
ICEAA 2016 International Training Symposium
17-20 October 2016

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Overview

- NASA / Air Force Cost Model (NAFCOM) History
- Project Cost Estimating Capability (PCEC) Introduction
- PCEC Analysis Approach
  - Robotic SC
  - Crewed and Space Transportation Systems
- PCEC Capabilities
- Summary
NAFCOM History
NAFCOM Overview

- **Overview**
  - Parametric cost estimating tool for launch vehicles, robotic spacecraft, human spacecraft, landers, rovers, and other flight hardware systems
  - Development began in 1990 with 12 major releases providing increased accuracy, data content, & functionality
  - Based on over 155 NASA and U.S. Air Force space flight hardware projects
  - Used by over 1000 Government and Contractor employees
  - Two cost estimating methodologies are available:
    - Multi-Variable CERs
    - Weight/Analogy based CERs
  - Incorporates Liquid Rocket Engine Cost Model (LRECM) and Space Operations Cost Mode (SOCM)
  - Allows user input CERs and throughput costs
  - Performs probabilistic risk analysis using FRISK

- **Versions of NAFCOM**
  - **Government**: Includes modeling capability and access to all underlying data
  - **Contractor**: Includes Government version capability (CERs, etc) but no underlying cost & mass data
NAFCOM Over the Years

1990
- NASCOM database in hardcopy only
- Estimators' hand-entered data into spreadsheets
- Database contained 65 data points

1992
- Allowed online searches and copying of data
- Cost estimates developed in spreadsheets with CERs created by individuals
- Database contained 70 data points

1994
- Fully functional cost model with user defined WBS and data access
- CERs built automatically within NASCOM using “1st Pound” method
- Database contained 91 data points

1996
- Combined NASA and Air Force data
- Enhanced search and filtering of data
- Standardized WBS elements created
- Database contained 102 data points

1999
- First non-weight based CERs for five subsystems (multi-variable CERs)
- Government and contractor versions distributed
- Database contained 114 data points

2002
- Total rewrite of all NASCOM program code
- Multi-variable CERs for all subsystems
- Major user interface improvements
- Database contained 112 data points

2004-2006
- Cost Risk Analysis Module
- CER Improvements
- SOFCM
- Component level multi-variable CER
- Allocation of Risk Dollars by WBS Elements
- WBS Generator
- Expanded drag and drop manipulation
- Dynamic display of Weight Based standard errors

2008
- 17 New Components Level multi-variable CERs
- New statistics integrated into database
- Historical Schedule Data integrated into toolbar
- Converted to .NET Platform and SQL Databases
- New interface for risk analysis outputs
- Database contains 135 data points

2011
- Thruput $ in any fiscal year
- Historical weight units sensitive to global selection
- Two new templates (Earth Orbiting and Planetary)
- Historical Database QA
- Multi-Variable CER Mission indicator
- Database contains 149 data points

2007
- Calibration Module
- Matrix Consistency Checker
- Ability to send full NASCOM Cost Report directly to Excel
- Database contains 133 data points
Why Move Away from NAFCOM?

• **CER Issues**
  – Non-Homogeneous data set
  – Input parameters that are statistically insignificant
  – Subjective variables have significant explanatory value
  – Documentation for assigning subjective variables limited
  – Oversubscribed CERs
  – Some CERs yield nonsensical results

• **Software Issues**
  – “Black box” to users
  – Calculation errors
  – Data protection requirements

• **Analysis Issues**
  – Results produced in standalone environment
  – Over-reliance on exercising the model
Moving to a Data Centric Approach

Model Centric
- Focus is on how to use the model
- Model becomes a medium for communication with the technical community
- Model gets all the credit (or blame) for the estimate
- Estimate becomes an evaluation of the present, rather than a prediction of the future

Data Centric
- Focus is on the relationship of the data to the estimating problem
- Analyst must access and know the underlying data
- Puts onus for the quality of the estimate on the estimator
- Done properly, can lead to value-added solutions
PCEC Introduction
What is PCEC?

