Process-based Cost Estimation for Ramjet/Scramjet Engines

Brijendra Singh and Felix Torres of NASA Glenn Research Center
Miles Nesman and John Reynolds of Boeing Canoga Park.

Process-based cost estimation plays a key role in effecting cultural change that integrates distributed science, technology and engineering teams to rapidly create innovative and affordable products. Working together, NASA Glenn Research Center and Boeing Canoga Park have developed a methodology of process-based cost estimation bridging the methodologies of high-level parametric models and detailed bottoms-up estimation.

The NASA GRC/Boeing CP process-based cost model provides a probabilistic structure of layered cost drivers. High-level inputs characterize mission requirements, system performance, and relevant economic factors. Design alternatives are extracted from a standard, product-specific work breakdown structure to pre-load lower-level cost driver inputs and generate the cost-risk analysis. As product design progresses and matures the lower level more detailed cost drivers can be re-accessed and the projected variation of input values narrowed, thereby generating a progressively more accurate estimate of cost-risk.

Incorporated into the process-based cost model are techniques for decision analysis, specifically, the analytic hierarchy process (AHP) and functional utility analysis. Design alternatives may then be evaluated not just on cost-risk, but also user defined performance and schedule criteria. This implementation of full-trade study support contributes significantly to the realization of the integrated development environment.

The process-based cost estimation model generates development and manufacturing cost estimates. The development team plans to expand the manufacturing process base from ~80 manufacturing processes to over 250 processes. Operation and support cost modeling is also envisioned.

Process-based estimation considers the materials, resources, and processes in establishing cost-risk and rather depending on weight as an input, actually estimates weight along with cost and schedule.

Biographical Information

Brijendra. Singh is team leader of the Economic Assessment and Forecasting Team within the Airbreathing Systems Analysis Office of NASA Glenn Research Center. He has 30+ years experience, both in industry and government.

Felix Torres is an aerospace engineer responsible for engine cost analysis on the Economic Assessment and Forecasting Team within the Airbreathing Systems Analysis Office of NASA Glenn Research Center. Mr. Torres was the Technical Monitor of the contract under which the Process-based Development Cost Model was developed. He has 20+ years experience in industry and government

Miles Nesman is the affordability team leader in Systems Synthesis and Architecture section of the Systems Engineering and Software Development Process at Boeing Canoga Park. He has 30+ years systems engineering experience in the aerospace industry. He is the Boeing Canoga Park representative in the Space Systems Cost Analysis Group and contributing author of the process-based cost model.

John Reynolds is an affordability analyst in Systems Synthesis and Architecture section of the Systems Engineering and Software Development Process at Boeing Canoga Park. He has 20+ years in the industrial engineering and cost estimation. He is the principal author and programmer for the process-based cost model.

Process-based Estimation Program

Cost Analysis: Path to Better Management

Prepared by

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with
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Preview

- Introduction
- Methodology
- Description of Model
- Steps in Preparing an Estimate
  - Inputs
  - Outputs
- Status
- Summary

Introduction

NASA Motivation & Objective

- NASA Motivation
  - Revolutionary technology/architecture studies require use of advanced technology for which no reliable, non-proprietary cost estimating relationships exist.
  - Need exists to identify enabling technologies and architectures to guide NASA's investment strategy to high payoff technologies.
- NASA Objective
  - Develop non-proprietary, process-based cost estimation program suitable for integration with advanced physics based design and analysis tools.

Introduction

Key Features

- Process-based cost estimating relationships are product independent.
- Process-based cost estimating relationships can be effectively applied during any phase of the product life cycle, including during the concept development phase.
- Historic data can be obtained which adequately describes the characteristics required by process-based cost estimating relationships.
- Historic data can be used for validation.

Methodology

- Summary
- Development Schedule
- Schedule Estimate & Analysis
- Cost Estimation & Analysis
- Objective Analysis
- Expected Cost Output
- Application of Development Cost Model
- Estimate Steps

Methodology

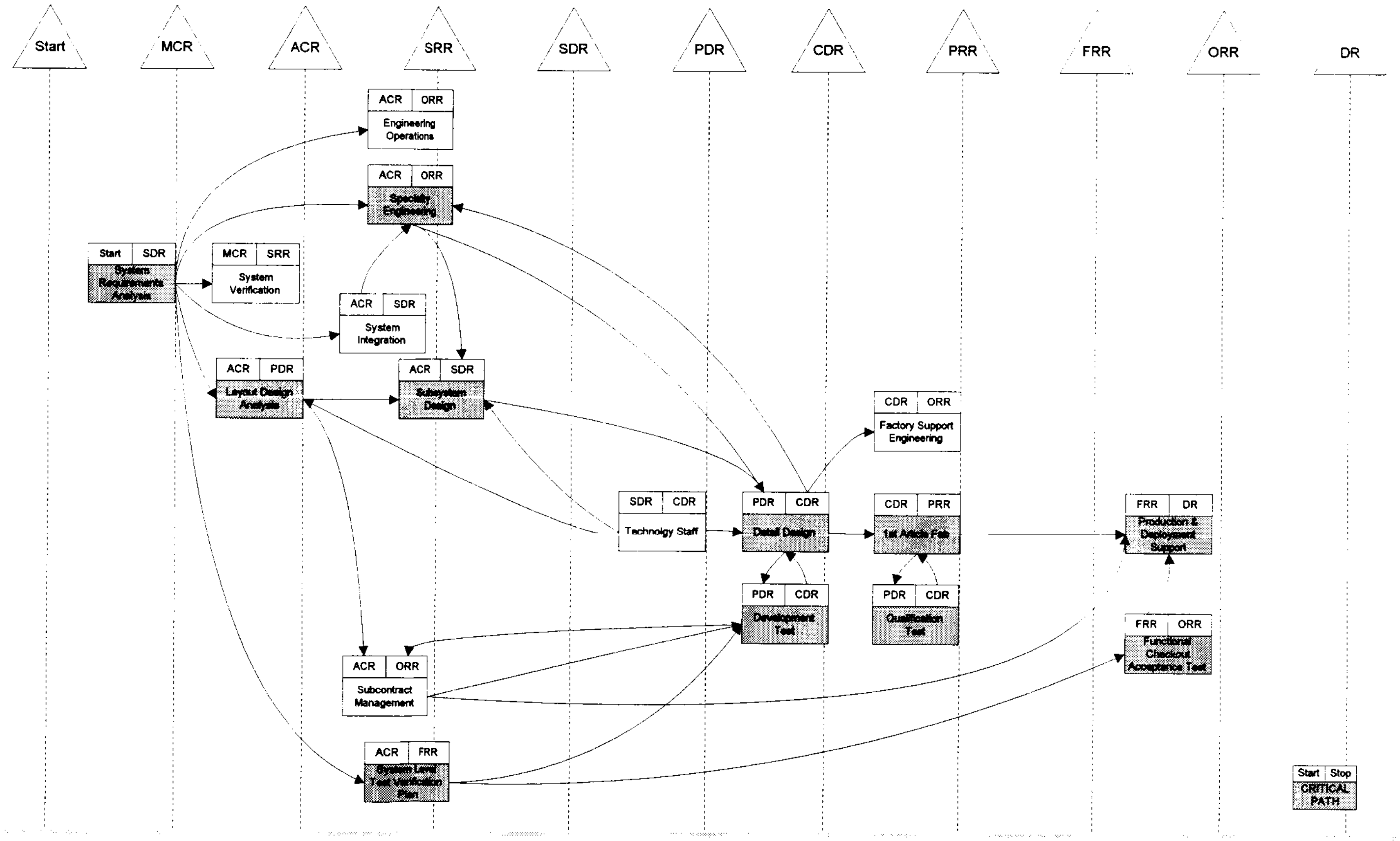
Summary

- Intended to correct deficiencies found in existing cost estimating methodologies
  - Parametric and detailed work breakdown structure methodologies
- Intended scope to cover the entire product life cycle
  - Conceptual design
  - Preliminary design
  - Detailed design
  - Prototype development and test
  - Production
  - Operation and support
  - Retirement and disposal
- Model to employ both a top-down and bottoms-up approach
  - Probabilistic model includes elements of both methodologies
  - Makes use of cost via analogy when cost data is not readily available.

Methodology

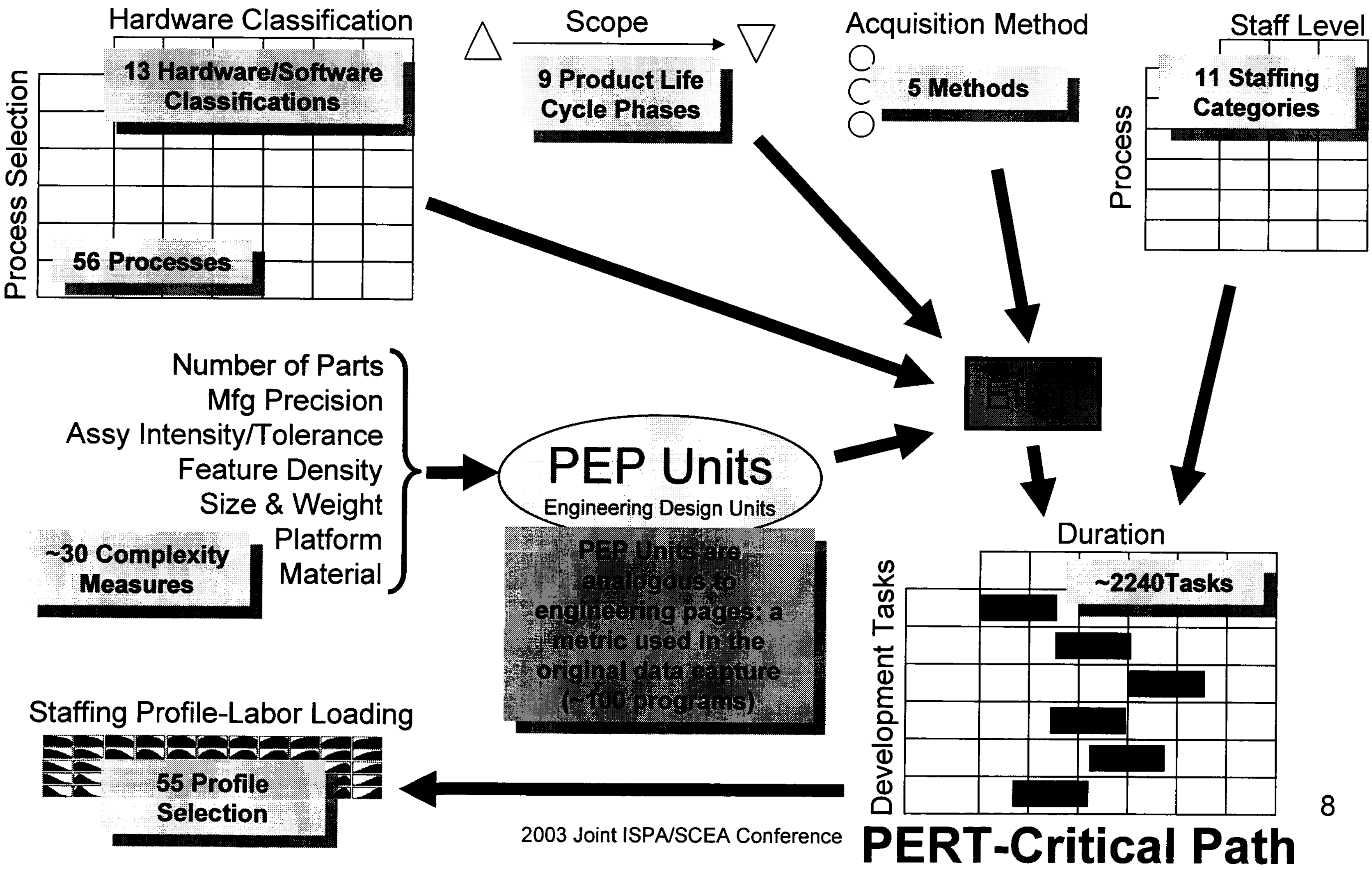
Development Schedule - Critical Path Method

2200+ development tasks included



Methodology

Schedule Estimate & Analysis



Hardware Classification

Process Selection

13 Hardware/Software Classifications

56 Processes

Scope

9 Product Life Cycle Phases

Acquisition Method

○
○
○

5 Methods

Staff Level

Process

11 Staffing Categories

Number of Parts
Mfg Precision
Assy Intensity/Tolerance
Feature Density
Size & Weight
Platform
Material

~30 Complexity Measures

PEP Units

Engineering Design Units

PEP Units are analogous to engineering pages: a metric used in the original data capture (~100 programs)

Duration

Development Tasks

~2240Tasks

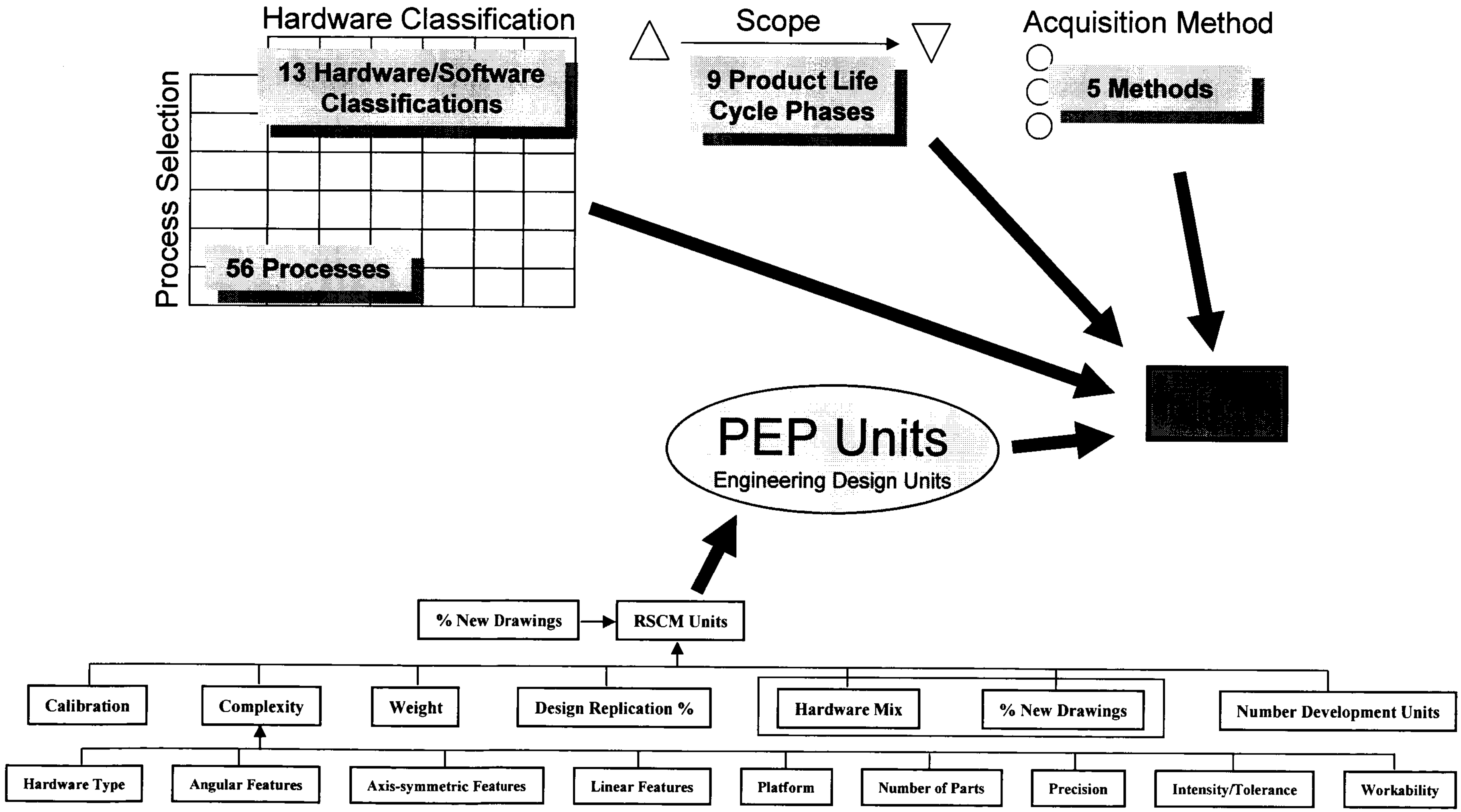
PERT-Critical Path

Staffing Profile-Labor Loading

55 Profile Selection

Methodology

Cost Estimation & Analysis



Hardware Classification

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9 Product Life Cycle Phases

Acquisition Method

○
○
○

5 Methods

[illegible]

PEP Units

Engineering Design Units

% New Drawings → RSCM Units

Calibration

Complexity

Weight

Design Replication %

Hardware Mix

% New Drawings

Number Development Units

Hardware Type

Angular Features

Axis-symmetric Features

Linear Features

Platform

Number of Parts

Precision

Intensity/Tolerance

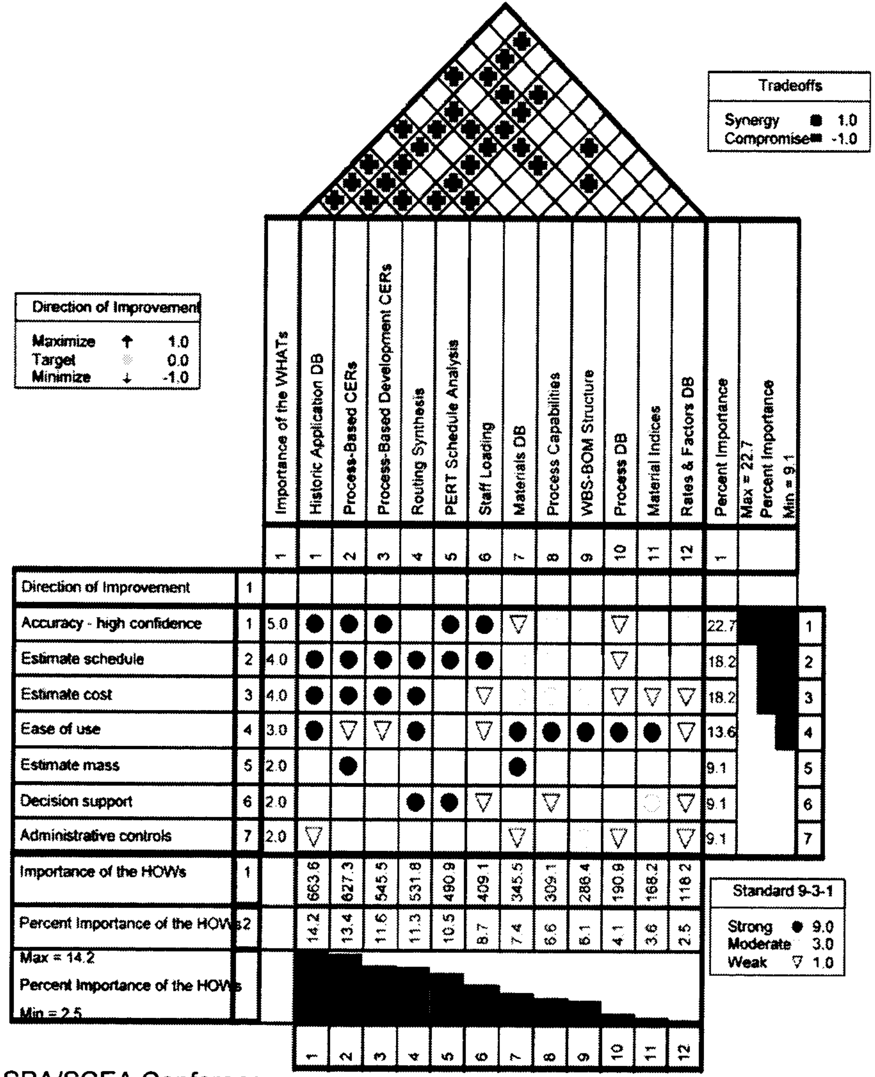
Workability

Methodology

Objective Analysis

Customer 'wants'
- Accuracy-High Confidence
  - Estimate Mass
  - Estimate Cost
  - Estimate Schedule
- Easy to use
  - Decision Support
  - Administrative Controls

