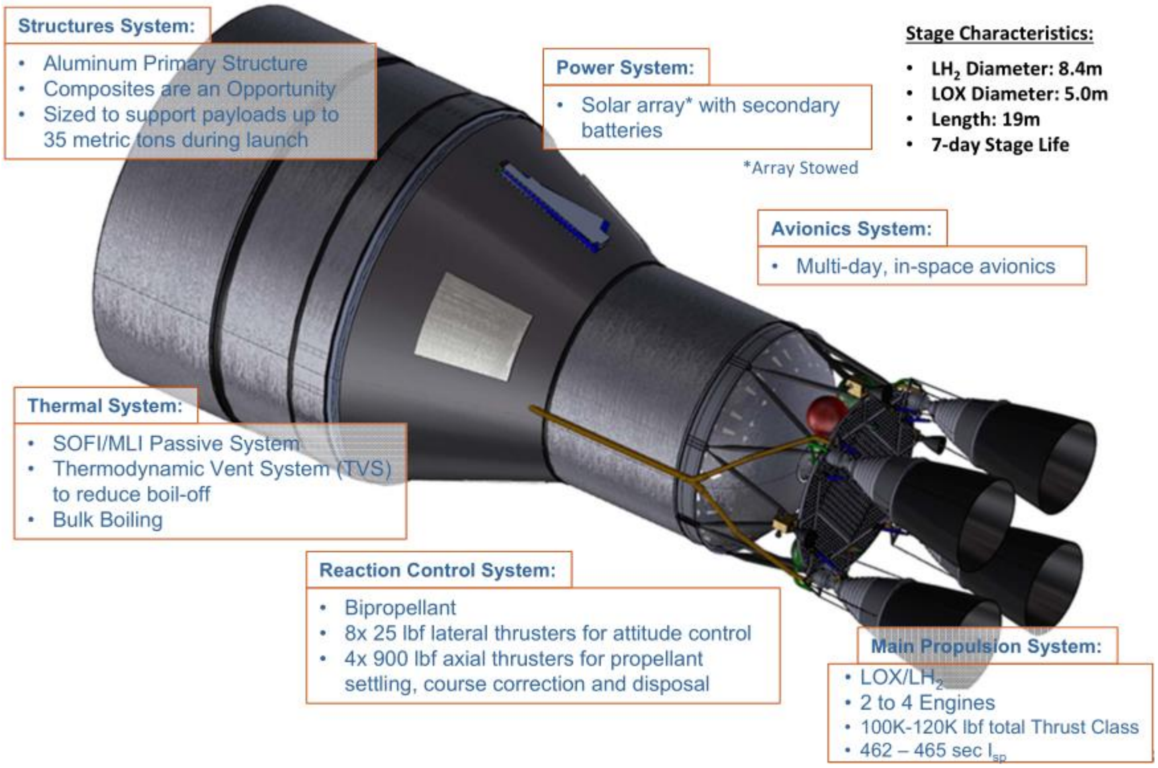


Figure 42: Overview of Exploration Upper Stage Key Subsystems [58]

5.1 Problem Definition

With the configuration of the SLS core stage (i.e. Block I) being fixed, and an assumption of fixed EUS geometry, the trade consists of comparing two distinct fuel tank concepts of the same size. The first concept is a metallic tank and the second is a composite tank, each described in Table 17, below. The assumptions used for the remaining elements are based upon [58] and NASA SME input. These will be unchanged for each of the two studies such that the trends which emerge are a result of the fuel tank variation and not confounded with variations in the other elements.

Table 17: EUS Fuel Tank Alternatives for Method Application to Real World Problem

	Metallic	Composite [112]
Material	Al-Li 2195	IM7/977-2
Stiffening	Orthogrid	Honeycomb
Number of Barrel Panels	6	one-piece tank
Panel Fabrication	Bump Form	Automated Fiber Placement
Dome Gore Fabrication	Stretch Form	
Dome Cap Fabrication	Spin Formed	
Trimming	Mechanical (NASA Vertical Trim Tool)	
Joining	FSW	Bonding
Curing	N/A	Autoclave

5.2 Schedule Permutations

In light of the absence of publicly available launch vehicle development schedules, the logical permutations of P-BEAT tasks — developed in Sections 3.6.2.1 and 3.8.1.2 — shall be used for both alternatives. Figure 128 portrays the binned uniform distribution used for the uncertainty propagation described in subsequent sections. To ensure traceability, the uniform distribution is divided into three bins of equal size. Each bin represents a unique task order permutation such that a random sample of the uniform distribution would have an equal probability of falling into each of the three bins; thus the likelihood of each permutation occurring is 33.33%.

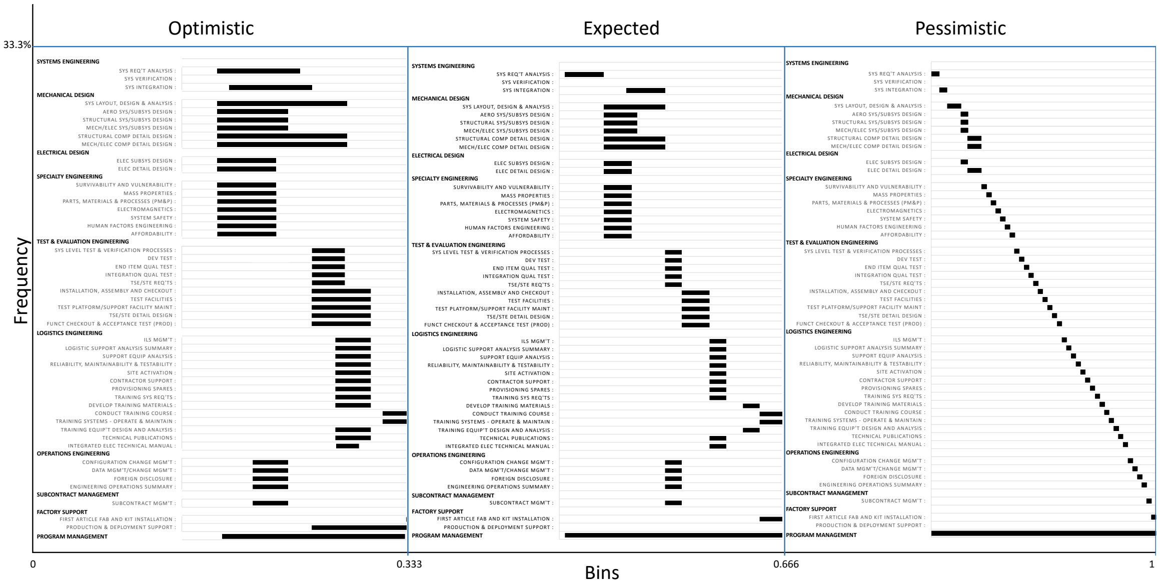


Figure 128: Binned Uniform Distribution with Optimistic, Expected, and Pessimistic Task Order Permutations

5.3 Element Assessment

The performance assessment of these two unique concepts have been carried out using the EUS MInD Environment developed in Section 3.5, with the analysis flow repeated in Figure 51, below. The vehicle definition required the enumeration of geometry and properties which describe the SLS core stage, and the proposed EUS configuration. The SLS core information was extracted from various literature sources and thorough collaboration with NASA MSFC, and the EUS configuration was provided by NASA MSFC ACO in the form of a Nastran/Patran model [146, 58]. These, coupled with experience from previous NASA sponsored research facilitated the appropriate setup for INTROS, LVA, and POST.

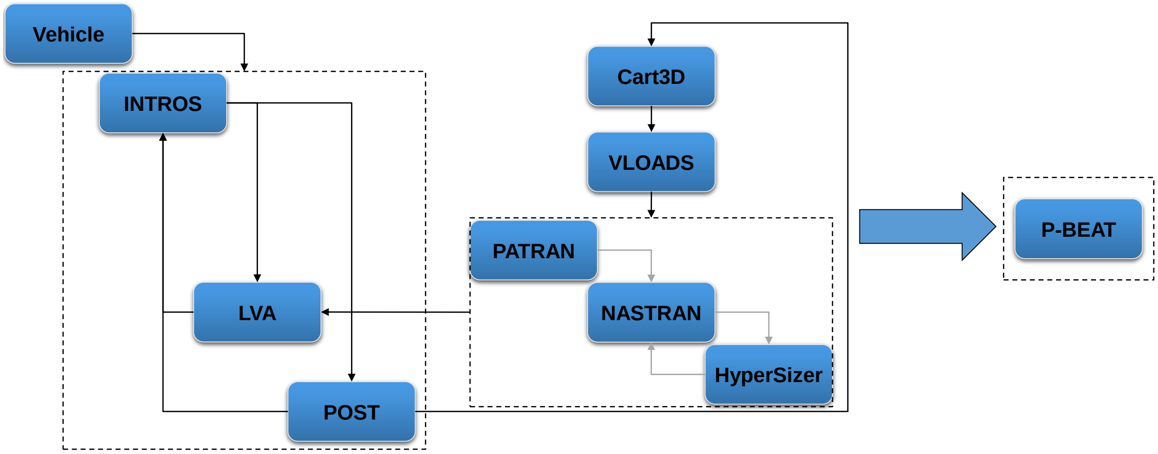


Figure 51: EUS MInD Analysis Overview

However, as mentioned previously, the INTROS,LVA, and POST analysis loop is incapable of differentiation between specific manufacturing variables — such as number of barrel panels, specific fabrication techniques. As such, the higher fidelity loop was included to provide the required granularity and update the secondary and tertiary masses in INTROS to result in a final system mass. Since the core stage and EUS geometry is fixed, any mass savings would materialize in the form of an increase in payload mass while mass increases would result in payload mass loss.

The major requirement within the higher fidelity loop, however, stresses the accurate definition of the material alternatives. While INTROS and LVA require basic material properties – such as density and modulus of elasticity and the number of material plies — Hypersizer requires significantly more detail and has the ability to tailor ply orientation to result in an optimum design. However, the detailed nature of the inputs poses a key challenge for the composite case, which has limited data available in the public domain. Use of sensitive material properties — furnish by NASA Marshall's Composite Cryotank Technologies Demonstration effort— were used to define IM7/977-2 as a quasi-isotropic material. This assumption (founded on the limited material data) precludes the ability to determine the true benefits of composites, which result from ply tailoring. As such, and as a caveat to this study, the results which follow do not depict the full trend variation between the materials. The major advantage of composites is the ability to tailor lamination schemes such that strength characteristics are aligned with load paths [178] Where metallics have uniform properties in all directions (isotropy), the case for composites argues that this material attribute is “wasteful” when certain requirements are only needed in certain directions (axial, longitudinal, etc). Thus, a quasi isotropic composite material acts as though it has the same properties in all directions which, in actuality, it does not. A future work is required to expand this analysis to include composite ply tailoring; only then can the true trends be realized. Thus, the results presented herein apply to a composite concept whose ply orientation does **NOT** represent the true potential benefits which can be gained by composites. Figure 129 portrays the comparison in fuel tank mass and the resulting payload mass variation for both concepts, showing the slight superiority of Al-Li 2195.

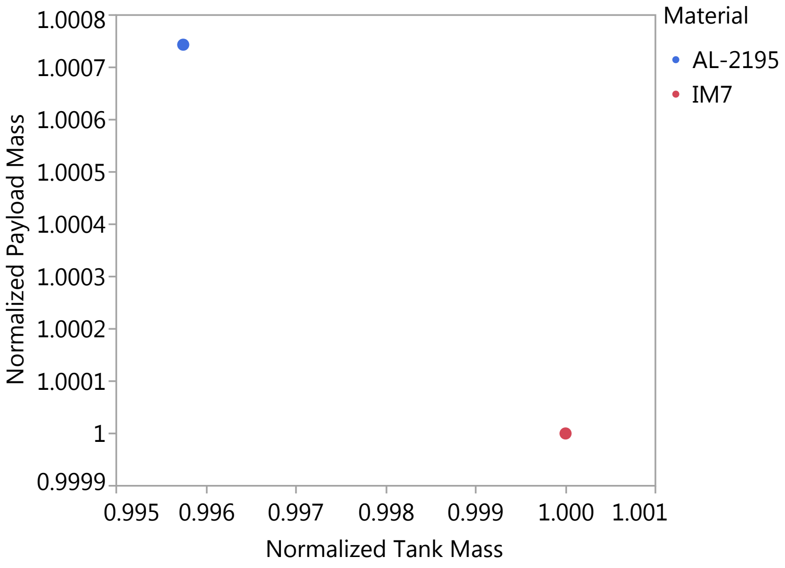


Figure 129: Sample Problem: Normalized Payload Mass Comparison

The Al-Li 2195 tank concept is portrayed as providing 0.5% weight savings, which translates into a 0.075% payload mass gain. For a Trans-Lunar Injection (TLI) mass of approximately 40 tonnes, this equates to a 30 pound payload benefit when using the metallic over the composite [58]. For all intents and purposes, this benefit is insignificant and it may be asserted that both concepts precisely meet the mission critical performance requirement of delivering the desired 40 tonne payload to a TLI orbit,

5.4 System Affordability Projection

Having access now to the mass of each tank, the uncertainty bounds on the attributes may be defined. The tank mass is assumed to vary by 30%, with the optimized value being that which resulted from the higher fidelity environment. The appropriate triangular distributions are defined for the P-BEAT inputs and the task order uncertainty shall be used in MCS to arrive at a probabilistic element affordability distribution for each fuel tank.

Figure 130 and 131 portray the resulting distributions, from which a few observations arise. The first, and most obvious distinction between them is the alacrity with which development completes for the IM7 tank; ranging from one to three years. The metallic concept, on the other hand, requires between four and nine years to complete Preliminary Design, Detailed Design, and First Build phases. The assumption on treating IM7 as a quasi isotropic material, thus precluding ply tailoring, is though to be the main catalyst behind this large difference in development times[1].

---

[1] Note that the representation of expenditure is assumed at the start of each year. This denotes that funding is received at the start of a fiscal year, through appropriations cycles, and then spent. As such, the value assigned to year 0 is spent during the first year, the value assigned to year 1 is spent during the second, and so on

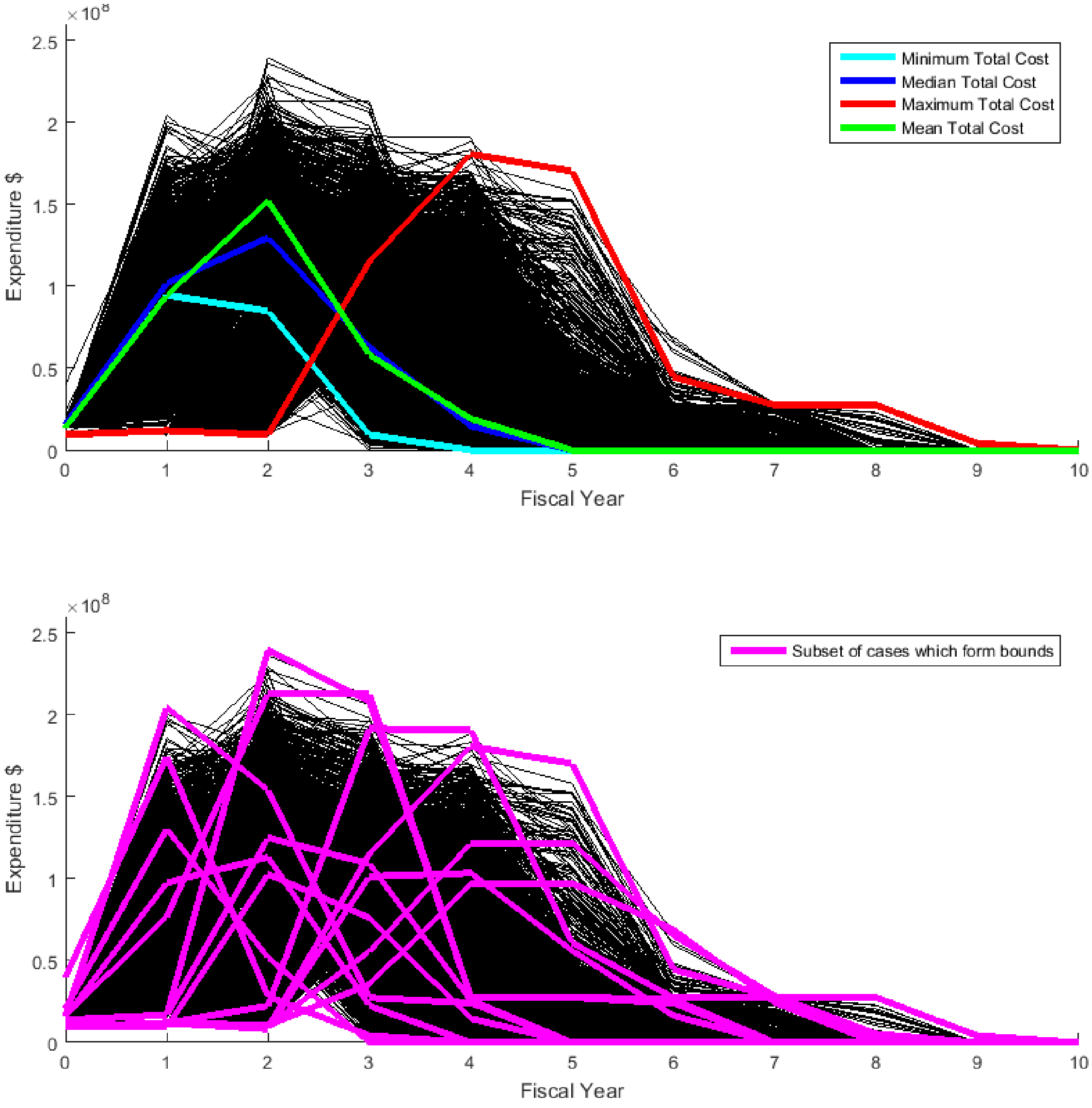


Figure 130: Sample Problem: Al-Li 2195 Fuel Tank Probabilistic Element Distribution

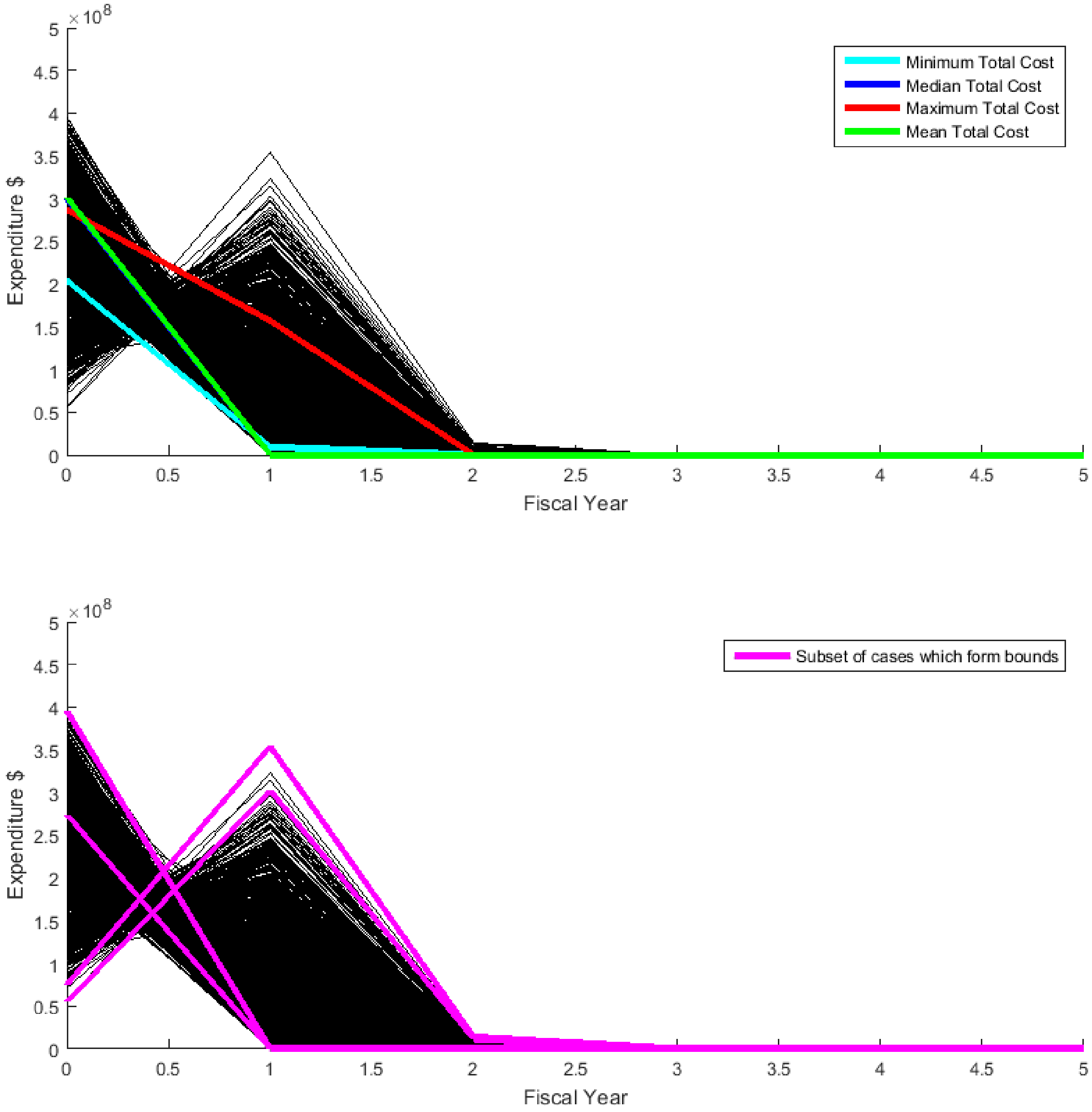


Figure 131: Sample Problem: IM7/977-2 Fuel Tank Probabilistic Element Distributions

In comparing the annual expenditure, however, it is evident that the IM7 concept incurs significantly higher spending on a year to year basis. While the metallic tank distribution is very tightly grouped at the start of development (year 0), the IM7 concept has a significant variation in its first year cost, on the order of 10 to 40 times that of the metallic.

Both distributions, however, portray the same trend with respect to assessing total cost (as has been performed traditionally). The maximum total cost curve does not correspond to that which forms the upper bound of the distribution. As such, selecting a baseline concept from a total cost perspective only would result in the inclusion of excess risk which would previously be unaccounted for — i.e. an "unknown unknown" which would materialize in cost overruns once development begins.

The generation of the system level affordability distributions has been performed under the assumption that the other 11 elements possess an affordability distribution which is photographically scaled from the Al-Li tank distribution. The scaling factors are portrayed in Table 16, where all barring the MPS is assumed to be less than the tank. In light of this, these assumptions will be used for both tank configurations such that any variation in affordability (and the robust start vector) shall be entirely a result of the variations in fuel tank concept.

5.5 Affordability Comparison

The final step in the methodology requires a comparison between the system level probabilistic affordability distributions and the POS of meeting certain cost-schedule constraints (i.e. scenarios). In developing the constraint pairs, the schedule constraint has been fixed such that launch occurs towards the end of 2025. With EM-3 being slated for no earlier than a 2023 mission, this time frame is reasonable[12]. While NASA may have committed to move the infusion of the EUS into EM-2, delays in the Orion spacecraft has resulted in the acknowledgment that this mission may not lift off until 2023 [87, 221]. The cost constraints have been created to represent three distinct scenarios. Flat funding, representing the environment which SLS development is experiencing, increasing funding to represent a more traditional funding profile, and decreasing funding to represent a more austere funding environment. These three constraints are shown below.

$$\text{Cost Constraint} = 1.2\text{e}9\ .* \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0.8 & 0.8 & 1 & 1 & 1 & 1.1 & 1.1 & 1.2 & 1.2 & 1.2 \\ 1.2 & 1.2 & 1.2 & 1.1 & 1.1 & 1 & 1 & 0.9 & 0.9 & 0.9 \end{bmatrix}$$

Performing the MCS bootstrapping, to generate the system-level probabilistic distribution and overlaying the constraints results in Figures 132 and 133 for AL-Li 2195 and IM7/977-2 tank concepts, respectively. Inspection of these figures unearths little to distinguish between them. The IM7 concept does have a greater peak expenditure, and the variation at the onset is commensurate with the variation of element distribution depicted in Figure 131. Beyond this, both concepts possess viable candidates whose development completes two years before the 10-year deadline, indicating that a 2023 EUS mission has a non-zero probability of success.

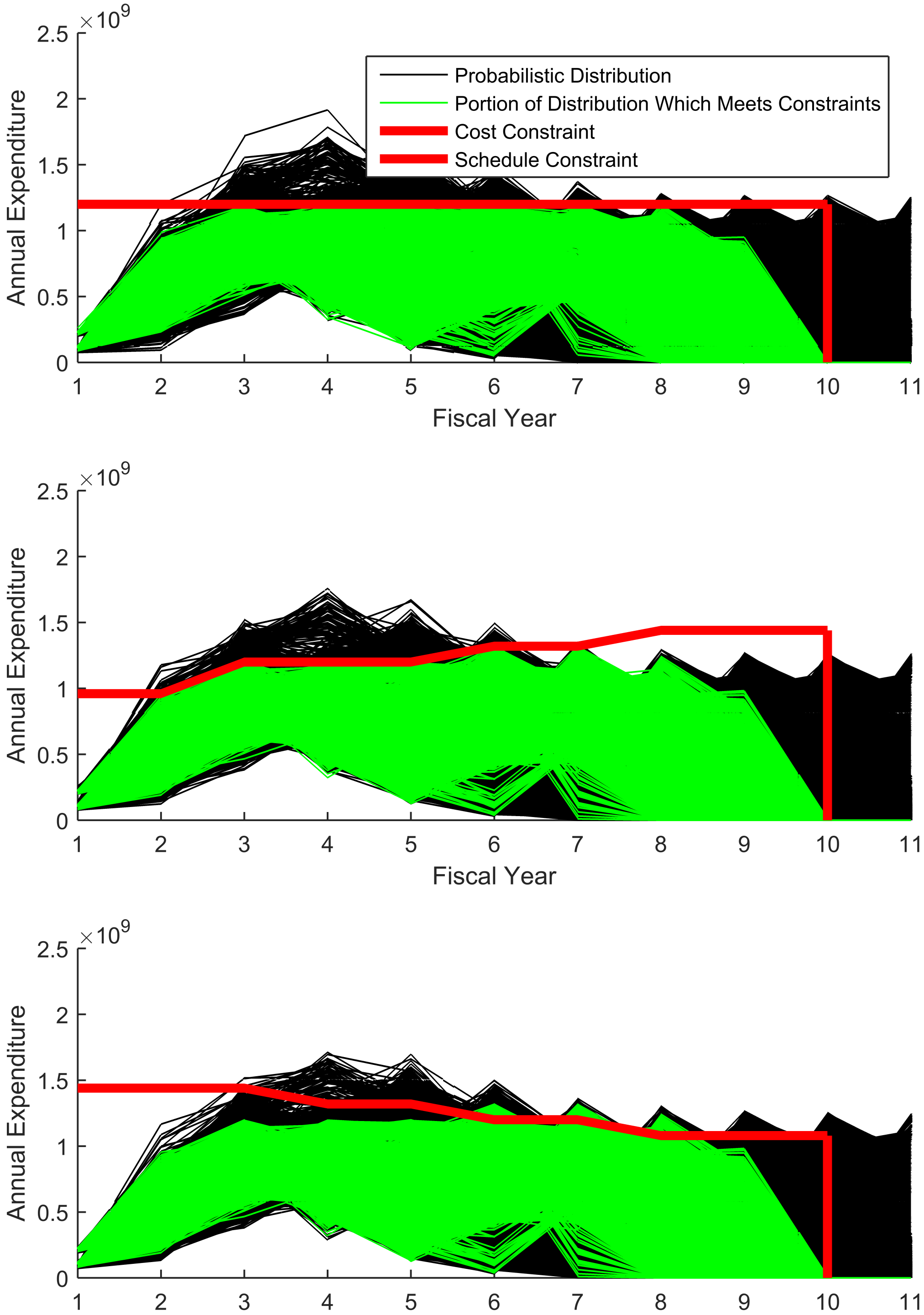


Figure 132: Sample Problem: System-Level Probabilistic Affordability Distribution for Al-Li 2195 Tank Concept

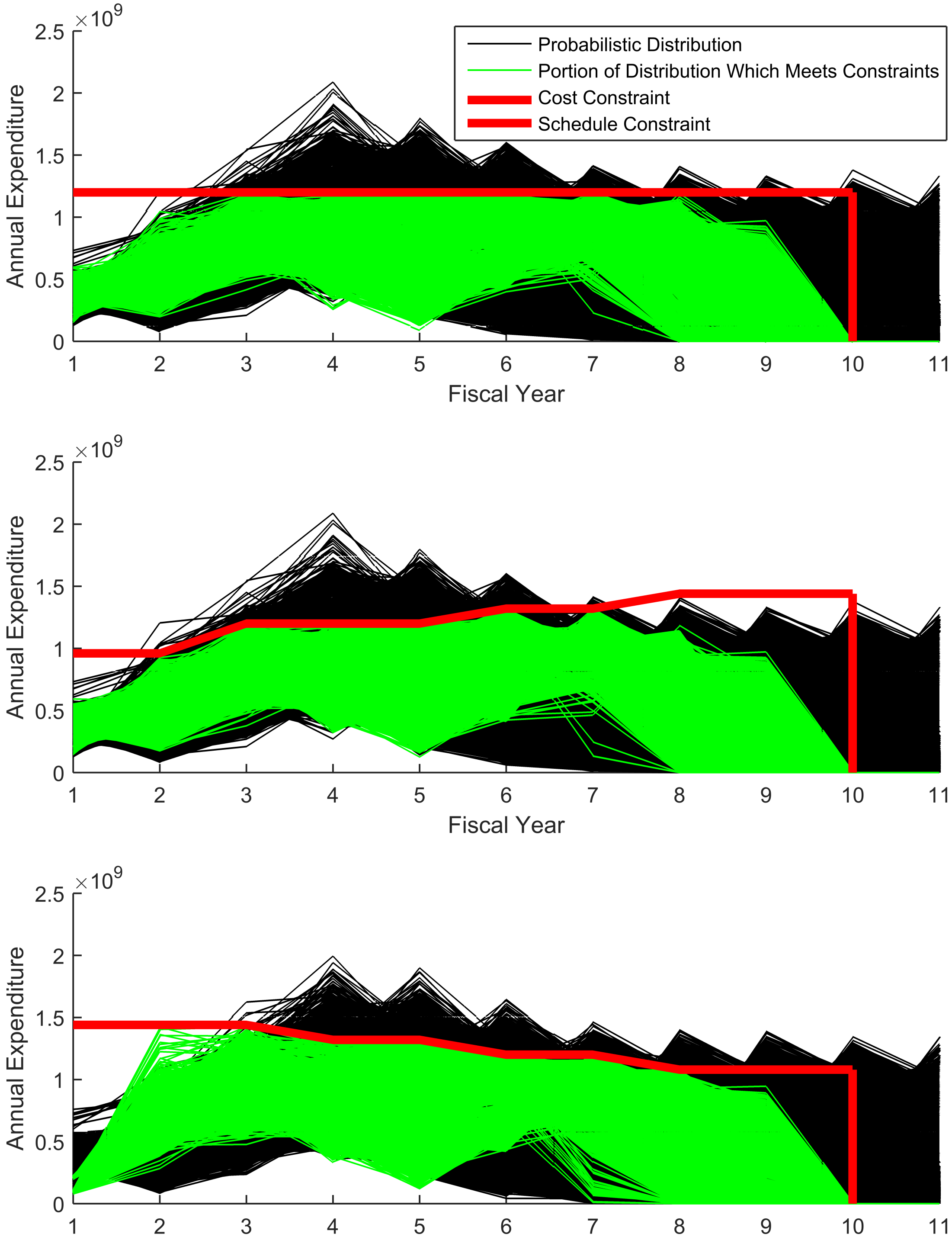


Figure 133: Sample Problem: System-Level Probabilistic Affordability Distribution for IM7/977-2 Tank Concept

The highlighted (green) curves represent those from the total distribution which meet the overlaid constraints. Figures 134 and 135 show the traditional total cost distributions with the cases which meet the constraints overlaid. Once again the portion of the distribution that meets the constraints cannot be captured by the traditional risk assessment wherein a vertical line constraint is placed on the total cost figure. The interrelated nature of cost and schedule would in excessive risk being carried through subsequent design phases if this traditional approach were taken. The same observation would hold true if total schedule risk were performed in the same traditional manner (not shown). A vertical line does not capture the true representation of risk in either case. The POS for each of these three cases is shown in Tables 18 and 19 where their performance has also been gaged for the constraints which were not used to measure their POS. Within this context, start scenario one is the optimum for flat funding, start scenario two the optimum for increasing funding, and start scenario three the optimum for decreasing funding.

