Maximising Parametric Model Utilisation by Developing Excellent Cost Estimating Relationships

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Introduction

- Parametric Cost Estimating Relationships (CERs):
  - are algorithms that forecast costs based upon the examination and validation of the relationships that exist between a project's technical, programmatic, and cost characteristics as well as the resources consumed during its development, manufacture, maintenance, and/or modification;
  - can be Simple (single parameter) or Complex (multiple parameters);
  - are inconsistently used for Defence projects;
  - suffer from a lack of support at higher levels due to poor understanding and lack of exposure to the levels of accuracy available from the tools.
- Similar algorithms are widely used in numerous industries to estimate outputs based on a number of technical and/or programmatic inputs, e.g.
  - size/mass estimation of aircraft components/systems;
  - reliability and maintainability metrics for complex systems;
  - manpower numbers required to operate and support complex systems, etc.

Introduction – General Method

Real World Data

- Acquisition data
- Operational data
- Cost data

Input Parameters

- System parameters; size, mass, technology, performance, complexity, stealth, etc.

Correlation & (Multiple) Regression

Parametric Equations

- Effort Consumed
  - Labour rates
- Equipment Costs

Predicted Total Effort

Predicted Whole Life Cost

Attributes of an ‘Excellent’ CER (1) – Data

- Quantity
  - Non-linear equations require a *minimum* of 11 data points for each parameter added to the equation
  - Never dismiss data for being ‘too old’ – technology (improvement) factors in the model could/**should** account for this
- Normalisation
  - All input data must be in consistent units, e.g. kg, m^2
  - All costs must all be converted to the same currency in the same financial year (preferably using recognised & authoritative currency exchange rates)
- Visibility
  - A lack of **total** transparency of the data values, sources, missing/estimated input parameters, etc. will exacerbate the lack of confidence that others have in any model
    - ‘Trust me’ is not good enough to convince others that you have a good model

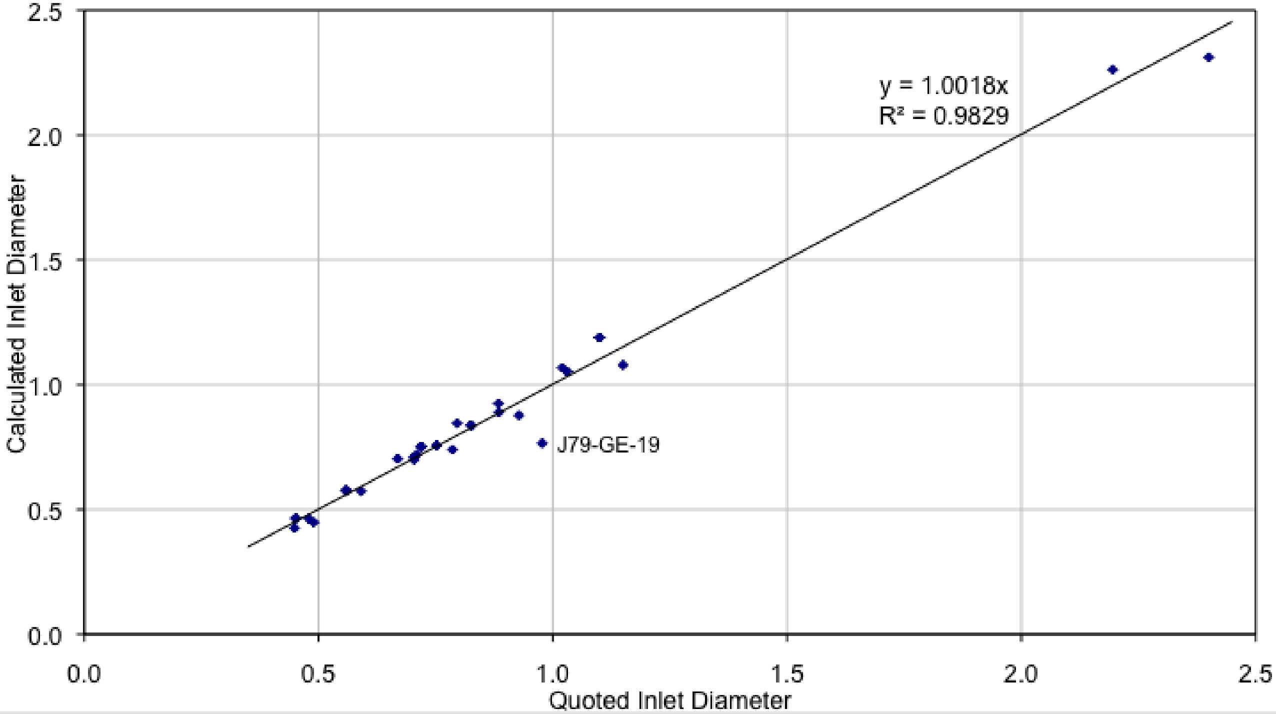
Attributes of an 'Excellent' CER (2) – Model Structure