Technical 'hows'
- Historic Application DB
- Process-based CERs
  - Development
  - Production
  - O&S
- Task Synthesis
- Staff Loading
- PERT (critical path analysis)
- Materials DB
- Process Capabilities DB



Tradeoffs
Synergy ● 1.0
Compromise ■ -1.0

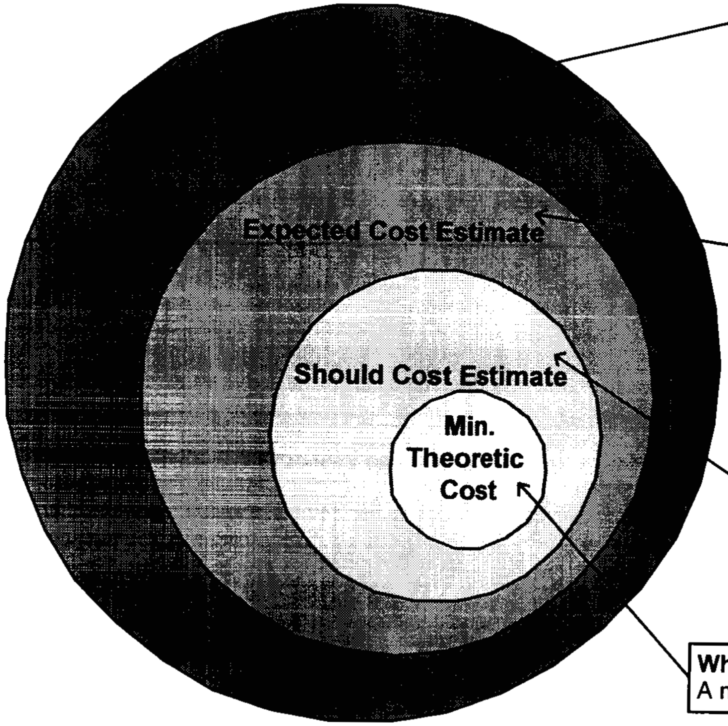
Direction of Improvement
Maximize ↑ 1.0
Target ○ 0.0
Minimize ↓ -1.0

		Importance of the WHATs	Historic Application DB	Process-Based CERs	Process-Based Development CERs	Routing Synthesis	PERT Schedule Analysis	Staff Loading	Materials DB	Process Capabilities	WBS-BOM Structure	Process DB	Material Indices	Rates & Factors DB	Percent Importance	Max = 22.7 Percent Importance Min = 9.1	
		1	1	2	3	4	5	6	7	8	9	10	11	12	1		
Direction of Improvement	1																
Accuracy - high confidence	1	5.0	●	●	●		●	●	▽			▽			22.7		1
Estimate schedule	2	4.0	●	●	●	●	●	●				▽			18.2		2
Estimate cost	3	4.0	●	●	●	●		▽	○	○	○	▽	▽	▽	18.2		3
Ease of use	4	3.0	●	▽	▽	●		▽	●	●	●	●	●	▽	13.6		4
Estimate mass	5	2.0		●					●						9.1		5
Decision support	6	2.0				●	●	▽		▽			○	▽	9.1		6
Administrative controls	7	2.0	▽						▽		○	▽		▽	9.1		7
Importance of the HOWs	1		663.6	627.3	545.5	531.8	490.9	409.1	345.5	309.1	286.4	190.9	168.2	118.2			
Percent Importance of the HOWs	2		14.2	13.4	11.6	11.3	10.5	8.7	7.4	6.6	5.1	4.1	3.6	2.5			
Max = 14.2 Percent Importance of the HOWs Min = 2.5																	
			1	2	3	4	5	6	7	8	9	10	11	12			

Standard 9-3-1
Strong ● 9.0
Moderate ○ 3.0
Weak ▽ 1.0

Methodology

Expected Cost Output



What is *planned* cost?
Planned cost accounts for other additional cost variation attributed to forced schedule changes, including accelerated or decelerated schedule resulting from crash programs, interrupted funding, restructuring, out-of-sequence work, design changes (due to complexity driven errors, late improvements and changes dictated by management, and customer requirements volatility), etc.

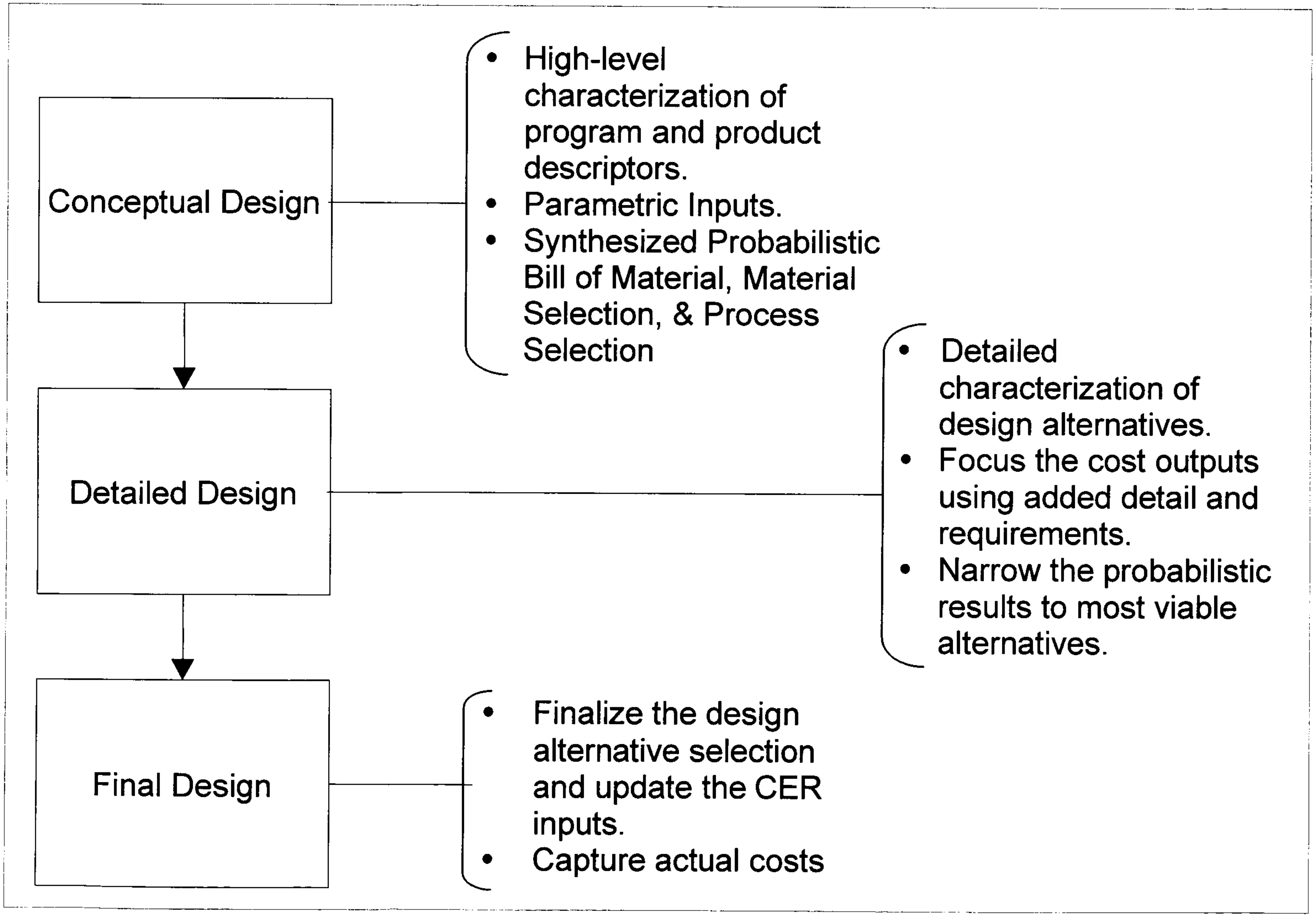
What is *expected* cost?
Expected cost accounts for cultural impact, contingency factors and risk. Cultural factors are typically characterized in cost modeling by definition of platform. The platform identifies the operational environment, which in turn dictates quality level requirements. Components for an unmanned space application might be over-qualified by a engineering team accustomed to a manned-space culture.

What is *should* cost?
A should cost estimate accounts for reasonable process variation but not for cultural variation. Process variation includes the potential variation of function, material, physical size and shape, etc.

What is *minimum theoretic* cost?
A minimum theoretic cost assumes no variation.

Methodology

Application of Development Cost Model



Conceptual Design

- High-level characterization of program and product descriptors.
- Parametric Inputs.
- Synthesized Probabilistic Bill of Material, Material Selection, & Process Selection

Detailed Design

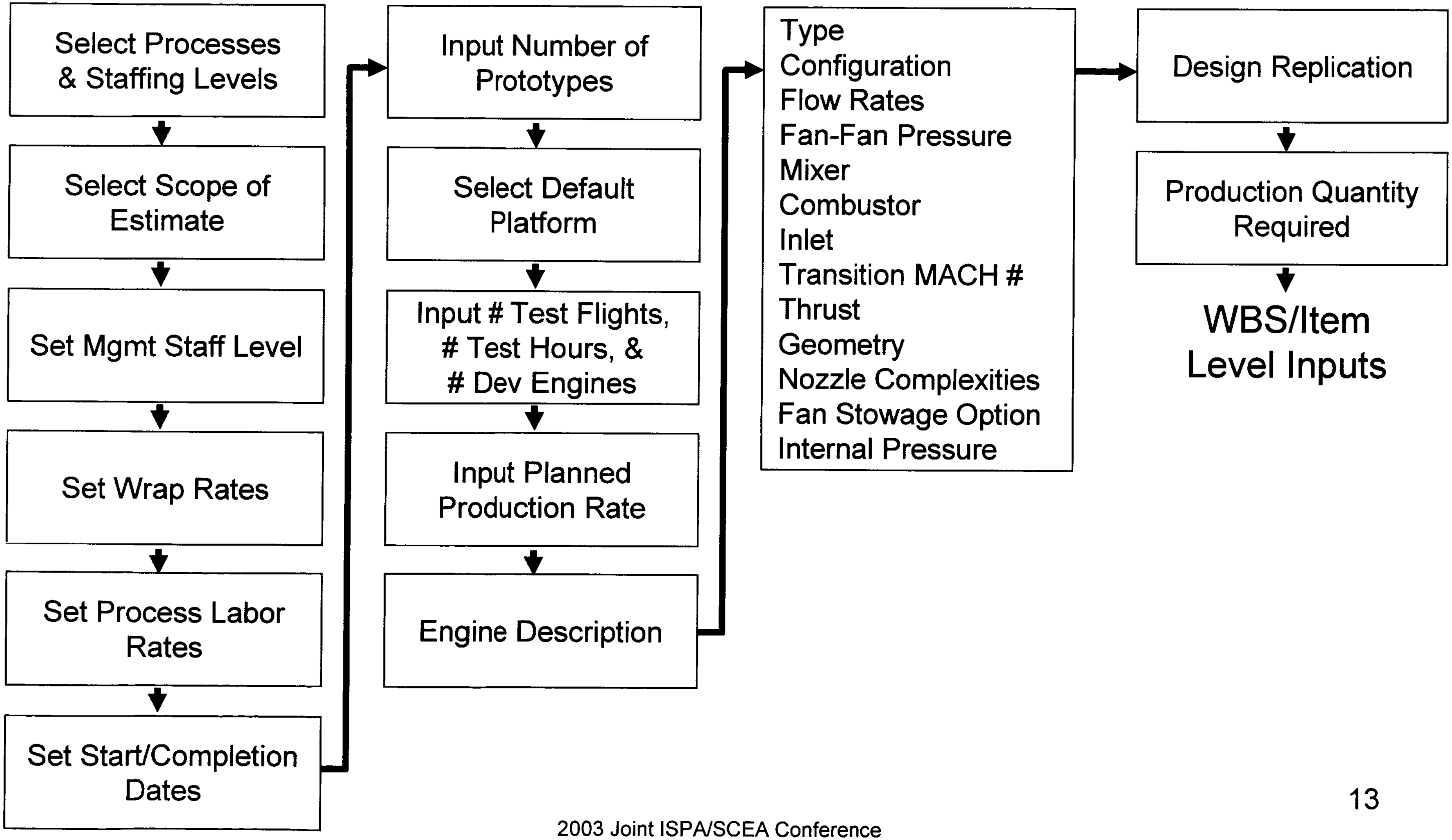
- Detailed characterization of design alternatives.
- Focus the cost outputs using added detail and requirements.
- Narrow the probabilistic results to most viable alternatives.

Final Design

- Finalize the design alternative selection and update the CER inputs.
- Capture actual costs

Methodology

Estimate Steps



- Select Processes & Staffing Levels
- Select Scope of Estimate
- Set Mgmt Staff Level
- Set Wrap Rates
- Set Process Labor Rates
- Set Start/Completion Dates

- Input Number of Prototypes
- Select Default Platform
- Input # Test Flights, # Test Hours, & # Dev Engines
- Input Planned Production Rate
- Engine Description

Type
Configuration
Flow Rates
Fan-Fan Pressure
Mixer
Combustor
Inlet
Transition MACH #
Thrust
Geometry
Nozzle Complexities
Fan Stowage Option
Internal Pressure

- Design Replication
- Production Quantity Required

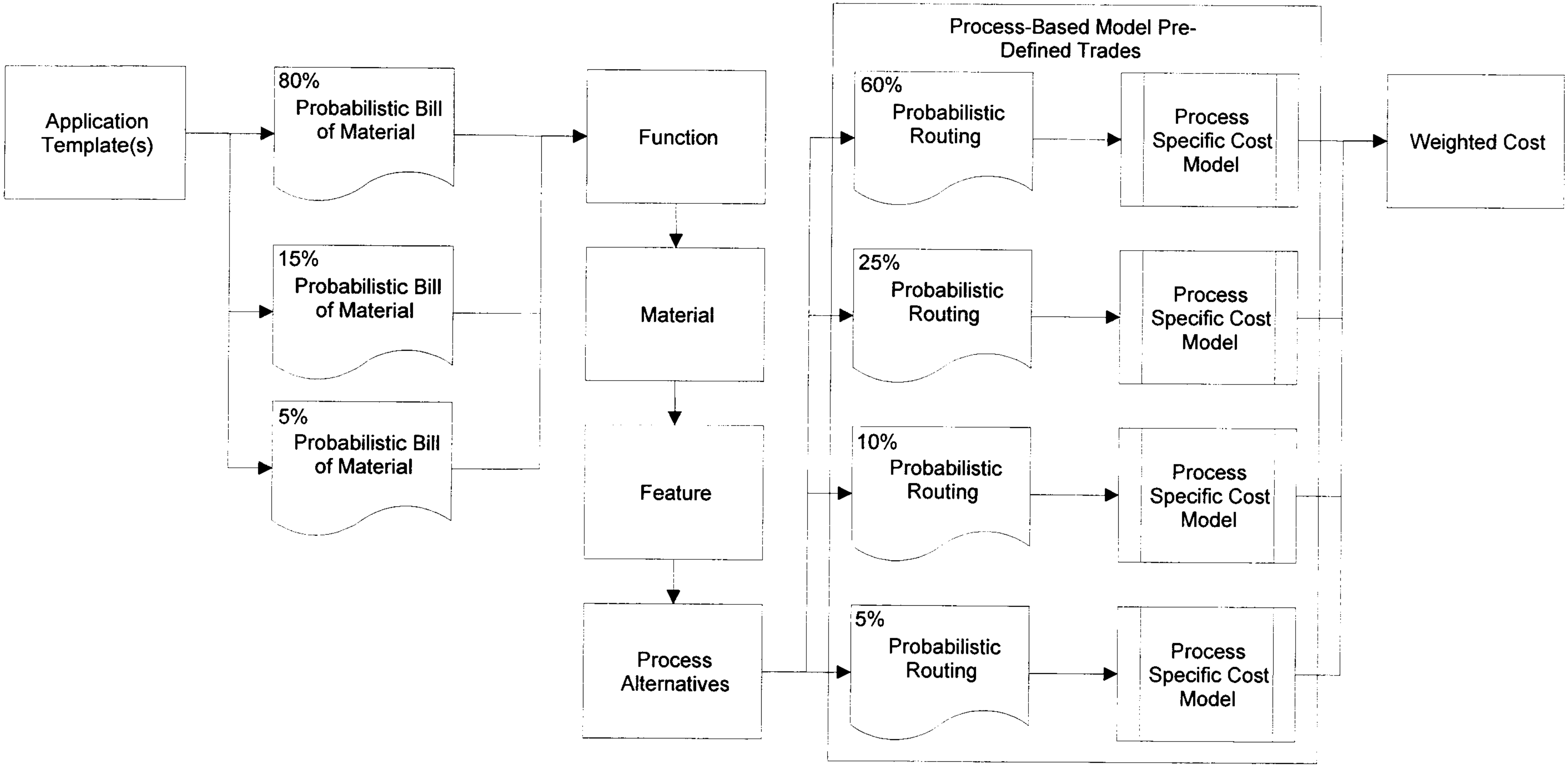
WBS/Item Level Inputs

Description of Model

- **Overview of Model Structure**
- **WBS >> Bill of Material**
- **High-level Parametric Inputs**
- **WBS-BOM Application Structure**
- **Model Structure Breakdown**
- **Functional Requirements**
- **Example of Function-Material Relationship**