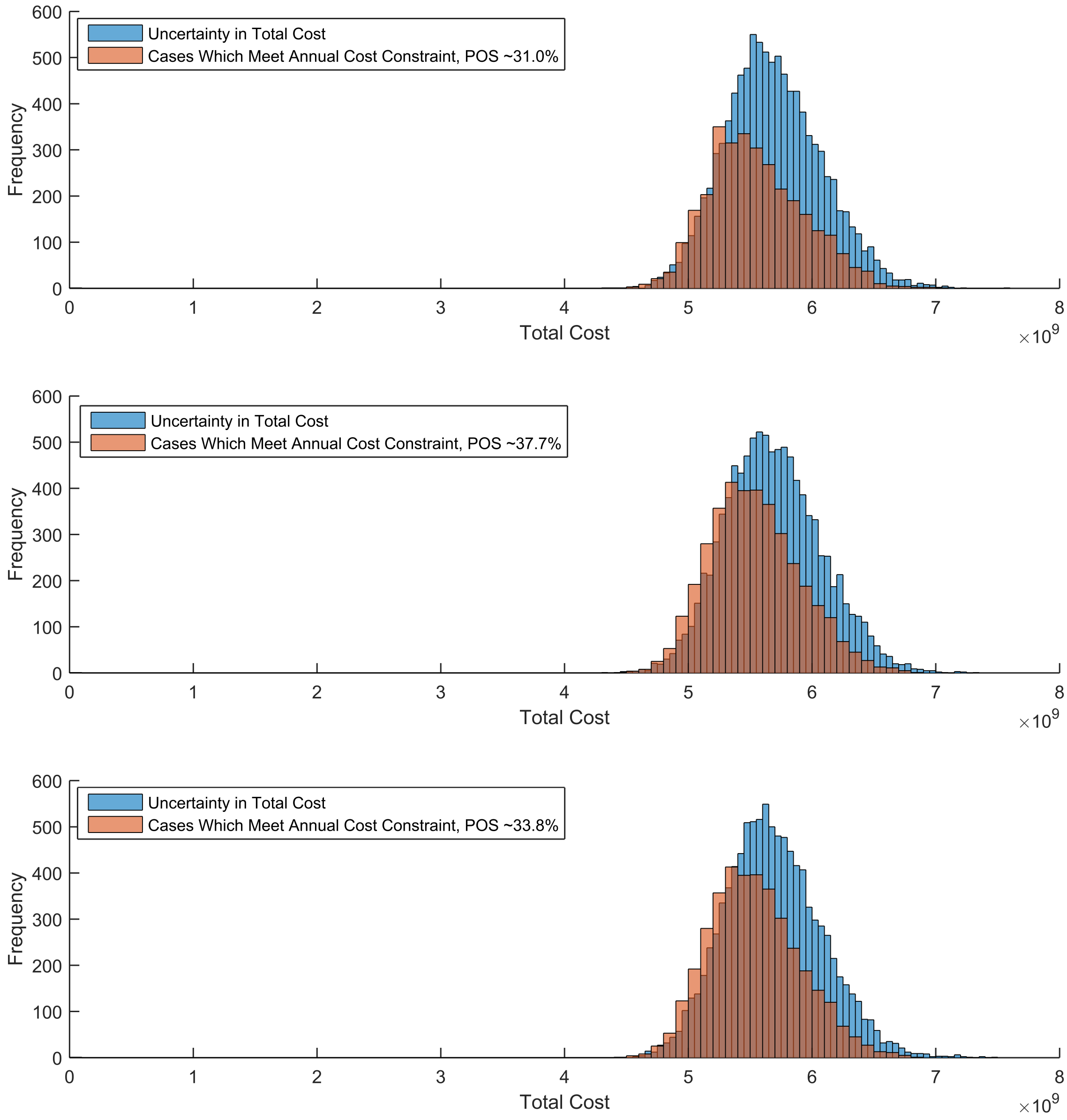


Figure 134: Sample Problem: Al-Li 2195 Concept System Affordability Distribution for Flat, Increasing, and Decreasing Funding Constraints

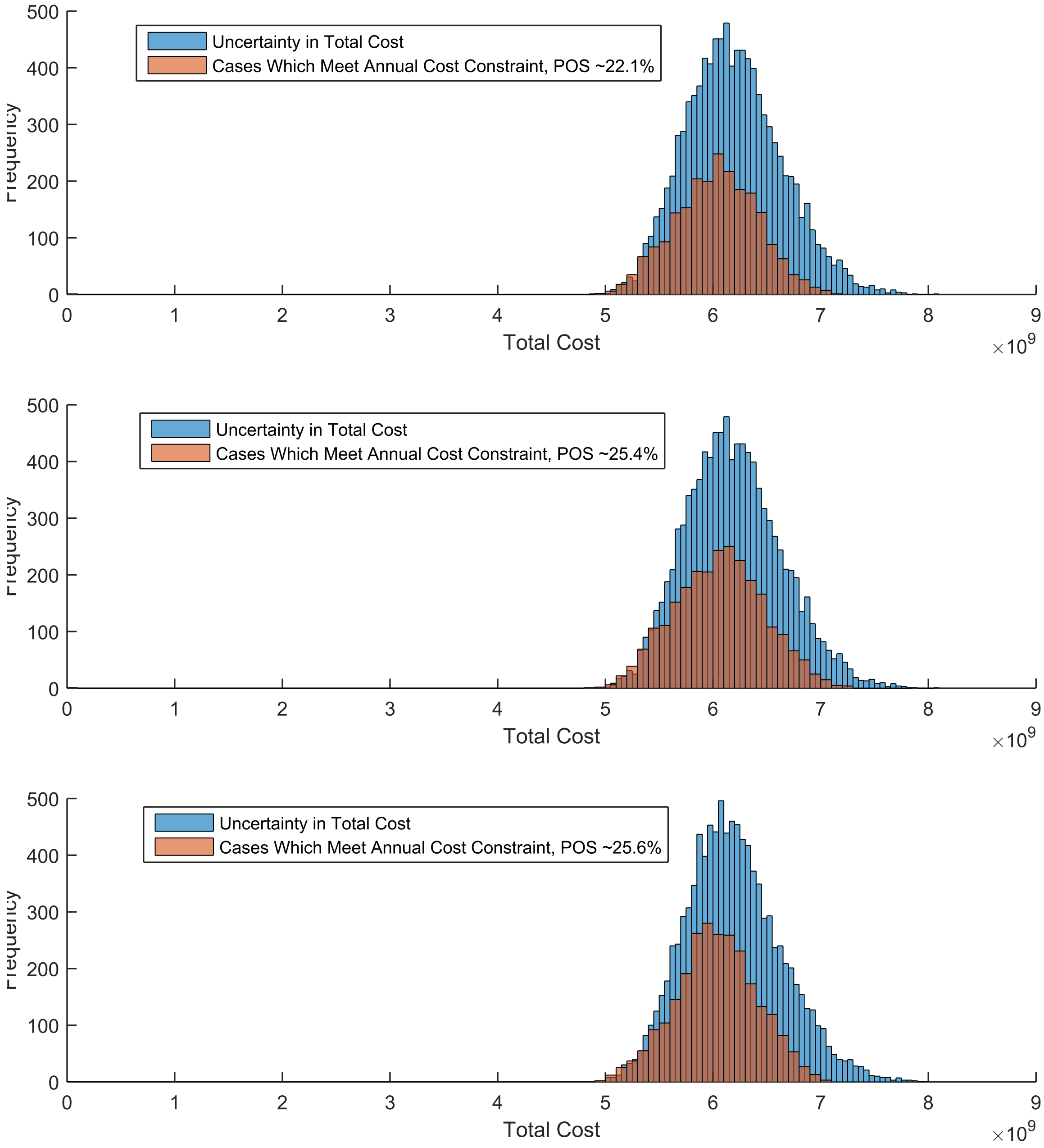


Figure 135: Sample Problem: IM7/977-2 Concept System Affordability Distribution for Flat, Increasing, and Decreasing Funding Constraints

Table 18: Sample Problem: Metallic Tank POS for Each Start Scenario

	Flat Funding	Increasing Funding	Decreasing Funding
Start Scenario 1	30.98%	37.30%	33.25%
Start Scenario 2	30.63%	37.74%	32.32%
Start Scenario 3	30.12%	36.90%	33.77%

Table 19: Sample Problem: Composite Tank POS for Each Start Scenario

	Flat Funding	Increasing Funding	Decreasing Funding
Start Scenario 1	22.12%	25.24%	24.63%
Start Scenario 2	20.67%	25.39 %	23.58%
Start Scenario 3	20.85 %	24.03 %	25.57%

Notably, the AL-Li-2195 scenarios possess a POS of between 8 and 12% greater than the composite counterpart. While the difference in maturity (Al-Li is a TRL of 5.5, while the composite is a TRL of 5) plays some role in this it is the quasi-isotropic assumption which is the driving factor. Removing this assumption is expected to decrease tank weight but increase the complexity of the Preliminary and Detailed Design phases resulting from the need to tailor plies. This is expected to translate into a longer duration for all three of the phases considered, and reduce the annual expenditure; thus increasing the POS. Additionally, this analysis precludes production considerations beyond First Build; which is where many of the cost savings is expected [161, 112].

Table 20: Sample Problem: Metallic Tank Optimum Start Scenario for Funding Constraints

Constraint	LH_2 Tank	LH_2 Fwd Skirt	LH_2 Aft Skirt	Intertank	LOx Tank	Thrust Structure	MPS	TPS	ATC	Power	Avionics	RCS
Flat	1	1	1	1	1	1	1	1	1	1	1	1
Increasing	1	1	1	1	1	1	1	1	1	1	1	2
Decreasing	1	1	1	1	1	2	1	1	1	1	1	1
Robust	1	1	1	1	1	1	1	1	1	1	1	1

The culmination of the analysis is to determine a robust DDTE&P plan (i.e. start vector) that is robust to the potential uncertainty in appropriated funding. This requires an assessment of each start scenario across all cost constraints considered such that the POS of meeting all constraints is maximized. Since the analysis to this point (whose code may be found in Appendix D) has tracked the POS for each start scenario against each constraint. Aggregating the POS values across the constraints will provide the average POS for each start scenario. The scenario with the highest average POS is the most robust to the defined uncertainty in funding.

Tables 20 and 5.5 show the three DDTE&P plans which correspond to the optimum for each individual scenario, as well as the robust plan. Figure 136 shows the two robust solutions with the AL-Li 2195 possessing a 10% greater POS than the composite counterpart.

Table 21: Sample Problem: Composite Tank Optimum Start Scenario for Funding Constraints

Constraint	LH_2 Tank	LH_2 Fwd Skirt	LH_2 Aft Skirt	Intertank	LOx Tank	Thrust Structure	MPS	TPS	ATC	Power	Avionics	RCS
Flat	1	1	1	1	1	1	1	1	1	1	1	1
Increasing	1	1	1	1	1	2	1	1	1	1	1	1
Decreasing	2	1	1	1	1	1	1	1	1	1	1	1
Robust	1	1	1	1	1	1	1	1	1	1	1	1

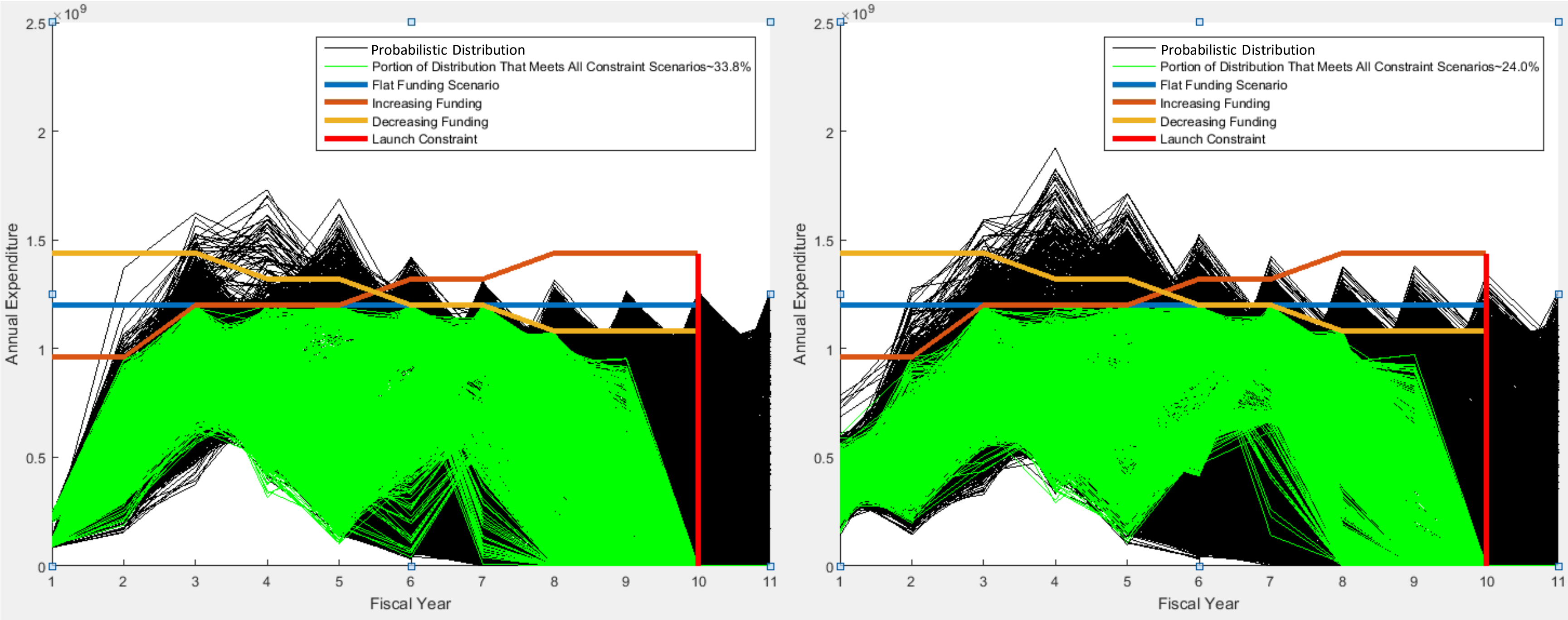


Figure 136: Sample Problem: Comparison between Al-Li 2195 (left) and IM7/977-2 (right) System Affordability Distributions

CHAPTER VI

CONCLUSION

6.1 Summary of Findings

The aim of this research was to develop a methodology which captures the affordability implications associated with manufacturing technology infusion and variations in technology development planning. Chapter 1 established the difficulty that recent launch vehicle programs have experience in achieving first flight. Cost overruns and schedule slippage resulted in the cancellation of these programs and the need to change the paradigm with which these programs were developed. With the majority of the overruns arising once fabrication begins, the need to consider manufacturing implications and development planning during Conceptual Design was established. This observation led to the development of an overarching research question, repeated below, which drove this thesis.

Research Objective

Support the development of affordable launch vehicles by quantitatively capturing the effects of manufacturing technology selection during Conceptual Design

---

The first implication which arose from this research objective was the need to establish a precise definition for affordability which captures the environment in which NASA programs are constrained. A review of various definitions resulted in a trend which requires the inclusion of the temporal nature of cost which is constrained by annual appropriation cycles. From this an overarching definition was developed.

Affordability: The ability to remain under the mandated funding curve for all points in a system's life cycle while simultaneously meeting schedule goals

The first research question posed addressed the need to establish a value metric against which a decision maker would compare various concepts to select a baseline configuration. With a significant amount of cost being committed in the early phases of design, the process of baseline vehicle selection was targeted as an optimal place to infuse advanced design methods. The necessary methods would be established by the conjecture formulated from literature review to address this question. Review of the evolution of the design paradigm suggested that performance improvements are no longer beneficial, and a commodity based approach has become the norm. Herein, mission critical requirements must be met, and then all other metrics are traded. The recent funding issues prevalent during the constellation program formed the second part of this conjecture, repeated below.

Research Question 1

What measure of value is appropriate for comparing launch vehicle manufacturing technology portfolios?

Conjecture to Research Question 1

The **risk of exceeding** a pre-established **budget** ceiling or **schedule goals—given that mission critical performance is met** — is the most desirable measure of value for launch vehicles.

The need to assess cost with respect to a budget ceiling provides a new dimension previously beyond the scope of Conceptual Design; the temporal nature of cost. The notion that a multi-year program is to be initiated when only a single years funding is certain provides a significant challenge in assessing affordability. Total cost and total duration are no longer viable decision metrics, instead a need for their correlated relationship — captured through a cost as a function of time perspective — has arisen. Furthermore, for a launch vehicle, the mission critical performance was reduced to a single dimension based upon its ultimate purpose. These two realizations led to two conjectures to the two parts which form Research Question 1.

Research Question 1.1

What measure of performance can be used to ensure that mission critical requirements are met?

Conjecture to Research Question 1.1

From a physics perspective, the payload delivered to a low-Earth orbit is an appropriate measure of performance as it represents the system capability and is often a hard requirement defined at the onset of a program.

Research Question 1.2

How can the risk of exceeding a pre-established budget ceiling or schedule goals be quantified?

Conjecture to Research Question 1.2

Establishing probabilistic affordability curves to identify the likelihood of remaining beneath budget ceiling and within schedule goals will provide a means to quantify a launch vehicle programs affordability risk

The latter of these two conjectures warranted the development of additional research questions regarding generating phase estimating relationships to describe annual cost for system elements, the appropriate decomposition of a launch vehicle system into major elements, and capturing integration. In light of the absence of publicly available historical data, a process-based cost estimation tool was selected to represent a “truth-model,” the results of which would be used to test whether a Weibull distribution could represent the expenditure behavior on either a cumulative or probability density perspective.

Hypothesis 2.1a

Utilizing a process-based cost estimation method, and extracting typically underused schedule information, will provide the capability to assess the interrelated cost and schedule of lower than system-level estimates.

Hypothesis 2.1b

For the purpose of generating lower than system-level PERs, what elements comprise a launch vehicle and would thus be leveraged to generate a system level affordability distribution?

Furthermore, the consideration of additional metrics needed to capture the phasing of cost associated with integration elements into a system was needed. Literature review was performed to establish an appropriate measure for system-level maturity which would capture the form, fit, and function of each element, as well as material composition of the system. A Weibull fit would be attempted to these results as well.

Hypothesis 2.3

The consideration of form, fit, and function of each technology, and the system composition (from a material standpoint) are required to capture the integration of system elements.

Execution of Experiment 1 and 2 — Sections 3.6 and 3.7, respectively — revealed that while process based costing adaptation provides results which meet published trends, regressing a Weibull curve is only possible for integration. While regression attempts did reveal that fitting the cumulative behavior (for system elements and their integration) is less erroneous than fitting the PDF, the need to leverage numerous mixed Weibull distributions outweighs the benefit of using a regression.

These two experiments were aimed at capturing the deterministic behavior of expenditure over time as a function of manufacturing inputs including material, stiffening concept, and various fabrication processes used to fabricate various sections of a metallic fuel tank. Having established that a concise regression was unattainable, the process-based cost tool would have to be used directly to capture uncertainty and its propagation.

Section 3.8 elaborates upon the notion of risk by establishing three subquestions aimed at determining: what is uncertain, the form of appropriate uncertainty distributions, and the appropriated propagation of the uncertainty in attributes to uncertainty in affordability curves. A decomposition of the problem elucidated two major areas of uncertainty; the first being the attributes which describe the design/manufacture — resulting in development process duration uncertainty— and the second is uncertainty in the order in which the development processes will occur. Literature review was performed on various forms of uncertainty distribution s and propagation methods, resulting in the following hypothesis.

Hypothesis 3

- If triangular distributions are used to represent the uncertainty of input variables and task order, the assumptions which define the shape will be more traceable than Weibull, Log-normal or Beta distributions.
- The propagation of this uncertainty through Monte Carlo simulation will provide the ability to compare manufacturing technology portfolios and their DDTE&P strategies

Experiment 3, discussed in Section 3.9, tests this hypothesis and culminates in the creation of a probabilistic affordability distribution for a fuel tank. One finding herein is that the leveraging a uniform distribution to describe uncertainty between discrete task order permutations is more traceable than a triangular distribution. This is primarily a result of the need to bin the distribution based on the number of discrete options; the assumption that all permutations are equal is captured by the uniform approach while the triangular requires the specification of the likelihood of each permutation occurring.

The primary observation from Experiment 3 is that the probabilistic distribution is not simply a photographic scaling of a common shaped curve. Not only does this justify the inability to fit a Weibull curve, a much greater implication arises. The maximum total cost curve does not form the upper bound for all years, suggesting the importance of considering annual cost. The bounds of the probabilistic affordability curve are formed by a variety of curves, each of which represents a distinct total cost option. This observation precludes the traditional total cost vs total schedule trades typically performed during Conceptual Design.

The final experiment in the development of this methodology assesses adding element probabilistic affordability distributions — and the integration distribution for these elements — to form a system level probabilistic affordability distribution. This experiment aims to determine an optimum DDTE&P plan, described by specifying the start year in which each element begins its development. The alacrity with which a full factorial analysis may be performed rules out the need for employing an optimization technique.

This experiment also develops a probability of success (POS) metric which describes the likelihood of a specific DDTE&P plan remaining affordable. This analysis is extended to a robust case in which the uncertainty in future funding must be captured, and a DDTE&P plan which is resilient to variations in funding is sought. The major finding herein further bolsters the need to consider the interrelated nature of cost and schedule. When translating POS into the total cost and total schedule domains, it is evident that risk is **not** defined by the area to one side of a vertical requirement line overlaid on an uncertain total cost/schedule curve. Instead, it is described by a seemingly symmetric curve, which has no physical meaning in the frequency domain in which uncertainty curves are generated. Use of the traditional vertical constraint approach results in a gross underestimation of the cost-schedule risk associated with a given concept. The selection of a baseline concept based upon this information results in excess risk of cancellation being carried into subsequent design phases; which is typically where some of this risk is uncovered, and the cost associated with mitigating this risk is exorbitant.

6.2 Contributions

The primary contribution of this thesis is the demonstration of the ability to predict the affordability implication resulting from the infusion of manufacturing technologies into launch vehicles. This method provides, not only a means to simultaneously assess cost and schedule risk, but also to determine an initial plan for the development of the elements which comprise a vehicle, such that budgetary constraints and schedule requirements are met simultaneously. The use of phase estimating relationships will allow decision makers insight into the expected outlay required to mature an element based upon the manufacturing technologies leveraged, as well as the impact these technologies have on the schedule and outlays for integration activities. Furthermore, the ability to establish the affordability risk of a particular concept (and its plan) will enable decision makers to determine the elements which possess the greatest opportunity for manufacturing technology infusion.

6.3 Future Work

Throughout the development of this thesis, the research has been scoped through the application of assumptions. The purpose of this approach is to establish a foundation upon which future work can build, through the peeling back assumptions and expanding capability. The following section enumerates the major areas of interest which will significantly increase the capability of this methodology, and thus provide a greater amount of information to the decision makers during Conceptual Design.

The assumptions on scoping form two categories, the first being the inclusion of program life cycle phases, and the second being analysis simplification. This research is founded on the difficulty of achieving first flight, and is aimed at decision making during Conceptual Design. As such, this method does not, directly, include architectural trades or production, operation and support. Expanding this methodology to include production of additional units would provide insight into learning curve effects, particularly for low-volume production such as launch vehicles. Furthermore, with P-BEAT intended to provide such insight, extending this would simply require additional inputs (e.g. desired lot size) and reconfiguring the estimate scope therein. With this addition, the methodology developed herein would provide affordability into the production of lots.

The second major category of assumptions are those used to simplify the analysis, and can be further subdivided into physical and programmatic assumptions. The physical assumptions simplify the high-fidelity performance analysis environment aimed at assessing whether a candidate configuration meets the mission critical performance requirements. These assumptions include fixing the vehicle geometry, limited ability to vary manufacturing technology infusion, the exclusion of composite ply tailoring, and the assessment of other performance metrics beyond mass delivered to orbit.

Fixing the geometry has reduced the ability to resize any given concept to be the minimum-possible vehicle which meets mission critical performance requirements. The assertion here being that any weight savings in one system element would cascade into weight savings in other elements. If a new material were applied to the EUS fuel tank such that a 10% weight reduction was achieved the vehicle could be completely resized such that the required payload delivery is precisely met. The reduction in tank weight would mean that the propulsive force needed to deliver the required payload to the desired orbit would be less. This translates into a reduction in propellant required, which in turn allows for the reduction in size of the fuel tanks such that free volume is minimized. Incorporating variable geometry would be invaluable and ultimately embodies the new design paradigm — there is no longer a benefit to providing performance improvements over and above those required. Incorporating variable geometry in the EUS MInD environment, however, one of the two most complex future work items listed herein.

The second, is extending the applicability of this methodology to the vehicle architecture level — one phase earlier in the program lifecycle phase. The implications of this are *ENORMOUS*. The method herein was applied to a single architecture, namely the SLS block I, whose propellant tanks are separate and inline, with the exception of a suspended oxidizer tank for the EUS. This architecture also includes 2 strap-on solid-rocket boosters. Architecture changes could include varying the number of boosters and/or their propellant type, as well as using common bulkhead or toroidal tanks for all stages, or adjusting the EUS configurations to include suspended fuel tanks. The most major of these implications is the ability to capture these large variations in a parametric FEA/CAD environment. The uniqueness of each of these architectures would require hundreds of hours, to appropriately model each architecture. Each architecture would provide its own set of insights and observations regarding the appropriate mix of manufacturing technologies. The incorporation of this and the variable geometry would be the holy grail of this methodology, but require immense computing hardware to analyze all permutations and arrive at the most affordable architecture. Before either variable geometry or mission architectures are varied, the other, more manageable, tasks should be completed.

The inclusion of vehicle reliability and safety models (See [227]) into the analysis environment would provide a more realistic picture of the mission critical requirements. Furthermore, the expansion of the current model to include more manufacturing technologies in more elements. As the EUS MInD environment stands now, there is an incomplete capture of the various manufacturing capabilities. This primarily relates to the discretization of the components such that a greater space may be analyzed, and applying this to all primary body structures. The 846 cases analyzed in Section 3.6 include limited variations on the fuel tank barrel panels, and only one variation on the domes (one-piece or ten gores). From a programmatic and logistic standpoint it is unlikely that a large number of different processes would be used to for a system. This would warrant an excessively diverse array of equipment to support. It is more likely that many of the elements (who share materials) would be fabricated using the same processes. Thus assessing the most efficient process to use on *ALL* panel-shaped pieces, for example, would be more insightful to decision makers in Conceptual Design. Additionally, introducing additional inputs which are driven by manufacturing processes would provide more accurate comparisons. One prime example is the inclusion of weld land structural integrity variations as a function of welding process.

The final, and perhaps most important for the short-term, expansion of the analysis is to remove the quasi-isotropic composite material assumption, and embrace ply tailoring. Removal of this assumption would model composites as they truly are, and provide a more realistic assessment of their capability. The importance of this is primarily to enable more accurate comparisons for the EUS, since composite tankage is a viable option with expected affordability benefits in production.

The programmatic assumptions are concerned with the task order permutations and the potential for discrete event simulation. As mentioned in Section 3.8.1.2, a limited number of task permutations has been considered. Due to the large combinatorial space, optimistic, expected, and pessimistic permutations were logically formulated and used in discrete uniform distribution sampling to propagate uncertainty. A viable option to expand this assessment is to enumerate the full factorial space — soliciting SME or historical data to establish compatibility and predecessors between development processes — and utilize it commensurate with the uniform sampling method developed herein.

The potential for discrete event simulation is also a viable expansion of this methodology, albeit mostly applicable to the First Build or production aspect of this methodology, particularly in light of the sensor installation issue discussed in the proceeding section. The creation of a DES model for the fabrication would enable a simulation of the actual time required to complete fabrication processes and supplant the use of CERs. This shift provides the ability to insert new processes, or vary their order, as well as capturing intangible durations commensurate with modeling production floor layout. The creation of this capability will model a more realistic production time estimate with the implications of tooling and the constraining production facility. This capability will facilitate the inclusion of processes and precludes the reliance on potentially limiting historical data, upon which CERs rely. This will prove indispensable when numerous additional steps/processes need to be considered.

6.3.1 Application to SLS Sensor Problem

A unique challenge currently facing Boeing, as the first SLS is being produced, is the need to include numerous sensors aimed at monitoring systems and gathering flight data. The shear number of sensors required dwarfs those used in any previous launch vehicle; making the assembly process particularly complex. Not only does the SLS need to be assemble expeditiously, but the sensors must be integrated at the “right” time. Adding a sensor in too early could result in unnecessary damage to that sensor, requiring replacement; inserting a sensor too late could require disassembly of the vehicle in order to access the appropriate sensor location.

Within the context of this thesis, the current SLS sensor installation challenge is specific to the First Build portion of the integration affordability distribution. Fundamentally, the inclusion of the installation processes would cause the integration portion of the curve — shown in Figure 137 — to increase in cost, and potentially increase the phase duration as well. Unfortunately, the process based cost tools typically base their CERs on the development of large components. As such their applicability to individual, or even a group of, sensors is questionable.