- There must be a direct (or strongly correlated) relationship between the inputs and the output of the model
  - If there is no good *engineering* link between parameters, they should be removed
  - Often, there is a *theoretical* link between input parameters & the output
    - This can be used to validate that the model coefficients are of the right order
- Complex systems will likely require more complex models to enable suitable fidelity to be captured
  - Consider splitting the overall output into several sub-CERs
    - Increases visibility and ability to correlate/validate individual elements

Attributes of an ‘Excellent’ CER (3) – Model Algorithms (1)

- Simple models can make use of algorithms with single factors and coefficients, e.g.:
  - Aero Engine Inlet Diameter (m) = A × [mass flow rate]^b
  - ‘A’ is a correlation *factor;* ‘b’ is a correlation *coefficient:* A = 131.5, b = 0.5

Note that ‘b’ aligns with the theoretical relationship between air mass flow rate and intake diameter for a fixed (i.e. ‘ideal’) compressor entry velocity

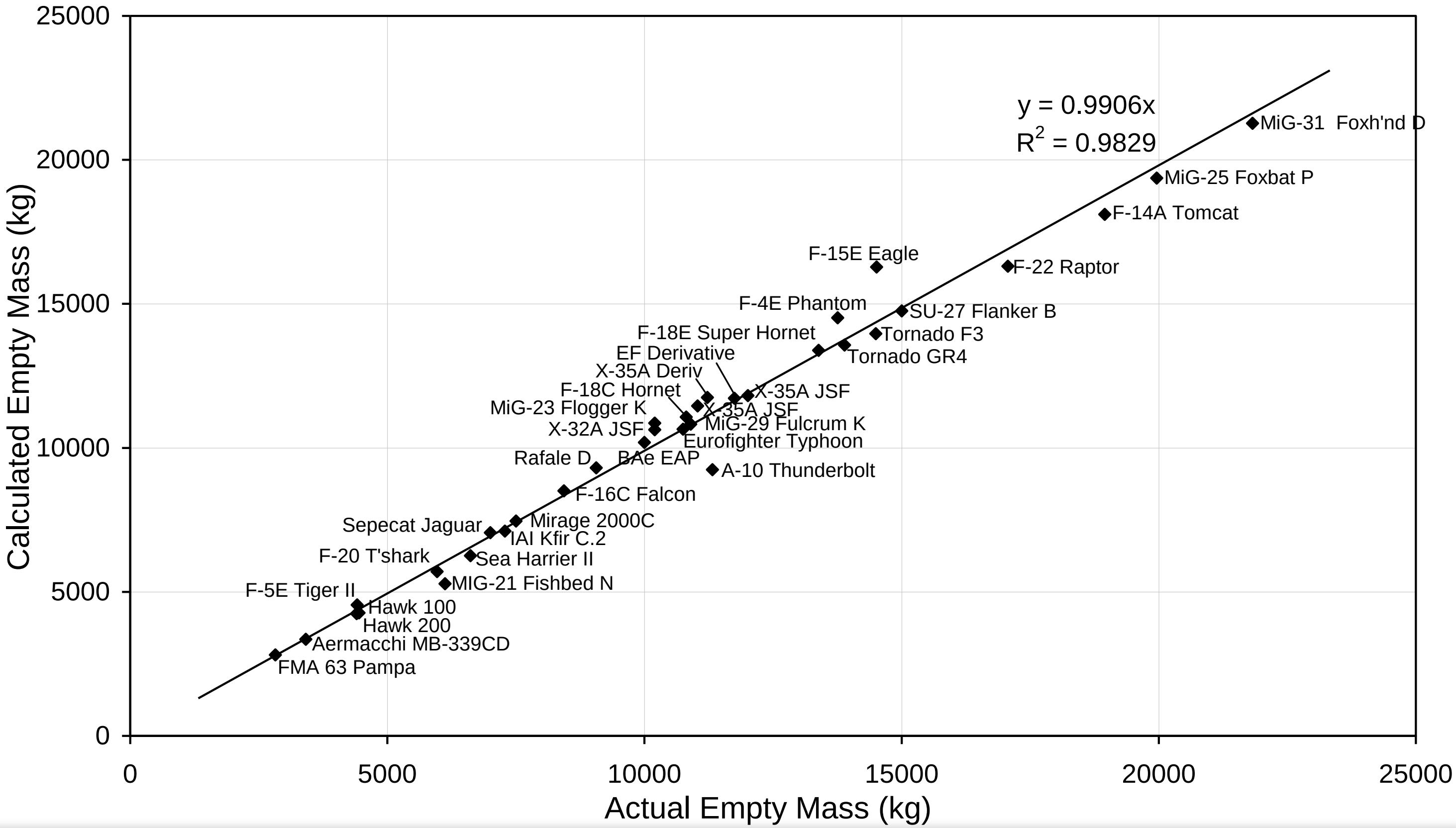


Attributes of an 'Excellent' CER (3) – Model Algorithms (2)

- Complex models may contain numerous inputs & coefficients, e.g.

$$\text{Wing Mass} = \text{A} \times \left[\frac{\text{Aspect Ratio}^{0.5}\ \text{Wing Area}^{1.5}}{\cos(\text{Quarter - chord Sweep})} \times \frac{(1+2\ \text{Taper Ratio})}{(3+3\ \text{Taper Ratio})} \times \frac{\text{Gross Mass}}{\text{Wing Area}} \times \text{Ultimate Load Factor}^{0.3} \times \left(\frac{\text{Design Diving Speed}}{\text{Thickness/Chord Ratio}} \right)^{0.5} \right]^{0.9}$$

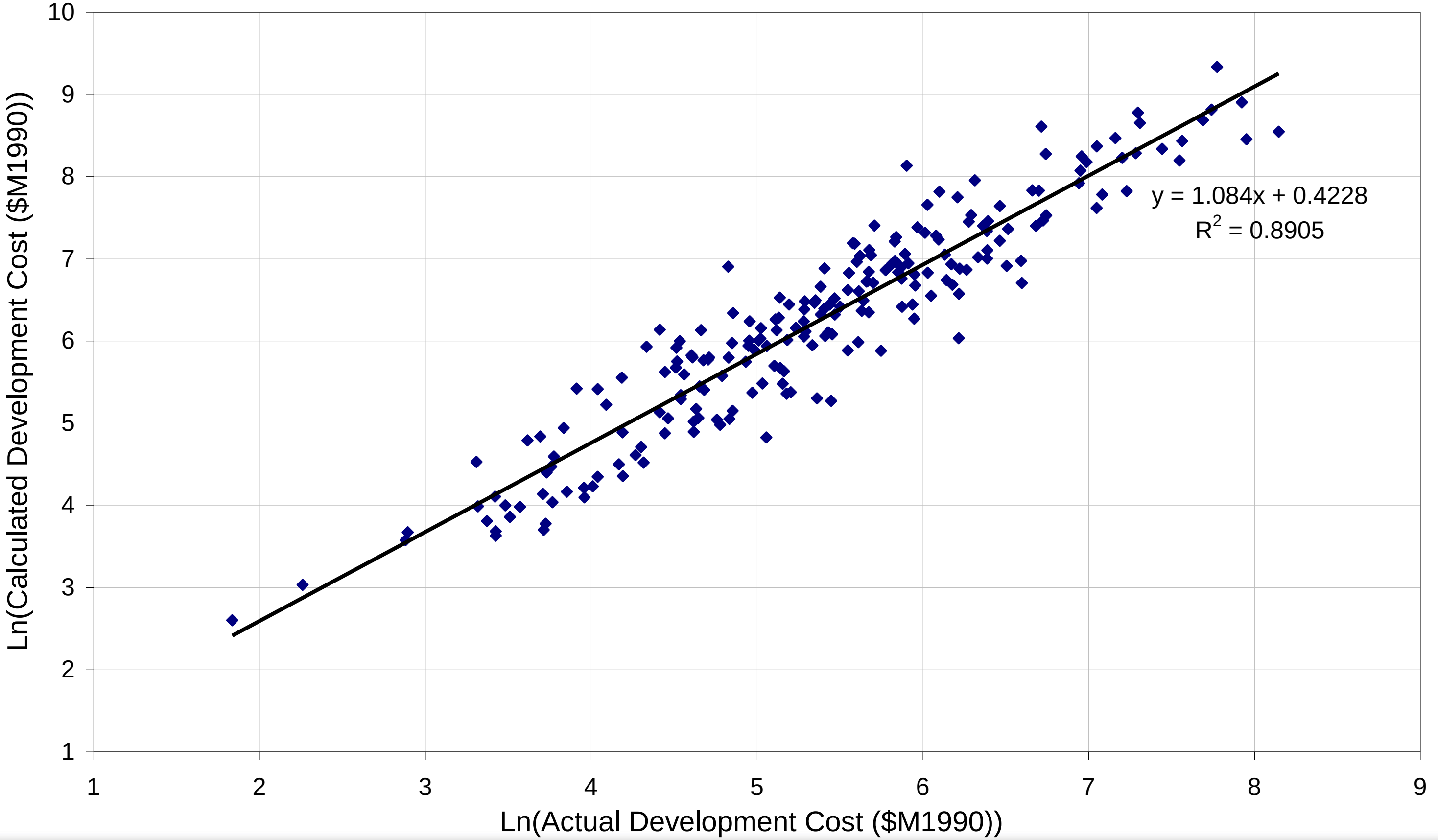
Empty Mass = Wing + Fuselage + Empennage + Undercarriage +Engine + Cockpit + Fuel System + APU + Flying Controls + Hydraulics + Pneumatics + Electrics + Env. Control + Avionics + Sensors + Trapped Fuel & Oil + Gun