Description of Model

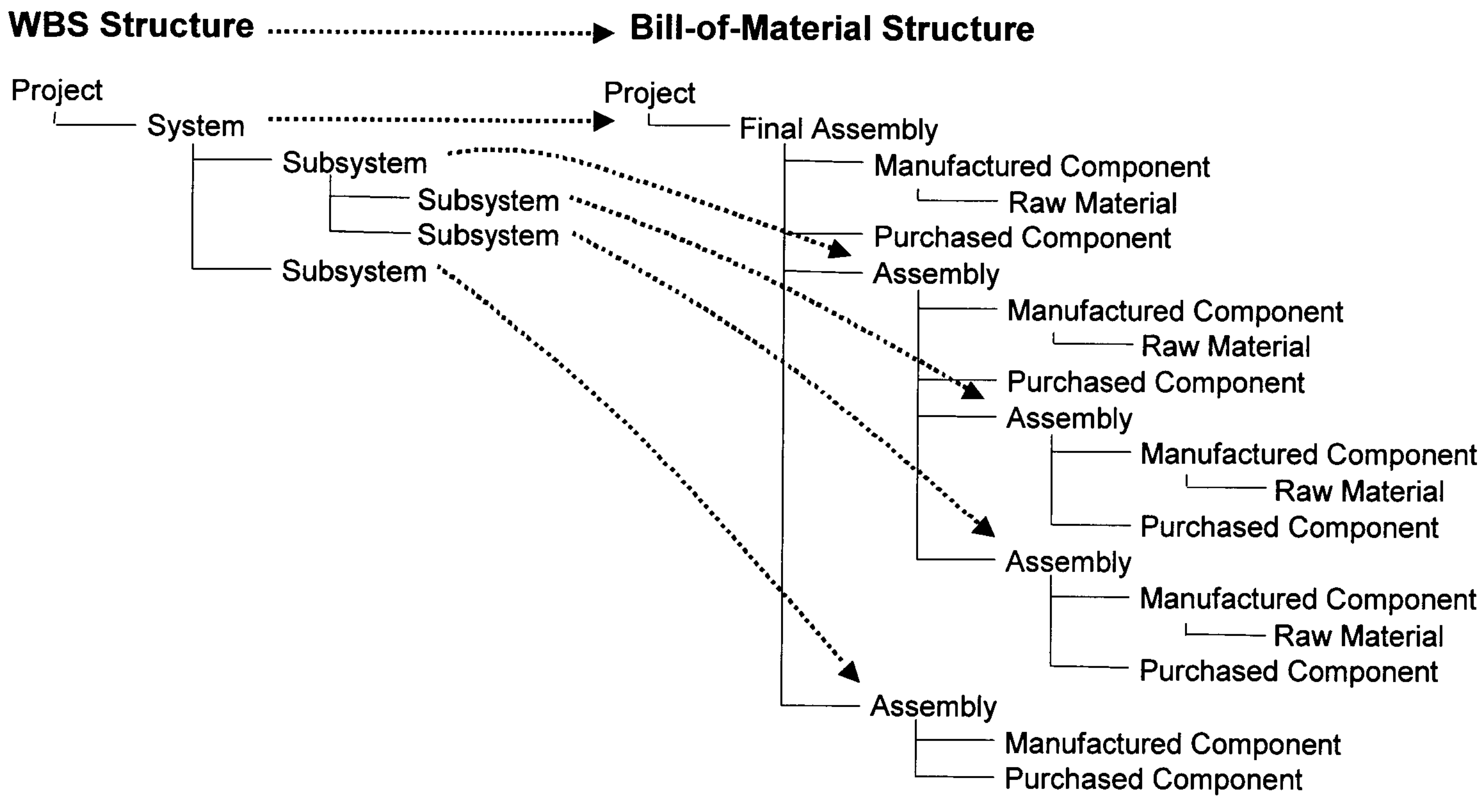
Overview of Model Structure



Description of Model

Work Breakdown Structure >> Bill of Material

WBS → BOM → Function → Material → Feature → Process



WBS Structure → **Bill-of-Material Structure**

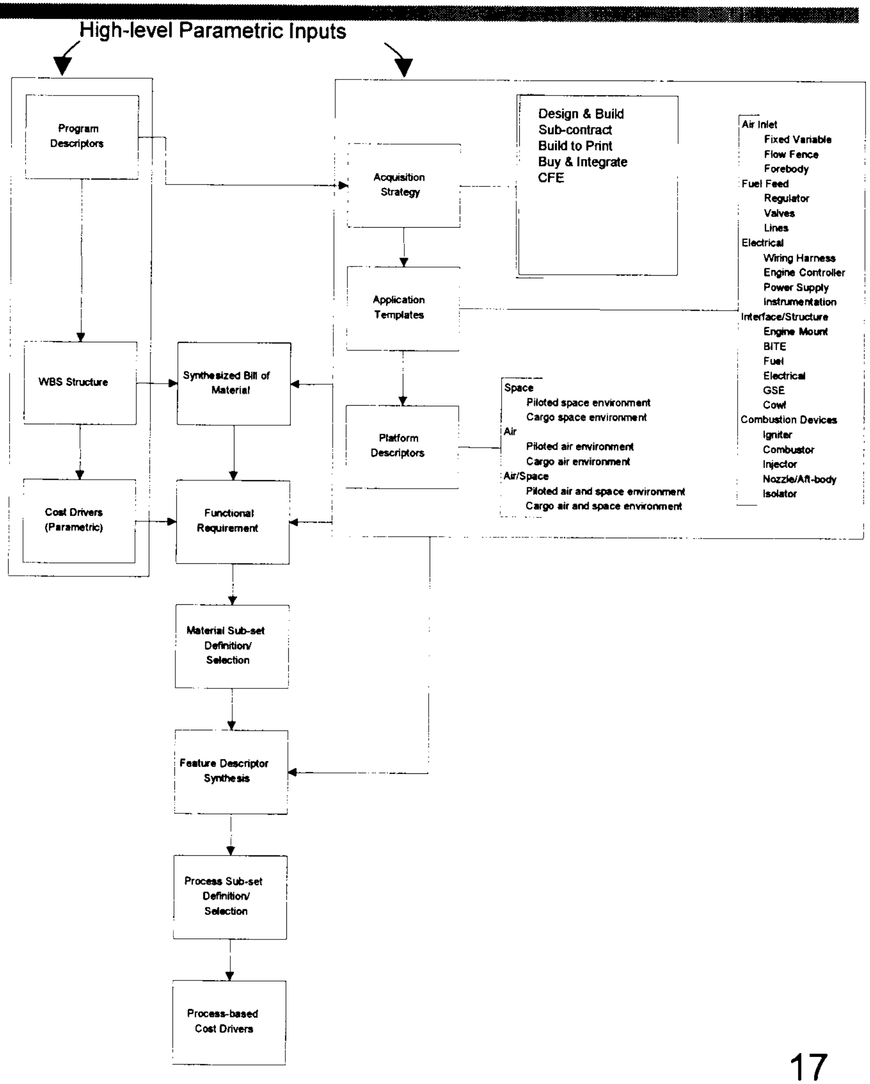
- Project
  - System
    - Subsystem
      - Subsystem
      - Subsystem
    - Subsystem

- Project
  - Final Assembly
    - Manufactured Component
      - Raw Material
    - Purchased Component
    - Assembly
      - Manufactured Component
        - Raw Material
      - Purchased Component
      - Assembly
        - Manufactured Component
          - Raw Material
        - Purchased Component
      - Assembly
        - Manufactured Component
          - Raw Material
        - Purchased Component
    - Assembly
      - Manufactured Component
      - Purchased Component

Description of Model

High-level Parametric Inputs

- **High-level parametric cost estimating relationship (CER) inputs - Descriptors of program and product characteristics.**
- **Operational Environment**
- **Standards**
- **Use/reuse**
- **Acquisition Philosophy**
- **Application Category**
  - **Structural**
  - **Mechanical**
  - **Electrical**
  - **Aero**



Description of Model

Example of WBS-BOM Structure

Ramjet-Scramjet Example:

- **Air Inlet** (Fixed-Variable)
  - Flow Fence
  - Forebody
- **Fuel Feed**
  - Regulator
  - Valves
  - Lines
- **Electrical**
  - Wiring harness
  - Engine controller
  - Power supply
  - Instrumentation
- **Interface/Structure**
  - Engine mount
  - BITE
  - Fuel
  - Electrical
  - GSE
  - Cowl
- **Combustion Devices**
  - Igniter
  - Combustor
  - Injector
  - Nozzle or aft-body
  - Isolator

Description of Model

Model Structure Breakdown

- Pre-established using the elements listed in the application template
- Additional WBS elements may be added, but require assignment by analogy
  - Existing process-based bill of material and routing data set
- WBS elements are related directly to manufacturing assemblies (or bill of material)
  - Identified by analysis of known ramjet-scramjet programs
  - Identified by analogy to similar hardware
    - Air breathing systems or subsystems
    - Rocket engine systems or subsystems
- Assignment by analogy of bill of material and routing data sets if facilitated by characterizing the predefined data sets
  - Complexity of form
  - Complexity of integration
  - Complexity of fit
  - Complexity of construction and assembly (as applicable)
- User added elements are characterized by choosing from the appropriate categories and comparable data sets.

Description of Model

Functional Requirements

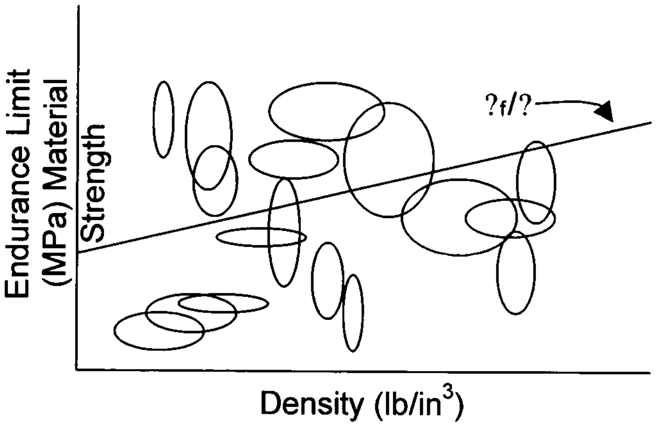
- Identifying the functional requirement of a item (element) being estimated is an optional method from which candidate materials may be derived.
- Material selection has a significant impact on cost. Material and form dictate applicable manufacturing process suitability.

Description of Model

Example of Function-Material Relationship

Function	Constraints	to minimize mass... Maximize	to minimize cost... Maximize	to minimize energy content... Maximize	to minimize environmental impact... Maximize
Tie (tensile strut)	stiffness, length specified; section area free	E/ρ	$E/C_m\rho$	$E/q\rho$	$E/I_e\rho$
Shaft (loaded in torsion)	stiffness, length, shape specified, section area free	$G^{1/2}/\rho$	$G^{1/2}/C_m\rho$	$G^{1/2}/q\rho$	$G^{1/2}/I_e\rho$
	stiffness, length, outer radius specified; wall thickness free	G/ρ	$G/C_m\rho$	$G/q\rho$	$G/I_e\rho$
	stiffness, length, width specified; height free	$G^{1/3}/\rho$	$G^{1/3}/C_m\rho$	$G^{1/3}/q\rho$	$G^{1/3}/I_e\rho$
Beam (loaded in bending)	stiffness, length, shape specified, section area free	$E^{1/2}/\rho$	$E^{1/2}/C_m\rho$	$E^{1/2}/q\rho$	$E^{1/2}/I_e\rho$
	stiffness, length, outer radius specified; wall thickness free	E/ρ	$E/C_m\rho$	$E/q\rho$	$E/I_e\rho$
	stiffness, length, width specified; height free	$E^{1/3}/\rho$	$E^{1/3}/C_m\rho$	$E^{1/3}/q\rho$	$E^{1/3}/I_e\rho$
Column (compression strut, failure by elastic buckling)	buckling load, length, shape specified; section area free	$E^{1/2}/\rho$	$E^{1/2}/C_m\rho$	$E^{1/2}/q\rho$	$E^{1/2}/I_e\rho$
Panel (flat plate, loaded in bending)	stiffness, length, width specified, thickness free	$E^{1/3}/\rho$	$E^{1/3}/C_m\rho$	$E^{1/3}/q\rho$	$E^{1/3}/I_e\rho$
Plate (flat plate, compressed in-plane, buckling failure)	collapse load, length and width specified, thickness free	$E^{1/3}/\rho$	$E^{1/3}/C_m\rho$	$E^{1/3}/q\rho$	$E^{1/3}/I_e\rho$
Cylinder with internal pressure	elastic distortion, pressure and radius specified; wall thickness free	E/ρ	$E/C_m\rho$	$E/q\rho$	$E/I_e\rho$
Spherical shell with internal pressure	elastic distortion, pressure and radius specified; wall thickness free	$E/(1-v)\rho$	$E/(1-v)C_m\rho$	$E/(1-v)q\rho$	$E/(1-v)I_e\rho$

Material down-select begins by defining functional constraints in terms of common material property indices.



Material	MPa	lb/in^3
Alt 1	xx	x.xx
Alt 2	xx	x.xx
Alt 3	xx	x.xx
Alt 4	xx	x.xx

Steps in Preparing an Estimate

- **Define Scope of Estimate**
- **Identify Processes to Estimate**
- **Prepare Inputs**
- **Evaluate Results**

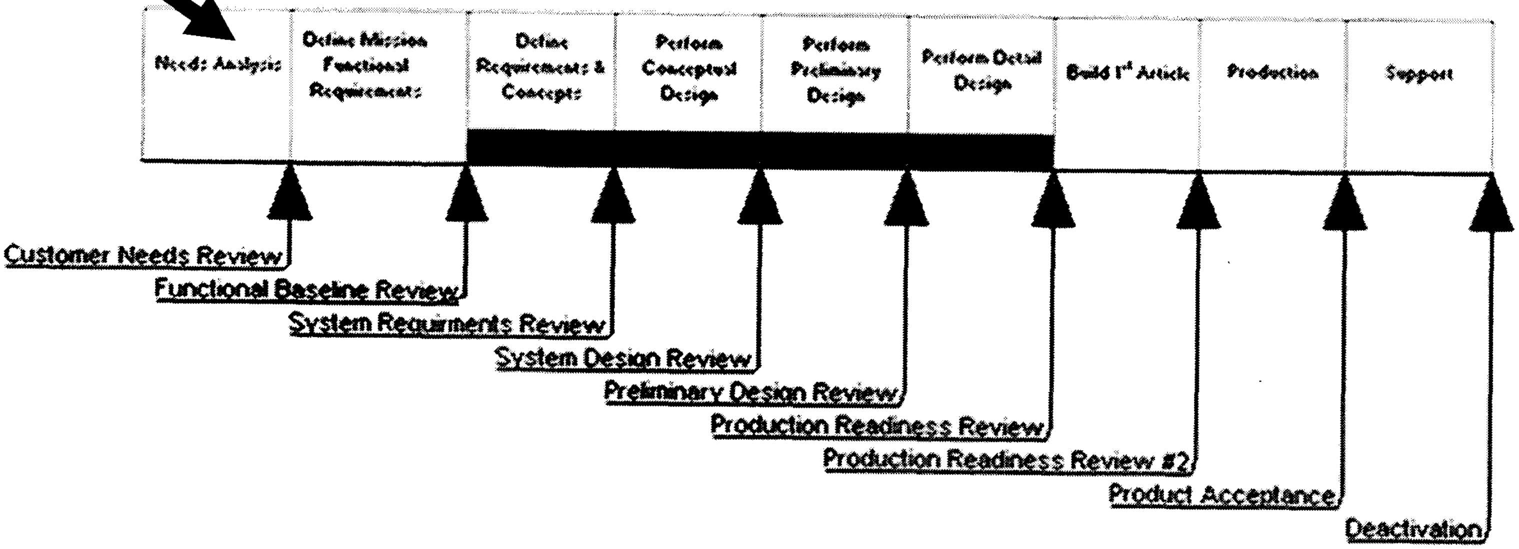
Steps in Preparing an Estimate

Define Scope of Estimate

Selection

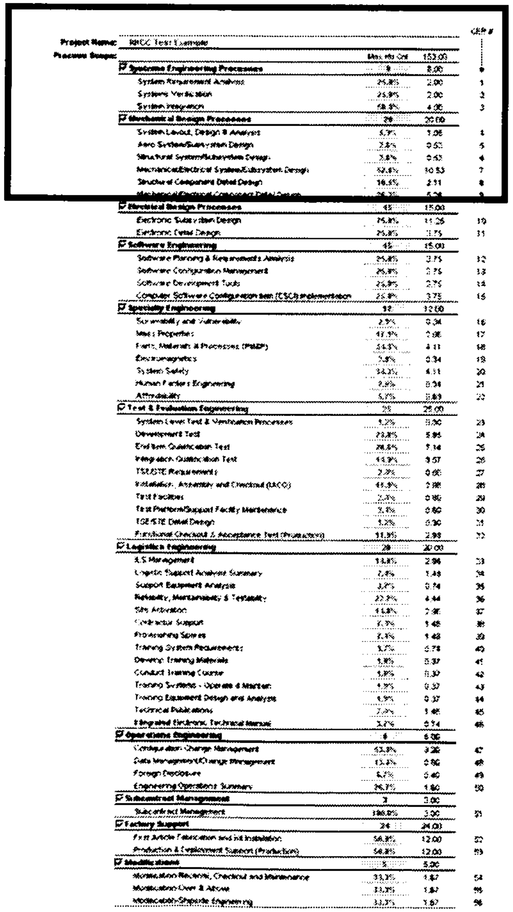
Product Life Cycle Scope:	Concluding Milestone
☐ Needs Analysis	*Customer Needs Review*
☐ Define Mission Functional Requirements	*Functional Baseline Review*
☑ Define Requirements and Concepts	*System Requirments Review*
☑ Perform Conceptual Design	*System Design Review*
☑ Perform Preliminary Design	*Preliminary Design Review*
☑ Perform Detailed Design	*Production Readiness Review*
☐ Build 1st Article	*Production Readiness Review #2*
☐ Production	*Product Acceptance*
☐ Support	*Deactivation*