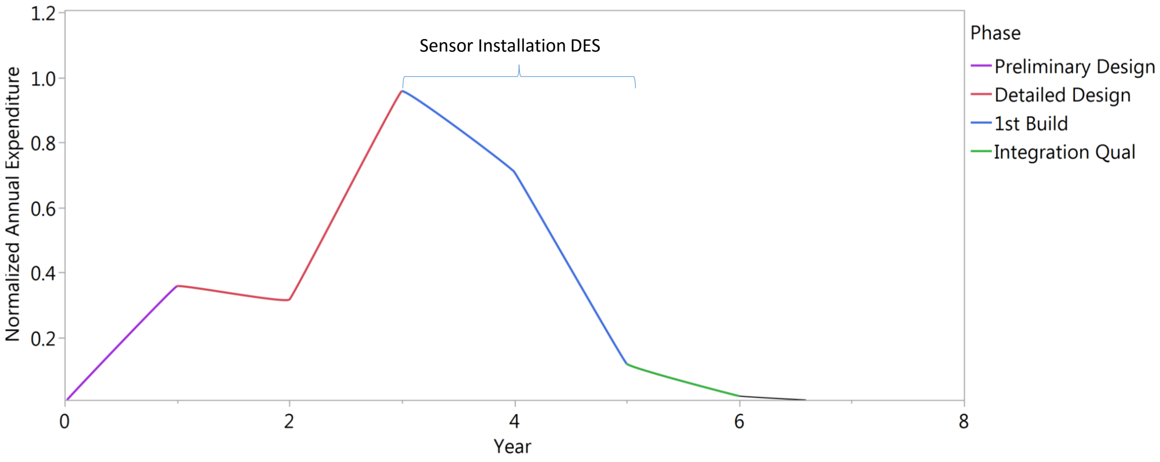


Figure 137: Sensor Installation Affected Area

The most appropriate method to accurately capture the various integration opportunities for each sensor is through a discrete event simulation (DES). This simulation would need to be fairly detailed and include the appropriate representation of system elements and each sensor, as well as an accurate layout of the production floor/assembly area. Such simulation could be facilitate through the use of Simio or DELMIA by Dassault Systems.

While these tools are typically used to simulate global/macro processes, they can be adapted to such a detailed level, with one *MAJOR* challenge: translating the physical complexities into mathematical relationships. How do you represent the potential to damage a sensor when it is installed too early, or the physical limitations of not having sufficient room to install a sensor towards the end of assembly? These are just the “tip of the iceberg” in representing physical constraints that change as a function of time in programs which were chiefly design to just add up task durations. The fundamental flaw of these simulation programs is the macro scale of the problems which they were designed to solve.

Unfortunately the only way to address this issue is with an excruciating amount of logic and compatibility, which is the approach researchers in ASDL are currently undertaking, with limited success due to the time sensitive nature of the problem.

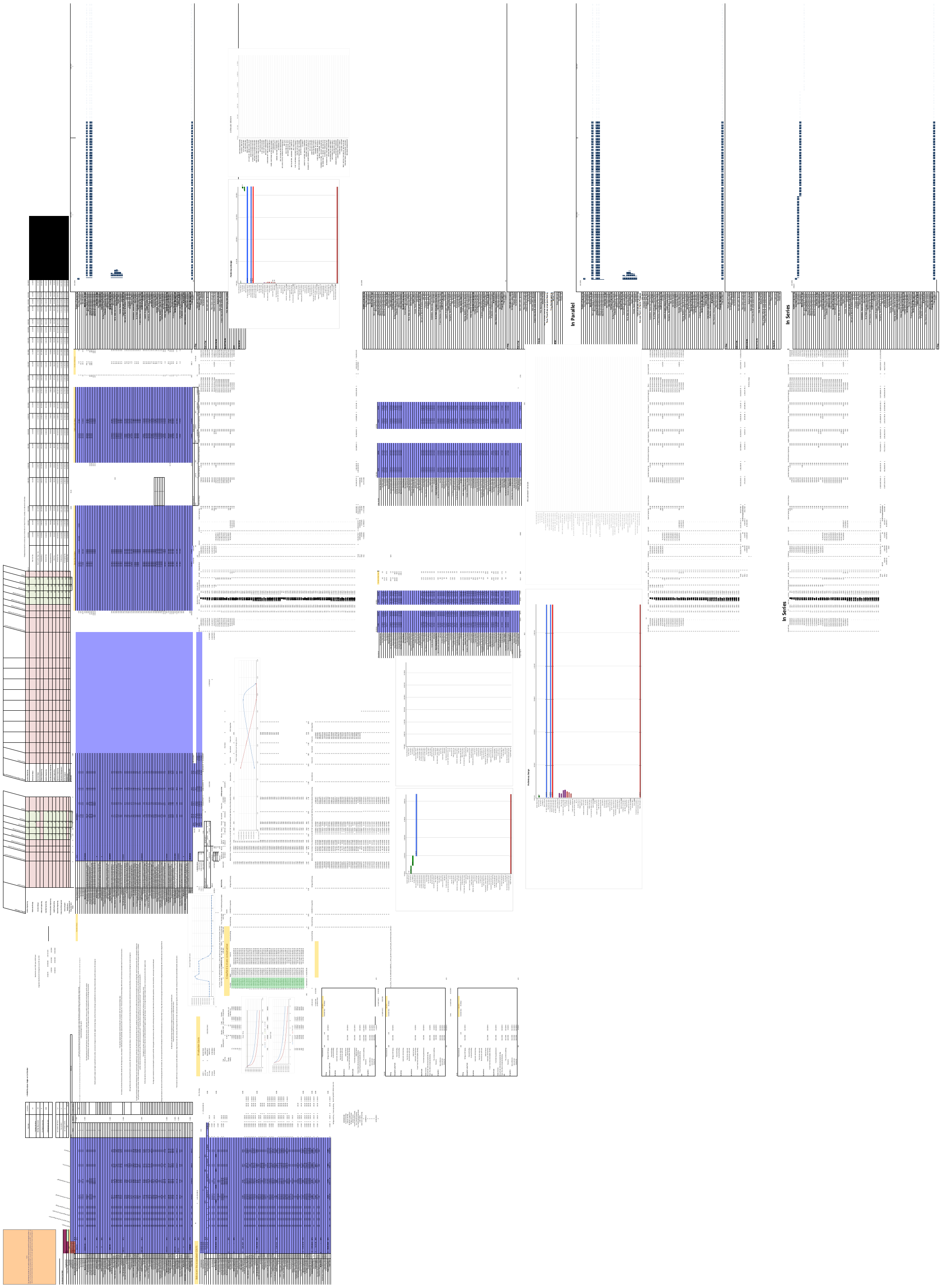
This approach warrants the elucidation of compatibility — which vehicle assembly processes can be performed in parallel with sensor installation. This depends on the location of each sensor and the realization that there is a likelihood of damaging a sensor if later tasks are performed near the sensor. Furthermore, consideration for access limitations would need to be tracked, for each sensor location, as vehicle assembly tasks are performed. A new metric could be defined to capture this accessibility, which would decrease proportionally to the addition of either vehicle components or other sensors in that same area.

Fundamentally, the results of this DES would provide an optimum task order (of vehicle component assembly and sensor installation tasks) which would form an affordability distribution which would supplant the First Build portion of the integration distribution. The additional implication on this, within the context of this methodology, is the propagation of uncertainty needed to represent the uncertainty in this process. The author envisions this process as being very similar to the bootstrapping process — described in Experiment 3 and 4 in Section 3.9 and D.2 — where the integration distribution would be comprised of bootstrapped process based cost results for the Preliminary and Detailed Design with samples from the DES added on to represent the First Build process.

In the future, however, the group of sensors could be included as a thirteenth element in order to capture additional Preliminary and Detailed Design impacts. This would require updating the CERs (or creating new ones in the various process based tools) to capture the implications of various sensor installations. This would be particularly applicable in the case where sensors were integral to the elements which comprise a system. Their installation could be performed during element First Builds, and such that there is limited (or no) issues associated with sensor damage during system assembly.

APPENDIX A

SCREENSHOT OF EXCEL-BASED HOUR TRANSLATOR



APPENDIX B

EXPERIMENT 1 FIT EQUATIONS

B.1 α and β Neural Network Equation

The equations listed in this section relate to the estimation of the Weibull parameters which describe the phase-specific temporal behavior of cost. These equations are intended to provide the user with an estimate of the expenditure in preliminary, detailed, and First Build life cycle phases. One would begin by using theβ relationships below to generate a Weibull. Thereafter, to estimate the expenditure in each phase, one would evaluate the resulting Weibull distribution at each of the three phase duration points described by the equations in the subsequent section of this appendix.

$$\alpha = 13.4984973601326 + -6.11211864262436 \ast H1_1 + 7.40950406514234 \ast H1_2 + 2.09259395504237 \ast H1_3 + -2.76756712906852 \ast H1_4 + -12.1289535435643 \ast H1_5 + 12.2979030280781 \ast H1_6 + -1.40743168039771 \ast H1_7 + -5.97996210986157 \ast H1_8 + 1.24922479378699 \ast H1_9 + -1.81442080763419 \ast H1_{10} + 4.90015480992004 \ast H1_{11} + -10.4424415979173 \ast H1_{12} + -4.50778241057293 \ast H1_{13} + 0.541411377125697 \ast H1_{14} + 2.30471526458191 \ast H1_{15}$$

$$\beta = 18.8775659152541 + 3.06361549984597 * H1_1 + -6.42407230041858 * H1_2 + 4.1310199629264 * H1_3 + -8.14819356293913 * H1_4 + -11.2754547152293 * H1_5 + 0.538077932883887 * H1_6 + -0.294971099945478 * H1_7 + 1.62460004007375 * H1_8 + 2.4801762029882 * H1_9 + -3.72326606700081 * H1_{10} + -13.0600231528643 * H1_{11} + 3.89405205521129 * H1_{12} + -1.53965994751411 * H1_{13} + -5.63495950106221 * H1_{14} + 5.27249860536059 * H1_1$$

where, the H variables represent the hidden layers, and are all functions of TRL, material, number of barrel panels, barrel stiffening concept, barrel and dome fabrication techniques and trimming techniques outlined in Table 11 and 12.

$H1_1$ = TanH(0.5 * ((-0.0689254862579335) + -0.0271461496005426 * :$H2_1$ + -0.100485644625854 * :$H2_2$ + -0.189180817446709 * :$H2_3$ + -0.319722515125035 * :$H2_4$ +-0.172509875143997 * :$H2_5$ + 0.195219610418588 * :$H2_6$ + 0.215559469312317 *:$H2_7$+ 0.214916882929402 * :$H2_8$ + 0.0905939184644643 * :$H2_9$ + -0.0421653704502324 * :$H2_{10}$ + 0.150666459542972 * :$H2_{11}$ + 0.527607868509756 *:$H2_{12}$ + 0.127865418442963 * :$H2_{13}$ + -0.144300315346129 * :$H2_{14}$+ 0.00523442692860537 * :$H2_{15}$))

$H1_2$ = TanH(0.5 * (0.0967657992979391 + -0.351898536165332 * :$H2_1$ + -0.0206091437788984 *:$H2_2$ + 0.108373426767035 * :$H2_3$ + 0.278265781058793 * :$H2_4$+ 0.0658153717520618 * :$H2_5$ + 0.36124619913259 * :$H2_6$ + 0.216489795192115 *:$H2_7$ + -0.253140920394919 * :$H2_8$ + 0.0595068762605288 * :$H2_9$ +-0.368996550751726 * :$H2_{10}$ + -0.00496865905873602 * :$H2_{11}$ + -0.180895782905953* :$H2_{12}$ + -0.264769669143932 * :$H2_{13}$ + 0.237517602445557 * :$H2_{14}$+ 0.291504369175629 * :$H2_{15}$))

$H1_3$ = TanH(0.5 * ((-0.143771897955744) + 0.0449350106650174 * :$H2_1$ + -0.0187470005045114 * :$H2_2$ + -0.0773463456787513 * :$H2_3$ + -0.0481277436639856 * :$H2_4$ + -0.112795238171301 * :$H2_5$ + 0.0988498353548794 * :$H2_6$ + -0.0632464090673118 * :$H2_7$ + 0.0855326553446633 * :$H2_8$ + -0.153472678830231 * :$H2_9$+0.190575458130164 * :$H2_{10}$ + 0.146284613114374 * :$H2_{11}$ + 0.055208766245688 * :$H2_{12}$ + 0.0412021507234095 * :$H2_{13}$ + -0.0508088555632308

* :H2$_{14}$+0.0441326466267454 * :H2$_{15}$))

$H1_4$ = TanH(0.5 * (0.0821753590627962 + -0.110280548514295 * :H2$_1$ + -0.138549592339418 * :H2$_2$ + 0.264560310742111 * :H2$_3$ + -0.0272315170271899 * :H2$_4$ + -0.0174495410505446 * :H2$_5$ + 0.256283859315725 * :H2$_6$ + 0.258366401931509 * :H2$_7$ + -0.0616380128765986 * :H2$_8$ + -0.153053091160216 * :H2$_9$+0.036780926042459 * :H2$_{10}$ + -0.359728655553925 * :H2$_{11}$ + -0.158247322867012 * :H2$_{12}$ + -0.237419826290637 * :H2$_{13}$ + 0.0802601417562869 * :H2$_{14}$+0.284286614119794 * :H2$_{15}$))

$H1_5$ = TanH(0.5 * (0.299078265319375 + -0.330202169718271 * :H2$_1$ + 0.157691992369655 * :H2$_2$ + 0.299563886992432 * :H2$_3$ + -0.449983467793966 * :H2$_4$ + -0.429523123476374 * :H2$_5$ + 0.138095575534753 * :H2$_6$ + -0.0205075432036872 * :H2$_7$ + -0.357641665252846 * :H2$_8$ + -0.302579626436247 * :H2$_9$+0.170626246234254 * :H2$_{10}$ + 0.280471314092909 * :H2$_{11}$ + 0.241050389591079 * :H2$_{12}$ + -0.133767501503665 * :H2$_{13}$ + 0.23129322091565 * :H2$_{14}$+0.496718463620953 * :H2$_{15}$))

$H1_6$ = 0.17738859351727 + -0.126061444107927 * :H2$_1$ + -0.147774694990062 * :H2$_2$ +0.00497551710787955 * :H2$_3$ + 0.00166200685422232 * :H2$_4$ + -0.0134600659553797 *:H2$_5$ + 0.0383826402792128 * :H2$_6$ + -0.010217458109691 * :H2$_7$ + 0.0500461420008685* :H2$_8$ + -0.0347548699237295 * :H2$_9$ + 0.063461303611661 * :H2$_{10}$ +-0.148166268351383 * :H2$_{11}$ + -0.0694953044850976 * :H2$_{12}$ + -0.0189423271141867 *:H2$_{13}$ + 0.195204961984598 * :H2$_{14}$ + 0.0699395538915182 * :H2$_{15}$

$H1_7$ = (-0.0944419719869336) + -0.13759541600704 * :H2$_1$ + 0.111270569543441

* :H2$_{2}$ + -0.135860197001088 * :H2$_{3}$ + 0.106573535063078 * :H2$_{4}$ + -0.206954139607489 * :H2$_{5}$+ -0.201250492644125 * :H2$_{6}$ + 0.0965072776727732 * :H2$_{7}$ + 0.139232332355763 *:H2$_{8}$ + 0.114290222902395 * :H2$_{9}$ + -0.203638286731015 * :H2$_{10}$ + -0.141012433943609* :H2$_{11}$ + -0.145010445098623 * :H2$_{12}$ + -0.112083494194467 * :H2$_{13}$ +-0.0593412428885909 * :H2$_{14}$ + -0.25573857147654 * :H2$_{15}$

$H1_{8}$ = (-0.251745326149774) + 0.18004011590995 * :H2$_{1}$ + 0.0306139166956669 * :H2$_{2}$+0.109084958301455 * :H2$_{3}$ + -0.0140470226543137 * :H2$_{4}$ + 0.0619059339442369 *:H2$_{5}$ + 0.236990591240662 * :H2$_{6}$ + 0.022494828273142 * :H2$_{7}$ + -0.0459583209012065* :H2$_{8}$ + -0.131516655555788 * :H2$_{9}$ + 0.0318755908174962 * :H2$_{10}$ +0.128374973644844 * :H2$_{11}$ + -0.0736633473923212 * :H2$_{12}$ + 0.0503190129585697 *:H2$_{13}$ + -0.0804153596419755 * :H2$_{14}$ + 0.0318487344423234 * :H2$_{15}$

$H1_{9}$ = (-0.130528125794853) + 0.0268176722664152 * :H2$_{1}$ + 0.0266100137928452 * :H2$_{2}$ +-0.174278756084285 * :H2$_{3}$ + -0.0921475072837208 * :H2$_{4}$ + -0.199969843021822 *:H2$_{5}$ + 0.295042675399168 * :H2$_{6}$ + 0.394052522433461 * :H2$_{7}$ + 0.458580391252343 *:H2$_{8}$ + 0.0014789371087356 * :H2$_{9}$ + -0.0459314279435462 * :H2$_{10}$+0.0863917614711115 * :H2$_{11}$ + -0.0260757296970448 * :H2$_{12}$ + 0.0453479152824809 *:H2$_{13}$ + 0.0416885098677254 * :H2$_{14}$ + 0.0711542461785265 * :H2$_{15}$

$H1_{10}$ = 0.00773582054841368 + -0.0791994893537163 * :H2$_{1}$ + 0.127217588191032 * :H2$_{2}$+0.0715105079107385 * :H2$_{3}$ + 0.154373315792316 * :H2$_{4}$ + -0.0200117556437272 *:H2$_{5}$ + -0.0736931223708699 * :H2$_{6}$ + 0.194568859441282 * :H2$_{7}$ + 0.0110587515629252* :H2$_{8}$ + -0.152698362087059 * :H2$_{9}$ + 0.17006244017117

* :H2$_{10}$+0.241241748601265 * :H2$_{11}$ + 0.0651103365282844 * :H2$_{12}$ + -0.204851937092237 *:H2$_{13}$ + -0.118408449285007 * :H2$_{14}$ + -0.157300744169027 * :H2$_{15}$

$H1_{11}$ = Exp(-(0.5 * (0.0914199668932632 + 0.0752230608911926 * :H2$_{1}$ + -0.250140350662049 * :H2$_{2}$ + -0.550726848230412 * :H2$_{3}$ + 0.0146573192223794 * :H2$_{4}$+0.0262244088225936 * :H2$_{5}$ + 0.0500789070167682 * :H2$_{6}$ + 0.024034670093349 * :H2$_{7}$ + -0.179296559616256 * :H2$_{8}$ + -0.302188065725189 * :H2$_{9}$+0.00962358322096442 * :H2$_{10}$ + -0.0730830244707257 * :H2$_{11}$ + -0.0175654195366499 * :H2$_{12}$ + -0.0249642759283737 * :H2$_{13}$ + 0.0363770769153608 * :H2$_{14}$ + 0.544913281477581 * :H2$_{15}$) ^{2}))

$H1_{12}$ = Exp(-(0.5 * ((-0.00743952023241223) + 0.121700555693054 * :H2$_{1}$ + -0.398985816300184 * :H2$_{2}$ + -0.0580240775446165 * :H2$_{3}$ + 0.427791986776375 * :H2$_{4}$+0.131464666723457 * :H2$_{5}$ + -0.0639246919979578 * :H2$_{6}$ + -0.0597442209981928 * :H2$_{7}$ + 0.0923782643592204 * :H2$_{8}$ + 0.371480075564033 * :H2$_{9}$ + -0.140716991610953 * :H2$_{10}$ + -0.538321794757845 * :H2$_{11}$ + -0.507297918873886 * :H2$_{12}$ + 0.106978343360222 * :H2$_{13}$ + 0.334885119322072 * :H2$_{14}$ + -0.244072223906669 * :H2$_{15}$) ^{2}))

$H1_{13}$ = Exp(-(0.5 * (0.315642374549969 + 0.104745796041709 * :H2$_{1}$ + -0.158864143202729 * :H2$_{2}$ + 0.0523633780190663 * :H2$_{3}$ + 0.188777431657776 * :H2$_{4}$ + -0.185849798507902 * :H2$_{5}$ + 0.0294902630487081 * :H2$_{6}$ + 0.00277263012796346 * :H2$_{7}$ + 0.0845842936304603 * :H2$_{8}$ + -0.0732976701440272 * :H2$_{9}$+0.0723490065009787 * :H2$_{10}$ + -0.328161531483043 * :H2$_{11}$ + -0.206434646752765 * :H2$_{12}$ + 0.270111009892167 * :H2$_{13}$ + 0.156041851883737 * :H2$_{14}$ + -0.0993223557590212 * :H2$_{15}$)^{2}))

$H1_{14}$ = Exp(-(0.5 * (0.0551928830290241 + 0.108077234259204 * :$H2_{1}$ + 0.0437754329044138 * :$H2_{2}$ + 0.167334391189983 * :$H2_{3}$ + -0.241679148200392 * :$H2_{4}$ + -0.126956442447467 * :$H2_{5}$ + 0.0762631223166856 * :$H2_{6}$ + 0.0984261585239452 * :$H2_{7}$ + -0.0117171905177243 * :$H2_{8}$ + -0.256862031953604 * :$H2_{9}$+0.140095266431197 * :$H2_{10}$ + 0.399551136893339 * :$H2_{11}$ + 0.165964210362018 * :$H2_{12}$ + 0.0146002939724111 * :$H2_{13}$ + -0.0411978512526571 * :$H2_{14}$+0.20906514254018 * :$H2_{15}$) ^{2}))

