Model-Based Design for Fuel System Development

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54,000
Employees

€49.2billion
Annual revenue*

6,726
Backlog

400
Operators

17,287
Aircraft sold

60
Produced monthly

10,561
Delivered

25,000+
Daily flights

System Development Perimeter and Interfaces

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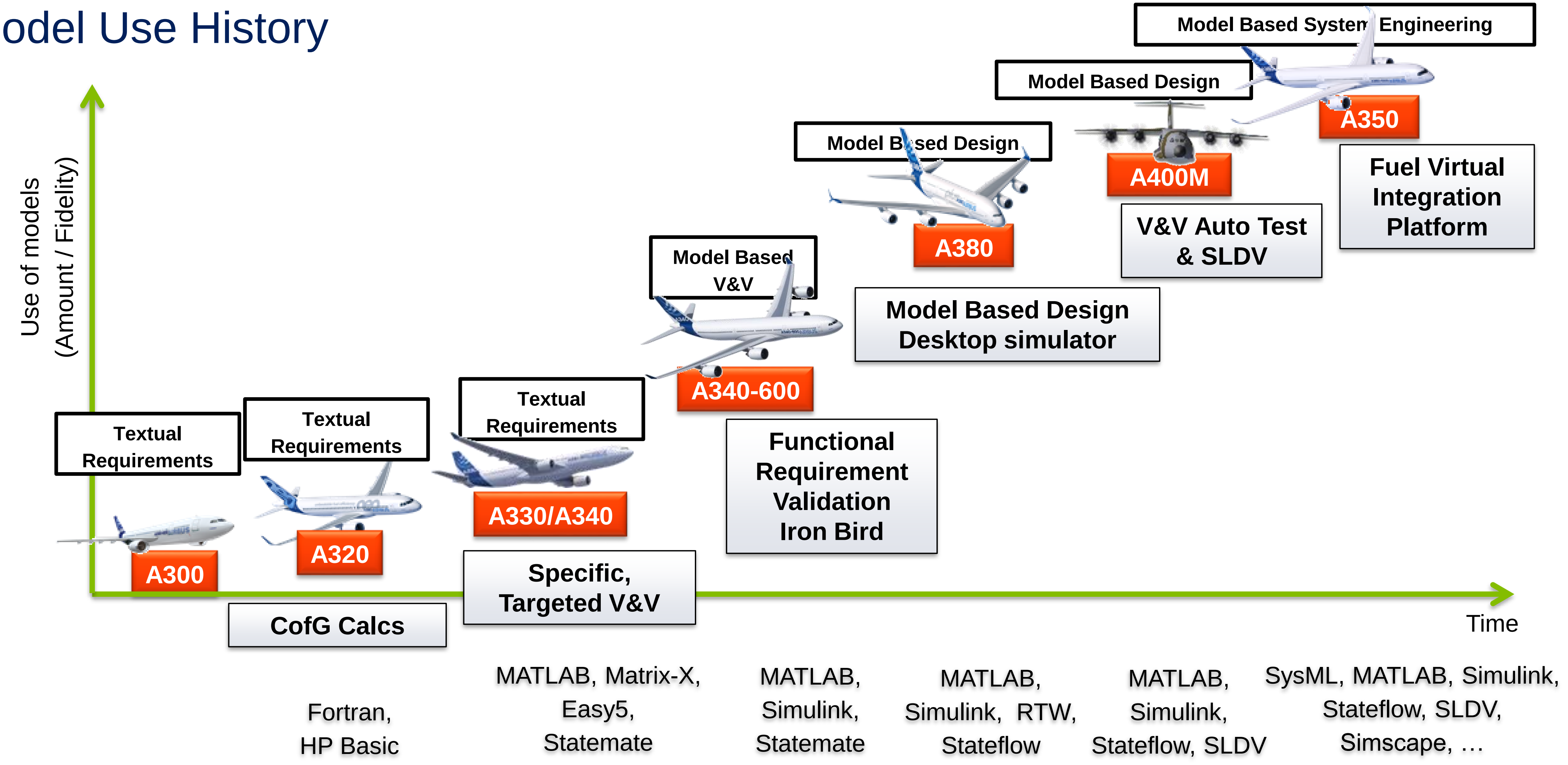
Model Use History



Towards Full MBSE

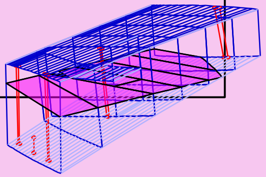
System Requirement Authoring, Validation and Verification

Model Based Design Lifecycle

MG3 MG5 MG7 MG9 MG11

A/C

Tank Modelling:
- Output for Gauging & Fuel Management
- Output for Wing design (stress, load, etc.)



Multi-systems

Architecture Design

Requirements

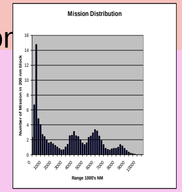
Detailed Design

Simulation

Suppliers s/w dev

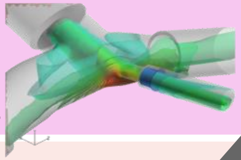
Integration Testing

Inerting Certification using Modelling



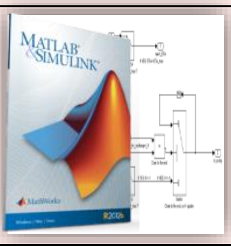
AMO & FSP for Test Rig and A/CO

Fluid and Thermal modelling



Systems

Matlab Simulink for Fuel Management **SSRD**
Req and **detailed design**



Fuel Virtual Integration Platform to support system tests

Equipments

Desktop simulator for **Validation of requirement** and **Verification** of detailed design