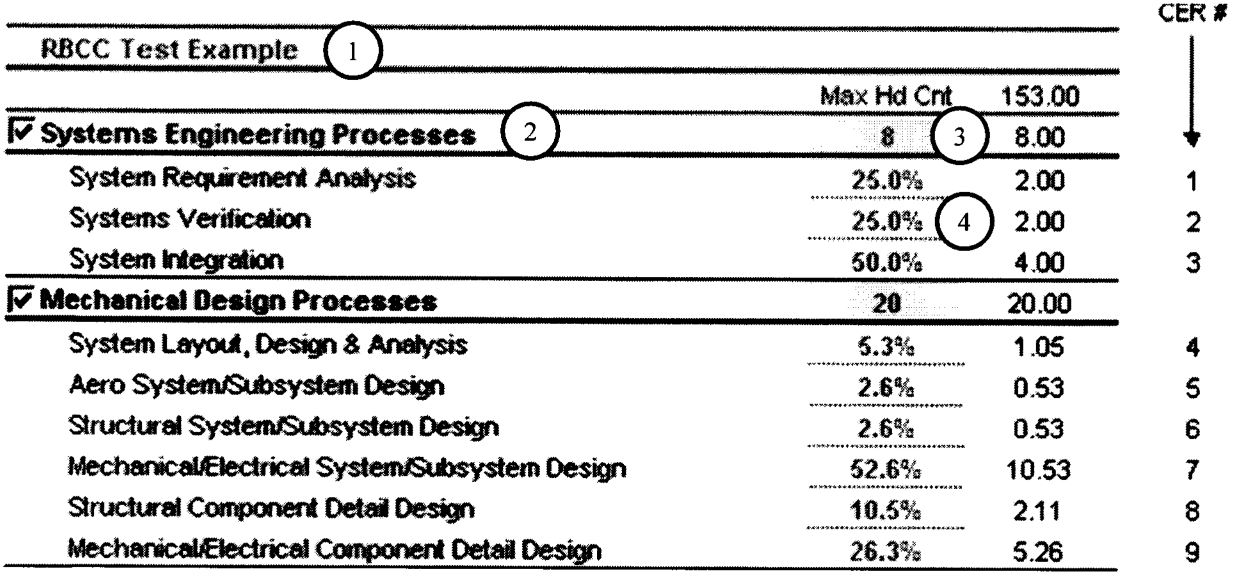
Output



Steps in Preparing an Estimate

Identify Processes to Estimate





Project Name: RBCC Test Example ①

Process Scope:

			CER #
	Max Hd Cnt	153.00	
☑ **Systems Engineering Processes** ②	8 ③	8.00	
System Requirement Analysis	25.0%	2.00	1
Systems Verification	25.0% ④	2.00	2
System Integration	50.0%	4.00	3
☑ **Mechanical Design Processes**	20	20.00	
System Layout, Design & Analysis	5.3%	1.05	4
Aero System/Subsystem Design	2.6%	0.53	5
Structural System/Subsystem Design	2.6%	0.53	6
Mechanical/Electrical System/Subsystem Design	52.6%	10.53	7
Structural Component Detail Design	10.5%	2.11	8
Mechanical/Electrical Component Detail Design	26.3%	5.26	9

Input: 1) Project Name

Select: 2) Processes to be included in estimate

Input: 3) Max Head Count (11 inputs)

Input: 4) Head Count Allocations (56 inputs)

Steps in Preparing an Estimate

Prepare Inputs

- Program Level Inputs
- Item Level Inputs
  - Summary
  - Materials
  - Complexity
  - Process

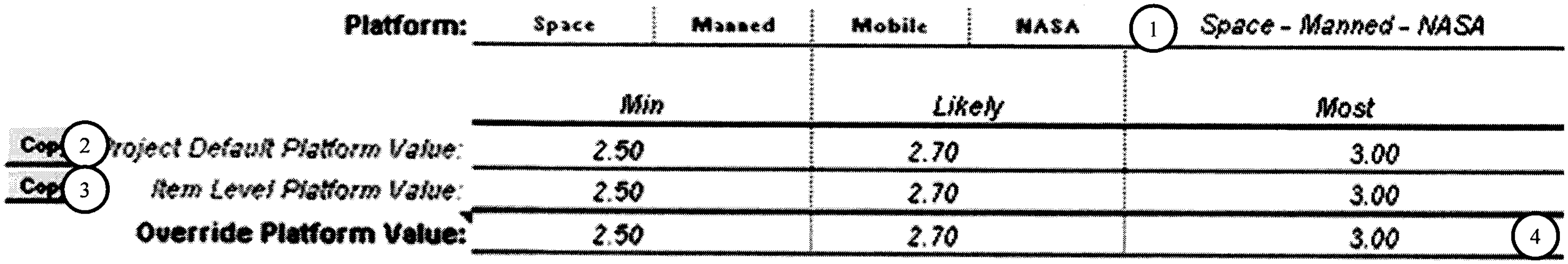
Prepare Inputs

Program Level Inputs

- Characterize Operational Platform
- Characterize Process
- Characterize Design Process
- Characterize Function
- Software Lines of Code
- Management Headcount & Wrap Rates
- Labor Rates
- Start-End Dates

Program Level Inputs

Characterize Operational Platform



Platform: Space | Manned | Mobile | NASA ① Space - Manned - NASA

	Min	Likely	Most
Cop ② roject Default Platform Value:	2.50	2.70	3.00
Cop ③ Item Level Platform Value:	2.50	2.70	3.00
Override Platform Value:	2.50	2.70	3.00 ④

Selection: 1) Platform

- Space, Airborne, Submersible, Water-based, or Land-based
- Manned or Unmanned
- Existing or Mature Process
- NASA, Military, Industrial or Commercial

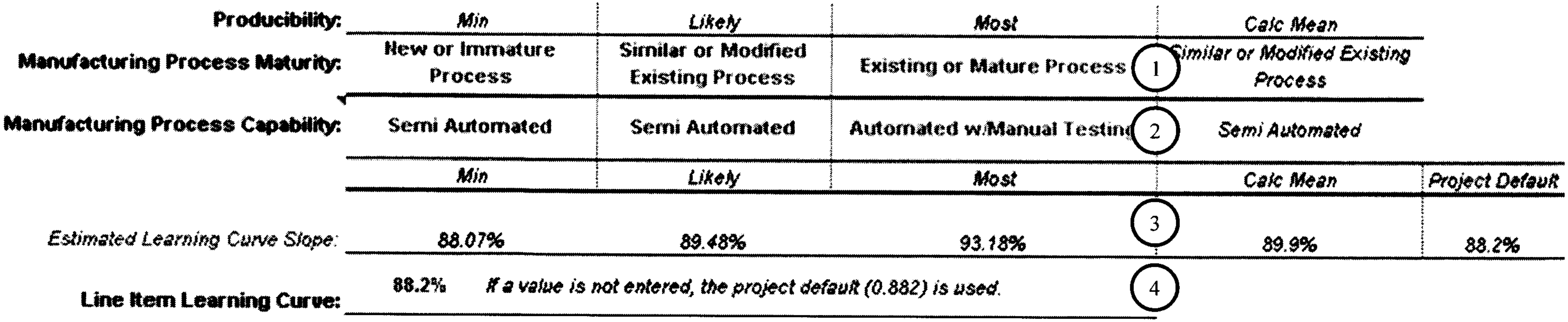
2) Copy Project Default Platform Values

3) Copy Item Level Platform Values

Input: 4) Override Platform Value

Program Level Inputs

Characterize Process



Producibility:	*Min*	*Likely*	*Most*	*Calc Mean*	
Manufacturing Process Maturity:	New or Immature Process	Similar or Modified Existing Process	Existing or Mature Process ①	*Similar or Modified Existing Process*	
Manufacturing Process Capability:	Semi Automated	Semi Automated	Automated w/Manual Testin ②	*Semi Automated*	
	Min	*Likely*	*Most*	*Calc Mean*	*Project Default*
Estimated Learning Curve Slope:	*88.07%*	*89.48%*	*93.18%* ③	*89.9%*	*88.2%*
Line Item Learning Curve:	88.2%	*If a value is not entered, the project default (0.882) is used.*	④		

Selection: 1) Manufacturing Process Maturity

- New or Immature Process
- Similar or Modified Existing Process
- Existing or Mature Process

2) Manufacturing Process Capability

- Labor Intensive
- Semi Automated
- Automated w/Manual Testing
- Fully Automated

Used in cost calculations for prototype hardware.

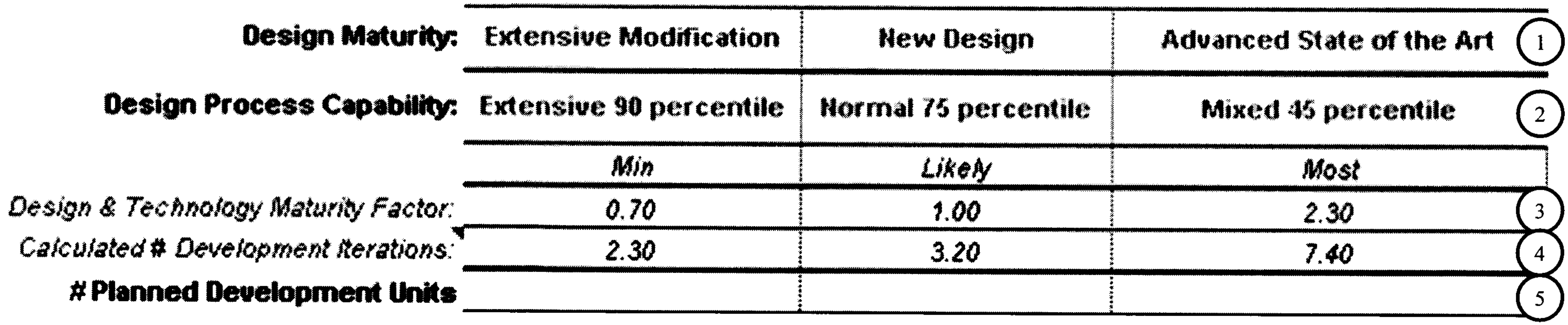
Estimated: 3) Estimated Improvement Curve – Project Default

Input: 4) Line Item Learning Curve

- **Improvement Curve inputs are not used in the Development Cost Model**

Program Level Input

Characterize Design Process



Design Maturity:	Extensive Modification	New Design	Advanced State of the Art	①
Design Process Capability:	Extensive 90 percentile	Normal 75 percentile	Mixed 45 percentile	②
	Min	*Likely*	*Most*	
Design & Technology Maturity Factor:	*0.70*	*1.00*	*2.30*	③
Calculated # Development Iterations:	*2.30*	*3.20*	*7.40*	④
# Planned Development Units				⑤

Selection: 1) Design Maturity

Simple Mod, Extensive Mod, New Design, New Product, New Technology or Advanced State of the Art

2) Design Process Capability

Extensive 90 percentile, Normal 75 percentile, Mixed 45 percentile or Inexperienced 30 percentile

Info: 3) Design & Technology Maturity Factor

4) Calculated # Development Iterations

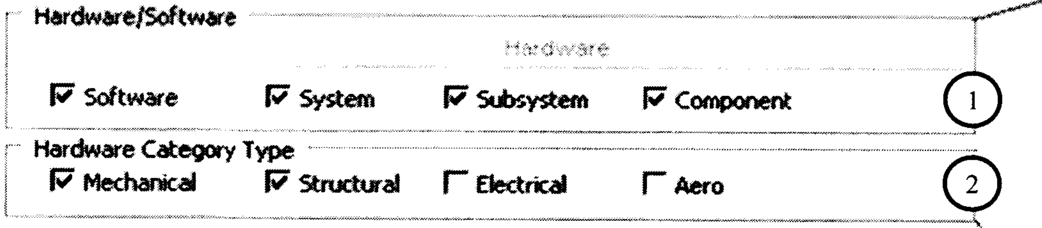
Input: 5) # Planned Development Units (iterations override)

Check the number of planned iterations versus the number of planned prototypes.

Program Level Input

Characterize Function

Component Classification:



Hardware/Software

Hardware

☑ Software ☑ System ☑ Subsystem ☑ Component ①

Hardware Category Type

☑ Mechanical ☑ Structural ☐ Electrical ☐ Aero ②

System/Mechanical

System/Structural

Subsystem/Mechanical

Subsystem/Structural

Component/Mechanical

Component/Structural

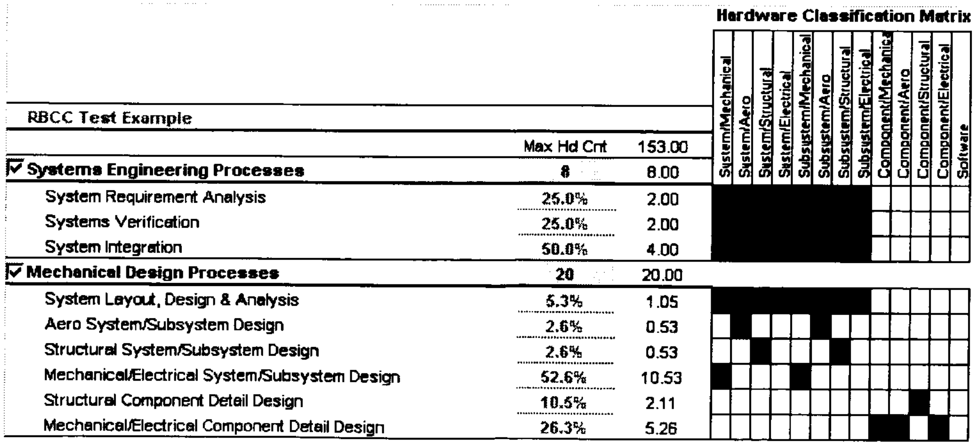
Software

Selection: 1) Hardware/Software

Select each type of hardware classification and/or software in this WBS element.

2) Hardware Category Type

Select each type hardware category to be included in this WBS element estimate.



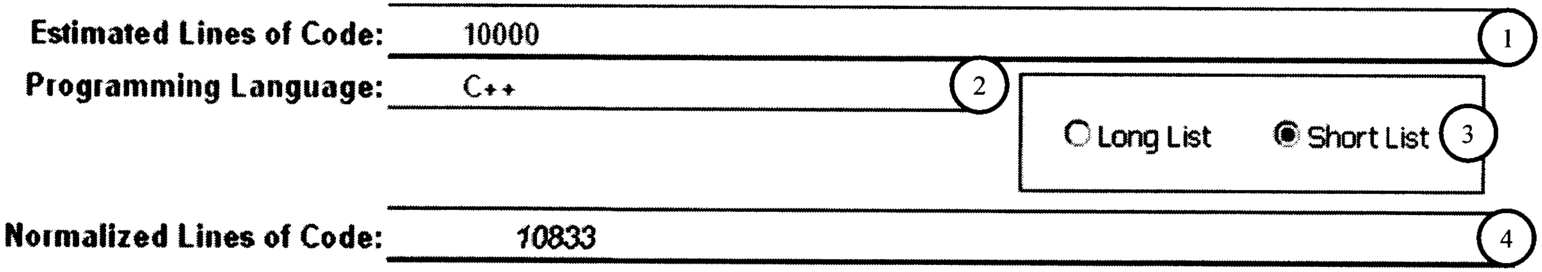
Hardware Classification Matrix

			System/Mechanical	System/Aero	System/Structural	System/Electrical	Subsystem/Mechanical	Subsystem/Aero	Subsystem/Structural	Subsystem/Electrical	Component/Mechanical	Component/Aero	Component/Structural	Component/Electrical	Software
RBCC Test Example															
	Max Hd Cnt	153.00													
☑ **Systems Engineering Processes**	**8**	8.00													
System Requirement Analysis	25.0%	2.00	■	■	■	■	■	■	■	■	□	□	□	□	□
Systems Verification	25.0%	2.00	■	■	■	■	■	■	■	■	□	□	□	□	□
System Integration	50.0%	4.00	■	■	■	■	■	■	■	■	□	□	□	□	□
☑ **Mechanical Design Processes**	**20**	20.00													
System Layout, Design & Analysis	5.3%	1.05	■	■	■	■	■	■	■	■	□	□	□	□	□
Aero System/Subsystem Design	2.6%	0.53	□	■	□	□	□	■	□	□	□	□	□	□	□
Structural System/Subsystem Design	2.6%	0.53	□	□	■	□	□	□	■	□	□	□	□	□	□
Mechanical/Electrical System/Subsystem Design	52.6%	10.53	■	□	□	□	■	□	□	□	□	□	□	□	□
Structural Component Detail Design	10.5%	2.11	□	□	□	□	□	□	□	□	□	□	■	□	□
Mechanical/Electrical Component Detail Design	26.3%	5.26	□	□	□	□	□	□	□	□	■	■	□	■	□

CER/Hardware & Software Classification Matrix from Project Level Input Sheet

Program Level Input

Software Lines of Code

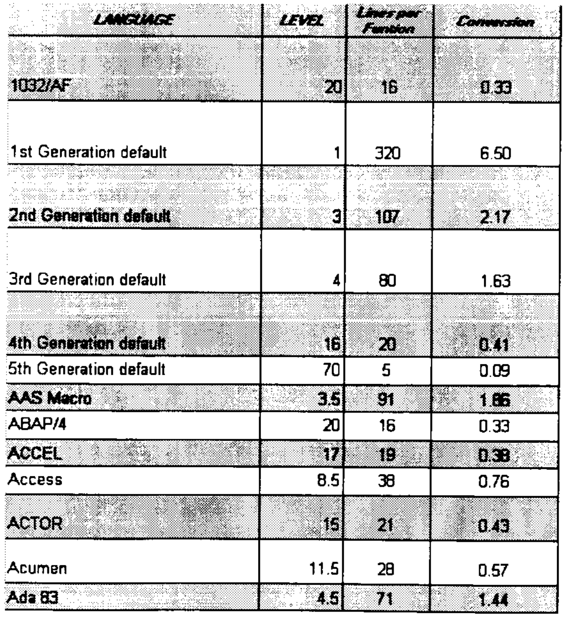


Estimated Lines of Code: 10000 ①

Programming Language: C++ ②

○ Long List ● Short List ③

Normalized Lines of Code: 10833 ④



LANGUAGE	LEVEL	Lines per Function	Conversion
1032/AF	20	16	0.33
1st Generation default	1	320	6.50
2nd Generation default	3	107	2.17
3rd Generation default	4	80	1.63
4th Generation default	16	20	0.41
5th Generation default	70	5	0.09
AAS Macro	3.5	91	1.86
ABAP/4	20	16	0.33
ACCEL	17	19	0.38
Access	8.5	38	0.76
ACTOR	15	21	0.43
Acumen	11.5	28	0.57
Ada 83	4.5	71	1.44

Long List Excerpt

Input: 1) Estimated Lines of Code

Selection: 2) Programming Language

Select the language that the code will be developed in.