H1$_{15}$=Exp(-(0.5 * (0.409153567516778 + -0.0211191505668593 * :$H2_{1}$ + 0.0939421690501 * :$H2_{2}$ + -0.251882103123305 * :$H2_{3}$ + 0.0147016597097071 * :$H2_{4}$ + -0.126375548625343 * :$H2_{5}$ + 0.288187558224654 * :$H2_{6}$ + -0.145578049924331 * :$H2_{7}$ + 0.265565023741437 * :$H2_{8}$ + -0.216386538620857 * :$H2_{9}$+0.39323632542319 * :$H2_{10}$ + -0.205628163963652 * :$H2_{11}$ + -0.115566629357857 * :$H2_{12}$ + 0.157486439895417 * :$H2_{13}$ + 0.310226339045336 * :$H2_{14}$+0.101777517036358 * :$H2_{15}$) ^{2}))

```
$H2_1$ = TanH(
0.5 * (0.152678950549573 + 0.120362937559386 * :TRL +Match( :Material,
" TI−6AL−4V", −0.0574312382211092,"2024, T81", 0.12416716809363,
"2090, T83", −0.066519184195772,"2219, T62", 0.0493407058137664,
"AlLi 2195",−((−0.0574312382211092) + 0.12416716809363 +
(−0.066519184195772)+0.0493407058137664)) + −0.245046711639854 *
 :No. Barrel Panels+Match( :Stiffener,"IBS", −0.115948076314247,
"Ortho", −0.15512563891165,"Unstiffened",
−((−0.115948076314247) + (−0.15512563891165))) + Match( :dome gore fab,
"1 piece spun dome + cap", 0.143258500900955,
"shot peendome gores", −0.118053410272401,
"stretchdome gores", −(0.143258500900955 + (−0.118053410272401))
```

```
) + Match( :barrel panel fab,"bumpbarrel panels", -0.030352961430877,
"peenbarrel panels", 0.093032674132735,
"stretchbarrel panels", -((-0.030352961430877) + 0.093032674132735)
) + Match( :trim,"Chemical", 0.0374241323116565,
"Machine (Vertical Tool)", -Add( 0.0374241323116565 ))))


$H2_2$ = TanH(
0.5 * (0.611411670912575 + -0.00713226397735169 * :TRL
+Match( :Material," TI-6AL-4V", 0.47712467130971,
"2024, T81", -0.14937518534624,"2090, T83", -0.0496646373077818,
"2219, T62", -0.231621695336854,"AlLi 2195",
-(0.47712467130971 + (-0.14937518534624) + (-0.0496646373077818) + (
-0.231621695336854))) + -0.269119362849762 * :No. Barrel Panels
+Match( :Stiffener,"IBS", -0.0112749795471506,
"Ortho", 0.0576089877879412,
"Unstiffened", -((-0.0112749795471506) + 0.0576089877879412)
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.13172975848901,
"shot peendome gores", -0.204750222391564,
"stretchdome gores", -(0.13172975848901 + (-0.204750222391564))
) + Match( :barrel panel fab,"bumpbarrel panels", -0.0283145175021658,
"peenbarrel panels", 0.0582966074208762,
"stretchbarrel panels", -((-0.0283145175021658) + 0.0582966074208762)
) + Match( :trim,"Chemical", -0.0530423887521073,
"Machine (Vertical Tool)", -Add( -0.0530423887521073 ))))


$H2_3$ = TanH(0.5 * ((-1.25779264483507) + 0.335383861008942 * :TRL
+Match( :Material," TI-6AL-4V", -0.137742792451643,
"2024, T81", 0.1006007707899,"2090, T83", -0.013924072885731,
"2219, T62", 0.0591461337879057,"AlLi 2195",
-((-0.137742792451643) + 0.1006007707899 + (-0.013924072885731)
```

```
+0.0591461337879057)) + –0.254178907371731 ⋆ :No. Barrel Panels
+Match( :Stiffener,"IBS", –0.00204593033794763,
"Ortho", –0.0249138388552221,
"Unstiffened", –((–0.00204593033794763) + (–0.0249138388552221))
) + Match( :dome gore fab,
"1 piece spun dome + cap", –0.621885490539213,
"shot peendome gores", 0.294589842559579,
"stretchdome gores", –((–0.621885490539213) + 0.294589842559579)
) + Match( :barrel panel fab,"bumpbarrel panels", –0.0278917756605622,
"peenbarrel panels", 0.0562917951144896,
"stretchbarrel panels", –((–0.0278917756605622) + 0.0562917951144896)
) + Match( :trim,"Chemical", –0.000646590106047494,
"Machine (Vertical Tool)", –Add( –0.000646590106047494 ))))


$H2_4$ = TanH(
0.5 ⋆ ((–1.15027582457961) + 0.0588729139194069 ⋆ :TRL
+Match( :Material," TI–6AL–4V", 0.0281201576659533,
"2024, T81", –0.0522417528885711,
"2090, T83", 0.0213138265669925,
"2219, T62", –0.0451577700021091,"AlLi 2195",
–(0.0281201576659533 + (–0.0522417528885711) + 0.0213138265669925 + (
–0.0451577700021091))) + 0.137972878384602 ⋆ :No. Barrel Panels
+Match( :Stiffener,"IBS", –0.673316143725105,
"Ortho", –0.740622493182658,
"Unstiffened", –((–0.673316143725105) + (–0.740622493182658))
) + Match( :dome gore fab,
"1 piece spun dome + cap", –0.631106157658204,
"shot peendome gores", –0.836482529997837,
"stretchdome gores", –((–0.631106157658204) + (–0.836482529997837))
) + Match( :barrel panel fab,"bumpbarrel panels", –0.134059996498429,
"peenbarrel panels", 0.00737891396133421,
```

```
"stretchbarrel panels", –((–0.134059996498429) + 0.00737891396133421)
) + Match( :trim,"Chemical", 0.150137953508659,
"Machine (Vertical Tool)", –Add( 0.150137953508659 ))))
```

```
$H2_5$ = TanH(
0.5 * (1.01488866242588 + –0.126763231396144 * :TRL
+Match( :Material," TI–6AL–4V", 0.0397490773956423,
"2024, T81", –0.0280679538447678,"2090, T83", 0.0555378444230437,
"2219, T62", –0.0443421818283784,"AlLi 2195",
–(0.0397490773956423 + (–0.0280679538447678) + 0.0555378444230437 + (
–0.0443421818283784))) + –0.110307900035038 * :No. Barrel Panels
+Match( :Stiffener,"IBS", –0.181734206239541,
"Ortho", 0.258082147808134,
"Unstiffened", –((–0.181734206239541) + 0.258082147808134)
) + Match( :dome gore fab,"1 piece spun dome + cap", –0.405881306483861,
"shot peendome gores", 0.494076680765752,
"stretchdome gores", –((–0.405881306483861) + 0.494076680765752)
) + Match( :barrel panel fab,"bumpbarrel panels", –0.171591590571141,
"peenbarrel panels", 0.0562342576813433,
"stretchbarrel panels", –((–0.171591590571141) + 0.0562342576813433)
) + Match( :trim,"Chemical", –0.196655871383565,
"Machine (Vertical Tool)", –Add( –0.196655871383565 ))))
```

```
$H2_6$ = TanH(
0.5 * (1.01488866242588 + –0.126763231396144 * :TRL
+Match( :Material," TI–6AL–4V", 0.0397490773956423,
"2024, T81", –0.0280679538447678,"2090, T83", 0.0555378444230437,
"2219, T62", –0.0443421818283784,"AlLi 2195",
–(0.0397490773956423 + (–0.0280679538447678) + 0.0555378444230437 + (
–0.0443421818283784))) + –0.110307900035038 * :No. Barrel Panels
```

```
+Match( :Stiffener,"IBS", −0.181734206239541,
"Ortho", 0.258082147808134,
"Unstiffened", −((−0.181734206239541) + 0.258082147808134)
) + Match( :dome gore fab,"1 piece spun dome + cap", −0.405881306483861,
"shot peendome gores", 0.494076680765752,
"stretchdome gores", −((−0.405881306483861) + 0.494076680765752)
) + Match( :barrel panel fab,"bumpbarrel panels", −0.171591590571141,
"peenbarrel panels", 0.0562342576813433,
"stretchbarrel panels", −((−0.171591590571141) + 0.0562342576813433)
) + Match( :trim,"Chemical", −0.196655871383565,
"Machine (Vertical Tool)", −Add( −0.196655871383565 ))))
```

```
$H2_7$ = (−0.0598611713356046) + −0.128519617464386 * :TRL
+Match( :Material," TI−6AL−4V", 0.0399884142390268,
"2024, T81", 0.140172669418069,"2090, T83", −0.187816944441954,
"2219, T62", 0.165480071516589,"AlLi 2195",
−(0.0399884142390268 + 0.140172669418069 + (−0.187816944441954)
+0.165480071516589)
) + 0.168153640925856 * :No. Barrel Panels + Match( :Stiffener,
"IBS", 0.151078320948259,"Ortho", −0.239485432166947,
"Unstiffened", −(0.151078320948259 + (−0.239485432166947))
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.122208966458989,
"shot peendome gores", 0.145929933850573,
"stretchdome gores", −(0.122208966458989 + 0.145929933850573)
) + Match( :barrel panel fab,"bumpbarrel panels", 0.238464050267793,
"peenbarrel panels", 0.0701738358485221,
"stretchbarrel panels", −(0.238464050267793 + 0.0701738358485221)
) + Match( :trim,"Chemical", −0.181855363201772,
"Machine (Vertical Tool)", −Add( −0.181855363201772 ))
```

```
$H2_8$ = 2.0880863273796 + −0.266728227792968 * :TRL + Match( :Material,
" TI−6AL−4V", −0.00840047044543816,"2024, T81", 0.108827444591329,
"2090, T83", −0.080562387168287,"2219, T62", 0.0514480703822751,
"AlLi 2195",−((−0.00840047044543816) + 0.108827444591329 +
(−0.080562387168287)+0.0514480703822751)
) + −0.153893348420843 * :No. Barrel Panels + Match( :Stiffener,
"IBS", 0.0503045945614627,"Ortho", 0.0360160896142219,
"Unstiffened", −(0.0503045945614627 + 0.0360160896142219)
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.513206954557644,
"shot peendome gores", −0.340368844960981,
"stretchdome gores", −(0.513206954557644 + (−0.340368844960981))
) + Match( :barrel panel fab,"bumpbarrel panels", −0.28844353678883,
"peenbarrel panels", 0.105632085094345,
"stretchbarrel panels", −((−0.28844353678883) + 0.105632085094345)
) + Match( :trim,"Chemical", −0.196002519938994,
"Machine (Vertical Tool)", −Add( −0.196002519938994 ))
```

```
$H2_9$ = 1.22193113885365 + −0.215342248579291 * :TRL + Match( :Material
," TI−6AL−4V", −0.0603280209151452,"2024, T81", 0.0315429445665682,
"2090, T83", −0.00592373349670775,"2219, T62", 0.0549212502987927,
"AlLi 2195",
−((−0.0603280209151452) + 0.0315429445665682 + (−0.00592373349670775)
+0.0549212502987927)
) + −0.10953515142143 * :No. Barrel Panels + Match( :Stiffener,
"IBS", −0.0419996074031493,"Ortho", 0.0655585158268339,
"Unstiffened", −((−0.0419996074031493) + 0.0655585158268339)
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.438932204458949,
"shot peendome gores", 0.0203061835977706,
"stretchdome gores", −(0.438932204458949 + 0.0203061835977706)
) + Match( :barrel panel fab,"bumpbarrel panels", 0.132357205793401,
"peenbarrel panels", −0.130861496545619,
```

```
"stretchbarrel panels", -(0.132357205793401 + (-0.130861496545619))
) + Match( :trim,"Chemical", 0.142837782616788,
"Machine (Vertical Tool)", -Add( 0.142837782616788 ))



$H2_10$ = (-0.458019871741185) + 0.204672850607159 * :TRL
+Match( :Material," TI-6AL-4V", -0.0422389548486497,
"2024, T81", 0.000944435348870713,"2090, T83", 0.00357054527408703,
"2219, T62", 0.0569272758917571,"AlLi 2195",
-((-0.0422389548486497) + 0.000944435348870713 + 0.00357054527408703
+0.0569272758917571)
) + -0.0480537437970711 * :No. Barrel Panels + Match( :Stiffener,
"IBS", 0.0953542648420203,"Ortho", 0.283143258717692,
"Unstiffened", -(0.0953542648420203 + 0.283143258717692)
) + Match( :dome gore fab,"1 piece spun dome + cap", -0.0364477250519651
,"shot peendome gores", -0.0873193335551792,
"stretchdome gores", -((-0.0364477250519651) + (-0.0873193335551792))
) + Match( :barrel panel fab,"bumpbarrel panels", -0.238633202932596,
"peenbarrel panels", 0.076807266646104,
"stretchbarrel panels", -((-0.238633202932596) + 0.076807266646104)
) + Match( :trim,"Chemical", -0.181229605232105,
"Machine (Vertical Tool)", -Add( -0.181229605232105 ))



$H2_11$ = Exp(
-(0.5 * (0.853930566743546 + 0.0272569204334044 * :TRL
+Match( :Material," TI-6AL-4V", -0.00844935306573506,
"2024, T81", 0.00400938105800761,"2090, T83", -0.00287499489342559,
"2219, T62", 0.00913086383211906,"AlLi 2195",
-((-0.00844935306573506) + 0.00400938105800761 + (-0.00287499489342559)
+ 0.00913086383211906)) + -0.0498364543446457 * :No. Barrel Panels
+Match( :Stiffener,"IBS", 0.667076108724359,
```

```
"Ortho", 0.573945286742961,
"Unstiffened", -(0.667076108724359 + 0.573945286742961)
) + Match( :dome gore fab,"1 piece spun dome + cap", -0.265504731001551,
"shot peendome gores", 0.779740670806569,
"stretchdome gores", -((-0.265504731001551) + 0.779740670806569)
) + Match( :barrel panel fab,"bumpbarrel panels", -0.313859727390184,
"peenbarrel panels", 0.6553326669491,
"stretchbarrel panels", -((-0.313859727390184) + 0.6553326669491)
) + Match( :trim,"Chemical", -0.0677941881934426,
"Machine (Vertical Tool)", -Add( -0.0677941881934426 ))) ^ 2))


$H2_12$ = Exp(-(0.5 * ((-0.496887697252912) + 0.0749751831842722 * :TRL
+Match( :Material," TI-6AL-4V", 0.0642020979116024,
"2024, T81", -0.0155204287214407,"2090, T83", -0.016284807352857,
"2219, T62", -0.018215879992721,"AlLi 2195",
-(0.0642020979116024 + (-0.0155204287214407) + (-0.016284807352857) + (
-0.018215879992721))) + 0.0581522594400542 * :No. Barrel Panels
+Match( :Stiffener,"IBS", 0.099390097679233,
"Ortho", 0.0632841624112512,
"Unstiffened", -(0.099390097679233 + 0.0632841624112512)
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.239811339046439,
"shot peendome gores", 0.928907076472113,
"stretchdome gores", -(0.239811339046439 + 0.928907076472113)
) + Match( :barrel panel fab,"bumpbarrel panels", 0.375352446042832,
"peenbarrel panels", -1.00911426685348,
"stretchbarrel panels", -(0.375352446042832 + (-1.00911426685348))
) + Match( :trim,"Chemical", -0.00794298162833172,
"Machine (Vertical Tool)", -Add( -0.00794298162833172 ))) ^ 2))


$H2_13$ = Exp(-(0.5 * ((-0.584692504335339) + 0.181956684380222 * :TRL
```

```
+Match( :Material," TI-6AL-4V", 0.520066768295379,
"2024, T81", -0.15055206906228,"2090, T83", -0.102423606938063,
"2219, T62", -0.166902618141955,"AlLi 2195",
-(0.520066768295379 + (-0.15055206906228) + (-0.102423606938063) + (
-0.166902618141955))) + -0.0821009316345751 * :No. Barrel Panels
+Match( :Stiffener,"IBS", 0.0854715070204224,
"Ortho", -0.0447794637795255,
"Unstiffened", -(0.0854715070204224 + (-0.0447794637795255))
) + Match( :dome gore fab,"1 piece spun dome + cap", -0.0864599381032643
,"shot peendome gores", 0.0538479965110491,
"stretchdome gores", -((-0.0864599381032643) + 0.0538479965110491)
) + Match( :barrel panel fab,"bumpbarrel panels", 0.0070448911900693,
"peenbarrel panels", 0.00423222094487279,
"stretchbarrel panels", -(0.0070448911900693 + 0.00423222094487279)
) + Match( :trim,"Chemical", 0.0569456773570411,
"Machine (Vertical Tool)", -Add( 0.0569456773570411 ))) ^ 2))


$H2_14$ = Exp(-(0.5 * (0.0237112828530752 + 0.0507699272261096 * :TRL
+Match( :Material," TI-6AL-4V", -0.504209884205367,
"2024, T81", 0.213167067983022,"2090, T83", 0.0201914337679751,
"2219, T62", 0.240662118825412,"AlLi 2195",
-((-0.504209884205367) + 0.213167067983022 + 0.0201914337679751
+0.240662118825412)) + 0.00474941884276695 * :No. Barrel Panels
+Match( :Stiffener,"IBS", 0.153914129655735,
"Ortho", 0.121170671894841,
"Unstiffened", -(0.153914129655735 + 0.121170671894841)
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.101848595352643,
"shot peendome gores", -0.124009178575849,
"stretchdome gores", -(0.101848595352643 + (-0.124009178575849))
) + Match( :barrel panel fab,"bumpbarrel panels", -0.0126302497035568,
"peenbarrel panels", -0.0138436706668579,
```

```
"stretchbarrel panels", -((-0.0126302497035568) + (-0.0138436706668579))
) + Match( :trim,"Chemical", -0.0519944236386989,
"Machine (Vertical Tool)", -Add( -0.0519944236386989 ))) ^ 2))
```

```
$H2_15$ = Exp(
-(0.5 * (0.314123277981335 + 0.0310749917654387 * :TRL
+Match( :Material," TI-6AL-4V", -0.100627144107298,
"2024, T81", 0.00421298974206572,"2090, T83", 0.0440762030225033,
"2219, T62", 0.00381182915044276,"AlLi 2195",
-((-0.100627144107298) + 0.00421298974206572 + 0.0440762030225033
+0.00381182915044276)) + -0.243501850206419 * :No. Barrel Panels
+Match( :Stiffener,"IBS", -0.015006433634065,
"Ortho", -0.0560891383438455,
"Unstiffened", -((-0.015006433634065) + (-0.0560891383438455))
) + Match( :dome gore fab,"1 piece spun dome + cap", 0.687521001096524,
"shot peendome gores", -0.233800417004246,
"stretchdome gores", -(0.687521001096524 + (-0.233800417004246))
) + Match( :barrel panel fab,"bumpbarrel panels", 0.0161272738173545,
"peenbarrel panels", -0.00133682822296331,
"stretchbarrel panels", -(0.0161272738173545 + (-0.00133682822296331))
) + Match( :trim,"Chemical", 0.0139479847320329,
"Machine (Vertical Tool)", -Add( 0.0139479847320329 ))) ^ 2))
```

B.2 Phase Duration Equations

B.2.1 Second Order Polynomials

```
Preliminary Design End =
7.91647433405023 + -0.793395865017289 * :TRL + Match( :Material,
" TI-6AL-4V", -0.166278645485624, "2024, T81", 0.173477585593149,
"2090, T83", -0.0654773131979304,"2219, T62", 0.0997930654024611,
"AlLi 2195", -0.0415146923120564,.)
+ -0.193591231854229 * :No. Barrel Panels + Match( :Stiffener,
"IBS", -0.0155099054155851,"Ortho", -0.0670665620909744,
"Unstiffened", 0.0825764675065595,.)
+ Match( :dome gore fab,"1 piece spun dome + cap", 1.56442749760728,
"shot peendome gores", -0.704740885382378,
"stretchdome gores", -0.859686612224903,.)
+ Match( :barrel panel fab,"bumpbarrel panels", -0.0144229919343964,
"peenbarrel panels", 0.0313870434112103,
"stretchbarrel panels", -0.0169640514768139,.)
+ Match( :trim,"Chemical", 0.0902750093155631,
"Machine (Vertical Tool)", -0.0902750093155631,.)
+ (:TRL - 4.98936170212766) * ((:TRL - 4.98936170212766) *
-0.0384169878442978) +(:TRL - 4.98936170212766) * Match( :Material,
" TI-6AL-4V", 0.0297905821442359,"2024, T81", -0.0132627764654641,
"2090, T83", 0,"2219, T62", 0,"AlLi 2195", -0.0165278056787718,.)
+ (:TRL - 4.98936170212766) * ((:No. Barrel Panels - 3.31914893617021) *
0.0255726469774898) + (:TRL - 4.98936170212766) *Match( :Stiffener,
"IBS", -0.0138800225083508,"Ortho", 0.00663859281445921,
"Unstiffened", 0.0072414296938915 5,.) + (:TRL - 4.98936170212766) *
Match( :dome gore fab,"1 piece spun dome + cap", -0.0418633376328053,
"shot peendome gores", 0,"stretchdome gores", 0.0418633376328053,.)
 + (:TRL - 4.98936170212766) * Match( :barrel panel fab,
"bumpbarrel panels", 0.00675908594603027,"peenbarrel panels",
```

```
-0.0103724068008112,"stretchbarrel panels", 0.00361332085478089,.)
+ (:TRL - 4.98936170212766) * Match( :trim,"Chemical",
-0.0201592965216031,"Machine (Vertical Tool)", 0.0201592965216031,.)
 + Match( :Material," TI-6AL-4V",Match( :Material,
" TI-6AL-4V", 0,"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,
"AlLi 2195", 0,.),"2024, T81",
Match( :Material," TI-6AL-4V", 0,"2024, T81", 0,
"2090, T83", 0,"2219, T62", 0,"AlLi 2195", 0,.),
"2090, T83",Match( :Material," TI-6AL-4V", 0,
"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,
"AlLi 2195", 0,.),"2219, T62",Match( :Material,
" TI-6AL-4V", 0,"2024, T81", 0,"2090, T83", 0,
"2219, T62", 0,"AlLi 2195", 0,.),"AlLi 2195",
Match( :Material," TI-6AL-4V", 0,"2024, T81", 0,"2090, T83", 0,
"2219, T62", 0,"AlLi 2195", 0,.),.) + Match( :Material,
" TI-6AL-4V", (:No. Barrel Panels - 3.31914893617021) *
0.0213966184364097,"2024, T81", (:No. Barrel Panels -
3.31914893617021) * -0.0152928346302035,"2090, T83",
(:No. Barrel Panels - 3.31914893617021) * 0.00355972687720041,
"2219, T62", (:No. Barrel Panels - 3.31914893617021)
* -0.0127272058145753,"AlLi 2195", (:No. Barrel Panels -
3.31914893617021) * 0.00306369513116866,.) + Match( :Material,
" TI-6AL-4V",Match( :Stiffener,
"IBS", -0.142789256710363,"Ortho", -0.0291878184533292,
"Unstiffened", 0.171977075163692,.),"2024, T81",
Match( :Stiffener,"IBS", 0.0408809914879305,
"Ortho", 0.0239356862891315,"Unstiffened", -0.064816677777062,.),
"2090, T83",Match( :Stiffener,"IBS", 0.0341377211163346,
"Ortho", -0.0127163191870088,"Unstiffened", -0.0214214019293257,.),
"2219, T62",Match( :Stiffener,"IBS", 0.0349555743125148,
"Ortho", 0.0264122837657283,"Unstiffened", -0.0613678580782432,.),
"AlLi 2195",Match( :Stiffener,"IBS", 0.0328149697935827,
```

```
"Ortho", —0.00844383241452182,"Unstiffened", —0.0243711373790609,.),.)
 + Match( :Material," TI—6AL—4V",Match( :dome gore fab,
"1 piece spun dome + cap", —0.0202685185184547,"shot peendome gores", 0
,"stretchdome gores", 0.0202685185184547,.),"2024, T81",
Match( :dome gore fab,"1 piece spun dome + cap", 0.00548816104658561,
"shot peendome gores", 0,"stretchdome gores", —0.00548816104658561,.),
"2090, T83",Match( :dome gore fab,"1 piece spun dome + cap",
0.0155074812872144,"shot peendome gores", —0.00405865127563993,
"stretchdome gores", —0.0114488300115745,.),"2219, T62",
Match( :dome gore fab,"1 piece spun dome + cap", 0,"shot peendome gores"
, 0,"stretchdome gores", 0,.),"AlLi 2195",Match( :dome gore fab,
"1 piece spun dome + cap", —0.000727123815345317,
"shot peendome gores", 0.00405865127563993,
"stretchdome gores", —0.00333152746029461,.),.) + Match( :Material,
" TI—6AL—4V",Match( :barrel panel fab,"bumpbarrel panels",
0.003346442952916,"peenbarrel panels", —0.00937921238449779,
"stretchbarrel panels", 0.00603276943158179,.),"2024, T81",
Match( :barrel panel fab,"bumpbarrel panels", —0.00085379881903852,
"peenbarrel panels", 0.00503878012837084,
"stretchbarrel panels", —0.00418498130933232,.),"2090, T83",
Match( :barrel panel fab,"bumpbarrel panels", —0.000306247791010787,
"peenbarrel panels", —0.00108473225563548,
"stretchbarrel panels", 0.00139098004664627,.),"2219, T62",
Match( :barrel panel fab,"bumpbarrel panels", —0.000645580650621348,
"peenbarrel panels", 0.00515187207603993,
"stretchbarrel panels", —0.00450629142541858,.),"AlLi 2195",
Match( :barrel panel fab,"bumpbarrel panels", —0.00154081569224534,
"peenbarrel panels", 0.000273292435722502,
"stretchbarrel panels", 0.00126752325652284,.),.) + Match( :Material,
" TI—6AL—4V",Match( :trim,"Chemical", —0.00766833787181142,
"Machine (Vertical Tool)", 0.00766833787181142,.),"2024, T81",
Match( :trim,"Chemical", 0.00134347125832874,
```

```
"Machine (Vertical Tool)", −0.00134347125832874,.),
"2090, T83",Match( :trim,"Chemical", 0.00283708303474178,
"Machine (Vertical Tool)", −0.00283708303474178,.),
"2219, T62",Match( :trim,"Chemical", 0.000465515358813982,
"Machine (Vertical Tool)", −0.000465515358813982,.),
"AlLi 2195",Match( :trim,"Chemical", 0.00302226821992692,
"Machine (Vertical Tool)", −0.00302226821992692,.),.
) + (:No. Barrel Panels − 3.31914893617021) ⋆ ((:No. Barrel Panels
−3.31914893617021) ⋆ 0.0197283609576432) + (:No. Barrel Panels
− 3.31914893617021)⋆ Match( :Stiffener,"IBS", 0.00432719946992397,
"Ortho", −0.00761994894131115,"Unstiffened", 0.00329274947138718,
.) + (:No. Barrel Panels − 3.31914893617021) ⋆ Match( :dome gore fab,
"1 piece spun dome + cap", −0.223296849542461,
"shot peendome gores", 0.109998922283669,
"stretchdome gores", 0.113297927258792,.) + (:No. Barrel Panels
− 3.31914893617021) ⋆ Match( :barrel panel fab,
"bumpbarrel panels", 0.00300729684908792,
"peenbarrel panels", 0.00337893864013263,
"stretchbarrel panels", −0.00638623548922055,.
) + (:No. Barrel Panels − 3.31914893617021) ⋆ Match( :trim,
"Chemical", −0.00207197346600335,
"Machine (Vertical Tool)", 0.00207197346600335,.) + Match( :Stiffener,
"IBS", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0, . ),
"Ortho", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0, . ),
"Unstiffened", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened",
0, . ),.) + Match( :Stiffener,"IBS",Match( :dome gore fab,
"1 piece spun dome + cap", −0.0112955123776584,
"shot peendome gores", −0.000206334468994291,
"stretchdome gores", 0.0115018468466526,.),
"Ortho",Match( :dome gore fab,"1 piece spun dome + cap",
−0.0318345133147167,"shot peendome gores", 0.0222193019862701,
"stretchdome gores", 0.00961521132844663,.),"Unstiffened",
```

```
Match( :dome gore fab,"1 piece spun dome + cap", 0.043130025692375,
"shot peendome gores", −0.0220129675172758,
"stretchdome gores", −0.0211170581750993,.),.) + Match( :Stiffener,
"IBS",Match( :barrel panel fab,"bumpbarrel panels", −0.00592728026534006
,"peenbarrel panels", 0.00275773908236602,
"stretchbarrel panels", 0.00316954118297403,.),"Ortho",
Match( :barrel panel fab,"bumpbarrel panels", 0.0216719734660034,
"peenbarrel panels", −0.00967053620784968,
"stretchbarrel panels", −0.0120014372581537,.),"Unstiffened",
Match( :barrel panel fab,"bumpbarrel panels", −0.0157446932006633,
"peenbarrel panels", 0.00691279712548366,
"stretchbarrel panels", 0.00883189607517965,.),.) + Match( :Stiffener,
"IBS",Match( :trim,"Chemical", −0.00650081076100974,
"Machine (Vertical Tool)", 0.00650081076100974,.),"Ortho",
Match( :trim,"Chemical", 0.00638929426939375,
"Machine (Vertical Tool)", −0.00638929426939375,.),"Unstiffened",
Match( :trim,"Chemical", 0.000111516491615989,
"Machine (Vertical Tool)", −0.000111516491615989,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),
"shot peendome gores",Match( :dome gore fab,"1 piece spun dome + cap", 0
,"shot peendome gores", 0,"stretchdome gores", 0,.),"stretchdome gores",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :barrel panel fab,"bumpbarrel panels", 0.020253860552176,
"peenbarrel panels", 0.0144411948214006,
"stretchbarrel panels", −0.0346950553735766,.),"shot peendome gores",
Match( :barrel panel fab,"bumpbarrel panels", −0.0277333132548114,
"peenbarrel panels", 0.00150280684461886,
"stretchbarrel panels", 0.0262305064101926,.),"stretchdome gores",
```

```
Match( :barrel panel fab,"bumpbarrel panels", 0.00747945270263543,
"peenbarrel panels", −0.0159440016660195,
"stretchbarrel panels", 0.00846454896338405,.),.)
+ Match( :dome gore fab,"1 piece spun dome + cap",
Match( :trim,"Chemical", 0.0278781911298295,
"Machine (Vertical Tool)", −0.0278781911298295,.),
"shot peendome gores",Match( :trim,"Chemical", −0.00652774804718426,
"Machine (Vertical Tool)", 0.00652774804718426,.),"stretchdome gores",
Match( :trim,"Chemical", −0.0213504430826452,
"Machine (Vertical Tool)", 0.0213504430826452,.),.
) + Match( :barrel panel fab,"bumpbarrel panels",
Match( :barrel panel fab,"bumpbarrel panels", 0,"peenbarrel panels", 0,
"stretchbarrel panels", 0,.),"peenbarrel panels",
Match( :barrel panel fab,"bumpbarrel panels", 0,"peenbarrel panels",
0,"stretchbarrel panels", 0,.),"stretchbarrel panels",
Match( :barrel panel fab,"bumpbarrel panels", 0,
"peenbarrel panels", 0,"stretchbarrel panels", 0,.),.
) + Match( :barrel panel fab,"bumpbarrel panels",Match( :trim,
"Chemical", −0.0191371158392435,"Machine (Vertical Tool)",
0.0191371158392435,.),"peenbarrel panels",Match( :trim,"Chemical",
0.0164657210401891,"Machine (Vertical Tool)", −0.0164657210401891,.),
"stretchbarrel panels",Match( :trim,"Chemical", 0.00267139479905438,
"Machine (Vertical Tool)", −0.00267139479905438,.),.) + Match( :trim,
"Chemical", Match( :trim, "Chemical", 0, "Machine (Vertical Tool)", 0,
. ),"Machine (Vertical Tool)",
Match( :trim, "Chemical", 0, "Machine (Vertical Tool)", 0, . ),.)
```

```
Detailed Design End = 11.6510317460768 + -0.439843668403521 * :TRL +
Match( :Material, " TI-6AL-4V", 1.49877319093343,
"2024, T81", 0.0161339738088934,"2090, T83", -0.689912801815559,
"2219, T62", -0.13771319282289,"AlLi 2195", -0.687281170103879,.
) + -0.40802358550121 * :No. Barrel Panels + Match( :Stiffener,
"IBS", -0.0311188378916914,"Ortho", -0.139157888318089,
"Unstiffened", 0.17027672620978,.) + Match( :dome gore fab,
"1 piece spun dome + cap", 5.40887796420606,
"shot peendome gores", -2.54798330452171,
"stretchdome gores", -2.86089465968435,.) + Match( :barrel panel fab,
"bumpbarrel panels", -0.0304179913270387,
"peenbarrel panels", 0.0650013768726563,
"stretchbarrel panels", -0.0345833855456176,.) + Match( :trim,
"Chemical", 0.186697764178074,
"Machine (Vertical Tool)", -0.186697764178074,.)
 + (:TRL - 4.98936170212766) * ((:TRL - 4.98936170212766) *
 -0.637400049430445)  +(:TRL - 4.98936170212766) * Match( :Material,
" TI-6AL-4V", 0.373435514721898,"2024, T81", -0.0300349263343446,
"2090, T83", 0,"2219, T62", 0,"AlLi 2195", -0.343400588387553,.)
 + (:TRL - 4.98936170212766) * ((:No. Barrel Panels - 3.31914893617021)
 *0.0524195203783639) + (:TRL - 4.98936170212766) *Match( :Stiffener,
"IBS", -0.0299450556563132,"Ortho", 0.0129867122253179,
"Unstiffened", 0.0169583434309953,.)
 + (:TRL - 4.98936170212766) * Match( :dome gore fab,
"1 piece spun dome + cap", -0.0809633314906009,
"shot peendome gores", 0,"stretchdome gores", 0.0809633314906009,.
) + (:TRL - 4.98936170212766) * Match( :barrel panel fab,
"bumpbarrel panels", 0.0127708235844641,
"peenbarrel panels", -0.0174795273748243,
"stretchbarrel panels", 0.00470870379036015,.
) + (:TRL - 4.98936170212766) * Match( :trim,
```

```
"Chemical", —0.0409296521603481,
"Machine (Vertical Tool)", 0.0409296521603481,.
) + Match( :Material," TI—6AL—4V",Match( :Material,
" TI—6AL—4V", 0,"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,
"AlLi 2195", 0,.),"2024, T81",Match( :Material," TI—6AL—4V", 0,
"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,"AlLi 2195", 0,.),
"2090, T83",Match( :Material," TI—6AL—4V", 0,"2024, T81", 0,
"2090, T83", 0,"2219, T62", 0,"AlLi 2195", 0,.),"2219, T62",
Match( :Material," TI—6AL—4V", 0,"2024, T81", 0,"2090, T83", 0,
"2219, T62", 0,"AlLi 2195", 0,.),"AlLi 2195",Match( :Material,
" TI—6AL—4V", 0,"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,
"AlLi 2195", 0,.),.) + Match( :Material,
" TI—6AL—4V", (:No. Barrel Panels — 3.31914893617021) ⋆
0.0439926633127886,"2024, T81", (:No. Barrel Panels — 3.31914893617021)
⋆ —0.0312154428061456,"2090, T83", (:No. Barrel Panels
— 3.31914893617021) ⋆ 0.00754611053925134,"2219, T62",
(:No. Barrel Panels — 3.31914893617021) ⋆ —0.0263615050772087,
"AlLi 2195", (:No. Barrel Panels — 3.31914893617021)
⋆ 0.0060381740313144,.) + Match( :Material," TI—6AL—4V",
Match( :Stiffener,"IBS", —0.294847477545818,"Ortho",
—0.0616684598086538,"Unstiffened", 0.356515937354472,.),
"2024, T81",Match( :Stiffener,"IBS", 0.0830548438975583,
"Ortho", 0.0503496466091419,"Unstiffened", —0.1334044905067,.),
"2090, T83",Match( :Stiffener,"IBS", 0.0681401097715658,
"Ortho", —0.0250815797084783,"Unstiffened", —0.0430585300630875,
.),"2219, T62",Match( :Stiffener,"IBS", 0.0754595040522176,
"Ortho", 0.0541473165318127,"Unstiffened", —0.12960682058403,.),
"AlLi 2195",Match( :Stiffener,"IBS", 0.0681930198244766,
"Ortho", —0.017469236238225,"Unstiffened", —0.0504460962006541,.),.
) + Match( :Material," TI—6AL—4V",Match( :dome gore fab,
"1 piece spun dome + cap", —0.0359444444442493,
"shot peendome gores", 0,"stretchdome gores", 0.0359444444442493,
```

```
.),"2024, T81",Match( :dome gore fab,
"1 piece spun dome + cap", 0.00494555002749225,
"shot peendome gores", 0,"stretchdome gores", −0.00494555002749225,
.),"2090, T83",Match( :dome gore fab,
"1 piece spun dome + cap", 0.238167740701314,
"shot peendome gores", −0.111473035635357,
"stretchdome gores", −0.126694705065957,.),"2219, T62",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),
"AlLi 2195",Match( :dome gore fab,
"1 piece spun dome + cap", −0.207168846284557,
"shot peendome gores", 0.111473035635357,
"stretchdome gores", 0.0956958106492003,.),.
) + Match( :Material," TI−6AL−4V",Match( :barrel panel fab,
"bumpbarrel panels", 0.00381494001422199,
"peenbarrel panels", −0.012770519639622,
"stretchbarrel panels", 0.00895557962540001,.),"2024, T81",
Match( :barrel panel fab,"bumpbarrel panels", −0.00141073330767263,
"peenbarrel panels", 0.00771290078360845,
"stretchbarrel panels", −0.00630216747593582,.),"2090, T83",
Match( :barrel panel fab,"bumpbarrel panels", −0.00131812359213548,
"peenbarrel panels", 0.0000980469546351566,
"stretchbarrel panels", 0.00122007663750033,.),"2219, T62",
Match( :barrel panel fab,"bumpbarrel panels", −0.000446971867957653,
"peenbarrel panels", 0.00621954963810135,
"stretchbarrel panels", −0.00577257777014369,.),"AlLi 2195",
Match( :barrel panel fab,"bumpbarrel panels", −0.00063911124645622,
"peenbarrel panels", −0.00125997773672296,
"stretchbarrel panels", 0.00189908898317918,.),.) + Match( :Material,
" TI−6AL−4V",Match( :trim,"Chemical", −0.0161831238312657,
"Machine (Vertical Tool)", 0.0161831238312657,.),"2024, T81",
Match( :trim,"Chemical", 0.00266445584948851,
```

```
"Machine (Vertical Tool)", —0.00266445584948851,.),
"2090, T83",Match( :trim,"Chemical", 0.00645971309273965,
"Machine (Vertical Tool)", —0.00645971309273965,.),"2219, T62",
Match( :trim,"Chemical", 0.000475785006174302,
"Machine (Vertical Tool)", —0.000475785006174302,.),
"AlLi 2195",Match( :trim,"Chemical", 0.00658316988286325,
"Machine (Vertical Tool)", —0.00658316988286325,.),.
) + (:No. Barrel Panels — 3.31914893617021) ⋆ ((:No. Barrel Panels
—3.31914893617021) ⋆ 0.04224524248005) + (:No. Barrel Panels
— 3.31914893617021) ⋆Match( :Stiffener,"IBS", 0.00857818848841093,
"Ortho", —0.0158287767838879,"Unstiffened", 0.00725058829547696,.
) + (:No. Barrel Panels — 3.31914893617021) ⋆ Match( :dome gore fab,
"1 piece spun dome + cap", —0.474448481924009,
"shot peendome gores", 0.234119265837627,
"stretchdome gores", 0.240329216086382,.
) + (:No. Barrel Panels — 3.31914893617021) ⋆ Match( :barrel panel fab,
"bumpbarrel panels", 0.00608126036484246,
"peenbarrel panels", 0.00693946932006633,
"stretchbarrel panels", —0.0130207296849088,.
) + (:No. Barrel Panels — 3.31914893617021) ⋆ Match( :trim,
"Chemical", —0.00401840796019905,
"Machine (Vertical Tool)", 0.00401840796019905,.) + Match( :Stiffener,
"IBS", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0, . ),
"Ortho", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0, . ),
"Unstiffened", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0,
 . ),.) + Match( :Stiffener,"IBS",Match( :dome gore fab,
"1 piece spun dome + cap", —0.0266259177343761,
"shot peendome gores", 0.00169923581577756,
"stretchdome gores", 0.0249266819185985,.),"Ortho",
Match( :dome gore fab,"1 piece spun dome + cap", —0.0690171238751317,
"shot peendome gores", 0.0482529234632711,
"stretchdome gores", 0.0207642004118606,.),"Unstiffened",
```

```
Match( :dome gore fab,"1 piece spun dome + cap", 0.0956430416095078,
"shot peendome gores", −0.0499521592790487,
"stretchdome gores", −0.0456908823304591,.),.
) + Match( :Stiffener,"IBS",Match( :barrel panel fab,
"bumpbarrel panels", −0.011112585222038,
"peenbarrel panels", 0.00470140040538053,
"stretchbarrel panels", 0.00641118481665749,.),"Ortho",
Match( :barrel panel fab,"bumpbarrel panels", 0.0450285148332413,
"peenbarrel panels", −0.0205451446471347,
"stretchbarrel panels", −0.0244833701861066,.),"Unstiffened",
Match( :barrel panel fab,"bumpbarrel panels", −0.0339159296112033,
"peenbarrel panels", 0.0158437442417542,
"stretchbarrel panels", 0.0180721853694491,.),.
) + Match( :Stiffener,"IBS",Match( :trim,
"Chemical", −0.0135770407223143,
"Machine (Vertical Tool)", 0.0135770407223143,.),"Ortho",
Match( :trim,"Chemical", 0.0135940759167127,
"Machine (Vertical Tool)", −0.0135940759167127,.),
"Unstiffened",Match( :trim,"Chemical", −0.0000170351943983831,
"Machine (Vertical Tool)", 0.0000170351943983831,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),
"shot peendome gores",Match( :dome gore fab,"1 piece spun dome + cap", 0
,"shot peendome gores", 0,"stretchdome gores", 0,.),
"stretchdome gores",Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :barrel panel fab,"bumpbarrel panels", 0.0400125435449486,
"peenbarrel panels", 0.0371307778297721,
"stretchbarrel panels", −0.0771433213747207,.),"shot peendome gores",
Match( :barrel panel fab,"bumpbarrel panels", −0.0567261299285027,
```

```
"peenbarrel panels", −0.000604396007084617,
"stretchbarrel panels", 0.0573305259355873,.),
"stretchdome gores",Match( :barrel panel fab,
"bumpbarrel panels", 0.0167135863835541,
"peenbarrel panels", −0.0365263818226875,
"stretchbarrel panels", 0.0198127954391334,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",Match( :trim,
"Chemical", 0.0611524463162294,
"Machine (Vertical Tool)", −0.0611524463162294,.),
"shot peendome gores",Match( :trim,"Chemical", −0.0161613295410934,
"Machine (Vertical Tool)", 0.0161613295410934,.),
"stretchdome gores",Match( :trim,"Chemical", −0.044991116775136,
"Machine (Vertical Tool)", 0.044991116775136,.),.
) + Match( :barrel panel fab,"bumpbarrel panels",
Match( :barrel panel fab,"bumpbarrel panels", 0,
"peenbarrel panels", 0,"stretchbarrel panels", 0,.),
"peenbarrel panels",Match( :barrel panel fab,
"bumpbarrel panels", 0,"peenbarrel panels", 0,
"stretchbarrel panels", 0,.),"stretchbarrel panels",
Match( :barrel panel fab,"bumpbarrel panels", 0,
"peenbarrel panels", 0,"stretchbarrel panels", 0,.),.
) + Match( :barrel panel fab,"bumpbarrel panels",
Match( :trim,"Chemical", −0.0393498817966903,
"Machine (Vertical Tool)", 0.0393498817966903,.),
"peenbarrel panels",Match( :trim,"Chemical", 0.0342316784869976,
"Machine (Vertical Tool)", −0.0342316784869976,.),
"stretchbarrel panels",Match( :trim,"Chemical", 0.00511820330969268,
"Machine (Vertical Tool)", −0.00511820330969268,.),.) + Match( :trim,
"Chemical", Match( :trim, "Chemical", 0, "Machine (Vertical Tool)", 0,
. ),"Machine (Vertical Tool)",
Match( :trim, "Chemical", 0, "Machine (Vertical Tool)", 0, . ),.)
```

```
First Build End = 14.0541567697973 + −0.705031812131538 ⋆ :TRL +
Match( :Material," TI−6AL−4V", 0.962690434571446,"2024, T81",
0.18011394563334,"2090, T83", −0.595851613096594,"2219, T62",
0.0164325022355193,"AlLi 2195", −0.563385269343711,.
) + −0.430597712695838 ⋆ :No. Barrel Panels + Match( :Stiffener,
"IBS", 0.118539194898601,"Ortho", −0.0594704997375583,
"Unstiffened", −0.0590686951610424,.) + Match( :dome gore fab,
"1 piece spun dome + cap", 5.24920339529893,
"shot peendome gores", −2.36455879866921,
"stretchdome gores", −2.88464459662972,.) + Match( :barrel panel fab,
"bumpbarrel panels", 0.0146247414451718,
"peenbarrel panels", 0.0239073305072984,
"stretchbarrel panels", −0.0385320719524702,.) + Match( :trim,
"Chemical", 0.141658527130252,"Machine (Vertical Tool)",
−0.141658527130252,.) + (:TRL − 4.98936170212766) ⋆
((:TRL − 4.98936170212766) ⋆ −0.538125520528856) + (
:TRL − 4.98936170212766) ⋆ Match( :Material,
" TI−6AL−4V", 0.308803855821384,"2024, T81", −0.0350852638710513,
"2090, T83", 0,"2219, T62", 0,"AlLi 2195", −0.273718591950333,.
) + (:TRL − 4.98936170212766) ⋆ ((:No. Barrel Panels − 3.31914893617021)
⋆0.0520649056151775) + (:TRL − 4.98936170212766) ⋆Match( :Stiffener,
"IBS", −0.0575932625601309,"Ortho", −0.00788998219511358,
"Unstiffened", 0.0654832447552445,.
) + (:TRL − 4.98936170212766) ⋆ Match( :dome gore fab,
"1 piece spun dome + cap", −0.0863609729131542,
"shot peendome gores", 0,"stretchdome gores", 0.0863609729131542,.
) + (:TRL − 4.98936170212766) ⋆ Match( :barrel panel fab,
"bumpbarrel panels", 0.00548607861488033,
"peenbarrel panels", 0.00195952269536773,
"stretchbarrel panels", −0.00744560131024806,.
) + (:TRL − 4.98936170212766) ⋆ Match( :trim,"Chemical",
−0.0399440414911863,"Machine (Vertical Tool)", 0.0399440414911863,.)
```

```
+ Match( :Material," TI—6AL—4V",Match( :Material," TI—6AL—4V", 0,
"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,"AlLi 2195", 0,.),
"2024, T81",Match( :Material," TI—6AL—4V", 0,"2024, T81", 0,
"2090, T83", 0,"2219, T62", 0,"AlLi 2195", 0,.),"2090, T83",
Match( :Material," TI—6AL—4V", 0,"2024, T81", 0,"2090, T83",
 0,"2219, T62", 0,"AlLi 2195", 0,.),"2219, T62",Match( :Material,
" TI—6AL—4V", 0,"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,
"AlLi 2195", 0,.),"AlLi 2195",Match( :Material," TI—6AL—4V", 0,
"2024, T81", 0,"2090, T83", 0,"2219, T62", 0,"AlLi 2195", 0,.),.
) + Match( :Material,
" TI—6AL—4V", (:No. Barrel Panels — 3.31914893617021) *
0.0378968277555239,"2024, T81", (:No. Barrel Panels —
3.31914893617021) * —0.034431835265395,"2090, T83",
(:No. Barrel Panels — 3.31914893617021) * 0.0131179604596727,
"2219, T62", (:No. Barrel Panels — 3.31914893617021) *
—0.0276771038856644,"AlLi 2195", (:No. Barrel Panels —
3.31914893617021) * 0.0110941509358628,.
) + Match( :Material," TI—6AL—4V",Match( :Stiffener,
"IBS", —0.439984240190061,"Ortho", —0.123701142316319,
"Unstiffened", 0.563685382506381,.),"2024, T81",Match( :Stiffener,
"IBS", 0.13682252954492,"Ortho", 0.0911331353457445,
"Unstiffened", —0.227955664890665,.),"2090, T83",
Match( :Stiffener,"IBS", 0.0878812816368032,
"Ortho", —0.036568965286487,"Unstiffened", —0.0513123163503161,.),
"2219, T62",Match( :Stiffener,"IBS", 0.126592269064656,
"Ortho", 0.0936093766969882,"Unstiffened", —0.220201645761644,.),
"AlLi 2195",Match( :Stiffener,"IBS", 0.0886881599436819,
"Ortho", —0.0244724044399264,"Unstiffened", —0.0642157555037555,.),.
) + Match( :Material," TI—6AL—4V",Match( :dome gore fab,
"1 piece spun dome + cap", —0.0295833333331921,"shot peendome gores", 0,
"stretchdome gores", 0.0295833333331921,.),"2024, T81",
Match( :dome gore fab,"1 piece spun dome + cap", 0.0036662520728886,
```

```
"shot peendome gores", 0,"stretchdome gores", —0.0036662520728886,.),
"2090, T83",Match( :dome gore fab,
"1 piece spun dome + cap", 0.188431429090868,
"shot peendome gores", —0.0886160738599876,
"stretchdome gores", —0.0998153552308802,.),"2219, T62",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),"AlLi 2195",
Match( :dome gore fab,"1 piece spun dome + cap", —0.162514347830564,
"shot peendome gores", 0.0886160738599876,
"stretchdome gores", 0.0738982739705767,.),.) + Match( :Material,
" TI—6AL—4V",Match( :barrel panel fab,
"bumpbarrel panels", —0.0197252782647366,
"peenbarrel panels", 0.0312415526485499,
"stretchbarrel panels", —0.0115162743838134,.),"2024, T81",
Match( :barrel panel fab,"bumpbarrel panels", 0.0108882180696893,
"peenbarrel panels", —0.0146707465247467,
"stretchbarrel panels", 0.00378252845505742,.),"2090, T83",
Match( :barrel panel fab,"bumpbarrel panels", —0.000966361137431593,
"peenbarrel panels", —0.000240798179848824,
"stretchbarrel panels", 0.00120715931728042,.),"2219, T62",
Match( :barrel panel fab,"bumpbarrel panels", 0.0104611404946017,
"peenbarrel panels", —0.0163978517394141,
"stretchbarrel panels", 0.00593671124481238,.),"AlLi 2195",
Match( :barrel panel fab,"bumpbarrel panels", —0.000657719162122872,
"peenbarrel panels", 0.0000678437954597169,
"stretchbarrel panels", 0.000589875366663155,.),.) + Match( :Material,
" TI—6AL—4V",Match( :trim,"Chemical", 0.00355576115160776,
"Machine (Vertical Tool)", —0.00355576115160776,.),"2024, T81",
Match( :trim,"Chemical", —0.00278770450637731,
"Machine (Vertical Tool)", 0.00278770450637731,.),"2090, T83",
Match( :trim,"Chemical", 0.00262271625905449,
"Machine (Vertical Tool)", —0.00262271625905449,.),"2219, T62",
```

```
Match( :trim,"Chemical", -0.00533447681766044,
"Machine (Vertical Tool)", 0.00533447681766044,.),"AlLi 2195",
Match( :trim,"Chemical", 0.00194370391337551,
"Machine (Vertical Tool)", -0.00194370391337551,.),.
) + (:No. Barrel Panels - 3.31914893617021) * ((:No. Barrel Panels
-3.31914893617021) * 0.0457381829343162) + (:No. Barrel Panels -
3.31914893617021)* Match( :Stiffener,"IBS", 0.0107150043360926,
"Ortho", -0.0200043275648716,"Unstiffened", 0.00928932322877899,.
) + (:No. Barrel Panels - 3.31914893617021) * Match( :dome gore fab,
"1 piece spun dome + cap", -0.490527024143681,
"shot peendome gores", 0.23260704441015,
"stretchdome gores", 0.257919979733531,.
) + (:No. Barrel Panels - 3.31914893617021) * Match( :barrel panel fab,
"bumpbarrel panels", -0.00540480928689879,
"peenbarrel panels", 0.0356116086235489,
"stretchbarrel panels", -0.0302067993366501,.
) + (:No. Barrel Panels - 3.31914893617021) * Match( :trim,
"Chemical", -0.00203946932006637,
"Machine (Vertical Tool)", 0.00203946932006637,.
) + Match( :Stiffener,
"IBS", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0, . ),
"Ortho", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0, . ),
"Unstiffened", Match( :Stiffener, "IBS", 0, "Ortho", 0, "Unstiffened", 0,
 . ),.) + Match( :Stiffener,"IBS",Match( :dome gore fab,
"1 piece spun dome + cap", 0.057188576239891,
"shot peendome gores", -0.150854072531225,
"stretchdome gores", 0.0936654962913341,.),"Ortho",
Match( :dome gore fab,"1 piece spun dome + cap", 0.0212904636531011,
"shot peendome gores", -0.118932006287577,
"stretchdome gores", 0.0976415426344762,.),"Unstiffened",
Match( :dome gore fab,"1 piece spun dome + cap", -0.0784790398929921,
"shot peendome gores", 0.269786078818802,
```

```
"stretchdome gores", −0.19130703892581,.),.
) + Match( :Stiffener,"IBS",Match( :barrel panel fab,
"bumpbarrel panels", 0.0315105306799335,
"peenbarrel panels", −0.0995133499170811,
"stretchbarrel panels", 0.0680028192371476,.),"Ortho",
Match( :barrel panel fab,"bumpbarrel panels", 0.0886197346600333,
"peenbarrel panels", −0.122284991708126,
"stretchbarrel panels", 0.0336652570480928,.),"Unstiffened",
Match( :barrel panel fab,"bumpbarrel panels", −0.120130265339967,
"peenbarrel panels", 0.221798341625207,
"stretchbarrel panels", −0.10166807628524,.),.) + Match( :Stiffener,
"IBS",Match( :trim,"Chemical", 0.0140467477427677,
"Machine (Vertical Tool)", −0.0140467477427677,.),"Ortho",
Match( :trim,"Chemical", 0.0452266261286161,
"Machine (Vertical Tool)", −0.0452266261286161,.),"Unstiffened",
Match( :trim,"Chemical", −0.0592733738713838,
"Machine (Vertical Tool)", 0.0592733738713838,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),
"shot peendome gores",Match( :dome gore fab,
"1 piece spun dome + cap", 0,"shot peendome gores", 0,
"stretchdome gores", 0,.),"stretchdome gores",
Match( :dome gore fab,"1 piece spun dome + cap", 0,
"shot peendome gores", 0,"stretchdome gores", 0,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :barrel panel fab,"bumpbarrel panels", 0.0572177377424214,
"peenbarrel panels", 0.041803020849582,
"stretchbarrel panels", −0.0990207585920034,.),
"shot peendome gores",Match( :barrel panel fab,
"bumpbarrel panels", −0.167261351140714,
"peenbarrel panels", 0.287041751986556,
```

```
"stretchbarrel panels", –0.119780400845842,.),
"stretchdome gores",Match( :barrel panel fab,
"bumpbarrel panels", 0.110043613398293,
"peenbarrel panels", –0.328844772836138,
"stretchbarrel panels", 0.218801159437846,.),.
) + Match( :dome gore fab,"1 piece spun dome + cap",
Match( :trim,"Chemical", 0.0592500519939698,
"Machine (Vertical Tool)", –0.0592500519939698,.),
"shot peendome gores",Match( :trim,
"Chemical", –0.0193590685501764,
"Machine (Vertical Tool)", 0.0193590685501764,.),
"stretchdome gores",Match( :trim,"Chemical", –0.0398909834437934,
"Machine (Vertical Tool)", 0.0398909834437934,.),.
) + Match( :barrel panel fab,"bumpbarrel panels",
Match( :barrel panel fab,"bumpbarrel panels", 0,
"peenbarrel panels", 0,"stretchbarrel panels", 0,.),
"peenbarrel panels",Match( :barrel panel fab,"bumpbarrel panels", 0,
"peenbarrel panels", 0,"stretchbarrel panels", 0,.),
"stretchbarrel panels",Match( :barrel panel fab,"bumpbarrel panels", 0,
"peenbarrel panels", 0,"stretchbarrel panels", 0,.),.
) + Match( :barrel panel fab,"bumpbarrel panels",Match( :trim,
"Chemical", –0.0356264775413711,
"Machine (Vertical Tool)", 0.0356264775413711,.),
"peenbarrel panels",Match( :trim,"Chemical", 0.034338061465721,
"Machine (Vertical Tool)", –0.034338061465721,.),
"stretchbarrel panels",Match( :trim,
"Chemical", 0.0012884160756501,
"Machine (Vertical Tool)", –0.0012884160756501,.),.) + Match( :trim,
"Chemical", Match( :trim, "Chemical", 0, "Machine (Vertical Tool)", 0,
. ),"Machine (Vertical Tool)",
Match( :trim, "Chemical", 0, "Machine (Vertical Tool)", 0, . ),.)
```