Model translation for software development

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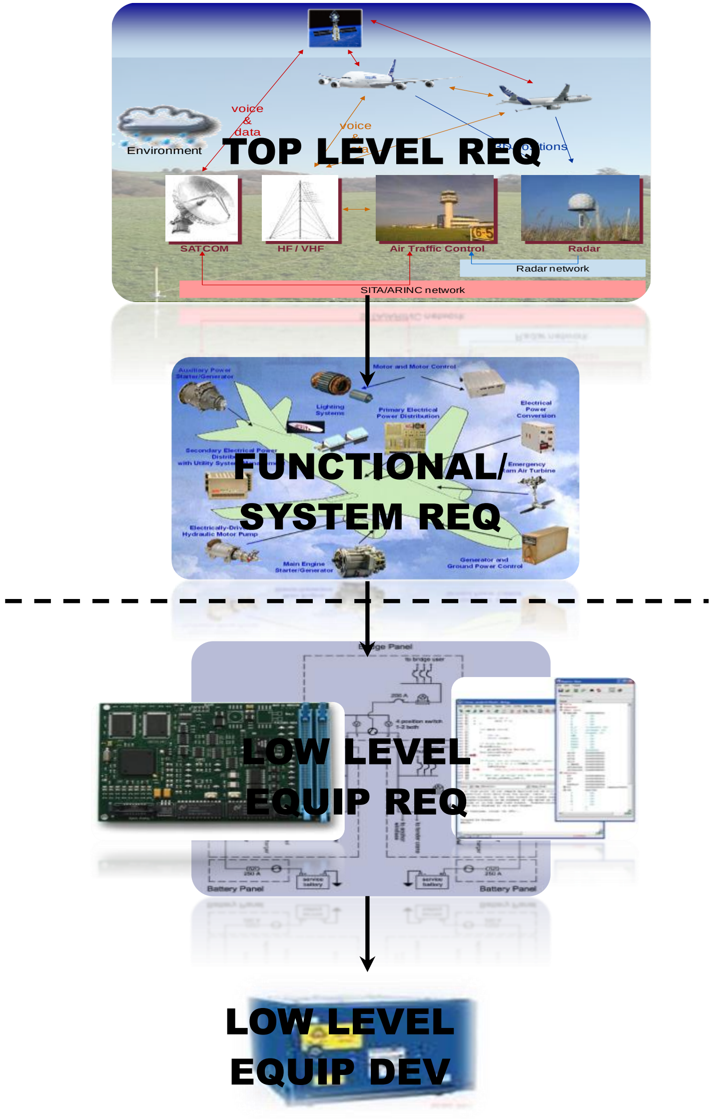
Model Based Design - In Practice

Develop models to specify system functionality
- Describes behavioural & functional aspects

Details become the System (and Sub-System) Requirements
- Exercise the model to Validate Requirements

Delivered to Fuel System Supplier
- Model contains Requirements *and* intent
- Model execution provides system understanding
- Minimal Work to turn into Code
- Separate layer for independent validation



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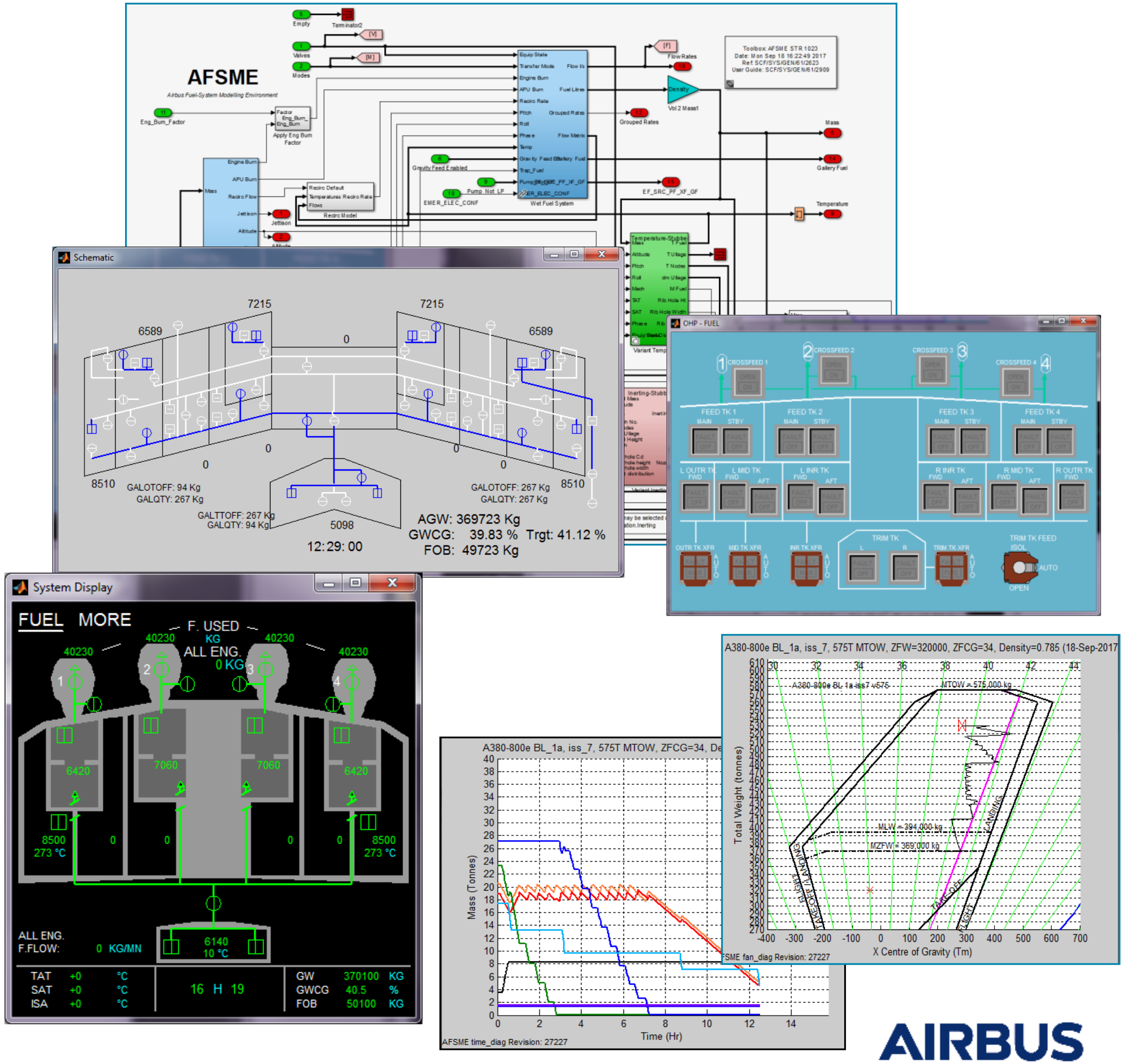
MBSE – Functional System Requirements

- MATLAB/Simulink/Stateflow Application
- Development of Control System Reqts
  - Normal and Failure Operating Modes
  - Crew Procedures
- Control Logic separated from Aircraft Environ
  - System Designers focus on
    - Control Functions
    - HMI
    - Robustness & Validation
  - Specialist Modellers focus on:
    - Aircraft & Environmental Simulation
    - Physics (Fuel, Thermal)
    - Auto-Test Capabilities