• PCEC is a new parametric cost model developed and maintained by NASA to replace NAFCOM
  – PCEC development started in late 2013 to begin a new course for space cost estimating, leveraging the historical analyses but expanding them to align with evolving NASA estimating needs

• Goals for PCEC
  – Emphasize good analysis as a critical component of credible cost estimating (model-focused approach vs. data-focused approach)
  – Create an environment that addresses the diverse estimating and analysis requirements across NASA
  – Enable the entire NASA cost community to have ownership and add value to an Agency-wide capability
  – Conduct new normalization and analyses to address the issues identified with NAFCOM
  – Address all elements of the NASA Standard WBS
**Tool Development**

- Simple, Robust, Transparent
- Focus on Flexibility and Capability versus Ease of Use
- Don’t Duplicate Existing Capabilities / Models / Tools
- Leverage Existing Software to the Greatest Extent Possible (e.g., Argo, @Risk, Crystal Ball)
- Expect NASA Cost Analysts to Know how to Use Spreadsheets and other Desktop Applications
- Keep the Data behind the NASA Firewall
- Modular, Open Source Architecture

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**Model Development**

- Use the Best Data Possible
- Total Transparency in the Analysis of the Data and the Development of the CERs
- No Cherry Picking the Data Points
- Minimize or Eliminate Subjective Inputs
  - Follow a Data Driven Process for the Derivation of Subjective Inputs
  - Allow the User to Follow the same Process for Determining Input Values
- Emphasize Quality of Input Parameters over Quantity
- Expect the User to Develop the Rationale for the Estimate
  - Model Centric to Data Centric
  - Know the Data
The PCEC Architecture

Key Elements of the PCEC Architecture

NASA Historical Cost Libraries

Data Sources

Data Normalization
CER Development
Source Documentation

PCEC Interface

Facilitates the use of the PCEC Library information for creating estimates

PCEC Library

Stores core cost estimating artifacts:
- CERs
- WBS
- Phasing
- Inflation

NASA IT Security Interface

accessible with NASA User ID and Account Approval

Publicly Releasable via NASA Software Release Authority Process

Victory Solutions MIPSS Team
PCEC Development
Primary Activities

Robotic Spacecraft (Robotic SC)
- New CERs for estimating cost of subsystems for all types of Robotic Spacecraft
- New model for estimating project, payload, and spacecraft support function costs (e.g., PM, I&T)

Crewed & Space Transportation Systems (CASTS)
- New CERs for estimating the cost of subsystems on launch vehicles, crewed space structures, and in-space transportation systems
- New cost-to-cost CERs for support functions

PCEC Software Development
- Coding of the Routines to Access cost artifacts used to build a complete space cost estimate
- Development of Estimating Templates for different types of methodologies
- Documentation
Robotic Spacecraft Model
Objectives

- Develop a set of cost estimating methodologies tailored for NASA’s robotic science missions: Earth Science, Heliophysics, Astrophysics, and Planetary
- Provide full traceability into the data normalization and CER development processes

Approach

**Data Collection & Normalization**
- Collect cost data from NASA Cost Analysis & Data Requirements (CADRe)
- Identify technical & programmatic input candidates
- Develop repeatable 8-step normalization process

**Data Analysis & Model Development**
- Explore multiple analysis options to determine most logical modeling approach
- Create, evaluate, and test CERs
  - Spacecraft
  - Support Function
  - Other

**Documentation**
- Cost Normalization Workbooks
- Cost Assessment Reports (CARs) summarizing data normalization
- CER Input workbooks
- PCEC CER Calculation Workbooks
- CER Validation analysis
PCEC Robotic SC Model
Data Normalization Process

START
Raw (Unadjusted) Project Data

STEP 1
Inflate to Common Fixed Year $

STEP 2
Allocate to NASA WBS

STEP 3
Account for Management, Fees, & Burdens

OUTPUT A
NASA WBS by Year w/o Fees or Burdens

STEP 4
Full Cost Accounting Adjustments

OUTPUT B
NASA WBS by Year w/FCA & Contributions but w/o Fees or Burdens

STEP 5
Account for Contributions

STEP 6
Development Profile Phasing – Schedule & Long Lead Items

OUTPUT C
NASA WBS by Phase (normalized to a single protoflight unit)