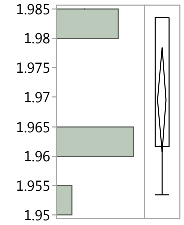
APPENDIX C

EXPERIMENT 2

C.1 Additional Statistics

Distributions Material= TI-6AL-4V

Preliminary Design



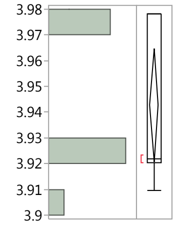
Quantiles

100.0%	maximum	1.9836
99.5%		1.9836
97.5%		1.9836
90.0%		1.9836
75.0%	quartile	1.9836
50.0%	median	1.9616
25.0%	quartile	1.9616
10.0%		1.9542
2.5%		1.9534
0.5%		1.9534
0.0%	minimum	1.9534

Summary Statistics

Mean	1.9696
Std Dev	0.0123
Std Err Mean	0.0039
Upper 95% Mean	1.9784
Lower 95% Mean	1.9608
N	10

Detailed Design



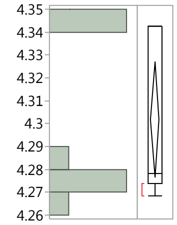
Quantiles

100.0%	maximum	3.9781
99.5%		3.9781
97.5%		3.9781
90.0%		3.9781
75.0%	quartile	3.9781
50.0%	median	3.9219
25.0%	quartile	3.9205
10.0%		3.9107
2.5%		3.9096
0.5%		3.9096
0.0%	minimum	3.9096

Summary Statistics

Mean	3.9427
Std Dev	0.0306
Std Err Mean	0.0097
Upper 95% Mean	3.9647
Lower 95% Mean	3.9208
N	10

First Build



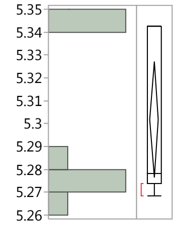
Quantiles

100.0%	maximum	4.3425
99.5%		4.3425
97.5%		4.3425
90.0%		4.3425
75.0%	quartile	4.3425
50.0%	median	4.2781
25.0%	quartile	4.274
10.0%		4.269
2.5%		4.2685
0.5%		4.2685
0.0%	minimum	4.2685

Summary Statistics

Mean	4.3016
Std Dev	0.0353
Std Err Mean	0.0112
Upper 95% Mean	4.3269
Lower 95% Mean	4.2764
N	10

Qual Test Completion



Quantiles

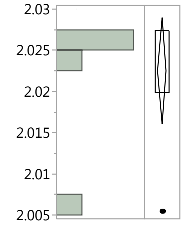
100.0%	maximum	5.3425
99.5%		5.3425
97.5%		5.3425
90.0%		5.3425
75.0%	quartile	5.3425
50.0%	median	5.2781
25.0%	quartile	5.274
10.0%		5.269
2.5%		5.2685
0.5%		5.2685
0.0%	minimum	5.2685

Summary Statistics

Mean	5.3016
Std Dev	0.0353
Std Err Mean	0.0112
Upper 95% Mean	5.3269
Lower 95% Mean	5.2764
N	10

Distributions Material=2024, T81

Preliminary Design



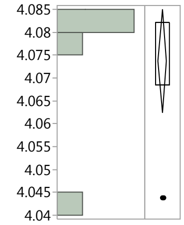
Quantiles

100.0%	maximum	2.0274
99.5%		2.0274
97.5%		2.0274
90.0%		2.0274
75.0%	quartile	2.0274
50.0%	median	2.0274
25.0%	quartile	2.0199
10.0%		2.0055
2.5%		2.0055
0.5%		2.0055
0.0%	minimum	2.0055

Summary Statistics

Mean	2.0225
Std Dev	0.009
Std Err Mean	0.0029
Upper 95% Mean	2.0289
Lower 95% Mean	2.016
N	10

Detailed Design



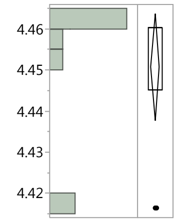
Quantiles

100.0%	maximum	4.0822
99.5%		4.0822
97.5%		4.0822
90.0%		4.0822
75.0%	quartile	4.0822
50.0%	median	4.0822
25.0%	quartile	4.0685
10.0%		4.0438
2.5%		4.0438
0.5%		4.0438
0.0%	minimum	4.0438

Summary Statistics

Mean	4.0737
Std Dev	0.0158
Std Err Mean	0.005
Upper 95% Mean	4.085
Lower 95% Mean	4.0624
N	10

First Build



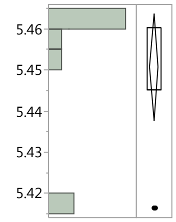
Quantiles

100.0%	maximum	4.4603
99.5%		4.4603
97.5%		4.4603
90.0%		4.4603
75.0%	quartile	4.4603
50.0%	median	4.4603
25.0%	quartile	4.4452
10.0%		4.4164
2.5%		4.4164
0.5%		4.4164
0.0%	minimum	4.4164

Summary Statistics

Mean	4.4507
Std Dev	0.0181
Std Err Mean	0.0057
Upper 95% Mean	4.4637
Lower 95% Mean	4.4377
N	10

Qual Test Completion



Quantiles

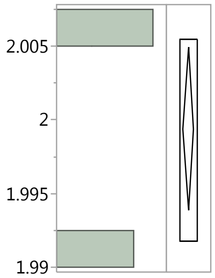
100.0%	maximum	5.4603
99.5%		5.4603
97.5%		5.4603
90.0%		5.4603
75.0%	quartile	5.4603
50.0%	median	5.4603
25.0%	quartile	5.4452
10.0%		5.4164
2.5%		5.4164
0.5%		5.4164
0.0%	minimum	5.4164

Summary Statistics

Mean	5.4507
Std Dev	0.0181
Std Err Mean	0.0057
Upper 95% Mean	5.4637
Lower 95% Mean	5.4377
N	10

Distributions Material=2090, T83

Preliminary Design



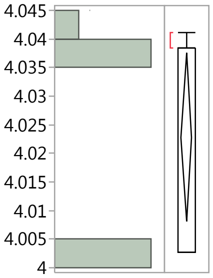
Quantiles

100.0%	maximum	2.0055
99.5%		2.0055
97.5%		2.0055
90.0%		2.0055
75.0%	quartile	2.0055
50.0%	median	2.0055
25.0%	quartile	1.9918
10.0%		1.9918
2.5%		1.9918
0.5%		1.9918
0.0%	minimum	1.9918

Summary Statistics

Mean	1.9994
Std Dev	0.0072
Std Err Mean	0.0024
Upper 95% Mean	2.0049
Lower 95% Mean	1.9938
N	9

Detailed Design



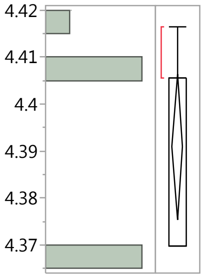
Quantiles

100.0%	maximum	4.0411
99.5%		4.0411
97.5%		4.0411
90.0%		4.0411
75.0%	quartile	4.0384
50.0%	median	4.0384
25.0%	quartile	4.0027
10.0%		4.0027
2.5%		4.0027
0.5%		4.0027
0.0%	minimum	4.0027

Summary Statistics

Mean	4.0228
Std Dev	0.0191
Std Err Mean	0.0064
Upper 95% Mean	4.0375
Lower 95% Mean	4.0082
N	9

First Build



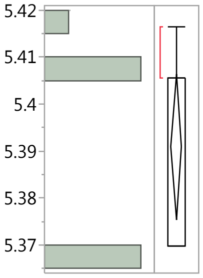
Quantiles

100.0%	maximum	4.4164
99.5%		4.4164
97.5%		4.4164
90.0%		4.4164
75.0%	quartile	4.4055
50.0%	median	4.4055
25.0%	quartile	4.3699
10.0%		4.3699
2.5%		4.3699
0.5%		4.3699
0.0%	minimum	4.3699

Summary Statistics

Mean	4.3909
Std Dev	0.0202
Std Err Mean	0.0067
Upper 95% Mean	4.4064
Lower 95% Mean	4.3753
N	9

Qual Test Completion



Quantiles

100.0%	maximum	5.4164
99.5%		5.4164
97.5%		5.4164
90.0%		5.4164
75.0%	quartile	5.4055
50.0%	median	5.4055
25.0%	quartile	5.3699
10.0%		5.3699
2.5%		5.3699
0.5%		5.3699
0.0%	minimum	5.3699

Summary Statistics

Mean	5.3909
Std Dev	0.0202
Std Err Mean	0.0067
Upper 95% Mean	5.4064
Lower 95% Mean	5.3753
N	9

Distributions Material=2219, T62

Preliminary Design

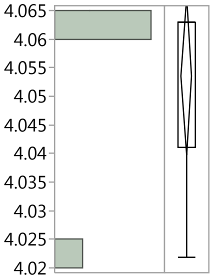
Quantiles

100.0%	maximum	2.0219
99.5%		2.0219
97.5%		2.0219
90.0%		2.0219
75.0%	quartile	2.0219
50.0%	median	2.0219
25.0%	quartile	2.0123
10.0%		2.0027
2.5%		2.0027
0.5%		2.0027
0.0%	minimum	2.0027

Summary Statistics

Mean	2.0177
Std Dev	0.0085
Std Err Mean	0.0028
Upper 95% Mean	2.0242
Lower 95% Mean	2.0112
N	9

Detailed Design



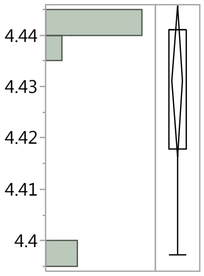
Quantiles

100.0%	maximum	4.063
99.5%		4.063
97.5%		4.063
90.0%		4.063
75.0%	quartile	4.063
50.0%	median	4.063
25.0%	quartile	4.0411
10.0%		4.0219
2.5%		4.0219
0.5%		4.0219
0.0%	minimum	4.0219

Summary Statistics

Mean	4.0536
Std Dev	0.018
Std Err Mean	0.006
Upper 95% Mean	4.0674
Lower 95% Mean	4.0398
N	9

First Build



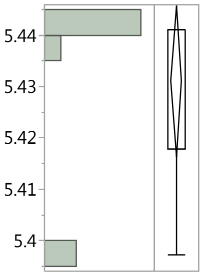
Quantiles

100.0%	maximum	4.4411
99.5%		4.4411
97.5%		4.4411
90.0%		4.4411
75.0%	quartile	4.4411
50.0%	median	4.4411
25.0%	quartile	4.4178
10.0%		4.3973
2.5%		4.3973
0.5%		4.3973
0.0%	minimum	4.3973

Summary Statistics

Mean	4.4311
Std Dev	0.0192
Std Err Mean	0.0064
Upper 95% Mean	4.4458
Lower 95% Mean	4.4163
N	9

Qual Test Completion



Quantiles

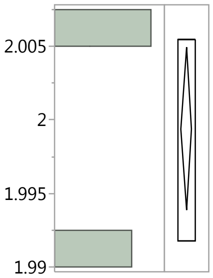
100.0%	maximum	5.4411
99.5%		5.4411
97.5%		5.4411
90.0%		5.4411
75.0%	quartile	5.4411
50.0%	median	5.4411
25.0%	quartile	5.4178
10.0%		5.3973
2.5%		5.3973
0.5%		5.3973
0.0%	minimum	5.3973

Summary Statistics

Mean	5.4311
Std Dev	0.0192
Std Err Mean	0.0064
Upper 95% Mean	5.4458
Lower 95% Mean	5.4163
N	9

Distributions Material=AlLi 2195

Preliminary Design



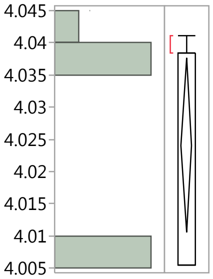
Quantiles

100.0%	maximum	2.0055
99.5%		2.0055
97.5%		2.0055
90.0%		2.0055
75.0%	quartile	2.0055
50.0%	median	2.0055
25.0%	quartile	1.9918
10.0%		1.9918
2.5%		1.9918
0.5%		1.9918
0.0%	minimum	1.9918

Summary Statistics

Mean	1.9994
Std Dev	0.0072
Std Err Mean	0.0024
Upper 95% Mean	2.0049
Lower 95% Mean	1.9938
N	9

Detailed Design



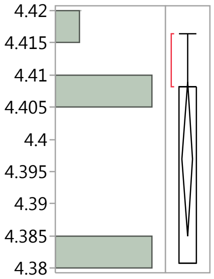
Quantiles

100.0%	maximum	4.0411
99.5%		4.0411
97.5%		4.0411
90.0%		4.0411
75.0%	quartile	4.0384
50.0%	median	4.0384
25.0%	quartile	4.0055
10.0%		4.0055
2.5%		4.0055
0.5%		4.0055
0.0%	minimum	4.0055

Summary Statistics

Mean	4.024
Std Dev	0.0176
Std Err Mean	0.0059
Upper 95% Mean	4.0376
Lower 95% Mean	4.0105
N	9

First Build



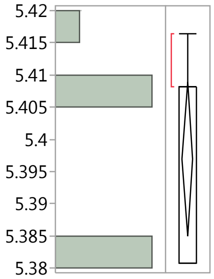
Quantiles

100.0%	maximum	4.4164
99.5%		4.4164
97.5%		4.4164
90.0%		4.4164
75.0%	quartile	4.4082
50.0%	median	4.4082
25.0%	quartile	4.3808
10.0%		4.3808
2.5%		4.3808
0.5%		4.3808
0.0%	minimum	4.3808

Summary Statistics

Mean	4.397
Std Dev	0.0155
Std Err Mean	0.0052
Upper 95% Mean	4.4089
Lower 95% Mean	4.385
N	9