Attributes of an 'Excellent' CER (3) – Model Algorithms (3)

- When conducting the regression analysis, choose the regression approach carefully

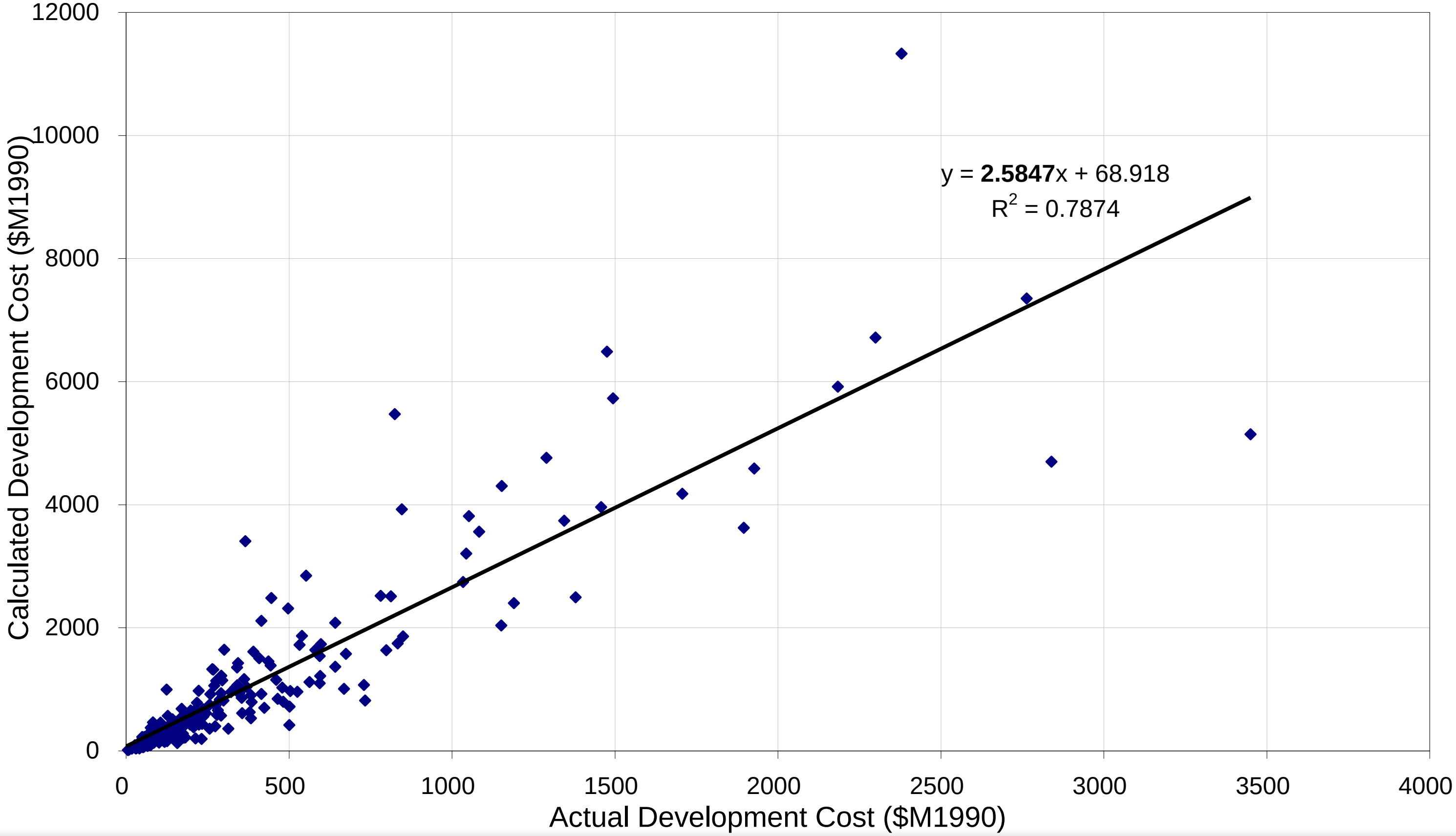
Logarithmic scales can produce **VERY** misleading results