STEP 7
Removal of Costs for Multiple Units

STEP 8
Removal of Costs from External Impacts

OUTPUT D
NASA WBS by Phase w/o External Impacts
PCEC Robotic SC Model  
Data Analysis Approach

• Effort began by defining a set of potential model inputs
  – Multiple information sources were reviewed to generate the initial input candidate list, including mass & performance metrics
  – More than 100 input candidates were identified

• Modeling effort explored three alternatives:
  1. Principal Component Analysis (PCA): Narrow the input data set to key parameters before running regression (~10-20 per subsystem)
  2. Regression using Expert Judgment: Use PCA results and expert judgment to narrow the input data set before running regression
  3. Hybrid Approaches: Use regression to develop the initial CERs, with adjustment factors to refine the CERs using additional inputs

Sample Inputs
PCA was selected as the initial modeling approach to investigate relevant independent variables, followed by iterative multiple regression to develop specific CERs.

For each Subsystem and Support Function, we iterated through the following general process:

- Segment & transform the normalized data
- Run PCA to identify variables explaining most of the variation
- Conduct multiple regression runs to identify potential CERs using from one to five independent variables
- Evaluate independent variables, statistics, coefficients
- Select CER for incorporation into the PCEC Library
PCEC Robotic SC Model
CER Example

Attitude Control Non-Recurring CER

Cost = 0.1 * WeightPerUnitKg^0.42 * OpEnvironment^0.75 * RadEnvironment^0.19 * SubsysDesignTime^0.26 * LaunchYearMinus1960^1.56

R^2 0.774
Adj R^2 0.740
F-Stat 22.602
F-Stat P-Value 0.000
PING Factor 1.088
SPE 5.49E-02

Regression DF 5
Residual DF 33
Total DF 38

Variable Name | Cost | WeightPerUnitKg | OpEnvrmt | RadEnvrmt | SubsysDesignTime | LYMinus1960
--- | --- | --- | --- | --- | --- | ---
Min | 574.157 | 0.610 | 1.000 | 1.000 | 3.467 | 36.000
Max | 17776.345 | 132.567 | 5.000 | 400.000 | 52.100 | 54.000
Mean | 4779.184 | 38.961 | 1.872 | 30.449 | 24.979 | 46.179
Median | 4172.519 | 34.240 | 2.000 | 15.000 | 24.200 | 47.000
SD | 3705.472 | 29.325 | 0.978 | 64.842 | 11.196 | 4.833

SSR 22.439
SSE 6.552
SST 28.992
SEE 0.446
Y_Bar 8.151
CV 0.055
Pearson's Co 0.880

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• Methodologies based on newly-normalized data from 42 recently-launched missions, with most data from CADRe

• One set of subsystem-level CERs for estimating Non-recurring and Recurring costs (15 CERs)
  – All are multi-variable power CERs developed using Ordinary Least Squares (OLS) regression of log-transformed data
  – Derived using PCA and multiple regression
  – Assume a protoflight approach for spacecraft development
  – Estimate Gov’t + Prime-costs for development and production

• Another set of CERs for estimating additional costs at the project, payload, and spacecraft levels (6 CERs)
  – New CERs that estimate the total PM, SE, MA, and I&T costs; allocations distribute costs to the project, payload, and spacecraft level
  – New CERs to estimate the Mission Operations Systems / Ground Data Systems (MOS/GDS) development costs
  – Developed using a PCA approach
Crewed and Space Transportation Systems (CASTS) Model
Objectives

- Develop a new, unique cost model for use in estimating space transportation systems, including crewed systems, earth-to-orbit systems, and in-space transportation systems
- Construct model from a historical database consisting exclusively of transportation/crew systems
- Empower users to create Credible, Supportable, Defendable estimates
1. Develop Overall WBS
2. Identify Source Data
   - NAFCOM-heritage systems: Trace back to original sources; re-evaluate using common definitions/assumptions; fit to CASTS WBS
   - New systems: Understand/analyze source data; evaluate using common definitions/assumptions; fit to CASTS WBS
3. Normalize Source Data
   - Convert to common year & units
   - Separate out elements of cost: Design & Development, First Unit, System Test Hardware, etc.
4. Assign to Appropriate CASTS WBS Elements
5. Develop CASTS CERs
   - Identify potential independent variables
   - Develop CER equations
   - Evaluate CER “goodness”
6. Document Analysis
Model Development Approach