Qual Test Completion



Quantiles

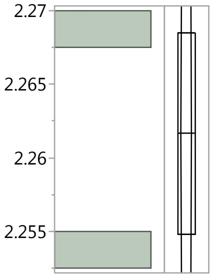
100.0%	maximum	5.4164
99.5%		5.4164
97.5%		5.4164
90.0%		5.4164
75.0%	quartile	5.4082
50.0%	median	5.4082
25.0%	quartile	5.3808
10.0%		5.3808
2.5%		5.3808
0.5%		5.3808
0.0%	minimum	5.3808

Summary Statistics

Mean	5.397
Std Dev	0.0155
Std Err Mean	0.0052
Upper 95% Mean	5.4089
Lower 95% Mean	5.385
N	9

Distributions Material=IM7

Preliminary Design



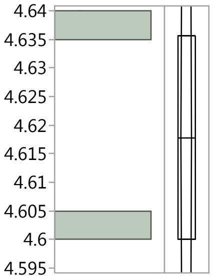
Quantiles

100.0%	maximum	2.2685
99.5%		2.2685
97.5%		2.2685
90.0%		2.2685
75.0%	quartile	2.2685
50.0%	median	2.2616
25.0%	quartile	2.2548
10.0%		2.2548
2.5%		2.2548
0.5%		2.2548
0.0%	minimum	2.2548

Summary Statistics

Mean	2.2616
Std Dev	0.0097
Std Err Mean	0.0068
Upper 95% Mean	2.3487
Lower 95% Mean	2.1746
N	2

Detailed Design



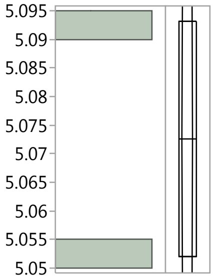
Quantiles

100.0%	maximum	4.6356
99.5%		4.6356
97.5%		4.6356
90.0%		4.6356
75.0%	quartile	4.6356
50.0%	median	4.6178
25.0%	quartile	4.6
10.0%		4.6
2.5%		4.6
0.5%		4.6
0.0%	minimum	4.6

Summary Statistics

Mean	4.6178
Std Dev	0.0252
Std Err Mean	0.0178
Upper 95% Mean	4.8441
Lower 95% Mean	4.3915
N	2

First Build



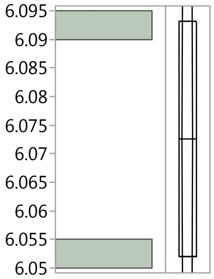
Quantiles

100.0%	maximum	5.0932
99.5%		5.0932
97.5%		5.0932
90.0%		5.0932
75.0%	quartile	5.0932
50.0%	median	5.0726
25.0%	quartile	5.0521
10.0%		5.0521
2.5%		5.0521
0.5%		5.0521
0.0%	minimum	5.0521

Summary Statistics

Mean	5.0726
Std Dev	0.0291
Std Err Mean	0.0205
Upper 95% Mean	5.3337
Lower 95% Mean	4.8115
N	2

Qual Test Completion



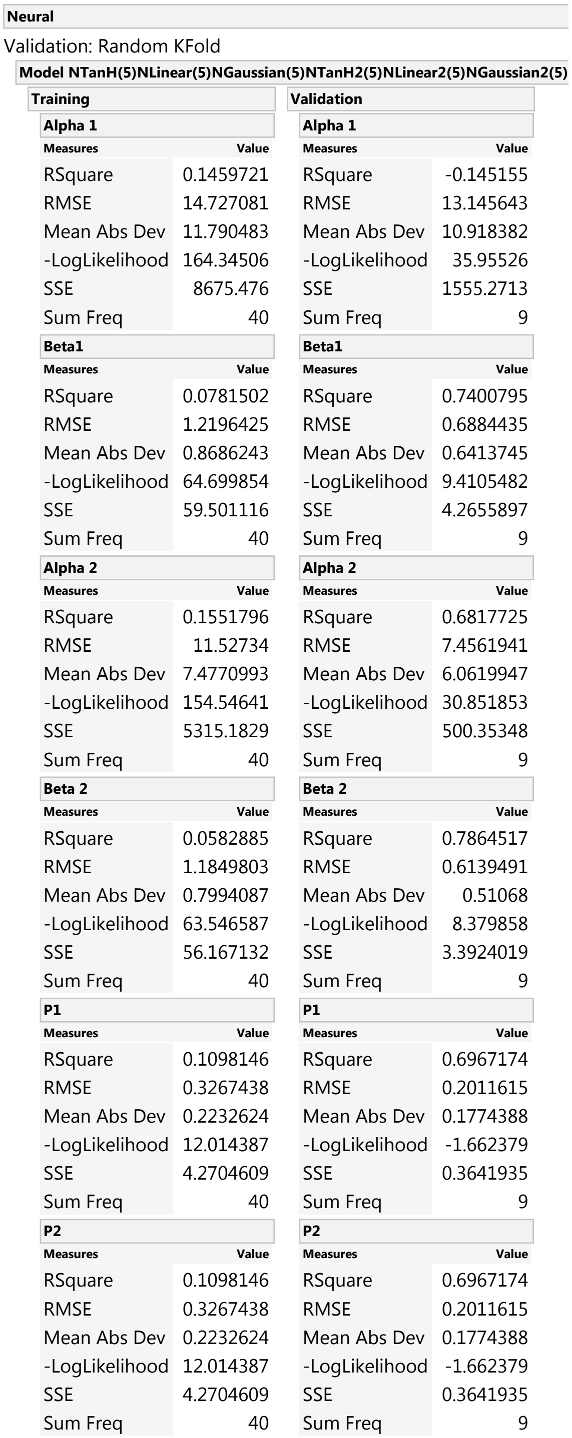
Quantiles

100.0%	maximum	6.0932
99.5%		6.0932
97.5%		6.0932
90.0%		6.0932
75.0%	quartile	6.0932
50.0%	median	6.0726
25.0%	quartile	6.0521
10.0%		6.0521
2.5%		6.0521
0.5%		6.0521
0.0%	minimum	6.0521

Summary Statistics

Mean	6.0726
Std Dev	0.0291
Std Err Mean	0.0205
Upper 95% Mean	6.3337
Lower 95% Mean	5.8115
N	2

C.2 Statistics for Best Neural Network Fit to 2-Weibull Mixed CDF Parameters



Neural

Validation: Random KFold

Model NTanH(5)NLinear(5)NGaussian(5)NTanH2(5)NLinear2(5)NGaussian2(5)

Training

Alpha 1

Measures	Value
RSquare	0.1459721
RMSE	14.727081
Mean Abs Dev	11.790483
-LogLikelihood	164.34506
SSE	8675.476
Sum Freq	40

Beta1

Measures	Value
RSquare	0.0781502
RMSE	1.2196425
Mean Abs Dev	0.8686243
-LogLikelihood	64.699854
SSE	59.501116
Sum Freq	40

Alpha 2

Measures	Value
RSquare	0.1551796
RMSE	11.52734
Mean Abs Dev	7.4770993
-LogLikelihood	154.54641
SSE	5315.1829
Sum Freq	40

Beta 2

Measures	Value
RSquare	0.0582885
RMSE	1.1849803
Mean Abs Dev	0.7994087
-LogLikelihood	63.546587
SSE	56.167132
Sum Freq	40

P1

Measures	Value
RSquare	0.1098146
RMSE	0.3267438
Mean Abs Dev	0.2232624
-LogLikelihood	12.014387
SSE	4.2704609
Sum Freq	40

P2

Measures	Value
RSquare	0.1098146
RMSE	0.3267438
Mean Abs Dev	0.2232624
-LogLikelihood	12.014387
SSE	4.2704609
Sum Freq	40

Validation

Alpha 1

Measures	Value
RSquare	-0.145155
RMSE	13.145643
Mean Abs Dev	10.918382
-LogLikelihood	35.95526
SSE	1555.2713
Sum Freq	9

Beta1

Measures	Value
RSquare	0.7400795
RMSE	0.6884435
Mean Abs Dev	0.6413745
-LogLikelihood	9.4105482
SSE	4.2655897
Sum Freq	9

Alpha 2

Measures	Value
RSquare	0.6817725
RMSE	7.4561941
Mean Abs Dev	6.0619947
-LogLikelihood	30.851853
SSE	500.35348
Sum Freq	9

Beta 2

Measures	Value
RSquare	0.7864517
RMSE	0.6139491
Mean Abs Dev	0.51068
-LogLikelihood	8.379858
SSE	3.3924019
Sum Freq	9

P1

Measures	Value
RSquare	0.6967174
RMSE	0.2011615
Mean Abs Dev	0.1774388
-LogLikelihood	-1.662379
SSE	0.3641935
Sum Freq	9

P2

Measures	Value
RSquare	0.6967174
RMSE	0.2011615
Mean Abs Dev	0.1774388
-LogLikelihood	-1.662379
SSE	0.3641935
Sum Freq	9

Figure 138: Summary Statistics

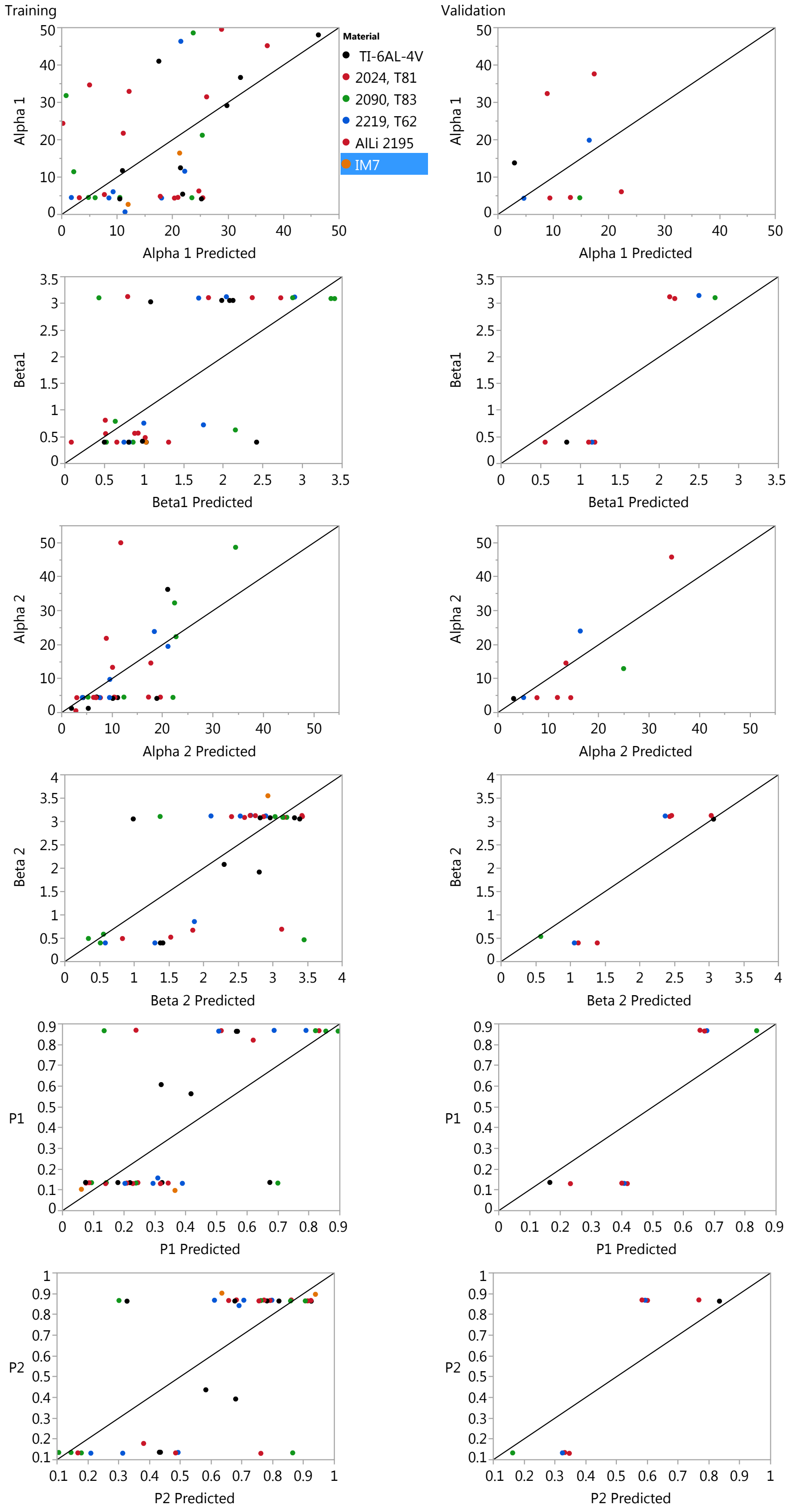


Figure 139: Actual by Predicted

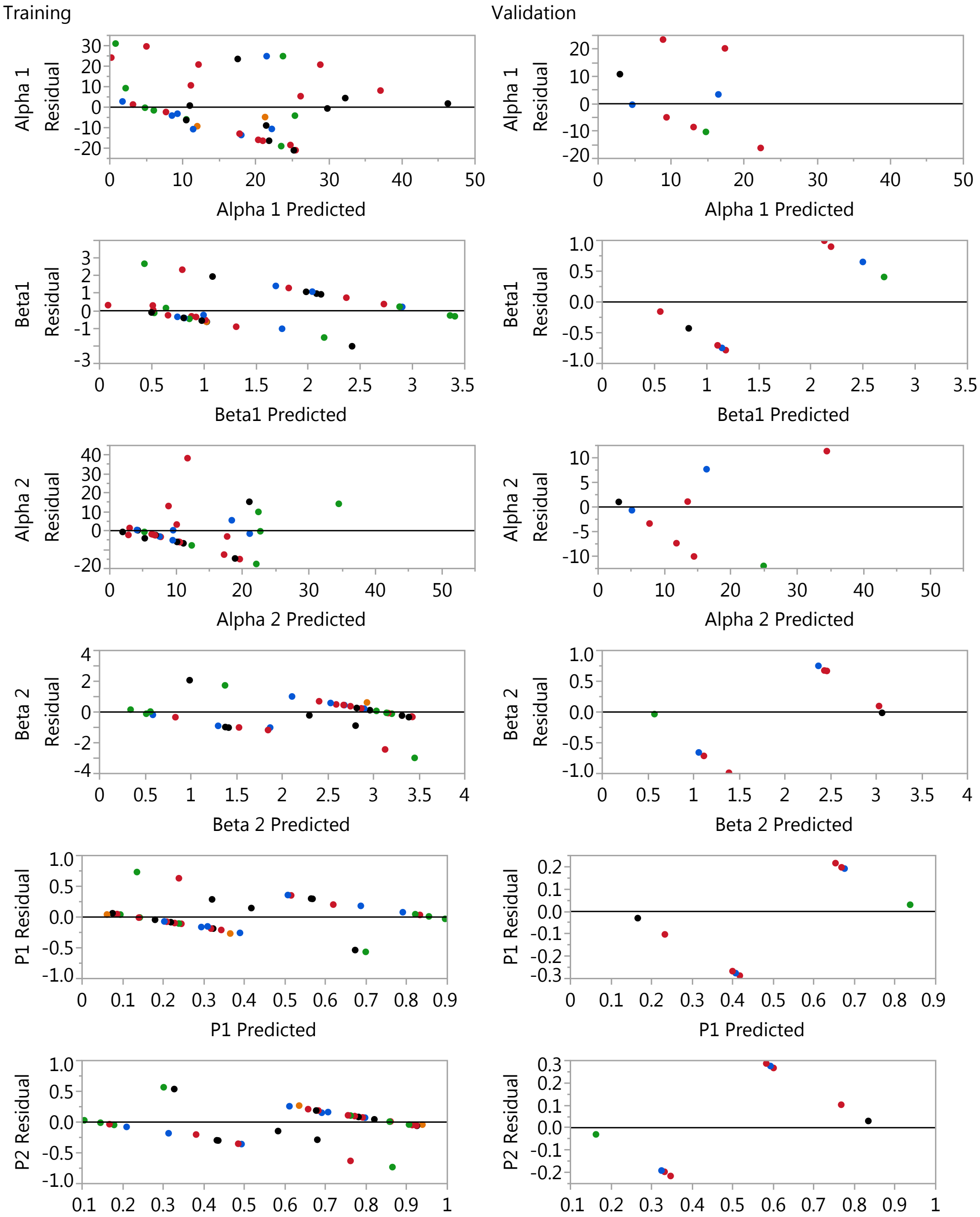


Figure 140: Residual by Predicted

APPENDIX D

MATLAB CODE

D.1 Experiment 3 Uncertainty Propagation

```
function [Random_Distribution,Random_Sample,idx] = ...
Uncertainty_propagation(min_dist,mean_dist,max_dist,N,k)

%This function propagates the uncertainty from the three
%uncertain attribute probability distributions based upon
%schedule uncertainty. %The first three inputs are the
%uncertainty distributions resulting form attribute uncertainty,
%and the last three inputs are the datasets which contain the
%milestones for each of the uncertain-attribute matrices. N
%represents the total number of samples desired to generate the
%final distribution

%K = the weighting assigned to the extreme values of task
%ordering (as a percent) from 0 - 1

%The milestone matrix has the following columns in the following
%order: Expenditure during Preliminary Design Expenditure during
%Detailed Design Expenditure during 1st build Expected year end
%of Preliminary design Expected year end of Detailed design
%Expected year end of 1st Build

Total_Expenditure_Distribution_Min = sum(min_dist(:,42:44),2);
Total_Expenditure_Distribution_Mean = sum(mean_dist(:,42:44),2);
Total_Expenditure_Distribution_Max = sum(max_dist(:,42:44),2);
```

```
figure(10)
subplot(3,2,1)
histogram(Total_Expenditure_Distribution_Min)
subplot(3,2,3)
histogram(Total_Expenditure_Distribution_Mean)
subplot(3,2,5)
histogram(Total_Expenditure_Distribution_Max)
subplot(3,2,2)
hold on
histogram(min_dist(:,end-2))
histogram(min_dist(:,end-1))
histogram(min_dist(:,end))
axis([0 10 0 200])
subplot(3,2,4)
hold on
histogram(mean_dist(:,end-2))
histogram(mean_dist(:,end-1))
histogram(mean_dist(:,end))
axis([0 10 0 200])
subplot(3,2,6)
hold on
histogram(max_dist(:,end-2))
histogram(max_dist(:,end-1))
histogram(max_dist(:,end))
axis([0 10 0 200])


% triangular distribution of the TOTAL cost for Series, Expected,
% and Parallel task order for Tyler Milner EX3. A discrete
% triangular distribution shall be created based upon the means
% of each of the incoming distributions.
```

```
%The foundation assumption for propagating this uncertainty is
%that a notional triangular distribution shall be created to
%determine which distribution shall be sampled.

%  pd = makedist('Triangular','a',0,'b',0.5,'c',1);
%If the random number is more than 1 stddev away from the
%expected value, then select from the other distributions
%appropriately
%   k = 0.5-std(pd);

%  uniform distribution
pd = makedist('Uniform','lower',0,'upper',1);
k=1/3; %divide distribution into equal thirds

%Now draw a random sample from this distribution:
Random_Sample = random(pd,N,1);
%Preallocate matrices for speed:
Random_Distribution = zeros(N,size(min_dist,2));
Distribution_Index_Designation = zeros(N,1);
idx = zeros(N,1);

for i = 1:N %This is repeated

% Random_Sample(i) = random(pd,1,1);

%The continuous triangular distribution states that the
%probability of the random sample being exactly equal to the
%extremes is precisely zero...so there needs to be some
%non-zero probability assigned to the two extreme values so
%that these concepts actually get pulled. Since these are
%designed to be absolute extremes of the space, the
```

```
%percentage should be relatively small...let's assume that if
%the random sample is within 15% of the extremes, then the
%random sample will be drawn from the corresponding
%distribution.

if Random_Sample(i)<=k
[Actual_Sample,idx(i)] = ...
datasample(Total_Expenditure_Distribution_Min,1);
Random_Distribution(i,:) = min_dist(idx(i),:);
Distribution_Index_Designation(i) = 0;
elseif Random_Sample(i)>=(1-k)
[Actual_Sample,idx(i)] = ...
datasample(Total_Expenditure_Distribution_Min,1);
Random_Distribution(i,:) = max_dist(idx(i),:);
Distribution_Index_Designation(i) = 1;
else
[Actual_Sample,idx(i)] = ...
datasample(Total_Expenditure_Distribution_Min,1);
Random_Distribution(i,:) = mean_dist(idx(i),:);
Distribution_Index_Designation(i) =0.5;
end

end

figure(3)
histogram(Distribution_Index_Designation)
```

D.2 Experiment 4 Addition of Element Expenditures

This section includes a series of Matlab scripts and functions used to perform experiment 4, and thereafter adapted for the sample problem presented in Chapter 5. The primary code, RunEX4_Final.m, pulls in the probabilistic Fuel Tank distribution from an excel sheet and manipulates these to get to the final robust Probabilistic affordability distribution for a launch vehicle system. The distributions are run through Uncertainty_propagation.m, where the uncertainty in task order is propagated using a uniform distribution between three viable schedule candidates. A series of plots are included which provide some statistics and distribution visualizations on the incoming Excel data, and the resulting uncertainty.