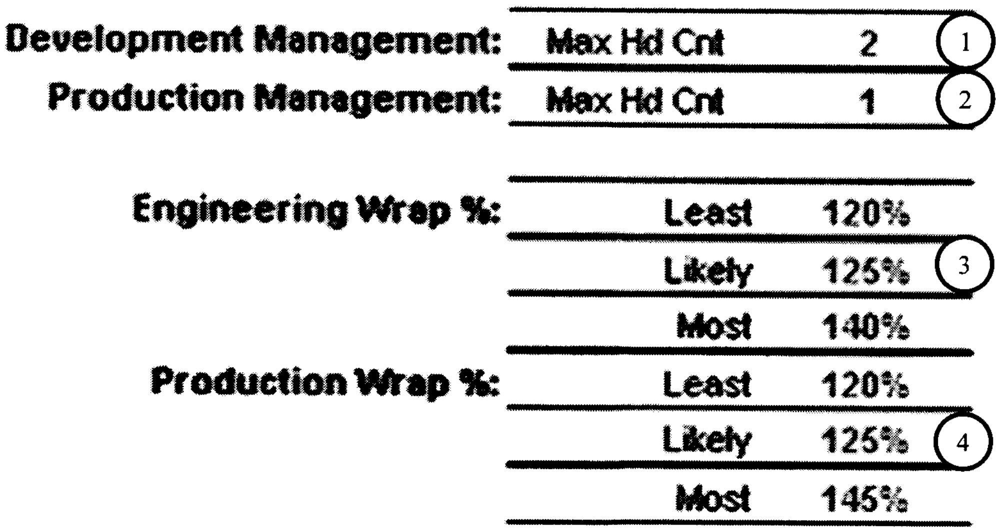
3) List Selection (Long or Short)

There are two tables of code languages, one long (~480 languages) and the other short (~60 languages).

Info: 3) Normalized Lines of Code

Program Level Input

Management Headcount & Wrap Rates



Development Management:	Max Hd Cnt	2	①
Production Management:	Max Hd Cnt	1	②
Engineering Wrap %:	Least	120%	
	Likely	125%	③
	Most	140%	
Production Wrap %:	Least	120%	
	Likely	125%	④
	Most	145%	

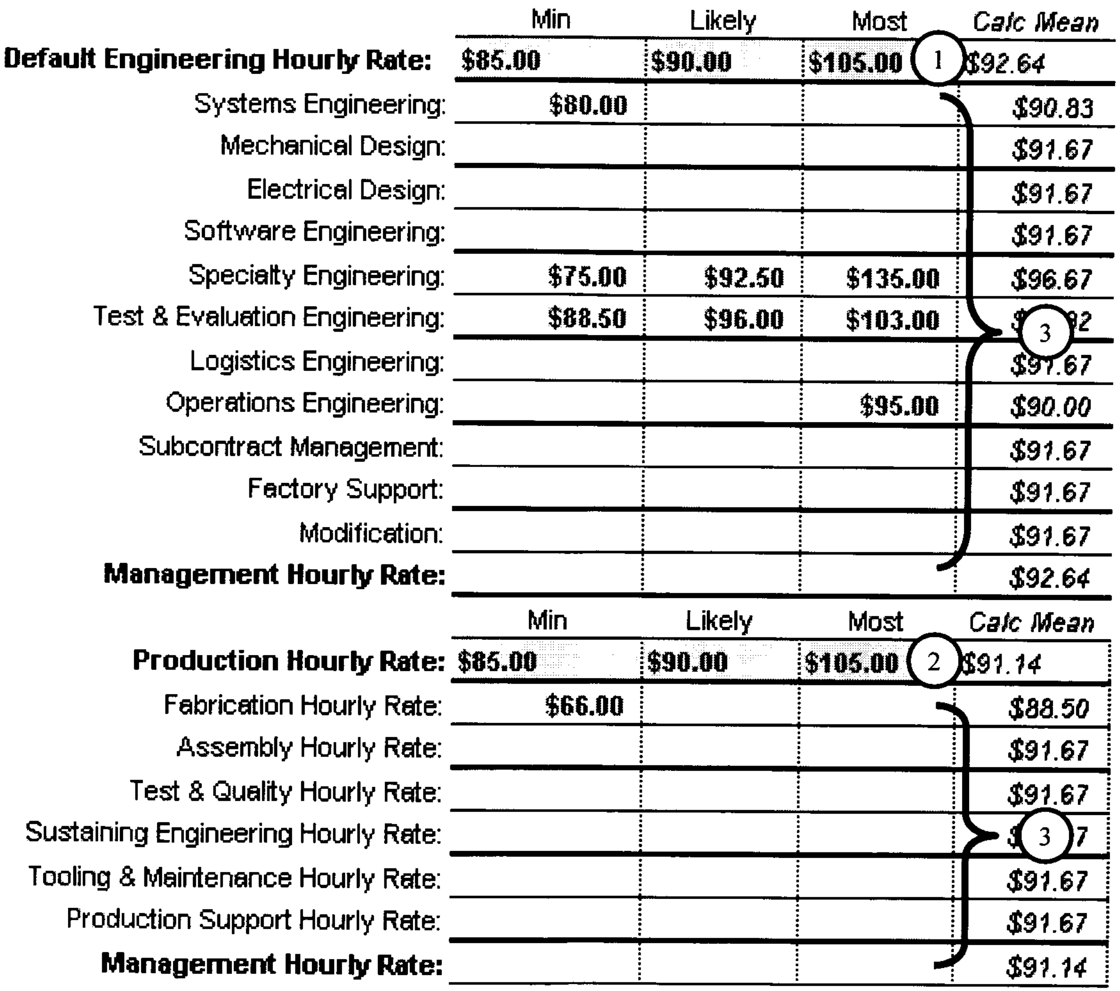
Inputs:

1) Dev Management Head Count
2) Production Management Head Count
3) Engineering Wrap %
4) Production Wrap %

Labor Cost will be calculated using process (labor) cost per hour plus the process cost multiplied by the wrap rate. Wrap rate should consider and include all costs not captured in the labor rate such as fees and reserves.

Program Level Input

Labor Rates



	Min	Likely	Most	*Calc Mean*
Default Engineering Hourly Rate:	$85.00	$90.00	$105.00 ①	*$92.64*
Systems Engineering:	$80.00			*$90.83*
Mechanical Design:				*$91.67*
Electrical Design:				*$91.67*
Software Engineering:				*$91.67*
Specialty Engineering:	$75.00	$92.50	$135.00	*$96.67*
Test & Evaluation Engineering:	$88.50	$96.00	$103.00	*$ ③ 2*
Logistics Engineering:				*$91.67*
Operations Engineering:			$95.00	*$90.00*
Subcontract Management:				*$91.67*
Factory Support:				*$91.67*
Modification:				*$91.67*
Management Hourly Rate:				*$92.64*

	Min	Likely	Most	*Calc Mean*
Production Hourly Rate:	$85.00	$90.00	$105.00 ②	*$91.14*
Fabrication Hourly Rate:	$66.00			*$88.50*
Assembly Hourly Rate:				*$91.67*
Test & Quality Hourly Rate:				*$91.67*
Sustaining Engineering Hourly Rate:				*$ ③ 7*
Tooling & Maintenance Hourly Rate:				*$91.67*
Production Support Hourly Rate:				*$91.67*
Management Hourly Rate:				*$91.14*

Inputs:

1) Eng Hourly Rate
2) Prod Hourly Rate
3) Exceptions

Overhead may be included in the labor rate or it may be captured as a wrap rate.

Program Level Input

Start-End Dates

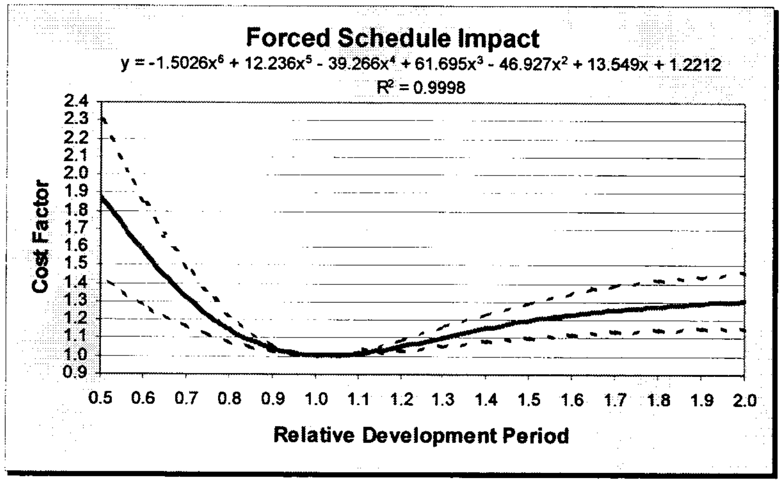
Development Start Date: 3/21/2002 ①

Required Completion Date: 6/1/2005 ②

Inputs:

1) Start Date
2) Required Completion Date

Inputting a required completion date impacts the calculated cost of effort. This assumes that reducing the schedule will drive cost up by forcing overtime and causing additional parallel effort. Increasing the schedule duration drives cost up by retention of personnel (standing army) in order to maintain required skills.



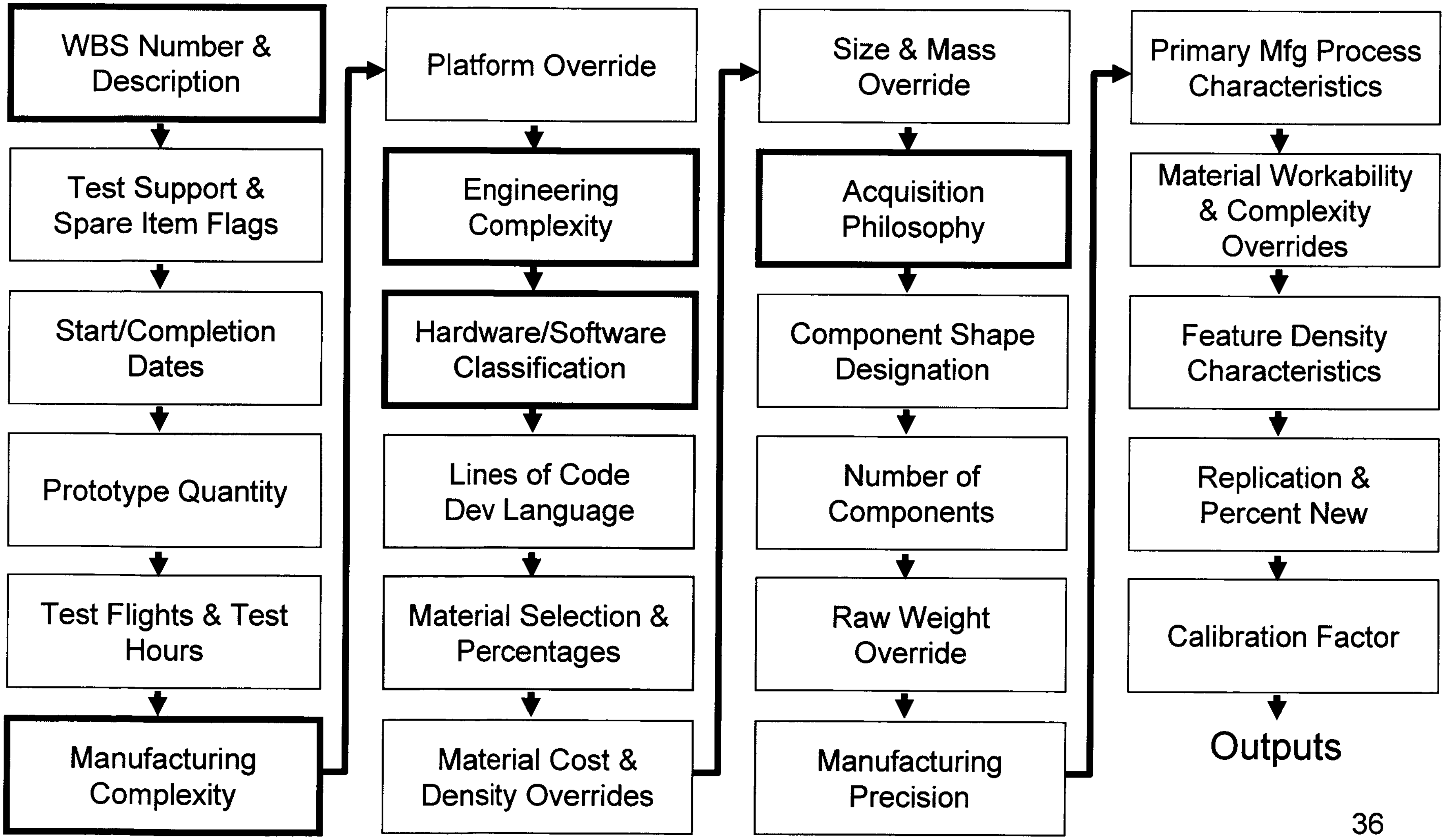
Prepare Inputs

Item Level Inputs

- Summary
- Examples
- Complexity
- Materials
- Process

Item Level Inputs

Summary



WBS Number & Description

Test Support & Spare Item Flags

Start/Completion Dates

Prototype Quantity

Test Flights & Test Hours

Manufacturing Complexity

Platform Override

Engineering Complexity

Hardware/Software Classification

Lines of Code Dev Language

Material Selection & Percentages

Material Cost & Density Overrides

Size & Mass Override

Acquisition Philosophy

Component Shape Designation

Number of Components

Raw Weight Override

Manufacturing Precision

Primary Mfg Process Characteristics

Material Workability & Complexity Overrides

Feature Density Characteristics

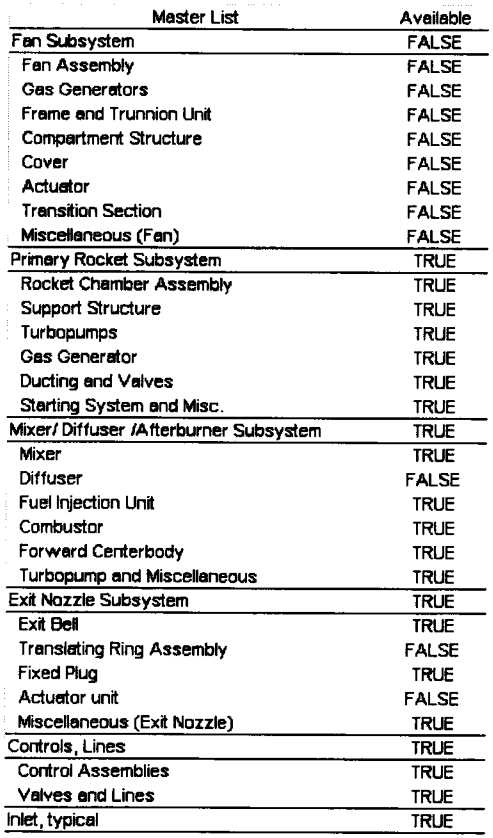
Replication & Percent New

Calibration Factor

Outputs

Item Level Inputs

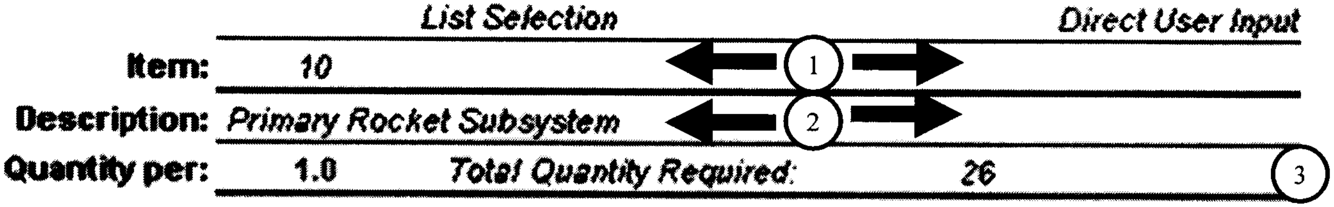
Example - Description



Master List	Available
Fan Subsystem	FALSE
Fan Assembly	FALSE
Gas Generators	FALSE
Frame and Trunnion Unit	FALSE
Compartment Structure	FALSE
Cover	FALSE
Actuator	FALSE
Transition Section	FALSE
Miscellaneous (Fan)	FALSE
Primary Rocket Subsystem	TRUE
Rocket Chamber Assembly	TRUE
Support Structure	TRUE
Turbopumps	TRUE
Gas Generator	TRUE
Ducting and Valves	TRUE
Starting System and Misc.	TRUE
Mixer/ Diffuser /Afterburner Subsystem	TRUE
Mixer	TRUE
Diffuser	FALSE
Fuel Injection Unit	TRUE
Combustor	TRUE
Forward Centerbody	TRUE
Turbopump and Miscellaneous	TRUE
Exit Nozzle Subsystem	TRUE
Exit Bell	TRUE
Translating Ring Assembly	FALSE
Fixed Plug	TRUE
Actuator unit	FALSE
Miscellaneous (Exit Nozzle)	TRUE
Controls, Lines	TRUE
Control Assemblies	TRUE
Valves and Lines	TRUE
Inlet, typical	TRUE

Master WBS DB

Item availability depends on engine configuration.



List Selection *Direct User Input*

Item: *10*

Description: *Primary Rocket Subsystem*

Quantity per: **1.0** *Total Quantity Required:* *26*

Input: 1) Item

The item number is automatically generated if the item description is selected from the validation list, rather than a direct input.