- Perform iterative multiple regression with a small set of potential independent variables; mass as primary input with additional variables unique to subsystems
- Create & evaluate CERs in both power and linear forms based on data

Why this approach? Significant data “clutter”

- Minimal number data points with multiple potential independent variables (overfitting, potential multi-collinearity)
- Lack of/dissimilar definitions of technical variables between sources
- Poor predictive value (P-values >> .05)
- Counter-intuitive results (cost ↑ over time, cost ↓ increased complexity)
- Conflicting/countervailing influences between potential variables

Calculated “adjustment factor” for each data point

- Ratio of the actual to predicted value for a data point
- Not a “complexity” factor – says nothing about why value is what it is
Adapters Design & Development CER

\[
\text{Cost} = 0.45 \times \text{WeightPerUnit}^{0.83}
\]

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\[
\begin{align*}
\text{R}^2 & = 0.691 \\
\text{Adj R}^2 & = 0.661 \\
\text{F-Stat} & = 22.412 \\
\text{F-Stat P-Value} & = 0.001 \\
\text{PING Factor} & = 1.213 \\
\text{SPE} & = 0.28647763 \\
\text{SSR} & = 10.405 \\
\text{SSE} & = 4.643 \\
\text{SST} & = 15.047 \\
\text{SEE} & = 0.681 \\
\text{Y_Bar} & = 2.554 \\
\text{CV} & = 0.267 \\
\text{Pearson's Co} & = 0.832
\end{align*}
\]
PCEC CASTS Model
Summary

• Methodologies based on data from ~34 historical launch vehicle stages, crewed vehicles, and related space transportation systems/subsystems

• One set of CERs for estimating subsystem-level costs of Design and Development (D&D) and Flight Unit (43 CERs)
  – Nearly all are single-variable power CERs (with weight as the independent variable); a small number are linear CERs or multi-variable power CERs
  – Adjustment factors provide an analogous estimating supplement
  – Estimate Prime costs

• Another set of CERs for estimating supporting costs (e.g., PM, ground support equipment, tooling) at the spacecraft level (8 CERs)
  – Most are cost-to-cost CERs (use flight system cost as base)
  – Estimate Prime-level costs only; factors used for Program/Project level
PCEC Capability Overview
The PCEC Interface…

- is an Excel Add-in that appears as its own tab in the Excel Ribbon, with buttons to access capabilities for building an estimate in Excel
- contains a compressed copy of the PCEC Library and associated artifacts needed to build an estimate, including…
  - CERs
  - Statistics about the CERs
  - Other worksheets with WBSs, Inflation, specialized methodologies, etc.
- is compatible with Windows versions of MS Office
  - Mac users must use a virtualization program to run Windows
- is completely open: no code passwords, protected sheets, etc.
The primary section contains the key elements used to create a cost estimate in an Excel workbook

- The “Launch” feature, which auto-generates a complete estimate from a user-customized WBS
- Ability to insert single CERs into a worksheet
- Ability to insert pre-formatted templates into a workbook that estimate the DDT&E and production costs of a subsystem
- Linking to other NASA-related cost models (e.g., NICM)

The middle section provides access for learning more about the specific estimating artifacts that are available to users

- Information about the CERs: regression statistics, descriptive statistics, missions used
- Definitions and variables, their input units, and lists of valid inputs

The final section contains supporting elements for adding elements to complete an estimate

- Starting NASA Standard WBSs
- Inflation worksheets for escalating
- Phasing options for developing a by-year profile for the cost estimate
- Auto-generation of a documentation workbook for all CERs used in an estimate
- Help documents
PCEC v2.1 Components

Robotic Science Missions

- Spacecraft Subsystem CERs
- Support Function CERs
- NASA Instrument Cost Model
- MOS/GDS Development CERs
- Science Team Wrap Factors
- Launch Services ROM Estimator
- PCEC v1 Legacy CERs
- First Pound Cost CERs