In this main script, the other elements are assumed to be a multiple of the LH2 tank distribution, but could easily be adapted to pull in Excel data for these. The individual elements are then added, in Thesis_EX4.m, which adds integration based upon assumptions presented herein. The addition is performed for 4096 variations of the start vector multiplied by the number of cost constraint vectors used, in this case 3 for a total of 12300 runs. During each run, the POS is assessed, using ObjectiveFunction.m, compared to the current best, using comparemax.m, and the final results are then saved to a mat file. The MAT files are later processed to determine start vector option which is the most robust to variations in cost and schedule constraints.

```
%This script brings in the variable info and runs the function which
%adds the distributions

%Bring in all the expenditure curves each sheet contains 1000MC runs
%which represent the uncertain affordability distributions for each
%element
```

```
%% bring in all the data
%Assign each distribution to its appropriate element

%Bring in the annual expenditure and milestone information
LH_2_Tank =xlsread('MC results for LH2 Tank Actual.xlsx',1,'B3:BB1002');
LH_2_Tank_Series = xlsread('MC results for LH2 Tank Actual.xlsx',1,...
'ATO3:AVO1002');
LH_2_Tank_Parallel = xlsread('MC results for LH2 Tank Actual.xlsx',1,...
'WW3:YW1002');

%The input data contains several columns, included in the matrices above,
%which are superfluous. So stripping them out:

LH_2_Tank = [LH_2_Tank(:,1:44) LH_2_Tank(:,51:end)];
LH_2_Tank_Series =[LH_2_Tank_Series(:,1:44) LH_2_Tank_Series(:,51:end)];
LH_2_Tank_Parallel = [LH_2_Tank_Parallel(:,1:44) LH_2_Tank_Parallel(...
:,51:end)];

%Yields the final matrices that shall be used throughout the remainder
%of this analysis. The first 41 columns represent the annual
%expenditure from year 0 to year 40. Columns 42—44 contain the
%expenditure during Preliminary Design, Detailed Design and first
%build, respectively and the last 3 columns include the expected
%end year of these phases.

figure(1)
hold on
plot(linspace(0,40,41),LH_2_Tank(:,1:41),'k')
plot(linspace(0,40,41),LH_2_Tank_Series(:,1:41),'r')
plot(linspace(0,40,41),LH_2_Tank_Parallel(:,1:41),'g')

%% Propagate Uncertainty
```

```
%These three inputs represent the probabilistic distributions resulting
%from uncertain design/manufacturing attributes for a series, expected,
%and parallel task order permutation. This cell will propagate this
%uncertainty based upon a discrete form of the triangular distribution:

[LH_2_Final_Distribution,Random_Sample,idx] =Uncertainty_propagation(...
LH_2_Tank_Parallel,LH_2_Tank,LH_2_Tank_Series,10001,0.15);
figure(2)
histogram(sum(LH_2_Final_Distribution(:,42:44),2))

%Remainder of distributions are assumed as TRL=7 and fixed configuration
%These are represented here as a relative percentage of the TRL7 Fuel
%Tank.

LH_2_Forward_Skirt = 0.5.*LH_2_Final_Distribution;
LH_2_Aft_Skirt = 0.5.*LH_2_Final_Distribution;
Intertank = 0.7.*LH_2_Final_Distribution;
LO_2_Tank = 0.8.*LH_2_Final_Distribution;
Thrust_structure = 0.4.*LH_2_Final_Distribution;
Main_Propulsion_System = 1.5.*LH_2_Final_Distribution;
Thermal_Protection_System = 0.5.*LH_2_Final_Distribution;
Active_Thermal_Conditioning = 0.5.*LH_2_Final_Distribution;
Power_Systems = 0.5.*LH_2_Final_Distribution;
Avionics_System = 0.5.*LH_2_Final_Distribution;
Reaction_Control_System = 0.5.*LH_2_Final_Distribution;
% Integration = 1.3.*LH_2_Final_Distribution;

%% Sample Problem data import
%Composite Tank data
% LH_2_Tank = xlsread('EXCEL Analysis Results for Sample Problem ...
12_2.xlsx',1,'B2524:BB3523');
% LH_2_Tank_Series = xlsread(...
```

```
%'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
%'ATO2524:AVO3523');
% LH_2_Tank_Parallel = xlsread(...
%'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
%'WW2524:YW13523');
%
% Integration = xlsread(...
%'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
%'B6528:BB7527');
% Integration_Series = xlsread(...
%'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
%'ATO6528:AVO7527');
% Integration_Parallel = xlsread(...
%'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
%'WW6528:YW7527');
%
%LH2 Tank Integration
Integration = xlsread(...
'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,'B5528:BB6527');
Integration_Series = xlsread(...
'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
'ATO5528:AVO6527');
Integration_Parallel = xlsread(...
'EXCEL Analysis Results for Sample Problem 12_2.xlsx',1,...
'WW5528:YW6527');

%The input data contains several columns, included in the matrices above,
%which are superfluous. So stripping them out:

Integration = [Integration(:,1:44) Integration(:,51:end)];
Integration_Series = [Integration_Series(:,1:44) Integration_Series(...
:,51:end)];
```

```
Integration_Parallel = [Integration_Parallel(:,1:44) ...
Integration_Parallel(:,51:end)];

%Now propagate the Task order uncertainty for the tank and
%integration:
% [LH_2_Final_Distribution,Random_Sample,idx] = ...
%Uncertainty_propagation(%LH_2_Tank_Parallel,LH_2_Tank,...
%LH_2_Tank_Series,10001,0.15);
[Integration,Random_Sample,idx] =Uncertainty_propagation(...
Integration_Parallel,Integration,Integration_Series,10001,0.15);
%%
Element_Struc = struct('LH2_Tank',LH_2_Final_Distribution,...
'LH2_Forward_Skirt',LH_2_Forward_Skirt,'LH2_Aft_Skirt',...
LH_2_Aft_Skirt,'Intertank',Intertank,'LOx_Tank',LO_2_Tank,...
 'Thrust_Structure',Thrust_structure,...
'MPS',Main_Propulsion_System,'TPS',Thermal_Protection_System,...
'Active_Thermal_Conditioning',Active_Thermal_Conditioning,...
'Power_Systems',Power_Systems,'Avionics',Avionics_System,'RCS',...
Reaction_Control_System,'Intergation',Integration);

%% Look at some overarching statistics
%compute the total expenditure for each case
LH_2_Tank_Expenditure_Distribution = sum(LH_2_Final_Distribution(...
:,42:44),2);
%Now let's look at the unique minimum, mean, median, and maximum:

LH_2_Tank_Final_Distribution_M = LH_2_Final_Distribution(...
find(LH_2_Tank_Expenditure_Distribution == median(...
LH_2_Tank_Expenditure_Distribution),1),1:41);
LH_2_Tank_Final_Distribution_Min = LH_2_Final_Distribution(...
find(LH_2_Tank_Expenditure_Distribution == min(...
LH_2_Tank_Expenditure_Distribution),1),1:41);
```

```
LH_2_Tank_Final_Distribution_Max = LH_2_Final_Distribution(...
find(LH_2_Tank_Expenditure_Distribution == max(...
LH_2_Tank_Expenditure_Distribution),1),1:41);

LH_2_Tank_Distribution_M_bar = mean(LH_2_Tank_Expenditure_Distribution);

%The expected value of the total cost does not (necessarily) represent a
%distinct discrete case. Instead, it is necessary to determine which of
%the discrete cases is closes to the actual mean (expected) value:

[Row_value1,row_index1] = min(abs(LH_2_Tank_Expenditure_Distribution ...
— LH_2_Tank_Distribution_M_bar));

LH_2_Tank_Final_Distribution_Mean = LH_2_Final_Distribution(...
row_index1,1:41);

%% Find all cases with points that form bounds
%Since the minimum and maximum total costs do NOT form the bounds of the
%probabilistic distribution, it is necessary to find all the cases which
%contain an annual expenditure value which comprises the lower or upper
%bound.

%Firstly, let's find the minimum and maximum values for each year:
%Annual expenditure is housed within the first 41 columns
[Row_value1,row_index1] = min(LH_2_Final_Distribution(:,1:41));
[Row_value2,row_index2] = max(LH_2_Final_Distribution(:,1:41));

%Now we want to ensure we aren't using any distribution twice.

Used_Indices = unique([row_index1,row_index2]);
%Strip out the 1, since the latter years often have no annual
%expenditure, the first row will be included in the above
```

```
%vectors. This value is not representative of any case which
%forms the boundary.

Used_Indices = Used_Indices(Used_Indices~=1);

%Now create a new subset matrix from these indices

LH2_subset = LH_2_Final_Distribution(Used_Indices,1:41);

%% Plot probabilistic distributions and overlay min, max, mean
%and median.
figure(4)

subplot(2,1,1)
hold on
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_Min,'c',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_M,'b',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_Max,'r',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_Mean,'g',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Final_Distribution(:,1:41),'k')
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_Min,'c',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_M,'b',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_Max,'r',...
'LineWidth',4)
plot(linspace(0,40,41),LH_2_Tank_Final_Distribution_Mean,'g',...
'LineWidth',4)
```

```
axis([0 10 0 26e7])
legend('Minimum Total Cost','Median Total Cost','Maximum Total Cost',...
'Mean Total Cost')
xlabel('Fiscal Year')
ylabel('Expenditure $')

subplot(2,1,2)
hold on
plot(linspace(0,40,41),LH2_subset,'m','LineWidth',4)
plot(linspace(0,40,41),LH_2_Final_Distribution(:,1:41),'k')
plot(linspace(0,40,41),LH2_subset,'m','LineWidth',4)
axis([0 10 0 26e7])
legend('Subset of cases which form bounds')
xlabel('Fiscal Year')
ylabel('Expenditure $')
%% Optimize development
%Now we can actually add the distributions based on an (initially)
%random start vector.

%Constellation Program (Ref:GAO-10-227SP) spent approximately 3-years
%in both conceptual and Preliminary Design, and the SLS
%(REF:GAO-15-320SP)spent approximately two years going through both
%(measured from Formulation Start to PDR). This it is not unreasonable
% to assume that all development activity (excluding integration)
%should start within the first 3 years. As such There are X*(3^12)
%permutations, where X represents the variations on how Integration
%considerations are ordered.

%Integration has two distinct steps which can only be completed AFTER
%all elements have been completed. Thus, the integration distribution
%is assumed to begin such that the start of its First Build phase
%coincides with the end of the last element 1st build
```

```
%Function call (Thesis_EX4 and ObjectiveFunction) takes approximately
%0.1s...from a reasonable standpoint, NASA programs would most likely
%not start development beyond the 5 year mark (i.e. such that the end
%of Preliminary Design is 7 years into the program) as such none of the
%elements(barring integration) would start later than year 5. Thus there
%are 12^5 combinations plus additional combinations for the constraints
%set upon the integration step. At a conservative 0.13 seconds per case
%in series, and 0.05s using parfor (i7-2600 with 16GB RAM) the total run
%time for a full factorial analysis is less than 9 hours, which can
%easily be performed overnight.

%Define matrix of Start values as the full number of permutations for
%twelve system elements starting within the first 3 years after the end
%of Conceptual Design. Thus the Preliminary Design phase will be 4 years
%or more.
[Start_Matrix,idx]=npermutek([1 2],12);

%Constraints
%10 years to get from start of preliminary to first flight
Schedule_Constraint = 10;
%Assume flat funding
Cost_constraint1 = 1.2e9.* ones(1,Schedule_Constraint);
%Increasing Funding
Cost_constraint2 = 1.2e9.*[0.8 0.8 1 1 1 1.1 1.1 1.2 1.2 1.2];
%Decreasing Funding
Cost_constraint3 = 1.2e9.*[1.2 1.2 1.2 1.1 1.1 1 1 0.9 0.9 0.9];

Cost_constraint_vec  =[Cost_constraint1;Cost_constraint2;...
Cost_constraint3];

Outs_KEEP = zeros(size(LH_2_Final_Distribution,1),size(...
```

```
LH_2_Final_Distribution,2)+3);
SyS_Dist_KEEP = zeros(size(LH_2_Final_Distribution,1),size(...
LH_2_Final_Distribution,2)+3);
Sys_Dist_row_count = size(LH_2_Final_Distribution,1);
Sys_Dist_columns = size(LH_2_Final_Distribution,2);
Final = length(Start_Matrix);
POS  =zeros(length(Start_Matrix),1);
Outs_All = [];
System_distribution_All = [];
Adjusted_Element_Distribution_Structure_All = [];

for j = 1:size(Cost_constraint_vec,1)
tic
%     save(sprintf('Cost_constraint%d',j))

parfor i = 1:length(Start_Matrix)

[System_distribution,Adjusted_Element_Distribution_Structure]...
= Thesis_EX4(Start_Matrix(i,:),Element_Struc);
[Outs] = ObjectiveFunction(System_distribution,...
Cost_constraint_vec(j,:),Schedule_Constraint);

POS(i) = Outs(end,1);
%Now we wish only to keep the scenarios in which JCL>=70%
if POS(i)>=0.7 %Analogoues to a JCL>70%
%Each Out may be a different size, since it only contains the
%rows which meet the constraints, as such it is necessary to
%pad this matrix to ensure that concatenation is performed on
%matrices of the same size. To ensure that Outs(end,1) always
%contains the POS, we shall pad the matrix with a replication
%of the last row.
Outs_All(:,:,i) = padarray(Outs,[(size(...
```

```
System_distribution,1)-size(Outs,1)) 0],...
'replicate','post');
System_distribution_All(:,:,i) = System_distribution
Adjusted_Element_Distribution_Structure_All = ...
[Adjusted_Element_Distribution_Structure_All,...
Adjusted_Element_Distribution_Structure]

end

%While we are saving all outputs, this keeps track of the 'BEST'
Outs_KEEP = comparemax(Outs_KEEP,Outs)
SyS_Dist_KEEP = comparemax(SyS_Dist_KEEP,System_distribution)

end

Best_Outs = Outs_KEEP;
Best_Sys = SyS_Dist_KEEP;
Best_Start_Scenarios = Start_Matrix(find(POS==Best_Outs(end,1)),:);

%save data including time stamp to ensure multiple runs do not
%overwrite outputs.
FileName=[sprintf('Cost_Constraint%d_',j),datestr(now, ...
'dd-mmm-yyyy'),'.mat'];
save(FileName,'Best_Start_Scenarios','Best_Outs',...
'Best_Sys','Outs_All','System_distribution_All',...
'Adjusted_Element_Distribution_Structure_All','POS')

%To free up memory for the next iteration, we need to clear some
%variables
clear X Y Best_Start_Scenarios
%     Outs_All = []; System_distribution_All = [];
%     Adjusted_Element_Distribution_Structure_All = [];
```

```
toc
end

%% plotting

figure(7)
hold on
plot(linspace(1,size(Best_Sys(:,1:end-9),2),size(Best_Sys(:,1:end-9),...
2)),Best_Sys(:,1:end-9),'k')
plot(linspace(1,size(Best_Outs(1:end-1,1:end-9),2),size(Best_Outs(...
1:end-1,1:end-9),2)),Best_Outs(1:end-1,1:end-9),'g')
plot(linspace(1,Schedule_Constraint,Schedule_Constraint),...
Cost_constraint1,'r','linewidth',9)
plot(Schedule_Constraint.*ones(100,1),linspace(0,...
Cost_constraint1(end)),'r','linewidth',9)

% Want to add the points which represent the transition between phases.
%The  year is already kept in the Outs/System_distribution matrix, BUT
%we need  to extract the expenditure IN THE PARTIAL YEAR

%This is commented out due to the inclusion of figure(9). It is easier
%to visualize the distribution of phase ends in a histogram than on the
%affordability distribution itself.
% for i = 1:size(Best_Outs,1)-1
%
%     Preliminary_End = Best_Outs(i,floor(Best_Outs(i,end-5))) +
%     (Best_Outs(i,end-5)-floor(Best_Outs(i,end-5)))*(Best_Outs(...
%i,ceil(Best_Outs(i,end-5)))-Best_Outs(i,floor(Best_Outs(i,end-5))));
%     Detailed_end =  Best_Outs(i,floor(Best_Outs(i,end-4))) +
%     (Best_Outs(i,end-4)-floor(Best_Outs(i,end-4)))*(Best_Outs(...
%i,ceil(Best_Outs(i,end-4)))-Best_Outs(i,floor(Best_Outs(i,end-4))));
%     First_build_end = Best_Outs(i,floor(Best_Outs(i,end-3))) +
```

```
%     (Best_Outs(i,end-3)-floor(Best_Outs(i,end-3)))*(Best_Outs(...
%i,ceil(Best_Outs(i,end-3)))-Best_Outs(i,floor(Best_Outs(i,end-3))));
%     plot(Best_Outs(i,end-5),Preliminary_End,'ro')
%     plot(Best_Outs(i,end-4),Detailed_end,'bo')
%     plot(Best_Outs(i,end-3),First_build_end,'mo')
% end

legend('Constraints','All Cases','Feasible Points')% @ POS =
% ')%,Y(end,1))
axis([1 Schedule_Constraint+1 0 1.2*max(max(Best_Sys(:,1:end-9)))])
xlabel('Fiscal Year')
ylabel('Annual Expenditure')
figure(8)
hold on
histogram(sum(Best_Sys(:,end-8:end-6),2))
histogram(sum(Best_Outs(:,end-8:end-6),2))
% sum(Cost_constraint)
xlabel('Total Cost')
ylabel('Frequency')
legend('Uncertainty in Total Cost',sprintf(...
'Cases Which Meet Annual Cost Constraint, POS ~%d',max(POS)*100,'%'))

%Look at the distribution of phase end dates
figure(9)
hold on
histogram(Best_Outs(1:end-1,end-5))
histogram(Best_Outs(1:end-1,end-4))
histogram(Best_Outs(1:end-1,end-3))

%% Load Outputs for comparison
% get the list of files
d=dir([sprintf('Cost_Constraint*_'),datestr(now, 'dd-mmm-yyyy'),'.mat']);
```

```
x=[];            % start w/ an empty array

for i=1:length(d) % Only need to bring in
x=[x; load(d(i).name)];   % read/concatenate into x
end

%Now we need to look at the POSs and find the one closest to the
%positive ideal

for i = length(d)
POS_ALL(:,i) = x(i).POS;
end

%The ideal solution is 100% POS. Thus, if we average the column-wise
%POS (representative of averaging the POS for each cost constraint
%scenario)
Closeness_to_Ideal = find(max((sum(POS_ALL,2)/size(POS,2))));
Robust_Start = Start_Matrix(Closeness_to_Ideal,:);

%Now we reanalyze for this Robust Case and overlay all constraints

[Robust_System_distribution,...
Robust_Adjusted_Element_Distribution_Structure] = ...
Thesis_EX4(Robust_Start,Element_Struc);
[Robust_Outs] = ObjectiveFunction(Robust_System_distribution...
,min(Cost_constraint_vec,[],1),Schedule_Constraint);

figure(11)
hold on
h1 = plot(linspace(1,size(Robust_System_distribution(:,1:end-9),2),...
size(Robust_System_distribution(:,1:end-9),2)),...
Robust_System_distribution(:,1:end-9),'k');
```

```
h2 = plot(linspace(1,size(Robust_Outs(1:end-1,1:end-9),2),...
size(Robust_Outs(1:end-1,1:end-9),2)),Robust_Outs(1:end-1,1:end-9),'g');
h3 = plot(linspace(1,Schedule_Constraint,Schedule_Constraint)...
,Cost_constraint_vec,'linewidth',4);
h4 = plot(Schedule_Constraint.*ones(100,1),linspace(0,max(...
Cost_constraint_vec(:,end))),'r','linewidth',4);
legend([h1(1,1) h2(1,1) h3(1,1) h3(2,1) h3(3,1) h4(1,1)],...
'Probabilistic Distribution',...
'Portion of Distribution That Meets All Constraint Scenarios',...
'Flat Funding Scenario','Increasing Funding','Decreasing Funding',...
'Launch Constraint')
axis([1 Schedule_Constraint+1 0 1.2*max(max(...
Robust_System_distribution(:,1:end-9)))])
xlabel('Fiscal Year')
ylabel('Annual Expenditure')
```

```matlab
function [System_distribution,Expenditures] = Thesis_EX4(...
Start,Element_Structure)

%This function sums Expenditures based on the corresponding start time.
%The Start Vector contains the fiscal year in which each vehicle element
%begins, and excludes the integration step, as that is assumed to occur
%such that the First Build of integration commences once the last
%element completes its First Build stage.
%its development cycle. The Element_Structure input is a structure array
%which contains the name and expenditure for each element.
%NOTE: The values contained in the Start array are assumed to match the
%structural array entries in Expenditure, i.e. the first field in the
%Element_Structure structure with start based upon the first entry in
%the Start array. Furthermore, each element in the Element_Structure
%structure is the same size, i.e. the same number of monte carlo runs
% have been performed for each Element which comprises the system.

%First, define the distributions for each LV Element
%time vector spans 41 years
Time = linspace(0,40+max(Start),40+max(Start));

%Now need to create the vectors which will be added

x = fieldnames(Element_Structure);

%Preallocate the System_Distribution vector such that it is not growing
%inside a for loop
System_distribution = zeros(length(Element_Structure.(char(x(1)))),...
length(Time));

for i=1:length(x)-1 %the last member of this structure is integration
%which must be added separately based on assumptions
```

```
%Shift the row vectors over such that the first non-zero expenditure
%occurs in the year defined by Start(i). The operation must only be
%performed on the annual expenditure (i.e. the first 41 columns, and
%the last 6 columns must be kept

%add column of zeros to array based upon the start vector to represent
%a shift in the expenditure. It is also necessary to add the shift in
%years to the milestone dates which are kept in the last three cols.
-
Expenditures.(char(x(i)))=[zeros(length(...
Element_Structure.(char(x(i)))),(Start(i)-1)),...
Element_Structure.(char(x(i)))(:,1:41),...
zeros(length(Element_Structure.(char(x(i)))),max(Start)-...
Start(i)) Element_Structure.(char(x(i)))(:,42:44) (...
Element_Structure.(char(x(i)))(:,45)+Start(i)) (...
Element_Structure.(char(x(i)))(:,46)+Start(i)) (...
Element_Structure.(char(x(i)))(:,47)+Start(i))];

end

%Now add the distributions...once again, since these are all random
%distributions, the addition must be performed in the form of a random
%draw...
%Since all of the matrices in the structure include the same number of
%rows, it is appropriate to re-perform the same number of random samples
Iterations = size(Expenditures.(char(x(1))),1);
Columns = size(Expenditures.(char(x(1))),2);
%Prealoacate system distribution for speed:
System_distribution = zeros(Iterations,Columns);



%Since I know that I have twelve elements plus one integration
```

```
%distribution, I can create the system distribution by summing
%random draws from the annual distributions. Thereafter, the
%system milestone is dictated by the milestone of the element
%distribution which finishes last.


A = datasample(Expenditures.(char(x(1))),Iterations,1);
B = datasample(Expenditures.(char(x(2))),Iterations,1);
C = datasample(Expenditures.(char(x(3))),Iterations,1);
D = datasample(Expenditures.(char(x(4))),Iterations,1);
E = datasample(Expenditures.(char(x(5))),Iterations,1);
F = datasample(Expenditures.(char(x(6))),Iterations,1);
G = datasample(Expenditures.(char(x(7))),Iterations,1);
H = datasample(Expenditures.(char(x(8))),Iterations,1);
I = datasample(Expenditures.(char(x(9))),Iterations,1);
J = datasample(Expenditures.(char(x(10))),Iterations,1);
K = datasample(Expenditures.(char(x(11))),Iterations,1);
L = datasample(Expenditures.(char(x(12))),Iterations,1);


System_distribution = [(A(:,1:(40+max(Start)))+ ...
B(:,1:(40+max(Start)))+...
C(:,1:(40+max(Start)))+ D(:,1:(40+max(Start)))+ ...
E(:,1:(40+max(Start)))+ F(:,1:(40+max(Start)))+ ...
G(:,1:(40+max(Start)))+ H(:,1:(40+max(Start)))+ ...
I(:,1:(40+max(Start)))+ J(:,1:(40+max(Start)))+ ...
K(:,1:(40+max(Start)))+ L(:,1:(40+max(Start)))),...
(A(:,end-5) + B(:,end-5) + C(:,end-5) + D(:,end-5) + ...
E(:,end-5) + F(:,end-5) + G(:,end-5) + H(:,end-5) + ...
I(:,end-5) + J(:,end-5) + K(:,end-5) + L(:,end-5)),...
(A(:,end-4) + B(:,end-4) + C(:,end-4) + D(:,end-4) + ...
E(:,end-4) + F(:,end-4) + G(:,end-4) + H(:,end-4) + ...
```

```
I(:,end-4) + J(:,end-4) + K(:,end-4) + L(:,end-4)),...
(A(:,end-3) + B(:,end-3) + C(:,end-3) + D(:,end-3) + ...
E(:,end-3) + F(:,end-3) + G(:,end-3) + H(:,end-3) + ...
I(:,end-3) + J(:,end-3) + K(:,end-3) + L(:,end-3)),...
max(A(:,end-2),max(B(:,end-2),max(C(:,end-2),...
max(D(:,end-2),max(E(:,end-2),max(F(:,end-2),max(G(:,end-2),...
max(H(:,end-2),max(I(:,end-2),max(J(:,end-2),max(K(:,end-2),...
L(:,end-2))))))))))),...
max(A(:,end-1),max(B(:,end-1),max(C(:,end-1),max(D(:,end-1),...
max(E(:,end-1),max(F(:,end-1),max(G(:,end-1),max(H(:,end-1),...
max(I(:,end-1),max(J(:,end-1),max(K(:,end-1),L(:,end-1))))))))))),...
max(A(:,end),max(B(:,end),max(C(:,end),max(D(:,end),max(E(:,end),...
max(F(:,end),max(G(:,end),max(H(:,end),max(I(:,end),max(J(:,end),...
max(K(:,end),L(:,end)))))))))))];

%Now we need to add the integration step. First we take random draw of
%the integration:

M = datasample(Element_Structure.(char(x(13))),Iterations,1);
%Before we begin, need to ensure that M is the same size as the other
%elements, specifically the number of columns
M = [M(:,1:41) zeros(size(M,1),(size(L,2)-size(M,2))) M(:,end-5:end)];

%then determine the start year of the integration based on First Build
%start coinciding with First Build end of all other elements. NOTE: In
%all practicality it is likely that some integration efforts may begin
%before ALL elements are complete. This, coupled with the fact that the
%applied resolution (one year) would often result in months of no work
%integration is assumed to begin at the beginning of the fiscal year in
%which the last element(s) complete First Build if no more than 3 months
%of no work would result
```

```
Integration_Start = round(System_distribution(:,end) - M(:,end-1),2);
Integration_Start(Integration_Start<0)=0;
Integration_Start_Check = floor(System_distribution(:,end)-M(:,end-1));
Integration_Start_Check(Integration_Start_Check<0)=0;

%Now we check to see which cases should start in the following fiscal
%year
Remainder = Integration_Start-Integration_Start_Check;
Changes = find(Remainder>=9/12);
Integration_Start = Integration_Start_Check;

Integration_Start(Changes,1) = Integration_Start(Changes,1)+1;

%Now we need to shift the integration distribution over, based on this
%start year, so we shall use indexing

%We only wish to work on the annual expenditure portion, so we shall
%define a temporary matrix which contains these columns only
%Adapted from http://www.mathworks.com/company/newsletters/articles/
%matrix-indexing-in-matlab.html
tmp = M(:,1:end-6); % remove the last 6 columns
m=size(tmp,1);
n=size(tmp,2);
k = -1.*Integration_Start-1;
% index vectors for rows and columns
p = 1:m;
q = 1:n;
% index matrices for rows and columns
[P, Q] = ndgrid(p, q);
% create a matrix with the shift values
KK = repmat(k(:), [1 n]);
```

```
% update the matrix with the column indices
Q = 1 + mod(Q+KK, n);
% create matrix of linear indices
ind = sub2ind([m n], P, Q);
% finally, create the output matrix and add last 6 columns being sure to
% include the shift to the last 3 columns
M_New =[tmp(ind) M(:,end-5:end-3) (M(:,end-2:end)+(Integration_Start)...
*ones(1,3))];


%Adding three additional columns to the System Distribution matrix such
%that one may distinguish between the phase ends of integration and the
%ends of the max element phase
System_distribution = [(System_distribution(:,1:end-6)+ ...
M_New(:,1:end-6)) (System_distribution(:,end-5)+...
M_New(:,end-5)) (System_distribution(:,end-4)+...
M_New(:,end-4)) (System_distribution(:,end-3)+...
M_New(:,end-3)) System_distribution(:,end-2) ...
System_distribution(:,end-1) System_distribution(:,end) ...
M_New(:,end-2) M_New(:,end-1)  M_New(:,end)];

% figure(10)
% histogram(sum(System_distribution(:,end-5:end-3),2))
% figure(11)
% hold on
% size(System_distribution(:,1:40+max(Start)))
%  plot(Time,System_distribution(:,1:40+max(Start)))
% % for i = 1:length(x)
% %     plot(Time, Expenditures.(char(x(1))))
% % end
```

```
function [Outs] = ObjectiveFunction(System_Distribution,...
Cost_constraint,Schedule_Constraint)

%The primary purpose of this is to determine the degree to which any
%System Distribution candidate exceeds the provided constraints.
%Ultimately we are looking for the candidate with the greatest
%probability of success, defined as the likelihood of remaining
%below the budget ceiling for all time in the life cycle, AND
%completing ON TIME.

%Cost_constraint is a vector of values and Schedule_constraint is
%an Integer value which depicts the year in which first launch must
%occur. The Cost_constraint vector is assumed to span from 0 to
%Schedule_Constraint

%As such, we are looking for the proportion of the system curve
%contained within the constraint box:

%To reduce the space for the more complex cost constraint check,
%first we shall check to see whether the time constraint is met.
%Check the column which represents the year of the time constraint.
%If there is no annual expenditure in that year, then the candidate
%meets the criteria

Success_row_index = sum(...
System_Distribution(:,Schedule_Constraint:end-9),2)==0;
Outs = System_Distribution(Success_row_index,:);

%Depending on the cost constraint input, two separate methods can be
%employed. If the cost constraint is flat (all vector elements are the
%same, then:
```

```
%Check to see how many unique values are i the constraint
Case_Check = length(unique(Cost_constraint));

%Check to ensure Schedule constraint didn't rule out all options

if isempty(Outs)~=1

if Case_Check == 1 %If all values are the same

Success_row_index = find(sum(Outs(:,1:end-9)<=Cost_constraint(1),2)==...
length(Outs(1,1:end-9))==1);
Outs = Outs(Success_row_index,:);

else %Now for the case that there is a fluctuating cost per year:
%Simply find the difference between the cost
Diff_Matrix = ones(size(Outs,1),1)*Cost_constraint - Outs(...
:,1:Schedule_Constraint);
Success_row_index = sum(Diff_Matrix>=0,2)==Schedule_Constraint;
Outs = Outs(Success_row_index,:);
end

%Check again to ensure Outs is not empty

if isempty(Outs)~=1

%The major criteria for goodness is the Probability of Success
%(POS). Within the context of this problem, if the entire
%uncertainty distribution meets the criteria, then the candidate
%start_vector has 100% probability of meeting the provided
%constraint. Similarly, if only half of the uncertainty
%distribution meets the criteria, then there is only a 50% POS, and
%so on.
```

```
Probability_of_success = size(Outs,1)/size(System_Distribution,1);

Outs_Mean = mean(sum(Outs(:,end-8:end-6),2));
[Row_value1 row_index1] = min(abs(sum(Outs(:,end-8:end-6),2) - ...
Outs_Mean));

Standard_Deviation =std(sum(Outs(:,end-8:end-6),2));

%add a zero ROW to store probability information
Additional_Info = zeros(1,size(Outs,2));
Additional_Info(1) = Probability_of_success;
Additional_Info(2) = row_index1; %Row index of mean expenditure
Additional_Info(3) = Standard_Deviation;
Outs = [Outs;Additional_Info];
else
Outs = zeros(1,size(System_Distribution,2));
end

else
Outs = zeros(1,size(System_Distribution,2));
end

%% plotting

% figure(7)
% hold on
% plot(linspace(1,Schedule_Constraint,Schedule_Constraint),...
%Cost_constraint,'r','linewidth',9)
% plot(Schedule_Constraint.*ones(100,1),...
linspace(0,Cost_constraint(end))%,'r','linewidth',9)
% plot(linspace(1,size(System_Distribution(:,1:end-9),2),size(...
```

```
%System_Distribution(:,1:end-9),2)),System_Distribution(:,1:end-9),'k')
% plot(linspace(1,size(Outs(1:end-1,1:end-9),2),size(Outs(1:end-1,...
%1:end-9),2)),Outs(1:end-1,1:end-9),'g')
% plot(linspace(1,Schedule_Constraint,Schedule_Constraint),...
%Cost_constraint,'r','linewidth',9)
% plot(Schedule_Constraint.*ones(100,1),linspace(0,...
%Cost_constraint(end)),'r','linewidth',9)
%
% Want to add the points which represent the transition between phases.
% The year is already kept in the Outs/System_distribution matrix, BUT
% we need to extract the expenditure IN THE PARTIAL YEAR
%
% axis([1 Schedule_Constraint 0 1.2*max(max(System_Distribution(...
%:,1:end-9)))])
% figure(8)
% hold on
% histogram(sum(System_Distribution(:,end-8:end-6),2))
% histogram(sum(Outs(:,end-8:end-6),2))
% sum(Cost_constraint)



function mc = comparemax(A,B)
% Custom reduction function where A and B are both matrices

if A(end,1) >= B(end,1) % Compare the two input data values
mc = A;      % Return the vector with the larger result
else
mc = B;
end
```

REFERENCES

[1] "Q&A: A380 delays," *BBC News [Online]*, 2006.

[2] "Manufacturing readiness assessment tool users manual," *Air Force*, November 2008.

[3] Aerojet Rocketdyne, "Space shuttle main engine," *http://www.rocket.com/space-shuttle-main-engine*, Accessed Feb 2015.

[4] Aeronautics, N. and Administration, S., "Workforce information profile for NASA," Start of FY2016.

[5] Alexander, R. A., "Space vehicle systems analysis: MSFC tools and processes," 2005.

[6] Archer, N. P. and Ghasemzadeh, F., "An integrated framework for project portfolio selection," *International Journal of Project Management*, vol. 17, no. 4, pp. 207–216, 1999.

[7] Arena, M. V., *Impossible Certainty: Cost Risk Analysis for Air Force Systems*, vol. 415. Rand Corporation, 2006.

[8] Ausick, P., "Why a boeing 787-9 dreamliner costs 250 million," *24/7 Wall Street*, June 2014.

[9] Badiru, A. B., "A simulation approach to PERT network analysis," *Simulation*, vol. 57, no. 4, pp. 245–255, 1991.

[10] Bergin, "Preliminary NASA plan shows evolved SLS vehicle is 21 years away," *NASASpaceFlight.com*, July 2011.

[11] Bergin, C., "RS-25 second life: SLS core stage engine set for summer testing," *NASASpaceFlight.com*, February 2014.

[12] Bergin, C., "NASA lines up exploration upper stage workhorse for SLS," *NASASpaceFlight.com*, October 2014.

[13] Bhat, B. N., "Materials, processes and manufacturing in Ares I–upper stage: Integration with systems design and development," *NASA-MSFC, Sep*, vol. 22, 2008.

[14] Bilbro, J. W., "Systematic assessment of the program/project impacts of technological advancement and insertion revision a," *Unpublished, JB Consulting International*, 2007.

[15] Bilbro, J. W., "Integrated TRL and AD2 calculator." Electronic, February 2009.

[16] Bilbro, J. W., "Technology assessment calculator." Electronic, Excel File, March 2012.

[17] Bilbro, J. W., "Using the advancement degree of difficulty (AD2) as an input to risk management," tech. rep., DTIC Document, 2008.

[18] Bilbro, J. W. and Sackheim, R. L., "Managing a technology development program," *A White Paper, George C. Marshall Space Flight Center*, 2002.

[19] Bitten, R. E., Freaner, C. W., and Emmons, D. L., "Optimism in early conceptual designs and its effect on cost and schedule growth: An update," in *Aerospace Conference, 2010 IEEE*, pp. 1–12, IEEE, 2010.

[20] Blair, J., Ryan, R., and Schutzenhofer, L., "Launch vehicle design process: characterization, technical integration, and lessons learned," *2001.*, 2001.

[21] Boeing, "Boeing rolls out first 787 dreamliner at increased production rate," *Boeing Media Room*, January 2014.

[22] Boeing, "787 dreamliner," 2015.

[23] Boeing, "Boeing 787 all model order report," January 2015.

[24] Boeing, "First 777x autoclave 'busts a move' to the future at everett site," September 2015.

[25] Boeing, "'grand-scale' autoclave for boeing's biggest wings nears completion," June 2015.

[26] Boothroyd, G., "Product design for manufacture and assembly," *Computer-Aided Design*, vol. 26, no. 7, pp. 505–520, 1994.

[27] Braun, R. D., "Collaborative optimization: an architecture for large-scale distributed design," 1996.

[28] Broad, W., "For U.S. satellite makers, a no-cost bailout bid," *The New York TImes*, April 2009.

[29] Brown, T. W., "Forecasting research & development program budgets using the weibull model," tech. rep., Air Force Institute of Technology, 2002.

[30] Buehler, R., Griffin, D., and Ross, M., "Exploring the "planning fallacy": Why people underestimate their task completion times.," *Journal of personality and social psychology*, vol. 67, no. 3, p. 366, 1994.

[31] Burgess, E., "R&D budget profiles and metrics," *Journal of Parametrics*, vol. 25, no. 1, pp. 11–29, 2006.

[32] Bush, L. B., Unal, R., Rowell, L. F., and Rehder, J. J., "Weight optimization of an aerobrake structural concept for a lunar transfer vehicle," 1992.

[33] Callahan, M. T., Quackenbush, D. G., and Rowings, J. E., *Construction project scheduling.* 1992.

[34] Camarda, C. J. and Adelman, H. M., "Static and dynamic structural-sensitivity derivative calculations in the finite-element-based engineering analysis language (eal) system," 1984.

[35] Ceisel, J., Witte, P., Carr, T., Pogaru, S., and Mavris, D. N., "A non-weight based, manufacturing influenced design (MInD) methodology for preliminary design," in *28th International Congress of the Aeronautical Sciences, Brisbane, Australia*, 2012.

[36] Cerro, J., Martinovic, Z., Su, P., and Eldred, L., "Structural weight estimation for launch vehicles," 2002.

[37] Cerro, J. and Shore, C., "Sizing structures and predicting weight of a spacecraft," 2006.

[38] Chandrashekar Sundaresan, Zilin Elizabeth Tang, J. C. and Mavris, D. N., "A methodology for parametric production planning in preliminary aircraft design,"

[39] Chang, K., "Telescope behind schedule and over budget, panel says," *The New York Times*, November 2010.

[40] Chaplain, C. e. a., "NASA: Actions needed to improve transparency and assess long-term affordability of human exploration programs," tech. rep., Government Accountability Office, May 2014.

[41] Chaplain, C., Morrison, J., Campbell, G., Cederholm, R. A., Culley, B. S., Feldman, N. D., Gill, L. S., Girshick, R. L., Heuwinkel, K. R., Laufer, D. R., Oakley, S. S., Patton, K. E., Schatz, S., and Watson, L. T., "NASA assessments of selected large-scale projects," Tech. Rep. GAO-09-306SP, Government Accountability Office, March 2011.

[42] Chaplain, C., Oakley, S. S., Berkholtz, J. M., Greifner, L., Nemo, R. N., Patton, K. E., Rogers, C., Schatz, S., Singleton, D., Sun, R. T., Van Wychen, K., and Williams, H., "NASA assessments of selected large-scale projects," Tech. Rep. GAO-15-320P, Government Accountability Office, April 2015.

[43] Charania, A. and Olds, J. R., "Prioritization of advanced space transportation technologies utilizing the abbreviated technology, identification, evaluation, and selection (ATIES) methodology for a reusable launch vehicle (RLV)," *Georgia Tech SSDL Masters Projects*, July 2000.

[44] Chen, T., "Technology demonstration missions program," *NASA SPACE TECHNOLOGY MISSION DIRECTORATE*, December 2014.

[45] Chien, C.-F., "A portfolio–evaluation framework for selecting R&D projects," *R&D Management*, vol. 32, no. 4, pp. 359–368, 2002.

[46] Clark, S., "NASA's latest soyuz seat procurement may be its last," *spaceflightnow.com*, May 2014.