Selection: 2) Description

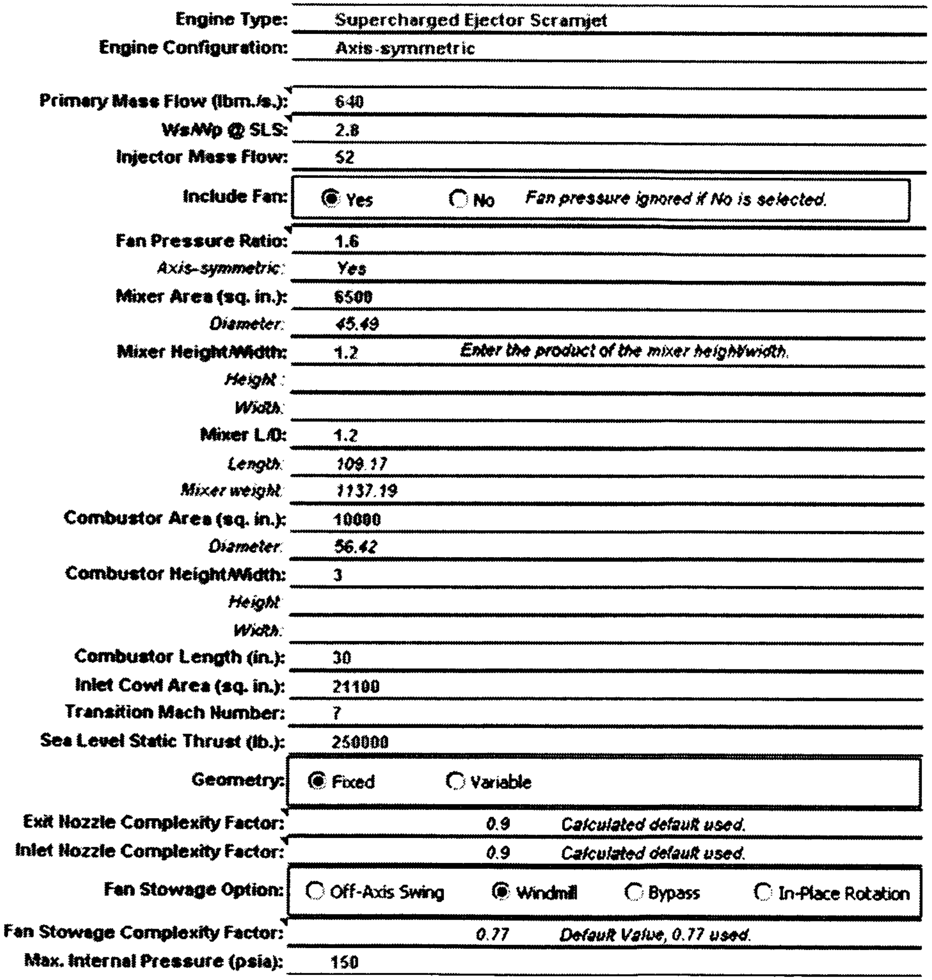
The WBS item description may be selected from the drop down list. The list is automatically generated from the Master WBS DB, dependent on the engine configuration.

Input: 3) Quantity per

Enter the quantity of this item found in the parent item's bill of material.

Item Level Inputs

Example - Hardware Characteristics



Engine Type: Supercharged Ejector Scramjet
Engine Configuration: Axis-symmetric

Primary Mass Flow (lbm./s.): 640
Ws/Wp @ SLS: 2.8
Injector Mass Flow: 52
Include Fan: ● Yes ○ No *Fan pressure ignored if No is selected.*
Fan Pressure Ratio: 1.6
Axis-symmetric: *Yes*
Mixer Area (sq. in.): 6500
Diameter: *45.49*
Mixer Height/Width: 1.2 *Enter the product of the mixer height/width.*
Height:
Width:
Mixer L/D: 1.2
Length: *109.17*
Mixer weight: *1137.19*
Combustor Area (sq. in.): 10000
Diameter: *56.42*
Combustor Height/Width: 3
Height:
Width:
Combustor Length (in.): 30
Inlet Cowl Area (sq. in.): 21100
Transition Mach Number: 7
Sea Level Static Thrust (lb.): 250000
Geometry: ● Fixed ○ Variable
Exit Nozzle Complexity Factor: *0.9* *Calculated default used.*
Inlet Nozzle Complexity Factor: *0.9* *Calculated default used.*
Fan Stowage Option: ○ Off-Axis Swing ● Windmill ○ Bypass ○ In-Place Rotation
Fan Stowage Complexity Factor: *0.77* *Default Value, 0.77 used.*
Max. Internal Pressure (psia): 150

The engine description and use is based on the published work of Dr. Gary Olds*, data and information obtained from the Marquardt Aero-Propulsion Library and the High-Speed Propulsion Reference Room maintained by AFRL Propulsion Directorate at Wright-Patterson AFB. This data is used in setting up the project WBS, calculating mass and establishing number of components and feature density for the project.

*Weight Assessment Tool for Engine Scaling v1.xls

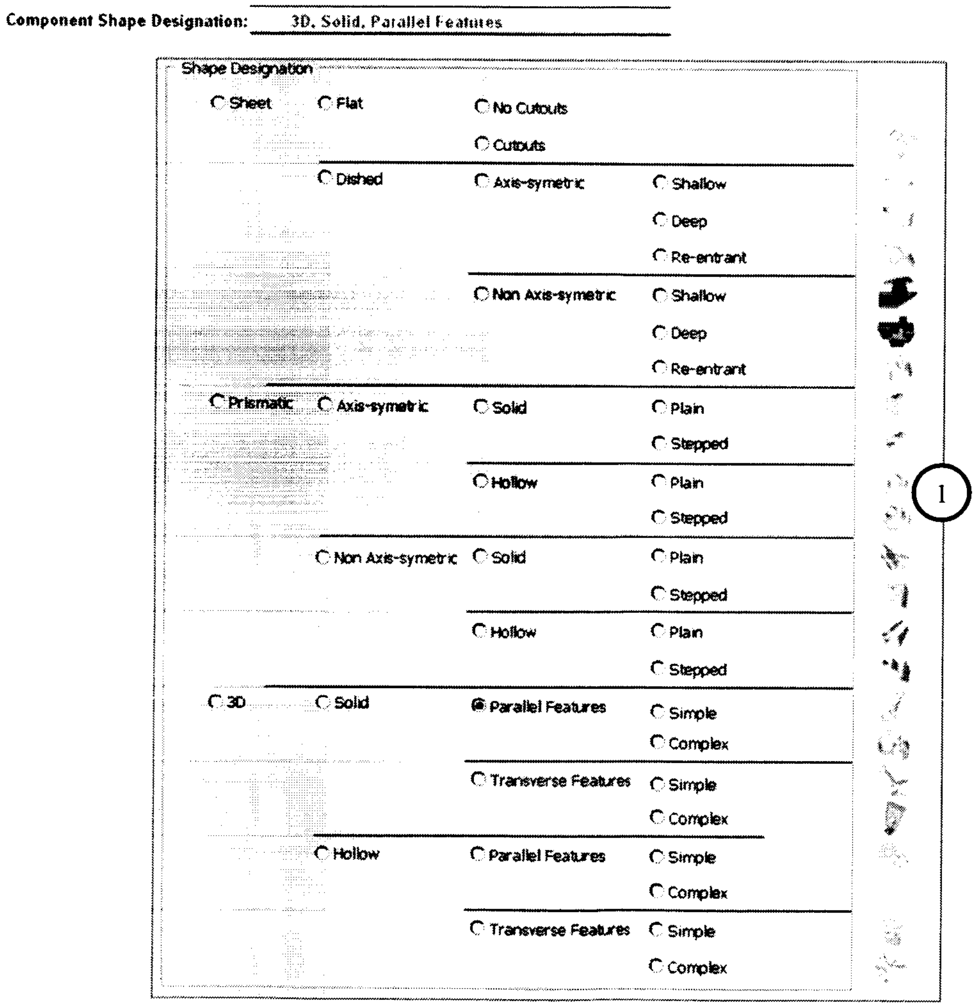
Item Level Inputs

Complexity

- Selection of Form
- Complexity of Form
- Detailed Form
- Form by Analogy
- Component Features
- Feature Characteristics
- Part Count
- Feature Count
- Volume & Mass

Item Level Inputs - Complexity

Selection of Form



Component Shape Designation: 3D, Solid, Parallel Features

Shape Designation

- ○ Sheet
  - ○ Flat
    - ○ No Cutouts
    - ○ Cutouts
  - ○ Dished
    - ○ Axis-symetric
      - ○ Shallow
      - ○ Deep
      - ○ Re-entrant
    - ○ Non Axis-symetric
      - ○ Shallow
      - ○ Deep
      - ○ Re-entrant
- ○ Prismatic
  - ○ Axis-symetric
    - ○ Solid
      - ○ Plain
      - ○ Stepped
    - ○ Hollow
      - ○ Plain
      - ○ Stepped
  - ○ Non Axis-symetric
    - ○ Solid
      - ○ Plain
      - ○ Stepped
    - ○ Hollow
      - ○ Plain
      - ○ Stepped
- ○ 3D
  - ○ Solid
    - ● Parallel Features
      - ○ Simple
      - ○ Complex
    - ○ Transverse Features
      - ○ Simple
      - ○ Complex
  - ○ Hollow
    - ○ Parallel Features
      - ○ Simple
      - ○ Complex
    - ○ Transverse Features
      - ○ Simple
      - ○ Complex

17% 3D, Solid, Parallel Features, Simple
83% 3D, Solid, Parallel Features, Complex ②

Selection: 1) Component Shape
Select a shape or shape category.

Info: 2) Shape Allocation
If a shape category is selected, the allocation percentage common to RBCC propulsion is used in deriving subsequent feature density defaults.

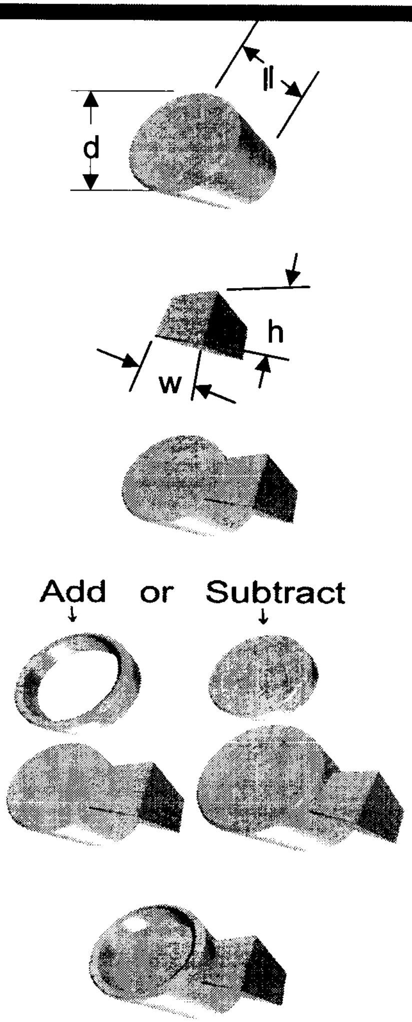
Item Level Inputs - Complexity

Complexity of Form

- Form, coupled with material, is a key process-based cost driver.
  - Environment and operational characteristics drive material selection.
  - Material and form drive process selection.
- Form may be captured in detail or by analogy.

Item Level Inputs - Complexity

Detailed Form



To facilitate the description of form and shape (as desired for manufacturing estimates), and the calculation of approximate mass and volume, the process-based cost model provides a volume calculator.

The calculated volume is used with material density to estimate mass.

Feature characteristics (linear, symmetric, and axis-symmetric) provide additional criteria for capability driven process selection.

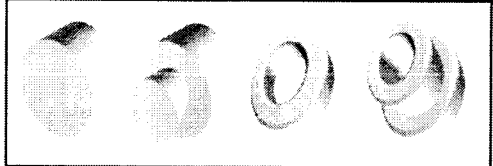
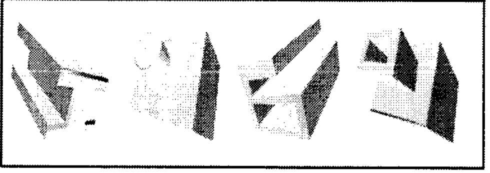
Item Level Inputs - Complexity

Form by Analogy

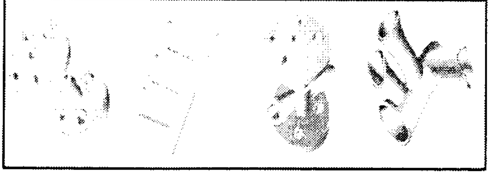
Sheet –
pressing,
stamping,
rolling,
spinning, etc.

		Dished					
Flat		Axis-symmetric			Non Axis-symmetric		
No-Cutouts	Cutouts	Shallow	Deep	Deep, re-entrant	Shallow	Deep	Deep, re-entrant
							

Prismatic –
extrusion,
drawing,
rolling,
turning, etc.

Axis-symmetric				Non Axis-symmetric			
Solid		Hollow		Solid		Hollow	
Plain	Stepped	Plain	Stepped	Plain	Stepped	Plain	Stepped
							

3-D –
molds,
dies, etc.

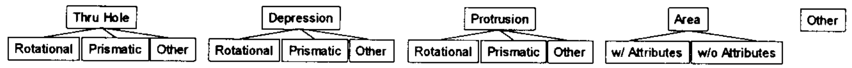
Solid				Hollow			
Parallel-Features		Transverse-Features		Parallel-Features		Transverse-Features	
Simple	Complex	Simple	Complex	Simple	Complex	Simple	Complex
							

Item Level Inputs - Complexity

Component Features

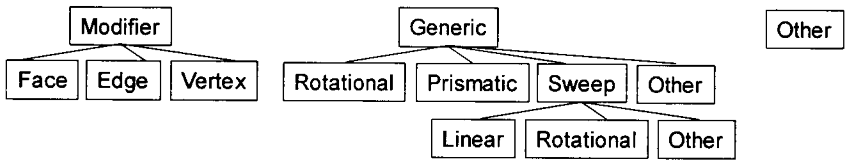
- Identifiable **component features** include:
  - projections-depressions,
  - uniform wall,
  - uniform section,
  - axis of rotation,
  - regular cross section,
  - captured cavities,
  - enclosure,
  - no draft,
  - part consolidation,
  - alignment features,
  - integrated fasteners,
  - others

Explicit Features



- Thru Hole
  - Rotational
  - Prismatic
  - Other
- Depression
  - Rotational
  - Prismatic
  - Other
- Protrusion
  - Rotational
  - Prismatic
  - Other
- Area
  - w/ Attributes
  - w/o Attributes
- Other

Implicit Features



- Modifier
  - Face
  - Edge
  - Vertex
- Generic
  - Rotational
  - Prismatic
  - Sweep
    - Linear
    - Rotational
    - Other
  - Other
- Other

Item Level Inputs - Complexity

Feature Characteristics

- Identifiable **feature** characteristics includes:
  - precision (or tolerance),
  - roughness (or surface finish),
  - overall part size-envelope,
  - shape geometry,
  - top-down versus bottoms-up,
  - access-entry-exit boundaries,
  - depth boundaries,
  - material treatment, such as heat treat, plating,
  - others

Item Level Inputs - Complexity

Part Count

						Default	
	Min	*Likely*	*Most*	*Calc Mean*	*Min*	*Likely*	*Most*
Number of Components			①	208	192	211	232 ②

		Components
	Program	397
1	Fan Subsystem	0
2	Fan Assembly	0
3	Gas Generators	0
4	Frame and Trunnion	0
5	Compartment Structu	0
6	Cover	0
7	Actuator	0
8	Transition Section	0
9	Miscellaneous (Fan)	0
10	Primary Rocket Subsys	211
11	Rocket Chamber Ass	30
12	Support Structure	15
13	Turbopumps	65
14	Gas Generator	55
15	Ducting and Valves	26
16	Starting System and	20
17	Mixer/ Diffuser /Afterbur	79
18	Mixer	8
19	Diffuser	0
20	Fuel Injection Unit	25
21	Combustor	6
22	Forward Centerbody	5
23	Turbopump and Misc	35
24	Exit Nozzle Subsystem	30
25	Exit Bell	12
26	Translating Ring Ass	0
27	Fixed Plug	6
28	Actuator unit	0
29	Miscellaneous (Exit	12
30	Controls, Lines	55
31	Control Assemblies	25
32	Valves and Lines	30
33	Inlet, typical	22

RBCC Components

Input: 1) Number of Components

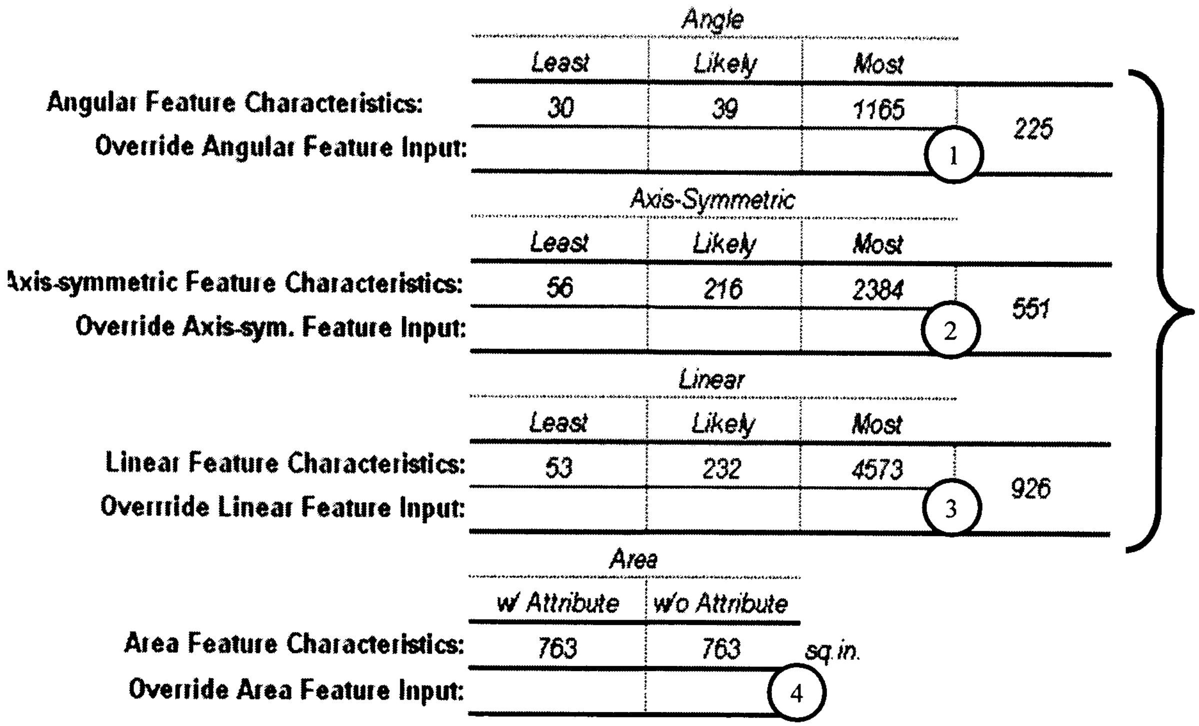
Input the number of components to override the defaults.

Info: 2) Default Number of Components

The default number of components is derived from the Selection Worksheet and is dependent upon engine configuration inputs.