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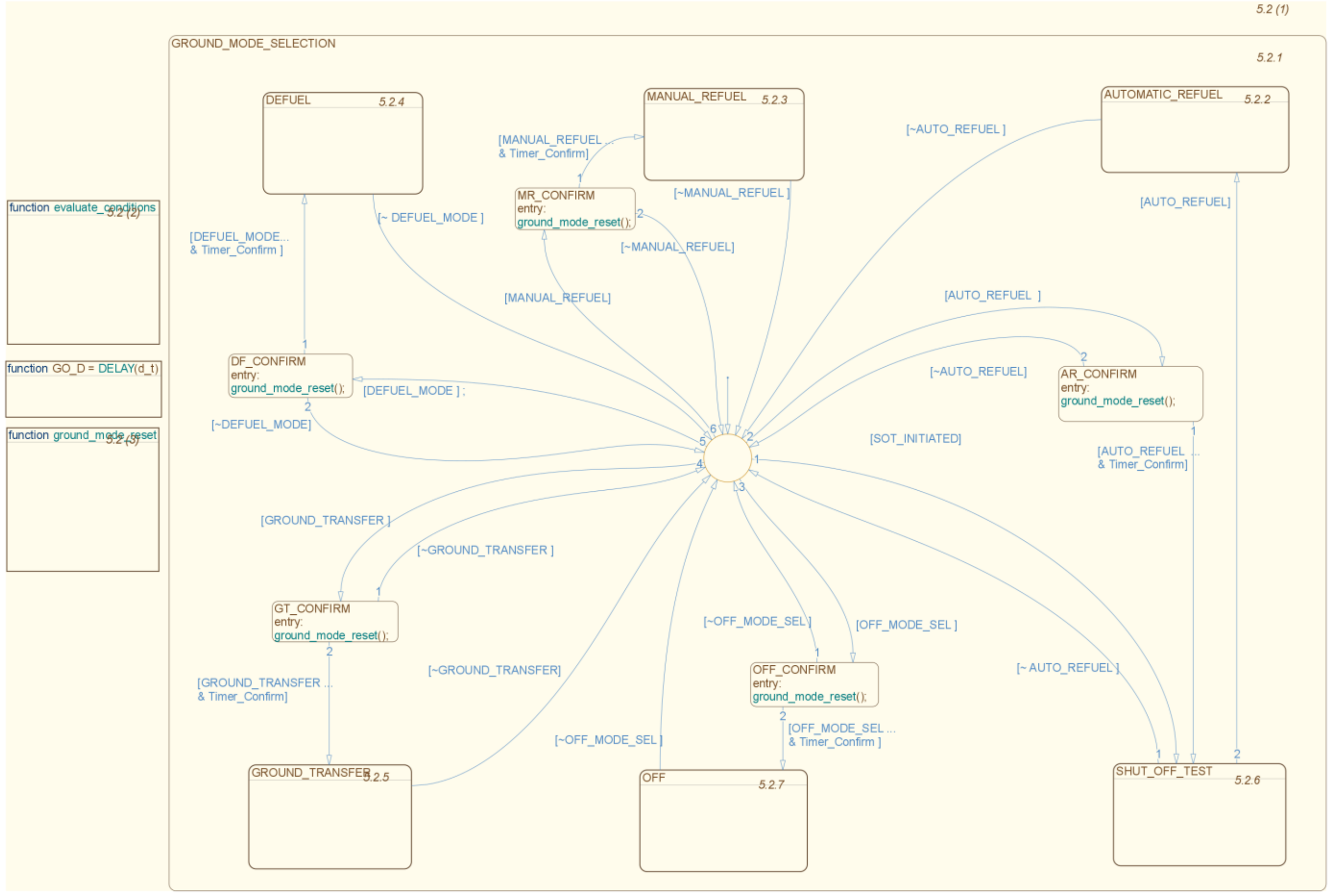
MBSE – Stateflow for Requirements Authoring

- Aircraft Fuel System Statecharts:
- Linked Requirements
  - System Requirements Documents Cascade
  - Requirements Database (DOORS)
- Separate Chart for each Major A/C Function
  - Allows for collaborative development
- Transition booleans calculated externally
  - Input from Simulink
  - Stateflow graphical function
- Driven behaviour of Stateflow logic separated from driving conditions
  - Allows easier readability and testing



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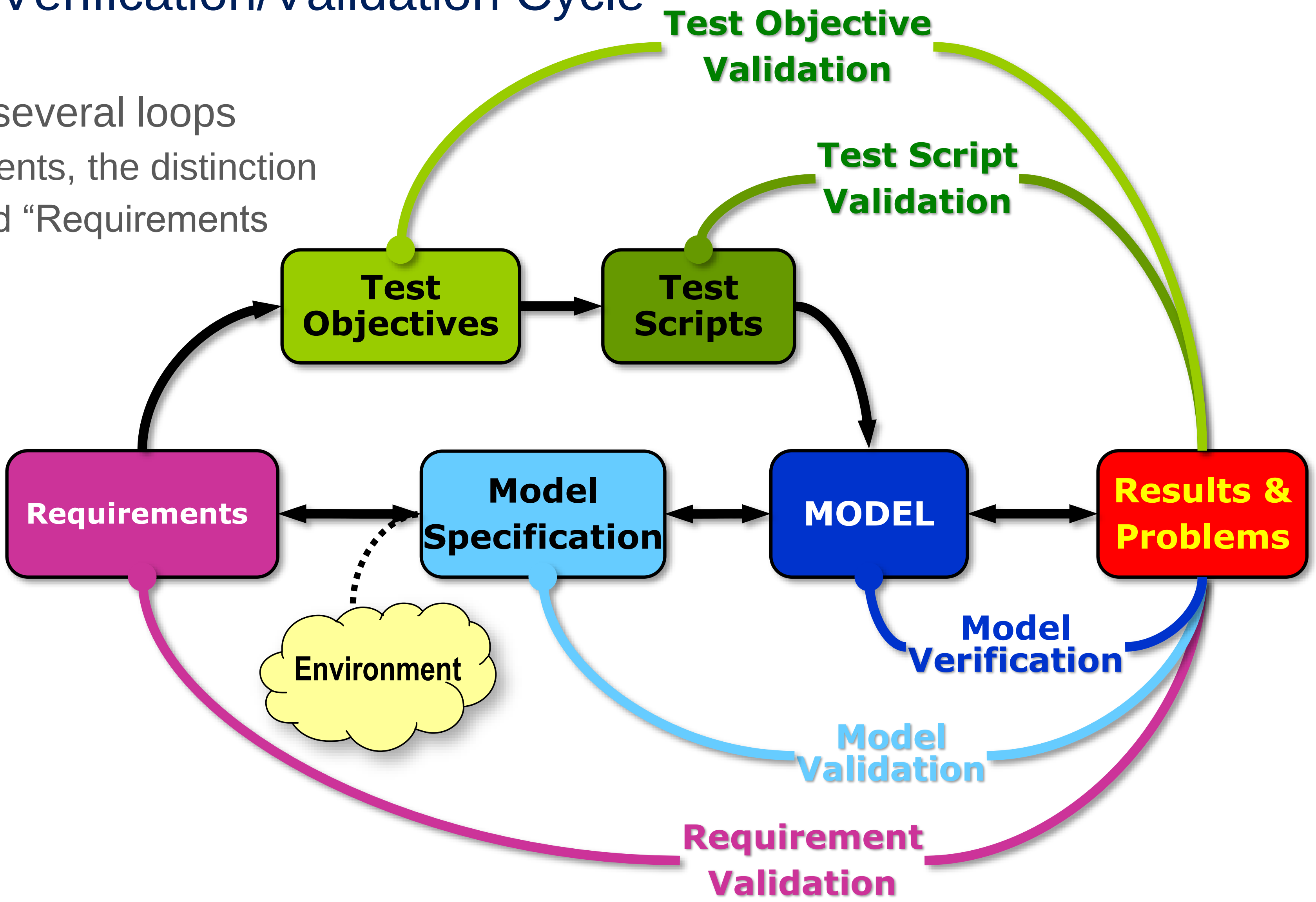
Model Based Design - Reuse