Launch Vehicles/Human Spaceflight Missions

- Crewed and Space Transportation Systems (CASTS) Subsystem CERs
- Cost-to-cost Support Function CERs
- PCEC v1 Legacy CERs
- First Pound Cost CERs
- Wrap Factors

Estimating Support

- Thruput Templates
- CER Library
- WBS Templates
- Help File
- Inflation Indices
- Cost Phasing

Outside of PCEC

- Robotic Spacecraft data analysis spreadsheets and cost analysis reports
- CASTS “Virtual Blackbooks”
- CASTS User’s Guide
- Cost Analysis Data Requirements (CADRe) documents & backup data
- Other historical cost and technical data in the REDSTAR Library
PCEC v2.1 Model Capabilities

• PCEC v2 is currently best suited for estimating the cost to design, develop, and produce the following types of space systems
  – **Spacecraft**: Earth Orbiting Satellites, Planetary Probes, Rovers
  – **Launch Vehicles**: Multi-stage rockets, liquid and solid engines
  – **Human Space Flight Systems**: Crew Capsules, Orbiters, Habitats

• PCEC v2 CERs are designed to estimate at the subsystem level
  – Historical v1 Legacy CERs can estimate at the lower level but are separate from the Robotic SC and CASTS Models

• PCEC v2 currently does not have the capability to estimate…
  – Cubesats, Balloons, Aircraft
  – Nanosat Launchers, Sounding Rockets
  – Human hardware elements (e.g., space suits)
PCEC Today

• PCEC v2.1 is the latest version available (released in Aug 2016), which includes enhancements for estimating more elements across the NASA Standard WBS
• The general public can obtain PCEC (with some export restrictions) via the NASA Software Repository

PCEC Email Contact:  MSFC-PCEC@mail.nasa.gov
Application Website:  https://software.nasa.gov/, search for PCEC

• Ongoing data analyses and code development will continue to evolve the tool for future releases
PCEC Summary

- PCEC replaces NAFCOM as NASA’s in-house developed parametric cost estimating tool, accessible by many organizations.
- PCEC is not just a software tool but also a set of underlying analytical efforts to provide quality models within the tool:
  - New normalizations and CERs for Robotic SC and CASTS that follow a traceable, consistent approach.
  - Transparent calculations within the tool.
  - Tailorable environment to meet an individual or organization’s unique estimating needs.

- Questions?
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<td>Cassini</td>
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<td>JPL</td>
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<td>Planetary/Outer Planets</td>
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<td>Mars Global Survey</td>
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<td>LMA</td>
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<td>2/17/96</td>
<td>API</td>
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<td>Planetary/Discovery</td>
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## Roster of systems currently included in CASTS CER datasets

<table>
<thead>
<tr>
<th>Launch Vehicles</th>
<th>Liquid Engines</th>
<th>Software</th>
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<tbody>
<tr>
<td>Atlas V Common Core Booster</td>
<td>F1</td>
<td>SSME Adv Health Mgt Sys</td>
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<tr>
<td>Atlas V Centaur</td>
<td>J2</td>
<td>Orbiter Cockpit Avionics Upgrade</td>
</tr>
<tr>
<td>Apollo Command/Service Module</td>
<td>J2X</td>
<td>Orbiter Primary Avionics Software Sys</td>
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<tr>
<td>Apollo Lunar Module</td>
<td>RS27</td>
<td>Orbiter Backup Flight Software</td>
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<td>Centaur D</td>
<td>RD180</td>
<td>BRAHMS</td>
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<td>Centaur G' (Shuttle Centaur)</td>
<td>RL10</td>
<td>DART</td>
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<td>Centaur G' CISS - ASE</td>
<td>RS68</td>
<td>X33</td>
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<td>Shuttle External Tank</td>
<td>SSME</td>
<td>Centaur G'</td>
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<tr>
<td>Shuttle Orbiter</td>
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<td>Atlas II</td>
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<td>Saturn V 1st Stage (SIC)</td>
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<td>Saturn V 2nd Stage (SII)</td>
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<td>Titan Centaur</td>
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<td>Titan IV 5m Fairing</td>
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<td>Atlas I, II, IIA, IIAS</td>
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<td>Super Lightweight External Tank</td>
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