[47] Collopy, P. D. and Hollingsworth, P. M., "Value-driven design," *Journal of Aircraft*, vol. 48, no. 3, pp. 749–759, 2011.

[48] Collopy, P., "Value-driven design and the global positioning system," *AIAA paper*, vol. 7213, p. 2006, 2006.

[49] Combier, R., *Risk-informed scenario-based technology and manufacturing evaluation of aircraft systems.* PhD thesis, Georgia Institute of Technology, 2013.

[50] Combier, R., Ceisel, J., Liu, Z., and Mavris, D., "A probabilistic risk-based methodology for manufacturing-influenced aircraft design," in *SAMPE International Symposium*, 2011.

[51] Congressional Budget Office, *A budgetary analysis of NASA's new vision for space exploration.* US Government Printing Office, 2004.

[52] Conrow, E., *Effective Risk Management: Some Keys to Success.* American Institute of Aeronautics and Astronautics, 2nd edition ed., 2003.

[53] Conrow, E. H., "Some long-term issues and impediments affecting military systems acquisition reform," *Acquisition Review Quarterly*, vol. 2, no. 3, pp. 199–212, 1995.

[54] Conrow, E. H., "Estimating technology readiness level coefficients," *Journal of Spacecraft and Rockets*, vol. 48, no. 1, pp. 146–152, 2011.

[55] Cooper, R. and Kaplan, R. S., "Profit priorities from activity-based costing," *Harvard Business Review*, vol. 69, no. 3, pp. 130–135, 1991.

[56] Cottrell, W. D., "Simplified program evaluation and review technique (PERT)," *Journal of construction Engineering and Management*, vol. 125, no. 1, pp. 16–22, 1999.

[57] Creech, D., "MSFC advanced concepts office and the iterative launch vehicle concept method," p. ACOINTROSiterations, February 2011.

[58] Creech, S., Holladay, J., and Jones, D., "SLS dual use upper stage (DUUS) opportunities," tech. rep., NASA, 2013.

[59] Crocker, A. M., Charania, A., and Olds, J., "An introduction to the ROSETTA modeling process for advanced space transportation technology investment," *AIAA*, vol. 4625, pp. 28–30, 2001.

[60] Crumbly, C., Bickley, F., and Hueter, U., "Space launch system advanced development office, FY 2013 annual report," 2013.

[61] Dasgupta, P. and Dodge, W., "High fliers: Creating the talent, leadership, culture and organization capabilities to meet the new business challenges of the aerospace and defense industry," *Accenture*, 2010.

[62] de Rocquigny, E., Devictor, N., and Tarantola, S., *Uncertainty in industrial practice: a guide to quantitative uncertainty management.* John Wiley & Sons, 2008.

[63] Department of Defense, *Risk Management Guide for DOD Acquisition.* sixth ed., August 2006.

[64] Department of Defense, *Defense Acquisition Handbook.* 2011.

[65] Dezfuli, H., Stamatelatos, M., Maggio, G., Everett, C., and Youngblood, R., "Risk-informed decision making," *Office of Safety and Mission Assurance, NASA Headquarters*, no. NASA/SP-2010-576, 2010.

[66] Dezfuli, H., Benjamin, A., Everett, C., Maggio, G., Stamatelatos, M., Youngblood, R., Guarro, S., Rutledge, P., Sherrard, J., Smith, C., and others, *NASA Risk Management Handbook.* No. SP-2011-3422, NASA, 2011.

[67] Dick, S. J. and Launius, R. D., *Critical issues in the history of spaceflight.* No. Section IV, Government Printing Office, 2006.

[68] Driels, M. R. and Shin, Y. S., "Determining the number of iterations for monte carlo simulations of weapon effectiveness," 2004.

[69] Drury, C., *Activity-based costing.* Springer, 1992.

[70] Drury, C., *Management and cost accounting.* Springer, 2013.

[71] Dubos, G. F., *Stochastic Modeling of Responsiveness, Schedule Risk and Obsolescence of Space Systems, and Implications for Design Choices.* PhD thesis, Georgia Institute of Technology, 2011.

[72] Dubos, G. F. and Saleh, J. H., "Spacecraft technology portfolio: Probabilistic modeling and implications for responsiveness and schedule slippage," *Acta Astronautica*, vol. 68, no. 7, pp. 1126–1146, 2011.

[73] Dumoulin, J., *NSTS 1988 News Reference Manual.* NASA Kennedy, 1988.

[74] Elliott, D., Burgess, E., Krause, C., and Sterbutzel, J., "Phasing estimation relationships," in *NASA Cost Symposium*, 2013.

[75] Elmaghraby, S. E., *Activity networks: Project planning and control by network models.* Wiley New York, 1977.

[76] Elton, E. J. and Gruber, M. J., "Modern portfolio theory, 1950 to date," *Journal of Banking & Finance*, vol. 21, no. 11, pp. 1743–1759, 1997.

[77] Erik Burgess, James Smirnoff, B. W., "Weibull analysis method," in *ICEAA Annual Symposium*, National Reconnaisance Office, June 2014.

[78] Eveker, K., "The budgetary implications of NASAs current plans for space exploration," *Congressional Budget Office, Washington DC*, 2009.

[79] Fabrycky, W. J. and Blanchard, B. S., *Life-cycle cost and economic analysis.* Prentice Hall, 1991.

[80] Fikes, J. and Vickers, J., "Composite cryotank technologies and demonstration project," *JANNAF Liquid Propulsion Subcommittee Meeting Materials Session*, 2011.

[81] Fontevecchia, A., "Boeing bleeding cash as 787 dreamliners cost 200m but sell for 116m, but productivity is improving," *Forbes*, May 2013.

[82] Freaner, C. W., Bitten, B., Bearden, D., and Emmons, D., "An assessment of the inherent optimism in early conceptual designs and its effect on cost and schedule growth," *Presentation to the Planetary Science Subcommittee, NASA Advisory Council*, 2008.

[83] Garvey, P., "Introduction to systems cost uncertainty analysis," *MITRE*, May 2006.

[84] Garvey, P. R., "A family of joint probability models for cost and schedule uncertainties," tech. rep., DTIC Document, 1993.

[85] Garvey, P. R., *Probability methods for cost uncertainty analysis: A systems engineering perspective.* CRC Press, 2000.

[86] Gates, D., "Boeing celebrates 787 delivery as program's costs top 32 billion," *The Seattle Times*, 2011.

[87] Gebhardt, C., "NASA confirms EUS for SLS block IB design and EM-2 flight," *NASAspaceflight.com*, June.

[88] Gillett, D., "Strategy in the commercial aircraft industry in the United States: A comparison of decisionmaking by McDonnell-Douglas and Boeing aircraft companies from 1977-1983.," tech. rep., DTIC Document, 1994.

[89] Government Accountability Office, *Constellation Program Cost and Schedule Will Remain Uncertain Until a Sound Business Case Is Established.* GAO-09-844, 2009.

[90] Government Accountability Office, "Cost estimating and assessment guide," no. GAO-09-3SP, 2009.

[91] Graettinger, C. P., Garcia, S., Siviy, J., Schenk, R. J., and Van Syckle, P. J., "Using the technology readiness levels scale to support technology management in the DOD's ATD/STO environments," tech. rep., DTIC Document, 2002.

[92] Griffin, A., "PDMA research on new product development practices: updating trends and benchmarking best practices," *Journal of product innovation management*, vol. 14, no. 6, pp. 429–458, 1997.

[93] Griffin, M. D. G. and French, J. R., *Space vehicle design.* AIAA, 2004.

[94] Grubbs, F. E., "Letter to the editor-attempts to validate certain PERT statistics or picking on PERT," *Operations Research*, vol. 10, no. 6, pp. 912–915, 1962.

[95] Guerra, L., "System hierarchy and work breakdown structure module," *University of Texas at Austin, Space Systems Engineering (SES405) Course Notes*, 2008.

[96] Guo, J. and Du, X., "Sensitivity analysis with mixture of epistemic and aleatory uncertainties," *AIAA journal*, vol. 45, no. 9, pp. 2337–2349, 2007.

[97] Gutowski, T., Henderson, R., and Shipp, C., "Manufacturing costs for advanced composites aerospace parts," *SAMPE JOURNAL*, vol. 27, no. 3, pp. 37–43, 1991.

[98] Hales, S., Tayon, W., and Domack, R., "Friction-stir-welded and spin-formed end domes for cryogenic tanks," in *Proceedings of the 41st Structures and Mechanical Behavior Meeting during the 2012 JANNAF Annual Meeting*, 2012.

[99] Hamaker, J., "So we have done a joint confidence level (JCL) risk analysisnow what?," *SEER by Galorath*, October 2014.

[100] Hamaker, J., *Improving the Predictive Capability of Spacecraft Cost Models.* PhD thesis, University of Alabama, 2005.

[101] Hammond, W. E., *Design methodologies for space transportation systems.* Aiaa, 2001.

[102] Harris, C., "SpaceX: Building rockets from the ground up," *National Council of Space Grant Directors Fall 2012 National Meeting*, 2012.

[103] Haskins, C. e. a., "Systems engineering handbook," 2006.

[104] Havskjold, G., "Developing innovative products on budget and on schedule – part 1: Identifying and measuring cost drivers correlates technical uncertainty with rework cycles," in *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, August 2009.

[105] Heckwolf, A. R., "Integration of demand variability into aircraft factory cost predictions using manufacturing influenced design (MInD)." Georgia Institute of Technology, Special Problems, Spring 2014.

[106] Hender, D. and others, "A miniature version of the ja70 aerodynamic heating computer program, h800 (miniver)," *NASA COSMIC, Athens*, 1970.

[107] Hertzfeld, H. R., Williamson, R. A., and Peter, N., "Launch vehicles: An economic perspective," *George Washington University Space Policy Institute, September*, 2005.

[108] Hill, B., "Status of the human exploration systems development division," *NASA ADVISORY COUNCIL HUMAN EXPLORATION & OPERATIONS COMMITTEE (NAC HEOC)*, January 2015.

[109] Hunt, C., "JCL journey: A look into NASAs joint cost and schedule confidence level policy," in *NASA: Virtual Program Management Challenge*, August 2013.

[110] Hunter, J., McCurdy, D., and Dunn, P., "GTX reference vehicle structural verification methods and weight summary," 2002.

[111] Jimenez, H. and Mavris, D. N., "Characterization of technology integration based on technology readiness levels," *Journal of Aircraft*, vol. 51, no. 1, pp. 291–302, 2014.

[112] Johnson, T. F., Sleight, D. W., and Martin, R. A., "Structures and design phase I summary for the NASA composite cryotank technology demonstration project," *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, April 2013.

[113] Jones, S. C., "Space shuttle orbiter status," *The Space Conference Proceedings*, vol. 17, pp. 1–62 to 1–65, April 1980.

[114] Kapurch, S. J., *NASA Systems Engineering Handbook.* DIANE Publishing, 2010.

[115] Keller, S., Collopy, P., and Componation, P., "What is wrong with space system cost models? a survey and assessment of cost estimating approaches," *Acta Astronautica*, vol. 93, pp. 345–351, 2014.

[116] Kirby, M. R., *A methodology for technology identification, evaluation, and selection in conceptual and preliminary aircraft design.* PhD thesis, Citeseer, 2001.

[117] Kohrs, R., "Human exploration & operation mission directorate update," *NASA ADVISORY COUNCIL HUMAN EXPLORATION & OPERATIONS COMMITTEE (NAC HEOC)*, March 2012.

[118] Larson, W. J. and Wertz, J. R., "Space mission analysis and design," tech. rep., Microcosm, Inc., Torrance, CA (US), 1992.

[119] Lee, D. A., Hogue, M. R., and Gallagher, M. A., "Determining a budget profile from a R&D cost estimate," *The Journal of Cost Analysis*, vol. 14, no. 2, pp. 29–41, 1997.

[120] Lee, J. A., "Risk assessment for titanium pressure vessels operating inside the ares i's liquid hydrogen tank environment," 2008.

[121] Lepsch, R. A., TANLEY, D. O., RUZ, C. I., and ORRIS, S. J., "Utilizing air-turborocket and rocket propulsion for a single-stage-to-orbit vehicle," *Journal of Spacecraft and Rockets*, vol. 28, no. 5, pp. 560–566, 1991.

[122] Liu, Z., Witte, P., and Cei, "An approach to infuse manufacturing considerations into aircraft structural designan approach to infuse manufacturing considerations into aircraft structural design," in *Society for the Advancement of Materials and Process Engineering (SAMPE)*, May 2011.

[123] Loch, C. and Kavadias, S., *Handbook of new product development management.* Routledge, 2008.

[124] Logsdon, J. M., Williamson, R. A., Launius, R. D., Acker, R. J., Garber, S. J., and Friedman, J. L., *Exploring the unknown: selected documents in the history of the U.S. civilian space program (The NASA history series) (NASA SP: 4407) Document IV*, vol. IV. 1999.

[125] Logsdon, J. M., Williamson, R. A., Launius, R. D., Acker, R. J., Garber, S. J., and Friedman, J. L., *Exploring the unknown: selected documents in the history of the U.S. civilian space program (The NASA history series) (NASA SP: 4407)*, vol. IV, Chapter IV. 1999.

[126] Louderback, P. M., "A software upgrade of the NASA aeroheating code MINIVER," Master's thesis, Florida Institute of Technology, 2013.

[127] MacCrimmon, K. R. and Ryavec, C. A., "An analytical study of the PERT assumptions," *Operations Research*, vol. 12, no. 1, pp. 16–37, 1964.

[128] MacKenzie, D. and Addison, B., "Space system cost variance and estimating uncertainty," in *22nd Annual ISPA Conference, Noordwijk, The Netherlands*, 2000.

[129] Malcolm, D. G., Roseboom, J. H., Clark, C. E., and Fazar, W., "Application of a technique for research and development program evaluation," *Operations research*, vol. 7, no. 5, pp. 646–669, 1959.

[130] Mankins, J. C., "Technology readiness levels," *White Paper, April*, vol. 6, 1995.

[131] Mankins, J. C., "Research & development degree of difficulty (R&D3)," *White Paper, March*, vol. 10, 1998.

[132] Mankins, J. C., "Approaches to strategic research and technology (R&T) analysis and road mapping," *Acta Astronautica*, vol. 51, no. 1, pp. 3–21, 2002.

[133] Mankins, J. C., "Technology readiness and risk assessments: A new approach," *Acta Astronautica*, vol. 65, no. 9, pp. 1208–1215, 2009.

[134] Martin Jr, C. J., "Documentation for a structural optimization procedure developed using the engineering analysis language (EAL)," 1996.

[135] Mavris, D. N., "Economic of aircraft manufacture and airline operation." Advanced Design Methods I Lecture Notes, October 2011.

[136] Mavris, D. N., DeLaurentis, D. A., Bandte, O., and Hale, M. A., "A stochastic approach to multi-disciplinary aircraft analysis and design," in *36th Aerospace Sciences Meeting & Exhibit, Reno, NV*, 1998.

[137] McAfee, J., Culver, G., and Naderi, M., "NASA Air Force cost model (NAFCOM): Capabilities and results," in *JANNAF MSS / LPS / SPS Joint Meeting*, 2011.

[138] McMahan, T. and Anderson, T., "Move over heavy metal, there's a new tank coming to town," *NASA Press Release*, 2014.

[139] McMillin, M., Rehder, J., Wilhite, A., Schwing, J., Spangler, J., and Mills, J., "A solid modeler for aerospace vehicle preliminary design," *AIAA Paper*, no. 2901, pp. 14–16, 1987.

[140] Milner, T., Volas, M., and Sanders, A., "Systems engineering methodology for linking requirements to design complexity and manufacturing trade space constraints," in *Conference on Systems Engineering Research*, vol. 16, pp. 947 – 956, 2013.

[141] Moder, J. J., Phillips, C. R., and Davis, E. W., "Project management with CPM, PERT, and precedence diagramming," 1983.

[142] Mooney, C. Z., Duval, R. D., and Duval, R., *Bootstrapping: A nonparametric approach to statistical inference.* No. 94-95, Sage, 1993.

[143] Morrison, J. a., "NASAS challenges to meeting cost, schedule, and performance goals," tech. rep., NASA's Office of the Inspector General, 2012.

[144] National Aeronautics and Space Administration, "Agency risk management procedural requirements," no. NPR 8000.4A.

[145] National Aeronautics and Space Administration, "Asteroid redirect mission crewed mission (ARCM) concept study,"

[146] National Aeronautics and Space Administration, "NASA Facts:space launch system core stage," no. FS-2013-05-052-MSFC.

[147] National Aeronautics and Space Administration, "NASA space flight program and project management requirements," *NASA Procedural Requirements*, no. NPR 7120.5D.

[148] National Aeronautics and Space Administration, "Fact sheet 7: The policy origins of the X-33," March 2000.

[149] National Aeronautics and Space Administration, "NASA reaches milestone in space launch initiative program," *NASA News Release 01-31*, March 2001.

[150] National Aeronautics and Space Administration, "Super lightweight external tank," *NASA Facts*, vol. FS-2005-04-025-MSFC, April 2005.

[151] National Aeronautics and Space Administration, "Cost estimating handbook," 2008.

[152] National Aeronautics and Space Administration, "General safety program requirements," March 2008.

[153] National Aeronautics and Space Administration, *Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis.* NASA/SP-2009-569, 2009.

[154] National Aeronautics and Space Administration, "Joint cost and schedule confidence level (JCL): A status report," February 2010.

[155] National Aeronautics and Space Administration, "Schedule management handbook," no. SP2010-3403, 2010.

[156] National Aeronautics and Space Administration, "Falcon 9 launch vehicle NAFCOM cost estimates," August 2011.

[157] National Aeronautics and Space Administration, "Preliminary report regarding NASAs space launch system and multi-purpose crew vehicle," 2011.

[158] National Aeronautics and Space Administration, "NASA uses twin processes to develop new tank dome technology," *News & Features*, 2012.

[159] National Aeronautics and Space Administration, "Policy directive: Policy for NASA aquisition," no. NPD1000.5, 2013.

[160] National Aeronautics and Space Administration, "About NASA," November 2014.

[161] National Aeronautics and Space Administration, "Composite cryotank technologies and demonstration (CCTD)," 2014.

[162] National Aeronautics and Space Administration, "FY 2014 complete budget estimates," 2014.

[163] National Aeronautics and Space Administration, *NASA's Space Flight Program and Project Management Handbook*. NASA, 2014.

[164] National Aeronautics and Space Administration, "Space launch system," *NASA Facts*, vol. FS-2014-08-123-MSFC, 2014.

[165] National Aeronautics and Space Administration, "Space launch system core stage," *NASA facts*, vol. FS-2014-09-132-MSFC, September 2014.

[166] National Aeronautics and Space Administration, "Vehicle analysis branch (VAB)," 03 2014. Retrieved on 20/05/2015 from http://sacd.larc.nasa.gov/branches/vehicle-analysis-branch-vab.

[167] National Aeronautics and Space Administration, "NASA - space shuttle and international space station," July 2015. Space Shuttle and Internation Space Station.

[168] National Aeronautics and Space Administration, "Space launch system," *NASA facts*, October 2015.

[169] National Aeronautics and Space Administration, "Technology demonstration missions-bridging the technology gap," *NASA facts*, October 2015.

[170] Nolte, W., Kennedy, B. C., and Dziegiel, R., "Technology readiness calculator," *White Paper*, 2004.

[171] Oberkampf, W. L., DeLand, S. M., Rutherford, B. M., Diegert, K. V., and Alvin, K. F., "Error and uncertainty in modeling and simulation," *Reliability Engineering & System Safety*, vol. 75, no. 3, pp. 333–357, 2002.

[172] of Defense, D., "Manufacturing readiness level (MRL) deskbook," *OSD Manufacturing Technology Program*, no. Ver 2.0, 2011.

[173] Pielke, R. and Byerly, R., "Shuttle programme lifetime cost," *Nature*, vol. 472, pp. 38–38, Apr. 2011.

[174] Pielke, R. A., "Data on and methodology for calculating space shuttle programme costs," *Space Policy*, vol. 10, no. 1, pp. 78–80, 1994.

[175] Pieniazek, L., "The NASA program/project life cycle process flow wall chart," *National Aeronautics and Space Administration*.

[176] Porter, P. H., "Revising R&D program budgets when considering funding curtailment with a weibull model," tech. rep., DTIC Document, 2001.

[177] Ramirez-Marquez, J. E. and Sauser, B. J., "System development planning via system maturity optimization," *Engineering Management, IEEE Transactions on*, vol. 56, no. 3, pp. 533–548, 2009.

[178] Raouf, R. A., "Tailoring the dynamic characteristics of composite panels using fiber orientation," *Composite structures*, vol. 29, no. 3, pp. 259–267, 1994.

[179] Rattigan, J., Neubek, D., Thomas, D., and Stegemoeller, C., "Constellation program lessons learned; volume 1: Executive summary," Tech. Rep. SP-2011-6127-VOL-1, NASA Johnson Space Center, 2011.

[180] Rattigan, J., Neubek, D., Thomas, D., and Stegemoeller, C., "Constellation program lessons learned; volume 2: Detailed lessons learned," Tech. Rep. SP-2011-6127-VOL-2, NASA Johnson Space Center, 2011.

[181] Ray, S., "Boeing's 787 finally takes flight," *Bloomberg Business Week*, 2009.

[182] Raymer, D. P., *Aircraft Design: A Conceptual Approach and RDS-student, Software for Aircraft Design, Sizing, and Performance Set (AIAA Education).* AIAA, 2006.

[183] Reed, R. P., Purtscher, P., Simon, N., McColskey, J., and Walsh, R., "Aluminum alloys for ALS cryogenic tanks: Comparative measurements of cryogenic mechanical properties of Al-Li alloys and alloy 2219," tech. rep., DTIC Document, 1991.

[184] Regan, H. M., Colyvan, M., and Burgman, M. A., "A taxonomy and treatment of uncertainty for ecology and conservation biology," *Ecological applications*, vol. 12, no. 2, pp. 618–628, 2002.

[185] Reynolds, J., "P-BEAT: A process-based economic analysis tool," *https://mdao.grc.nasa.gov/topstoryarchive014.html*, 2015.

[186] Robertson, B. E., *A hybrid probabilistic method to estimate design margin.* PhD thesis, Georgia Institute of Technology, 2013.

[187] Roussel, P. A., *Third generation R&D: managing the link to corporate strategy.* Harvard Business Press, 1991.

[188] Rush, C. and Roy, R., "Expert judgement in cost estimating: Modelling the reasoning process," *Concurrent Engineering*, vol. 9, no. 4, pp. 271–284, 2001.

[189] Sadin, S. R., Povinelli, F. P., and Rosen, R., "The NASA technology push towards future space mission systems," *Acta Astronautica*, vol. 20, pp. 73–77, 1989.

[190] Sanders, A., "21st century manufacturing modeling and simulation research and investment needs," tech. rep., National Defense Industrial Association, 2011.

[191] Sauser, B., Gove, R., Forbes, E., and Ramirez-Marquez, J. E., "Integration maturity metrics: Development of an integration readiness level," *Information, Knowledge, Systems Management*, vol. 9, no. 1, pp. 17–46, 2010.

[192] Sauser, B., Ramirez-Marquez, J., Verma, D., and Gove, R., "Determining system interoperability using an integration readiness level," in *Proceedings, NDIA Conference Proceedings*, Citeseer, 2006.

[193] Sauser, B., Verma, D., Ramirez-Marquez, J., and Gove, R., "From TRL to SRL: The concept of systems readiness levels," in *Conference on Systems Engineering Research, Los Angeles, CA*, 2006.

[194] Sauser, B. J., Ramirez-Marquez, J. E., Henry, D., and DiMarzio, D., "A system maturity index for the systems engineering life cycle," *International Journal of Industrial and Systems Engineering*, vol. 3, no. 6, pp. 673–691, 2008.

[195] Schankman, M. and John, R., "Advancing the art of technology cost estimatinga collaboration between NASA and Boeing," in *Proceedings of ISPA/SCEA International Conference, San Diego, California*, 2010.

[196] Schrader, A., "Lockheed Martin preparing to build new GPS satellites in Denver-area facility," *The Denver Post*, December 2011.

[197] Schrage, D. P., "Technology for rotorcraft affordability through integrated product/process development (IPPD)," in *Annual Forum Proceedings- American Helicopter Society*, vol. 2, pp. 2406–2424, Citeseer, 1999.

[198] Schrage, D. P. and Rogan, J. E., "The impact of concurrent engineering on aerospace systems design," *An Internal Paper to the School of Aerospace Engineering, Georgia Institute of Technology*, 1990.

[199] Schwenn, R. E., Brink, H., Mebane, C., Seales, S., and Wintfeld, J., "Defense acquisitions: Assessments of selected weapon programs," 2009.

[200] Scott, D., Ceisel, J., and Mav, "Leveraging high fidelity manufacturing models in conceptual and preliminary design," in *Society for the Advancement of Materials and Process Engineering (SAMPE)*, May 2012.

[201] Shishko, R. and Ebbeler, D., "A real-options approach for NASA strategic technology selection," 1999.

[202] Siedlak, D. J., Schlais, P. R., Pinon, O. J., and Mavris, D. N., "Supporting affordability-based design decisions in the presence of demand variability," in *ASME 2015 International Manufacturing Science and Engineering Conference*, pp. V002T04A004–V002T04A004, American Society of Mechanical Engineers, 2015.

[203] Siedlak, D. J., Schmidt, T. M., Pinon, O. J., and Mavris, D. N., "A methodology for the parametric exploration of the impact of production planning on the early stages of design," in *ASME 2014 International Manufacturing Science and Engineering Conference collocated with the JSME 2014 International Conference on Materials and Processing and the 42nd North American Manufacturing Research Conference*, pp. V001T04A003–V001T04A003, American Society of Mechanical Engineers, 2014.

[204] Sil, A. and Reynolds, J., "Process-based economic analysis tool user guide," vol. v2b, 2010.

[205] Singer, C. E. and Dumbacher, D. L., "Getting to first flight: Equipping space engineers to break the start-stop-restart cycle," in *AIAA Space 2010 Conference*, Spetember 2010.

[206] Singer, J. A., Cook, J. R., and Singer, C. E., "NASA space launch system operations strategy," 2012.

[207] Smart, C., Reese, G., Adams, L., Batchelor, A., and Redrick, A., "Process-based cost modeling," *Journal of Parametrics*, vol. 26, no. 1, pp. 79–100, 2007.

[208] Smith, J. D., "An alternative to technology readiness levels for non-developmental item (NDI) software," in *System Sciences, 2005. HICSS'05. Proceedings of the 38th Annual Hawaii International Conference on*, pp. 315a–315a, IEEE, 2005.

[209] Smith, M., "Did NASA really waste $20 billion in cancelled human space flight programs?," *Spacepolicyonline.com*, September 2012.

[210] Smith, R. M., "Ares I-X lessons learned: Integration, test and verification," *AIAA Complex Aerospace Systems Exchange*, September 2012. https://www.aiaa.org/uploadedFiles/Events/Conferences/2012_Conferences/2012-Complex-Aerospace-Systems-Exchange-Event/Detailed_Program/CASE2012_2-4_Smith_presentation.pdf.

[211] Sobieszczanski-Sobieski, J., *Multidisciplinary optimization for engineering systems: Achievements and potential.* Springer, 1989.

[212] Song, X. M. and Montoya-Weiss, M. M., "Critical development activities for really new versus incremental products," *Journal of Product Innovation Management*, vol. 15, no. 2, pp. 124–135, 1998.

[213] Stamatelatos, M. and Dezfuli, H., *Probabilistic Risk Assessment Procedure Guide for NASA Managers and Practitioners.* No. NASA/SP-2011-3421, 2 ed., December 2011.

[214] Stickler, P., "Composite materials for commercial transport-issues and future research directions," in *Americal Society for Composites 17th Technical Conference, West Lafayatte, Indiana, USA*, 2002.

[215] Sudol, A., *Methodology for Modeling the Verification, Validation, and Testing Process for Launch Vehicles.* PhD thesis, Georgia Institute of Technology, December 2015.

[216] Sudol, A. M., "Methodology for modeling the verification, validation, and testing process for launch vehicles: Proposal presentation." September 2014.

[217] Sullivan, M., "Best practices: An integrated portfolio management approach to weapon system investments could improve dods acquisition outcomes," *United States Government Accountability Office, Washington, DC, USA, Rep. GAO-07-388*, 2007.

[218] Thomas, B., Derup, M., Keener, K., and Masters, T., "Defense acquisitions: Assessments of selected weapon programs," 2013.

[219] Unger, E. J., "Relating initial budget to program growth with rayleigh and weibull models," Master's thesis, Air Force Institute of Technology, 2001.

[220] Volz, M., Chen, P., Gorti, S., and Salvail, P., "Development of aluminum-lithium 2195 gores by the stretch forming process," *Age*, vol. 3, p. 5.

[221] Wall, M., "NASA's 1st manned flight of orion space capsule may slip to 2023," *Space.com*, 2015.

[222] Walpole, R. E., Myers, R. H., Myers, S. L., and Ye, K., *Probability and statistics for engineers and scientists*, vol. 5. Macmillan New York, 1993.

[223] Walsh, J. L., "Application of mathematical optimization procedures to a structural model of a large finite-element wing," 1986.

[224] Whetstone, W., "EISI-EAL: A general engineering analysis and design language," *Finite Elements in Analysis and Design*, vol. 2, no. 1, pp. 219–235, 1986.

[225] Yang, K. Y. and Bilbro, J. W., "Technology integration and improved technology maturity assessments," *AIAA Southern California Aerospace Systems and Technology Conference*, 2009.

[226] Zio, E. and Apostolakis, G., "Two methods for the structured assessment of model uncertainty by experts in performance assessments of radioactive waste repositories," *Reliability Engineering & System Safety*, vol. 54, no. 2, pp. 225–241, 1996.

[227] Zwack, M. R., *A hybrid reliability growth method for projection of reliability and safety of conceptual launch vehicles.* PhD thesis, Georgia Institute of Technology, 2014.

VITA

Tyler R. Milner was born in Port Elizabeth South Africa in 1987. He immigrated to Scottsdale Arizona in August of 2003, where he completed high school and began his aerospace engineering journey, earning two bachelors degrees from Arizona State University. Graduating with high honors in 2010, having lead two capstone projects one of which placed second in the AIAA Team Space Transportation Competition 2010, he took a gap year before beginning his graduate career at Georgia Institute of Technology. Tyler is a rugby fanatic, he started a rugby club and later captained the state squad for a year before starting on the ASU team. After sustaining far too many injuries, Tyler retired from rugby and remains a dedicated Springbok fan. Tyler married the girl of his dreams in May 2014, shortly before celebrating their 9th anniversary as a couple, and they intend to live happily ever after. Upon completion of his PhD, Tyler will begin his engineering career as a Senior Multidisciplinary Systems Engineer at the MITRE Corporation in Bedford, MA.