- Integrated Desktop Simulator
  - Requirements & Environment Model
  - AutoCode using Simulink Coder
  - Optional Interfaces to Cockpit Display & Flight Warning
- OCASIME, VIP & Aircraft -1
  - Entire Software Simulation
  - Interfaces Identical to Full Flight Simulator
- Aircraft-0 (Iron Bird)
  - Cockpit Avionics & Displays
  - Integrated of Real & Simulated Systems
  - Virtual Hosting of Supplier's Code
- Full Flight Simulator
  - Single model for all platforms
  - Training Flight and Ground Crews

Model Development Test/Verification/Validation Cycle

- Model V&V has to go through several loops
  - When the model is the requirements, the distinction between “Model Verification” and “Requirements Validation” is somewhat blurred

If a test fails, what is at fault?
- the requirement?
- the model?
- the test?



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Using Simscape to Model A350 Refuel System

Component export, parameter estimation
And model simplification for Real Time performance

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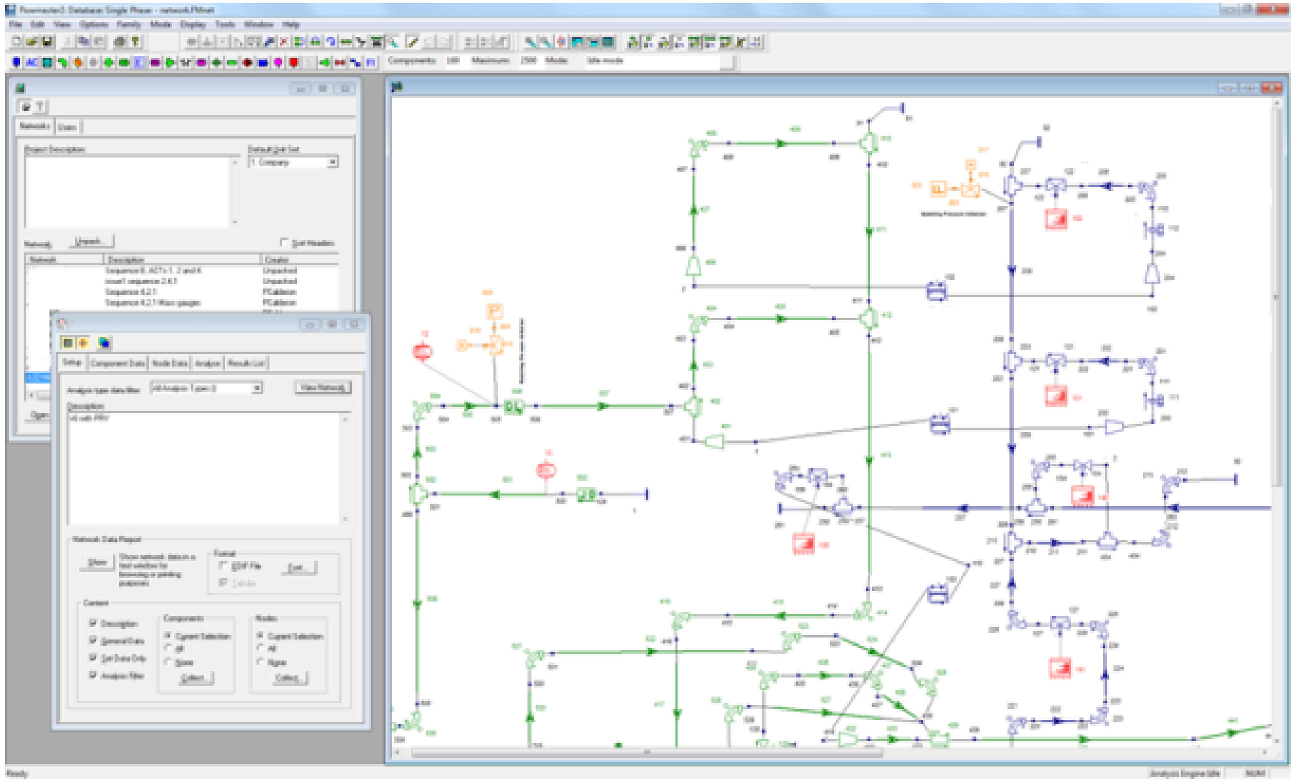
Use of Simscape

- Fuel Design Model Developed in Flowmaster
  - Architecture and Component Performance
  - Spec Model Only - not real-time
  - Cannot produce C-Code or embedded simulations

- Exploiting new SimHydraulics Toolbox

- Mathworks Consultancy
  - Airbus provision of core models and perf data
  - Majority of development by Mathworks



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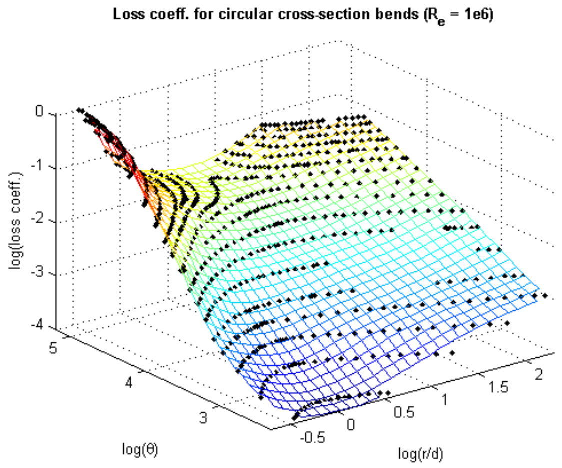
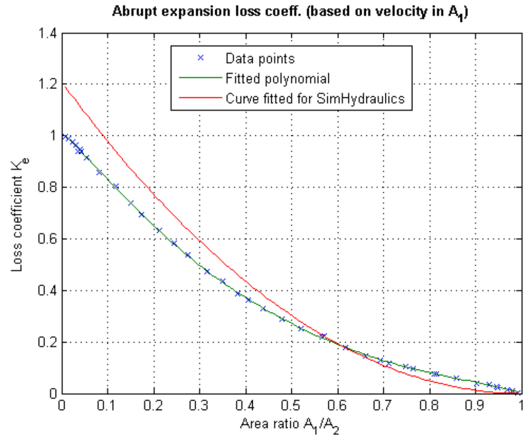
Component Development