Item Level Inputs - Complexity

Feature Count



	Angle			
	Least	Likely	Most	
Angular Feature Characteristics:	30	39	1165	225
Override Angular Feature Input:			①	

	Axis-Symmetric			
	Least	Likely	Most	
Axis-symmetric Feature Characteristics:	56	216	2384	551
Override Axis-sym. Feature Input:			②	

	Linear			
	Least	Likely	Most	
Linear Feature Characteristics:	53	232	4573	926
Override Linear Feature Input:			③	

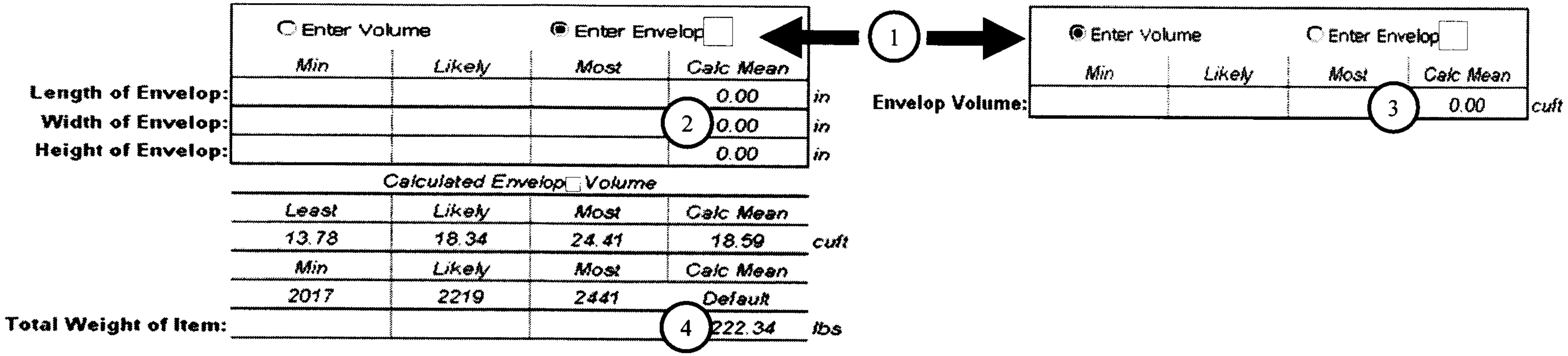
	Area		
	w/ Attribute	w/o Attribute	
Area Feature Characteristics:	763	763	sq.in.
Override Area Feature Input:		④	

Features count is defined as the sum of both explicit and implicit characteristics. This means that physical form characteristics, such as holes, depressions and protrusions are counted, along with the additional information required, such as tolerance, positional dimensions, surface finish are counted as features.

Input:
1) Override Angular Feature
2) Override Axis-symmetric Feature
3) Override Linear Feature
4) Override Area Feature

Item Level Inputs - Complexity

Volume & Mass



○ Enter Volume ● Enter Envelop☐

	Min	Likely	Most	Calc Mean	
Length of Envelop:				0.00	in
Width of Envelop:				0.00	in
Height of Envelop:				0.00	in

Calculated Envelop☐ Volume

Least	Likely	Most	Calc Mean	
13.78	18.34	24.41	18.59	cuft

	Min	Likely	Most	Calc Mean	
	2017	2219	2441	Default	
Total Weight of Item:				222.34	lbs

● Enter Volume ○ Enter Envelop☐

	Min	Likely	Most	Calc Mean	
Envelop Volume:				0.00	cuft

Selection: 1) Size: volume or envelope

Select either volume or envelope

2) Envelope input

Inputs if Volume was selected: Length, Width and Height.

3) Envelope input

Input if Volume was selected: Volume (cu.ft.)

4) Weight of Item

Input weight to override the estimated weight (default).

Item Level Inputs

Materials

- **Material Indices**
- **Material Down-selection**
- **Direct Material Selection**
- **Material Selection - example**

Item Level Inputs - Materials

Material Indices

Material Indices

$1/a = \rho C_p/\lambda$	$E^{1/3}/q\rho$	K_{IC}^2/E and σf	$\sigma f/C_m\rho$
$1/\lambda$	$E^{1/3}/\rho$	$K_{IC}^2/\sigma f$	$\sigma f/E$
$1/\rho_e$	$E^{1/3}/\rho$	λ/α	$\sigma f/E\alpha$
$1/\rho_e \rho C_m$	$G/C_m\rho$	$\lambda/a^{1/2} = (\lambda\rho C_p)^{1/2}$	$\sigma f/I_e\rho$
$a^{1/2} = (1/\lambda\rho C_p)^{1/2}$	$G/I_e\rho$	$\lambda/\Delta\alpha$	$\sigma f/q\rho$
$C_m\rho$	$G/q\rho$	$\lambda/p\Delta\alpha$	$\sigma f/\rho$
C_p/C_m	G/ρ	$\lambda\sigma f$	$\sigma f^{1/2}/C_m\rho$
$C_p\rho/\rho_e$	$G^{1/2}/C_m\rho$	$\lambda\sigma f/\rho$	$\sigma f^{1/2}/I_e\rho$
$E/(1-v)C_m\rho$	$G^{1/2}/I_e\rho$	$q\rho$	$\sigma f^{1/2}/q\rho$
$E/(1-v)I_e\rho$	$G^{1/2}/q\rho$	ρ	$\sigma f^{1/2}/\rho$
$E/(1-v)q\rho$	$G^{1/2}/\rho$	$\sigma e/E$	$\sigma f^{2/3}/C_m\rho$
$E/(1-v)\rho$	$G^{1/3}/C_m\rho$	$\sigma_e/E\rho_e$	$\sigma f^{2/3}/I_e\rho$
$E/C_m\rho$	$G^{1/3}/I_e\rho$	$\sigma e/\rho$	$\sigma f^{2/3}/q\rho$
$E/I_e\rho$	$G^{1/3}/q\rho$	σ_e/ρ_e	$\sigma f^{2/3}/\rho$
$E/q\rho$	$G^{1/3}/\rho$	$\sigma e^{1/2}/\rho$	$\sigma f^2/E$
E/ρ	$\eta E/\rho$	$\sigma e^{2/3}/\rho$	$\sigma f^2/EC_m\rho$
$E^{1/2}/C_m\rho$	$\eta E^{1/2}/\rho$	$\sigma e^2/E$	$\sigma f^2/EI_e\rho$
$E^{1/2}/I_e\rho$	$\eta E^{1/3}/\rho$	$\sigma e^2/E\rho$	$\sigma f^2/E\rho$
$E^{1/2}/q\rho$	$I_e\rho$	$\sigma_e^2/E\rho_e$	$\sigma f^{3/2}/E$
$E^{1/2}/\rho$	K_{IC} and σf	$\sigma e^{3/2}/E$	$\sigma f^{3/2}/E$ & $1/E$
$E^{1/3}/C_m\rho$	K_{IC}/E and σf	$\sigma e^{3/2}/E$ & $1/E$	$\sigma f^3/E^2$ & H
$E^{1/3}/I_e\rho$	$K_{IC}/\sigma f$	$\sigma e^3/E^2$ & H	σ_y

Material Properties

E	Young's modulus	G	shear modulus
ρ	density	q	energy content/kg
I_e	eco-indicator value/kg	C_m	material cost/kg
q	energy content per kg	σf	failure strength
σe	endurance limit	H	hardness
η	loss coefficient	K_{IC}	fracture toughness
λ	thermal conductivity	a	thermal diffusivity
C_p	specific heat capacity	T_{max}	maximum service temperature
α	thermal expansion coefficient	σy	yield strength
ρ_e	electrical resistivity		

Item Level Inputs - Materials

Material Down-selection

General	Minimum	Maximum	U/M
density			lb/in^3
energy content			MJ/kg
price			$/lb
recycle fraction			

Mechanical	Minimum	Maximum	U/M
ductility			
elestic limit			MPa
fracture toughness			$MPa.m^{1/2}$
hardness			MPa
Poisson's ratio			
shape factor			
Young's modulus			Gpa

Thermal	Minimum	Maximum	U/M
glass temperature			K
melting point			K
specific heat			J/kg.K

Electrical	Minimum	Maximum	U/M
breakdown potential			10^6V/m
resistivity			10^{-8}ohm.m

Environmental Resistance	Minimum	Maximum	U/M
flammability			
sea water			
UV			
wear			
weak acid			
weak alkalis			

The process-based cost model will provides the facility to constrain material properties to derive a suitable subset of potential candidates. This process step may follow the functional down-select or be used independently.

Item Level Inputs - Materials

Direct Material Selection

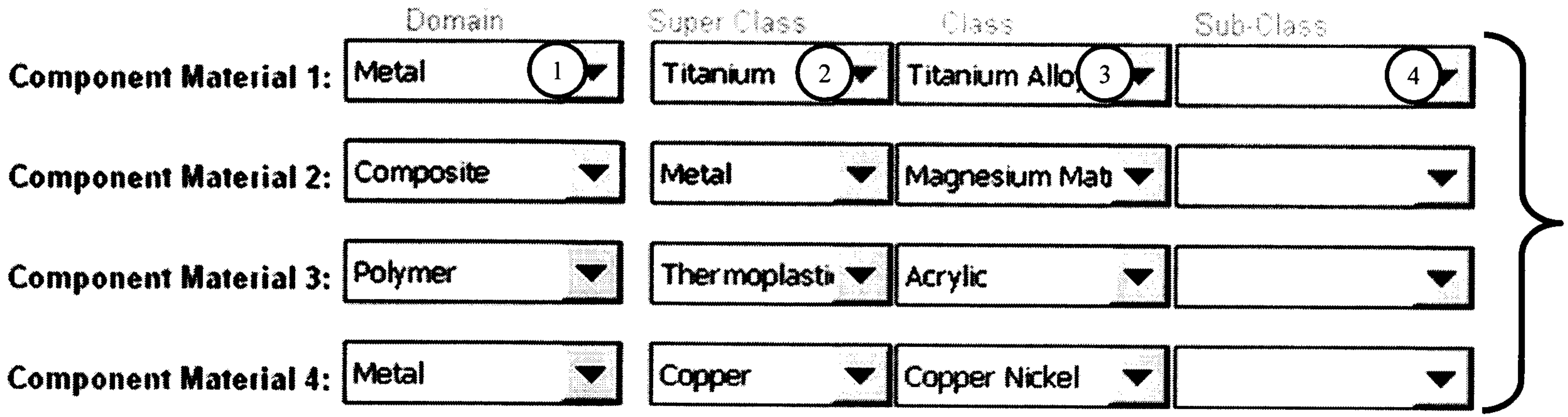
- Material Database Structure & Example

Material/Property	U/M
Domain	
Super-Class	
Class	
Sub-Class	
Name	
Density Least	{lb/in3}
Density Likely	{lb/in3}
Density Most	{lb/in3}
Heat of Fusion Least	{J/g}
Heat of Fusion Likely	{J/g}
Heat of Fusion Most	{J/g}
Cost Least	{$/lb}
Cost Likely	{$/lb}
Cost Most	{$/lb}
Recycle Fraction Least	{%}
Recycle Fraction Likely	{%}
Recycle Fraction Most	{%}
Ductility Least	{%}
Ductility Likely	{%}
Ductility Most	{%}
Elastic Limit Least	{Mpa}
Elastic Limit Likely	{Mpa}
Elastic Limit Most	{Mpa}
Hardness Least	{Mpa}
Hardness Likely	{Mpa}
Hardness Most	{Mpa}
Hardness, Vickers	
Hardness, Brinell	
Hardness, Rockwell C	
Hardness, Rockwell B	
Hardness, Rockwell A	
Hardness, Knoop	
Fracture Toughness Least	{Mpa1/2}
Fracture Toughness Likely	{Mpa1/2}
Fracture Toughness Most	{Mpa1/2}
Poissons Ratio Least	
Poissons Ratio Likley	
Poissons Ratio Most	
Shape Factor	
Young's Modulus Least	{Gpa}
Young's Modulus Likely	{Gpa}
Young's Modulus Most	{Gpa}
Glass Temperature Least	{K}
Glass Temperature Likley	{K}
Glass Temperature Most	{K}
Melting Point Least	{K}
Melting Point Likely	{K}
Melting Point Most	{K}
Specific Heat Least	{K}
Specific Heat Likely	{K}
Specific Heat Most	{K}
Breakdown Potential Least	{106 V/m}
Breakdown Potential Likely	{106 V/m}
Breakdown Potential Most	{106 V/m}
Resistivity Least	{10-8 ohm-m}
Resistivity Likely	{10-8 ohm-m}
Resistivity Most	{10-8 ohm-m}
Flammability	{1-5}
Sea Water	{1-5}
UV	{1-5}
Wear	{1-5}
Compressive Yield Strength	{Mpa}
Bearing Yield Strength	{Mpa}
Fatigue Strength	{Mpa}
Weak Acid	{1-5}
Ultimate Bearing Strength	{Mpa}
Thermal Conductivity	{W/m-K}
Tensile Strength, Yield	{Mpa}
Tensile Strength, Ultimate	{Mpa}
Solidus	{°C}
Shear Strength	{Mpa}
Shear Modulus	{Gpa}
Reflection Coefficient, Visible	(0-1)
Impact Strength, Unnotched C	{J}
Notched Tensile Strength	{Mpa}
Reduction of Area	{%}
Melting Point	{°C}
Maximum Service Temperatur	{°C}
Machinability	{%}
Magnetic Susceptibility	{cgs/g}
Magnetic Permeability	{%}
Impact Strength, Izod	{J}
Impact Strength, Charpy	{J}
Liquidus	{°C}
Heat Capacity	{J/g-°C}
Emissivity	(0-1)
Elongation; break	{%}
Electrical Resistivity	{Ohm-cm}
Curie Temperature	{°C}
CTE, linear 500°C	{µm/m-°C}
CTE, linear 250°C	{µm/m-°C}
CTE, linear 20°C	{µm/m-°C}
CTE, linear 1000°C	{µm/m-°C}
Critical Superconducting Tem	{K}
Critical Magnetic Field Strengt	{Oersted}
Bulk Modulus	{Gpa}

Domain	Metal
Super-Class	Alloy Steel
Class	AISI 4000 Series Steel
Sub-Class	Medium Carbon Steel
Name	AISI 4130H Steel, water quenched 855°C (1570°F), 540°C (1000°F) temper, 13 mm round
Density Least {lb/in^3}	0.281792862
Density Likely {lb/in^3}	0.283599227
Density Most {lb/in^3}	0.285405591
Heat of Fusion Least {J/g}	60
Heat of Fusion Likely {J/g}	66
Heat of Fusion Most {J/g}	72
Cost Least {$/lb}	1.212541
Cost Likely {$/lb}	1.6975574
Cost Most {$/lb}	2.1825738
Recycle Fraction Least	0.8
Recycle Fraction Likely	0.85
Recycle Fraction Most	0.9
Ductility Least	0.04
Ductility Likely	0.215
Ductility Most	0.39
Elastic Limit Least {Mpa}	305
Elastic Limit Likely {Mpa}	1030
Elastic Limit Most {Mpa}	1755
Hardness Least {Mpa}	1200
Hardness Likely {Mpa}	3425
Hardness Most {Mpa}	5650
Hardness, Vickers	319
Hardness, Brinell	302
Hardness, Rockwell C	32
Hardness, Rockwell B	99
Hardness, Rockwell A	
Hardness, Knoop	328
Fracture Toughness Least {Mpa$^{1/2}$}	12
Fracture Toughness Likely {Mpa$^{1/2}$}	52
Fracture Toughness Most {Mpa$^{1/2}$}	92
Poissons Ratio Least	0.285
Poissons Ratio Likley	0.29
Poissons Ratio Most	0.295
Shape Factor	48
Young's Modulus Least {Gpa}	205
Young's Modulus Likely {Gpa}	205

Item Level Inputs - Materials

Material Selection Example



	Domain	Super Class	Class	Sub-Class
Component Material 1:	Metal ①	Titanium ②	Titanium Allo ③	④
Component Material 2:	Composite	Metal	Magnesium Mat	
Component Material 3:	Polymer	Thermoplasti	Acrylic	
Component Material 4:	Metal	Copper	Copper Nickel	

4-Primary Materials

Selection: 1) Domain

Ceramic, Composite, Foam, Hydrated, Metal, Natural or Polymer

2) Super Class

Polymer example: Elastomer, Thermoplastic or Thermoset.

3) Class

Metal Composite example: Al Matrix, Cu Matrix, Lead Matrix, or Mg Matrix

3) Sub-Class

AISI 1000 Steel Alloy example: High Carbon, Low Carbon or Medium Carbon

Item Level Inputs

Process

- **Process Capability Characteristics**
- **Process Selection Inputs**
- **Process Database**
- **Development Processes**
- **Process Selection by Capability**

Item Level Inputs - Process

Process Capability Characteristics

The process database will include the following **numerical attributes**:
Mass range - maximum mass within process capability
Section - normal range of section thickness within process capability
Roughness - normal range of surface roughness
Tolerance - range of precision within process capability
Aspect Ratio - maximum length to thickness ratio
Adjacent Section Ratio - maximum practical ratio at a change of section
Hole Diameter - minimum hole diameter the process can produce
Minimum Corner Radius - minimum corner radius within process capability
Maximum Dimension - maximum dimension the process can produce
Quality Factor - probability of defects inherent in the process

The process database will include the following **economic attributes**:
Economic Batch Size - competitive lot quantity
Capital Cost - estimated cost of process equipment
Tooling Cost - cost of dedicated tooling, jigs & fixtures
Lead Time - planned and preparation of tooling schedule requirement
Material Utilization - material yield percentage
Production Rate - process output rate per hour
Tool Life - measure of output before tooling needs to be replaced

The process database will include the following **logical attributes**:
Process Class - top-level hierarchy designation
Process Sub-Class - mid-level hierarchy designation
Process - specific designation
Feature Map - identifies those features applicable to the process

The process database will include the following **text attributes**:
Name
Description

Features and form contribute to selection of a suitable process solution set.

The process based cost estimation methodology required defining a comprehensive list of development and manufacturing processes to be included in the model.