Attributes of an 'Excellent' CER (3) – Model Algorithms (4)

- When conducting the regression analysis, choose the regression approach carefully

Gradient is more than **twice** that expected & intercept is poor



Attributes of an 'Excellent' CER (3) – Model Algorithms (5)

- When conducting the regression analysis, choose the 'objective function' (of the internal optimisation) carefully
- R^2 is a very commonly used indicator of 'goodness of fit'
  - R^2 is the 'Coefficient of Determination' and is defined mathematically as:

    $$R^2 = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (f_i - \bar{y})^2}$$ where $\bar{y}$ is the mean of the observed data.
  - Therefore, using R^2 as part of the regression will 'skew' the observed error to reduce with increasing values of x
  - This is not a problem for some programmes, but across a range of results, it may be preferable to have a consistent percentage error for all outputs
    - Many programmes will be measured on a '% error basis', not on total error
- Consider using absolute percentage error instead of R^2
  - Generates consistent *percentage* errors across all values

Attributes of an ‘Excellent’ CER (4) – Accuracy

- Displaying/exposing model accuracy is a ‘two-edged sword’
  - Telling a customer that a model is ‘inaccurate’ can prevent its use (or significantly reduce their willingness to use it)
  - It is vitally important that we explain that no model can be 100% accurate
    - Must expose the level of modelling error in the modelling algorithm
    - Use multiple approaches to detail the inaccuracy and how it has been captured

- Example contained in later slide

Attributes of an ‘Excellent’ CER (5) – Model Documentation

- Model documentation must exist to explain the data, sources, normalisation, model structure, rationale, and applicability
  - Lack of documentation will guarantee that the model will not be used
- No-one likes producing model documentation, but it is a necessary evil
  - Must be complete, accurate, and synchronised with model developments
- Should be treated as a ‘log-book’ for the model
  - Can be a powerful source of evidence for use with Customers, CAAS, Scrutiny, etc.

Attributes of an ‘Excellent’ CER (6) – Expert Users

- Parametric models can very quickly generate highly inaccurate outputs in the hands of an inexperienced/poorly trained user
  - All parametric models have a limited applicability
  - Understanding the model and its applicability is key to generating realistic, accurate outputs
  - The user must understand:
    - the data, sources, normalisation, and validation
    - the model structure and the factors and coefficients
    - the optimisation approach and whether the model was generated with R^2, |%| error, or some other objective function
    - The units and economic conditions of the model output, and how to translate that value in to the value required to answer the question
- A ‘poor user’ will almost guarantee poor results

Example – Generation of an (almost) Excellent Aero Gas Turbine Development Cost Estimating Relationship

Data Sources and Processing

- Historical database obtained from US source
  - Contains 32 technical and programme parameter values for each engine, plus normalised development cost (1990 e.c.)
  - 307 data points made up of 10 engine types
    - Removed piston, rotary, auxiliary power units, automotive & rocket engines, leaving 236 data points
    - 17 mis-classified or highly outlying engines removed
  - 219 aero gas turbine engines remaining
    - 115 turbofan, 34 turbojet, 26 turboshaft, 44 turboprop
- 6 parameters difficult to estimate prior to start of development, therefore not used
  - Mass, Part count, Programme duration, Number of test hours, Number of stages, Number of rotating spools

Parametric CER Derivation

- Focused on the development of a model of the form:

  Cost = α x (Parameter A)^{a} x (Parameter B)^{b} x … x y$^{(\text{Parameter } \beta)}$ x z$^{(\text{Parameter } \gamma)}$

  - α = Constant x Type x Problem
  - β, γ = dummy variable parameters
  - a, b, y, z coefficients calculated using Generalised Reduced Gradient non-linear optimisation code (GRG2)
- Possible variables identified using a combination of engineering knowledge and statistical evidence
- Iterative process to identify significant variables to be included within the model & derive coefficient values
  - Relevance of variables checked using statistical checks, e.g. p-test, t-test…