- Mapping of Flowmaster components to Simscape/ SimHydraulics equivalents
  – Most 1:1 equivalents
  – Some required customisation from base library

Flowmaster		Simscape/SimHydraulics	
F P	Flow and pressure source		Ideal Hydraulic Flow Rate Source Ideal Hydraulic Pressure Source
	Abrupt transition		Sudden Area Change
	T-junction		T-junction
	Pipe (cyl)		Hydraulic Pipeline (R2008b) Hydraulic Pipe LP (R2009a)
	Smooth bend		Pipe Bend
	Discrete loss		Local Resistance
	Swing check valve		Check Valve Custom swing check valve

- Curve Fitting Toolbox
  – Fit source data to SimHydraulics block equations
  – Saved as Matlab Script for re-use

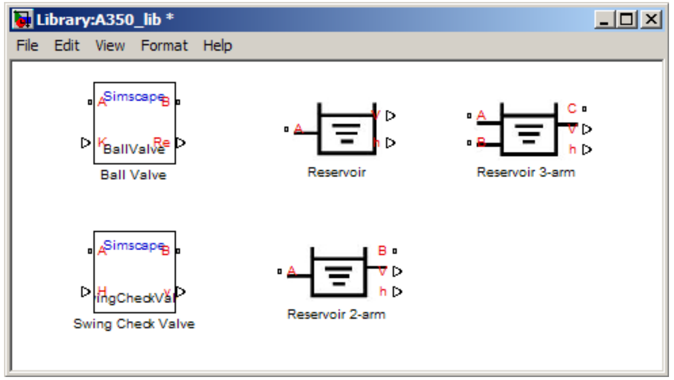




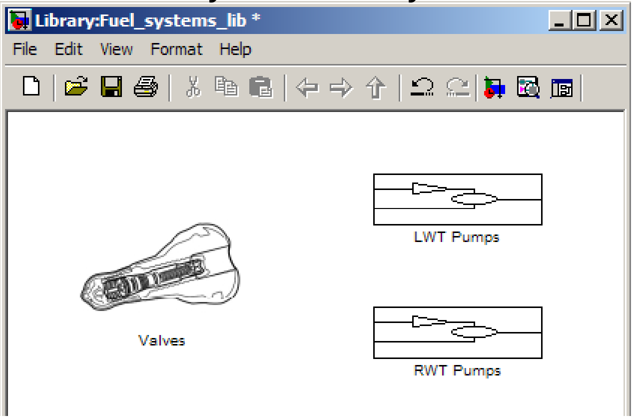
Library Construction and Parameterisation

- Component Library to customise standard Hydraulic Library Components
- System Library contains “System Level” Components
- Each System Palette contains Multiple Components
  – E.g. There are several different type of pumps
- System Palette constructed using MATLAB scripts
  – Self Documenting
  – Re-run if design model updated

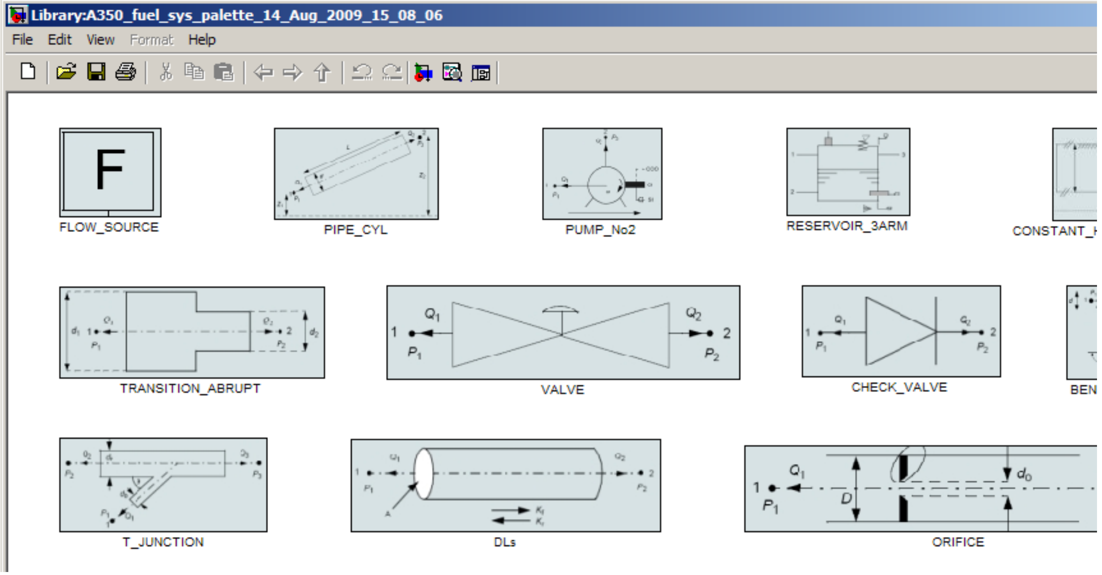
Component Library



System Library



System Palette



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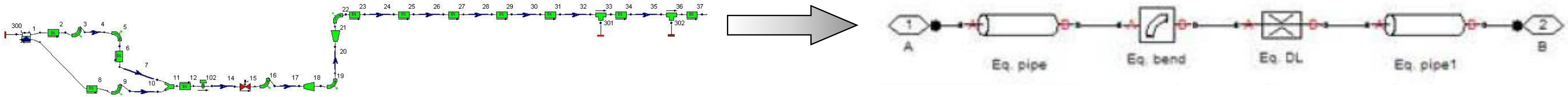
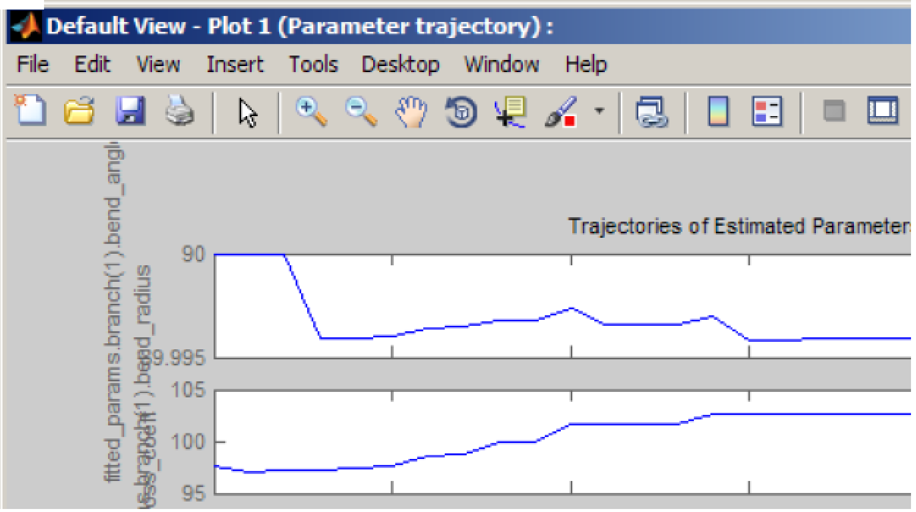
Model Simplification

- Design Model has ~900 individual Components
  - A reduction of the number of blocks by a factor of 10 can potentially yield a simulation speed improvement by a factor of 1,000.