Development Processes
~55

Manufacturing Process
~250 to 300

Item Level Inputs - Process

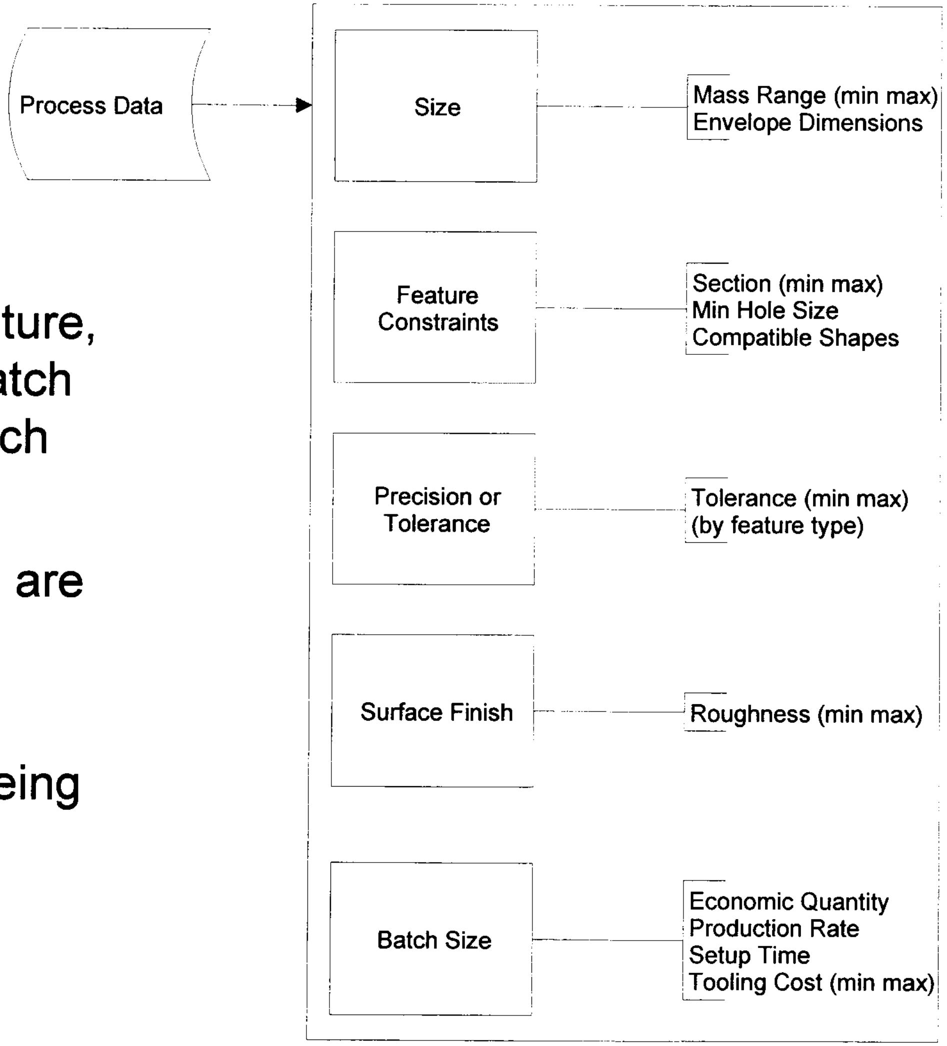
Process Selection Inputs

Process Specification:	Ratio	Percent
Forge Ratio/*Percent*:	5	*55.6%*
Forge Desciption:	Cold Forge	
Forge Material:	Titanium Alloy	
Forge Intensity/Assy Tolerance:	3	*2.8*
Composite Ratio/*Percent*:	2	*22.2%*
Composite Description:	3. Manual fab: pattern cutting, composite orientation, debulk, bagging, & curing.	
Composite Intensity/Assy Tolerance:	3	*2.0*
Machine/Fab Ratio/*Percent*:	1	*11.1%*
Machine/Fab Description:	1. Highest Precision, assembly tolerance < 0.001".	
Machine/Fab Intensity/Assy Tolerance:	2	*1.0*
Cast Ratio/*Percent*:	1	*11.1%*
Cast Description:	1. Simple pattern, no core box.	
Cast Material:	Aluminum	
Cast Intensity/Assy Tolerance:	5	*5.3*

Item Level Inputs - Process

Process Database

- The process database will include specific process capabilities such as size, feature, precision, roughness, and batch constraints that pertain to each process
- ~55 Development processes are included in the database
- ~250- 300 manufacturing processes are identified to being included in the database



Item Level Inputs - Process

Development Processes (1 of 2)

Systems Engineering Process (SE)
System Requirements Analysis
Systems Verification
System Integration
Aero/Structural/Mechanical Design Process (ASM)
Vehicle Layout, Design and Analysis
Aero Segment/Subsystem Design
Structural Segment/Subsystem Design
Mechl/Elect Segment/Subsystem Design
Structural End Item Detail Design
Mech/Elect Detail Design
Electronic Design Process (ED)
Electronic Subsystem Design
Electronic Detail Design
Software Design Process (SE)
Software Planning & Requirements Analysis
Software Configuration Management
Software Development Tools
Computer S/W Configuration Item Implementation

Specialty Engineering Process (SE)
Survivability and Vulnerability
Mass Properties
Parts, Materials & Processes (PM&P)
Electromagnetic
System Safety
Human Factors Engineering
Affordability and Life Cycle Cost
Test & Evaluation Engineering Process (TE)
System Level Test & Verification Planning
Developmental Test
End Item Qualification Test
Integration Qualification Test
TSE / STE Requirements
Installation, Assembly and Checkout (IACO)
Test Facilities
Test Platform / Support Facility Maintenance
TSE/STE Detail Design
Functional Checkout & Acceptance Test (Production)

Item Level Inputs - Process

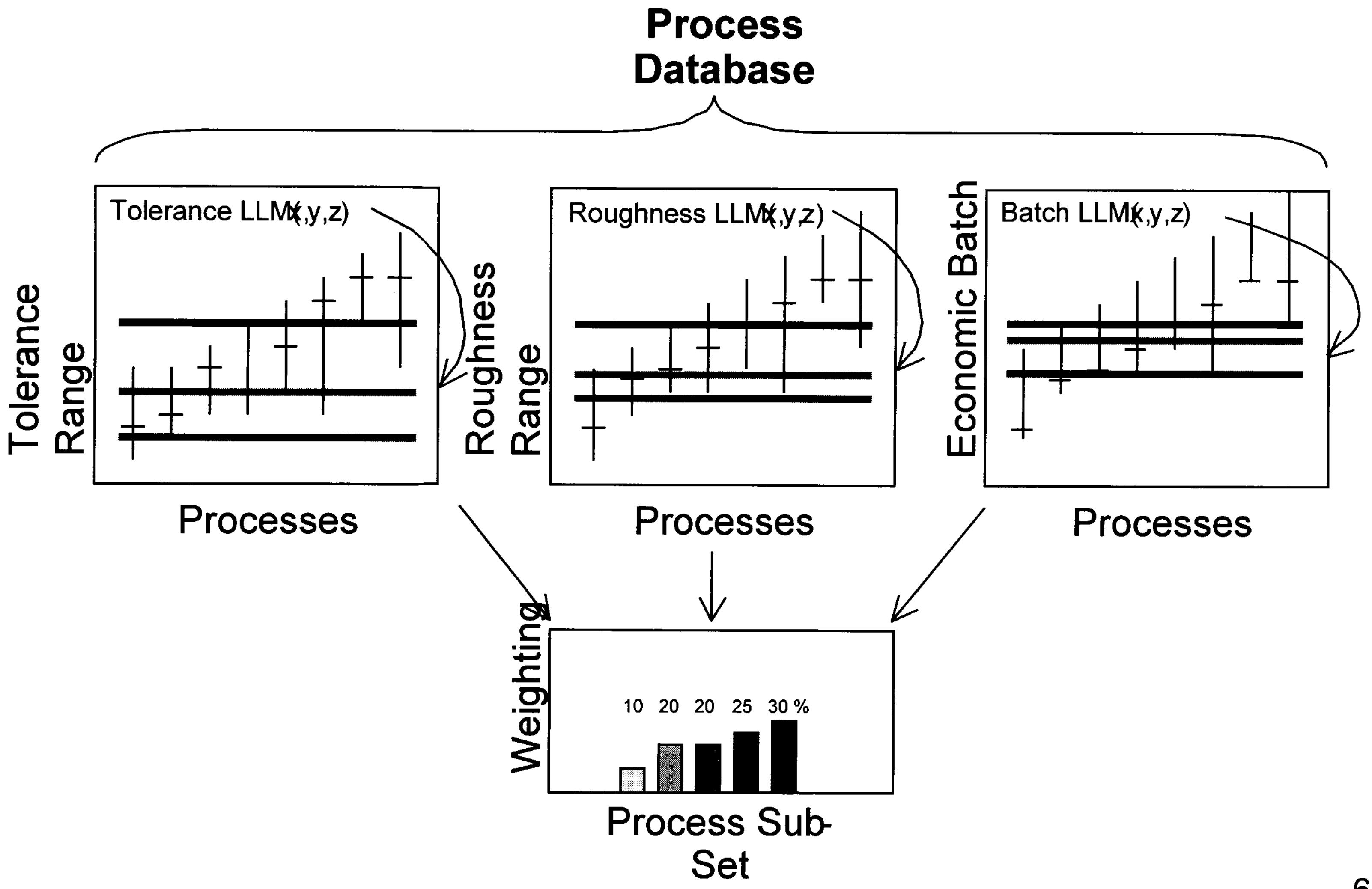
Development Processes (2 of 2)

Logistics Engineering Process (LO)
ILS Management
Logistics Support Analysis Total Summary
Support Equipment Analysis
Reliability, Maintainability & Testability
Site Activation
Contractor Technical Support
Provisioning Spares
Training System Requirements
Develop Training Materials
Training Course Conduct
Training Systems – Operate & Maintain
Training Equipment Design and Analysis
Technical Publications
Integrated Electronic Technical Manual
Engineering Operations Process (OP)
Configuration/Change Management
Data Management/Engineering Release
Foreign Disclosure
Engineering Operations Summary
Proposal Preparation

Technical Subcontract Management (SM)
Subcontract Management
Factory Support Process (FS)
First Article Fabrication and Kit Installation
Production & Deployment Support (Production)
Modifications (MO)
Modification-Receiving, Checkout and Maintenance
Modification-Over & Above
Modification-On-Site Engineering

Item Level Inputs - Process

Process Selection by Capability



Item Level Inputs - Process

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Development Processes
~55

Manufacturing Process
~250 to 300

Process-based Model

Outputs

- Sample of top-level cost estimate.
- Sample of top-level schedule estimate.
- Sample of detailed process estimate
- Sample of probabilistic estimate.

Process-based Model Outputs

Sample of Top-level Cost Estimate

Output:

Development Hours	500	
~Development Months	250.0	
Total Prototype Material Cost	$	2,000
Prototype Labor Cost	$	500
Development Labor Cost	$	1,500
Project Management Cost (includes fees)	$	1,000
Total Project Cost	$	3,000

Process-based Model Outputs

Sample of Top-level Schedule Estimate

Schedule Estimate:	Optimum Schedule	
	Start	Finish
Needs Analysis	**4/18/03**	5/24/03
Define Mission Functional Requirements	3/7/04	4/18/04
Define Requirements and Concepts	4/18/04	6/5/04
Perform Conceptual Design	6/5/04	8/5/04
Perform Preliminary Design	8/5/04	1/9/05
Perform Detailed Design	1/9/05	7/16/05
Build 1st Article	7/16/05	3/25/06
Production	3/25/06	12/22/09
Support	12/22/09	**12/23/09**

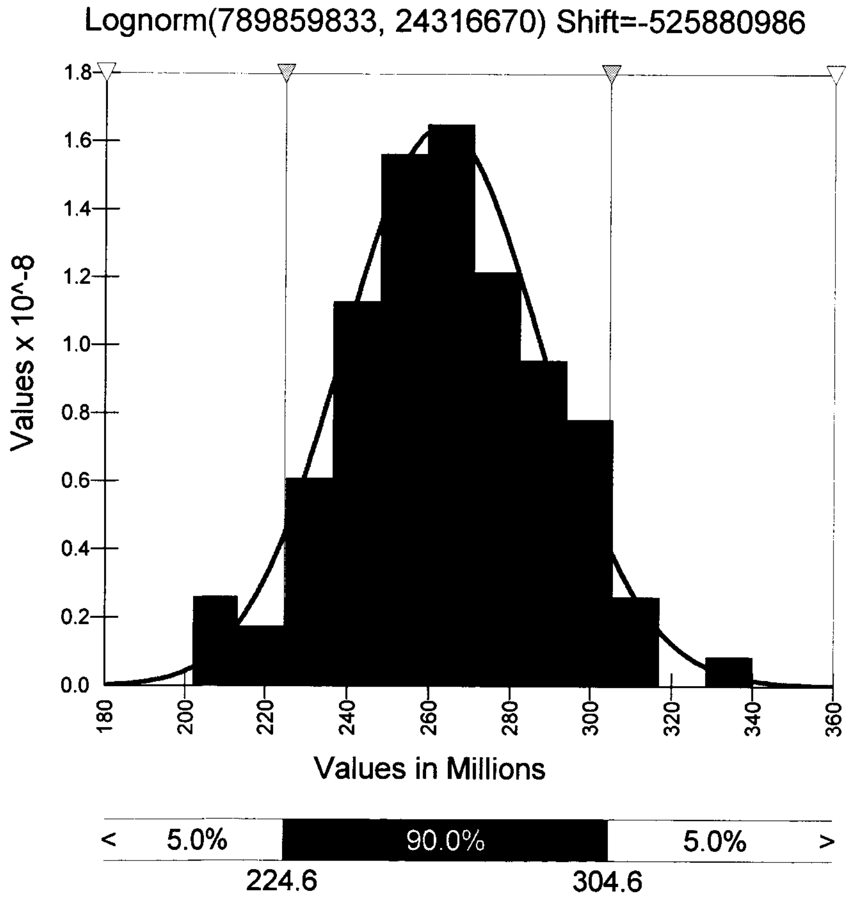
Process-based Model Outputs

Sample of Detailed Process Estimate

	Sys Engineering	Mechanical Design Processes	Electrical Design Processes
Needs Analysis	$ 750	$ -	$ -
Define Mission Functional Requireme	$ 1,000	$ 1,000	$ -
Define Requirements and Concepts	$ 1,200	$ 1,200	$ 1,000
Perform Conceptual Design	$ 1,000	$ 1,000	$ 1,200
Perform Preliminary Design	$ 500	$ 500	$ 1,000
Perform Detailed Design	$ 2,000	$ 2,000	$ 500
Build 1st Article	$ -	$ -	$ 2,000
Production	$ -	$ -	$ 400
Support	$ -	$ -	$ 20
Total	$ 6,450	$ 5,700	$ 6,120

Process-based Model Outputs

Sample of Probabilistic Estimate



Process-based Model

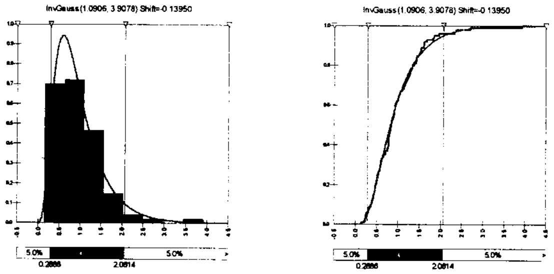
Status

- **Today**
- **Being implemented**
- **Planned**

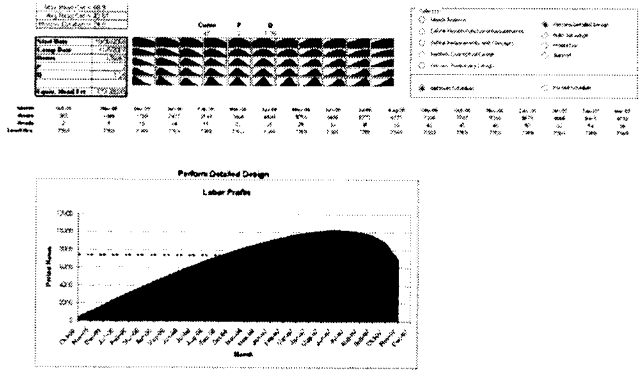
Process-based Model Status

Today

- Development Effort & Cost
  - Ramjet-Scramjet
  - Rocket-based Combined Cycle
- Development Schedule
- Application



Cost-Risk

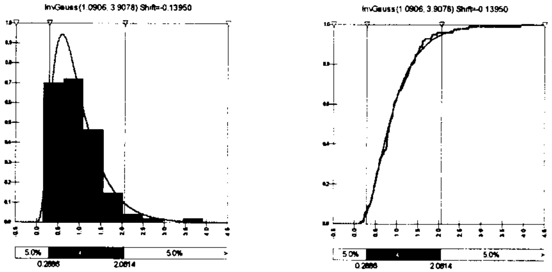


Schedule-Staff Load

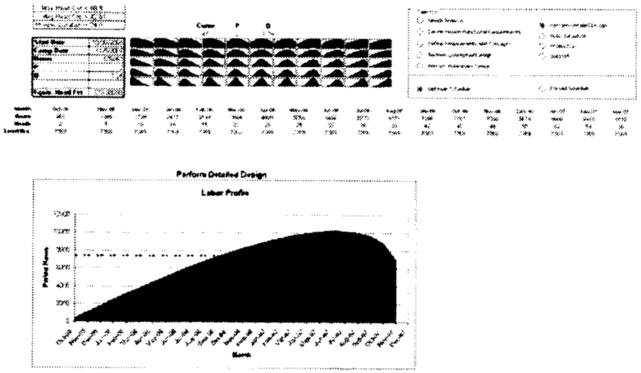
Process-based Model Status

Being Implemented

- Development Effort & Cost
  - Fuel Cell Technology
- Manufacturing effort & cost
  - Ramjet-Scramjet
  - Fuel Cell Technology
  - 250-300 processes and 2500-3000 materials
- Incorporating Analytical Hierarchy Process



Cost-Risk

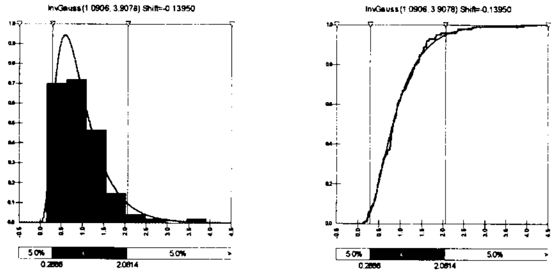


Schedule-Staff Load

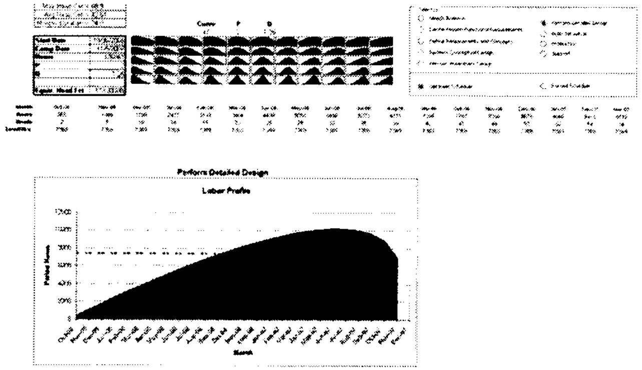
Process-based Model Status

Planned

- Operations & Support
- Life Cycle Cost
- Client-Server Implementation
- Expand model to include rocket engines



Cost-Risk



Schedule-Staff Load

Summary

- Process based development cost model completed in Alpha version.
- Initial implementation is for ramjet-scramjet engines.
- Method is general and model can be adapted to other products such as fuel cells.
- Program is continuing with preparation of production cost model.
- Ultimate goal is a life-cycle cost model.

For More Information

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