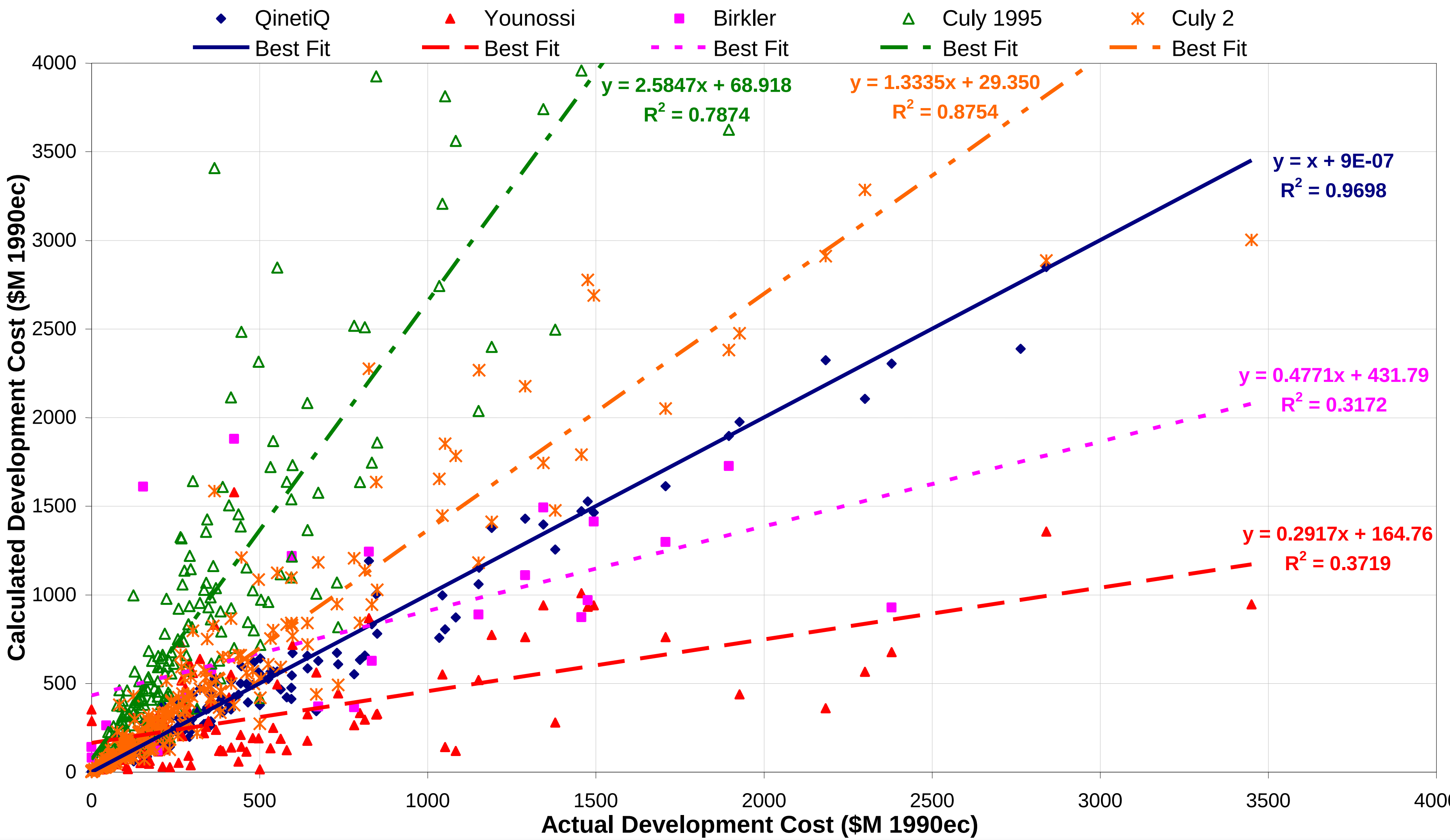
Common 'Errors' with Engine CERs

- Technical Parameter Separation (Engineering)
  - Thrust as a Technical Parameter
    - Thrust is a function of both engine size and technical advance. As such, it is not a good technical parameter for this model, despite statistical evidence
- Cross-correlation (Statistics)
  - Bypass Ratio (BPR) and Mass Flow Rate (WA)
    - Large civil aircraft have high WA and BPR. Small turbojets have low WA and BPR. Small engines are unlikely to have high BPR, as this results in a small, inefficient engine core
  - Turbine Entry Temp. (TET) and Overall Pressure Ratio (OPR)
    - Engines require high OPR to make use of efficiencies generated through high TET. Both are measures of technological advance, and should not appear in the same equation together