- Reduction Strategies
  - Reduce multiple serially Connected Pipes/Bends/Losses to a single Equivalent pipe/loss combination



- Design Optimisation toolbox
  - Established Equivalent Parameters



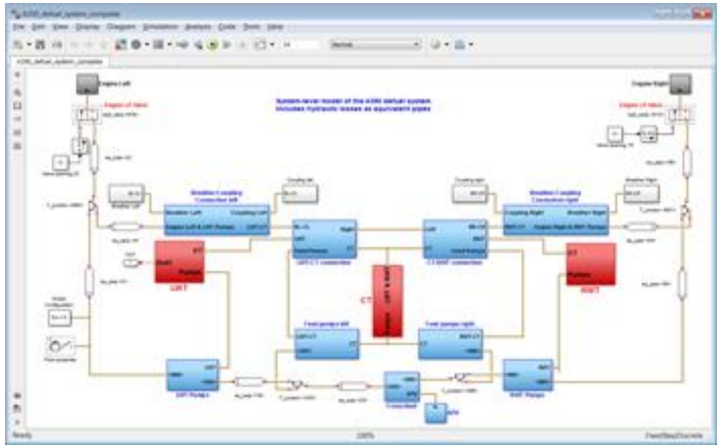
- Reduction in the number of components
  - Pipe components reduced from 290 to 60
  - Total Components reduced from 900 to 170

  - So would expect ~120 x speed-up

Model Reduction

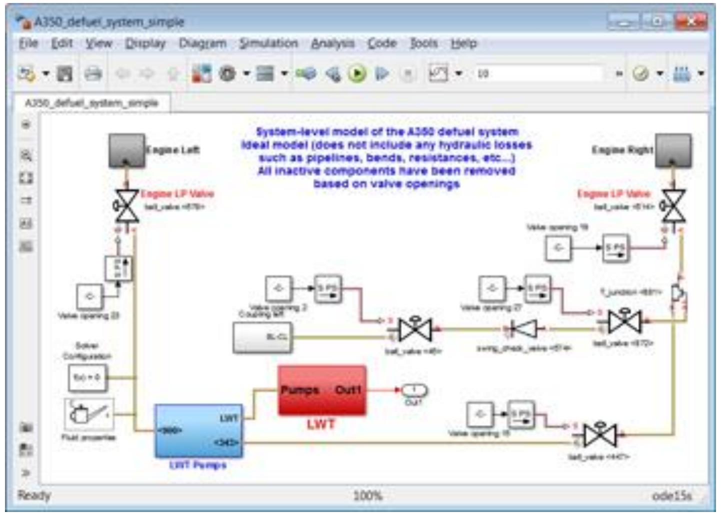
- During Refuel or Defuel, certain valves are not in use
  - Fluid network behind those closed valves do not contribute to pressure/flow calculations
  - Therefore can be removed

Complete Model



Refuel from
Left Wing
Only

Reduced Model



- This can be repeated for each combination of tank that needs to be studied.
  - The reduced model can be constructed automatically with MATLAB scripts that analysis network topology.

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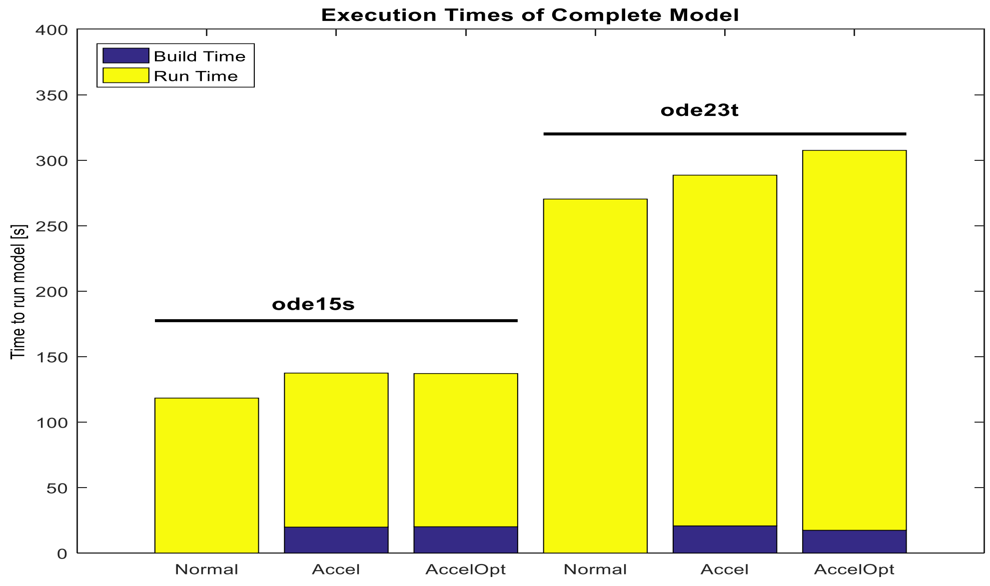
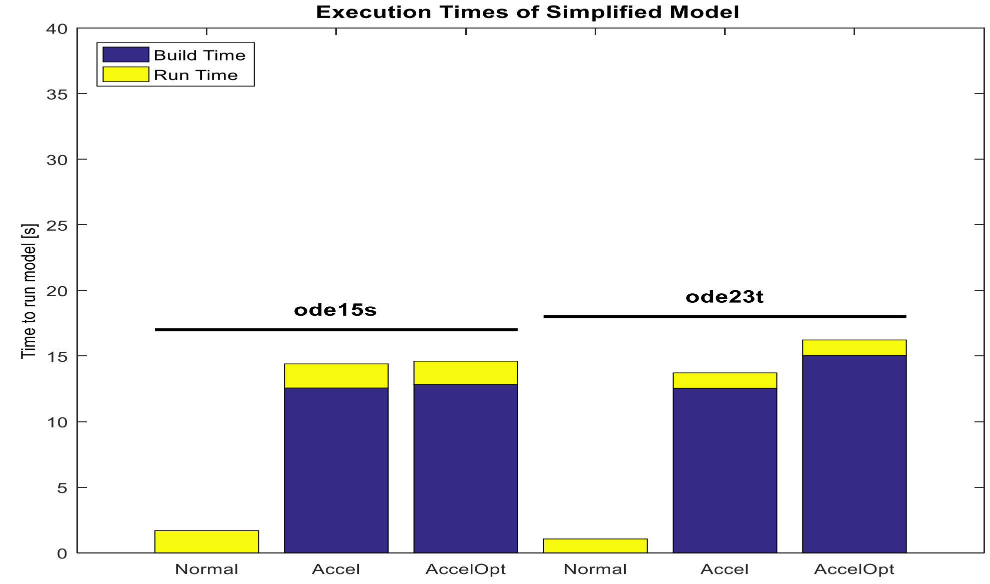
Simscape Summary of Results