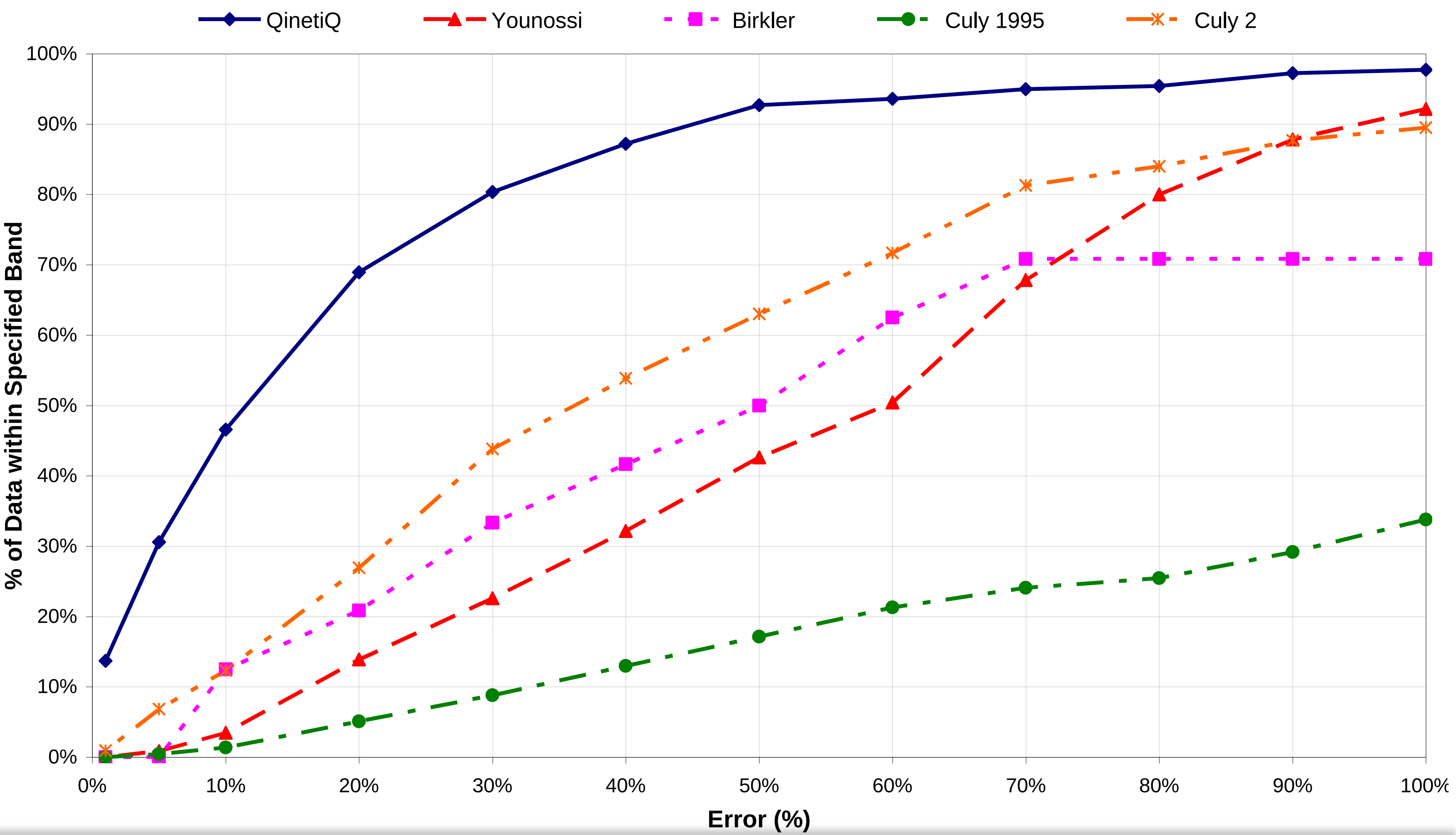
Results – Model Overview

- Best fitting model was found to contain:
  - Engine Type, Problem, WA, OPR, Joint Venture, No: test engines, Mach
- Includes factors for:
  - Complex Programmes, Military Engines, Country of Origin, “Skunk Works” Programmes
- ‘Type’ factor gives relative costs of Turboprop and Turboshaft engines, and Turbofan & Turbojet engines, with and without reheat
- ‘Problem’ factor gives cost variation according to novelty of proposed engine design
  - 11 levels from ‘All-New Design’ to ‘De-Rate’
- All factors are ‘trade-able’ – which is most beneficial?

Results & Comparison with Published Models

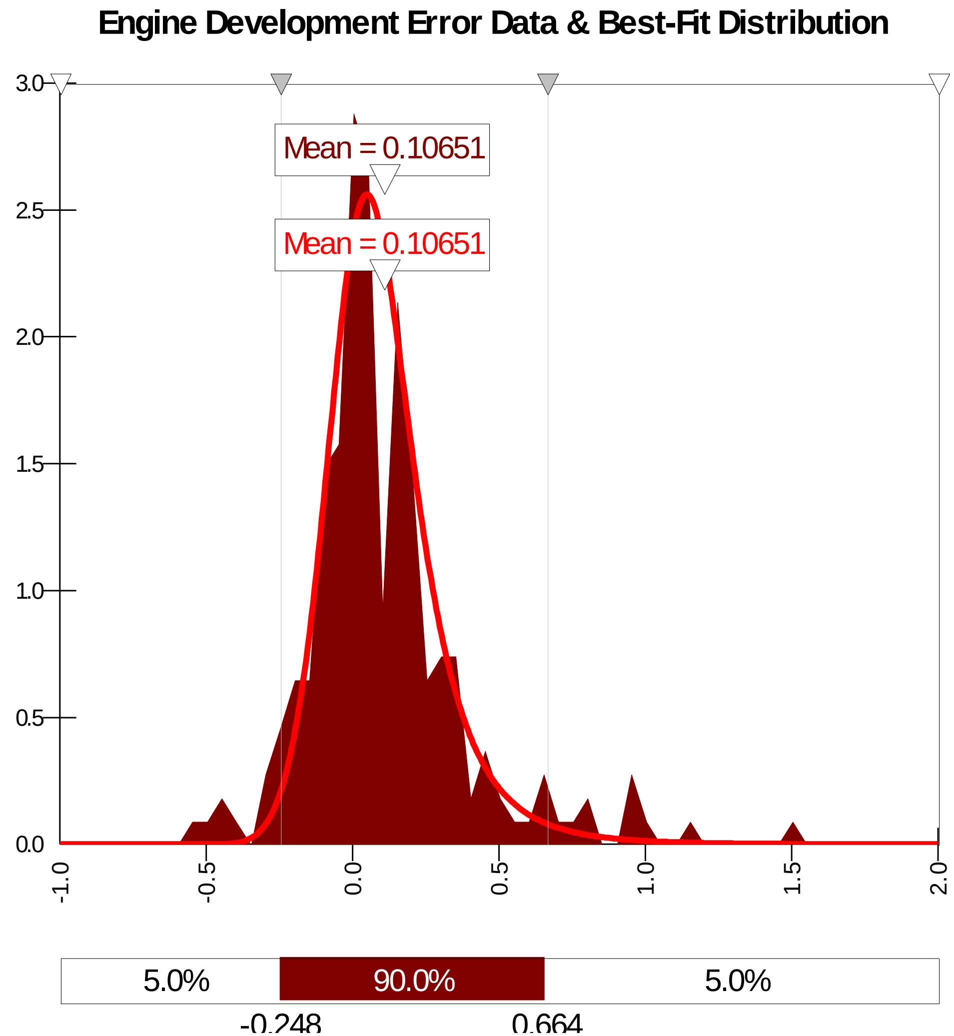


Accuracy & Comparison with Published Models



Accuracy – Capture & Addition to Model Algorithm

- Model 'inaccuracy' captured using 'best-fit distribution' tools within COTS software product
  - Gives clear link between 'accuracy' (e.g. R^2) and confidence levels
- Model algorithm updated to include 'inaccuracy' as part of the stochastic modelling process
  - Allows inclusion of model 'inaccuracy' as well as input 'uncertainty'



Conclusions

- Parametric CERs are used inconsistently across MoD projects
- The generation of Excellent CERS requires:
  - a large database of high-quality data points;
  - accurate and consistent data ‘cleansing’ and normalisation;
  - inclusion of parameters that are demonstrate theoretical/engineering links;
  - an appropriate level of complexity to reflect the engineering reality;
  - adoption of a powerful regression technique that does not hide error;
  - selection of an ‘objective function’ that is relevant for the question/model;
  - capture and usage of model ‘inaccuracy’ to enhance the model output;
  - comprehensive documentation that explains all of the above (and more!);
  - trained, expert users to ensure that the model is applied correctly.
- Generating Excellent CERs ***may*** increase their use within MoD projects
  - Doing so would increase quality and confidence in resulting cost forecasts

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Few things in life are as simple as Black and White