- Two system-level models of the Defuel system created in SimHydraulics
  - One complete: all components required to model the system behaviour included
  - One simplified: all “isolated” components located behind closed valves removed
- Performance of the simplified model sufficient for real-time
  - Tested with Simulink Real Time on industrial PC
- Performance of the complete model not sufficient for real-time implementation, despite simplifications made.
  - Depends on the solver chosen to a large extent
  - Improves substantially from with later Simscape versions
  - Near real-time performance in exploiting Simscape local solver
- New blocks and demos added to SimHydraulics as a direct result of this work



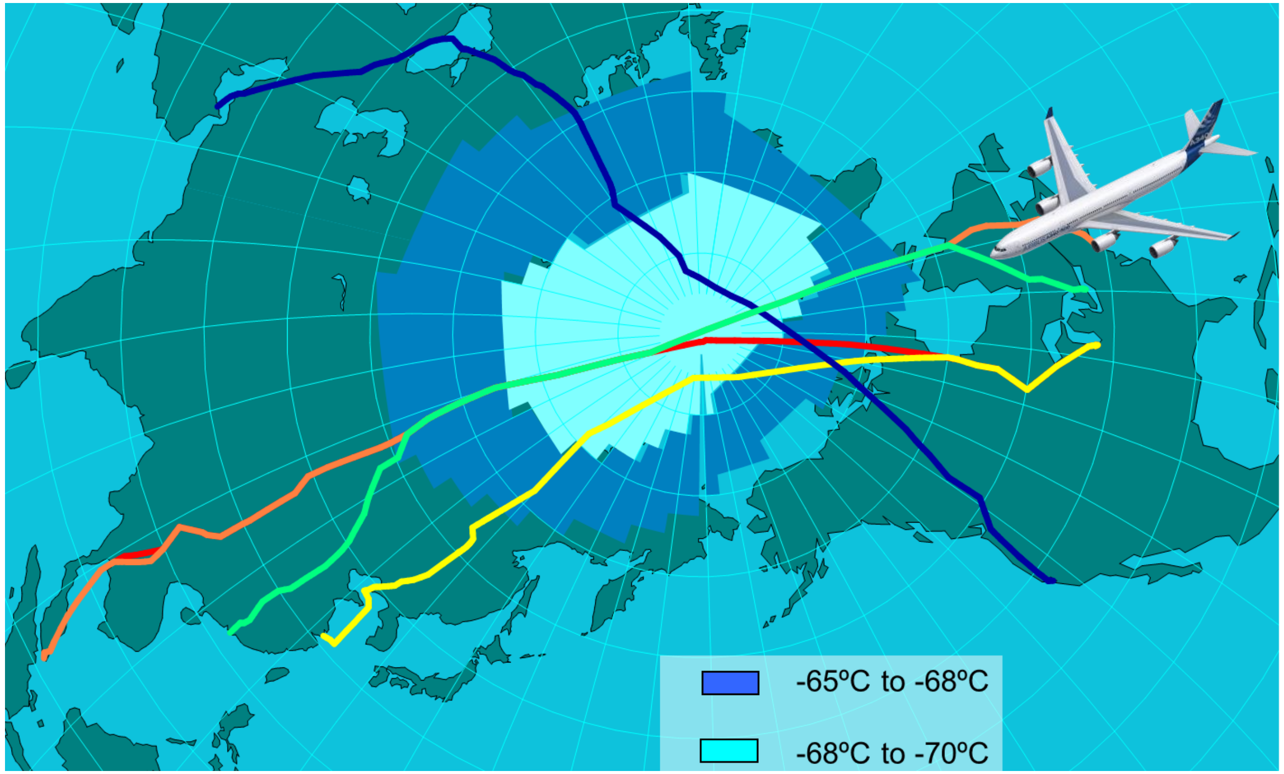


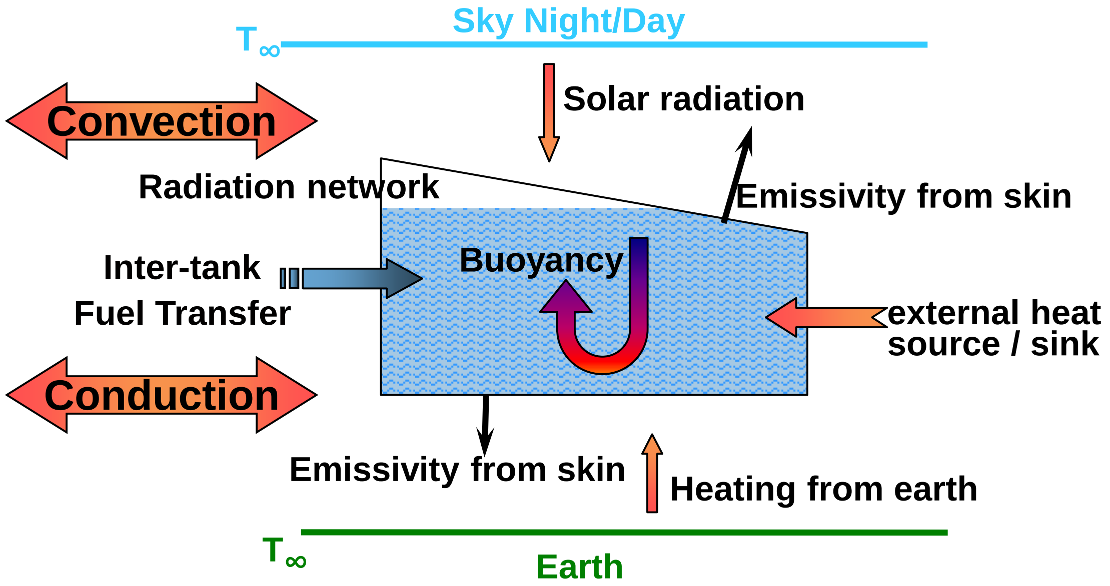
Code Efficiencies and Performance Enhancement

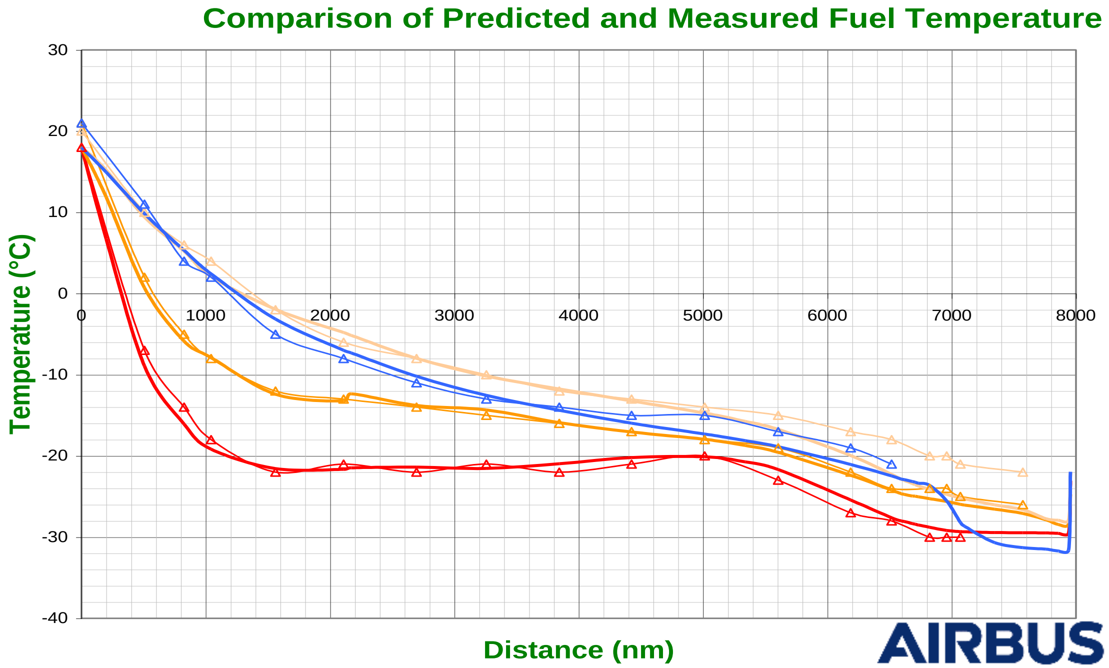
Fuel Temperature Prediction Software

Fuel Temperature Prediction for Airlines

An Exercise in Code Efficiencies



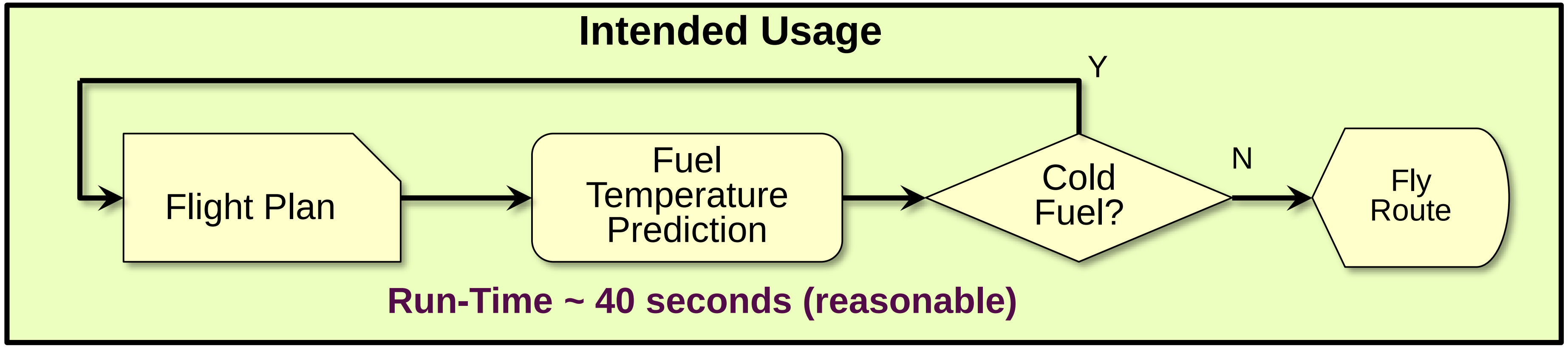


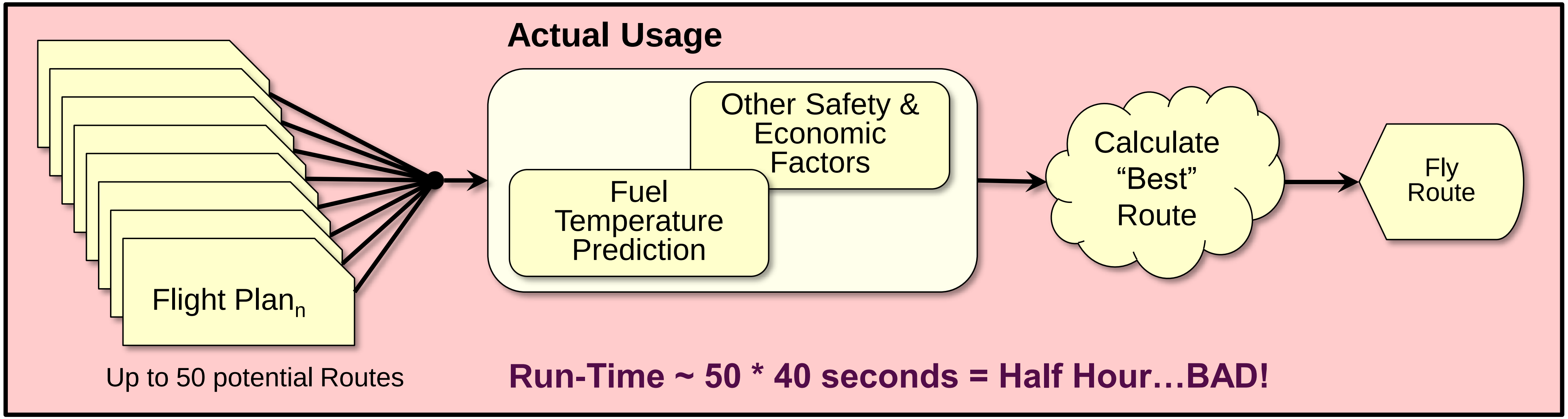


- Low outside temperatures with long exposure times
- Fuel temperature may drop close to or below freezing point
  - Software written in MATLAB
    - Predict fuel temperatures given Flight Profiles & Global Air Temperatures.

Fuel Temperature Prediction for Airlines

An Exercise in Code Efficiencies





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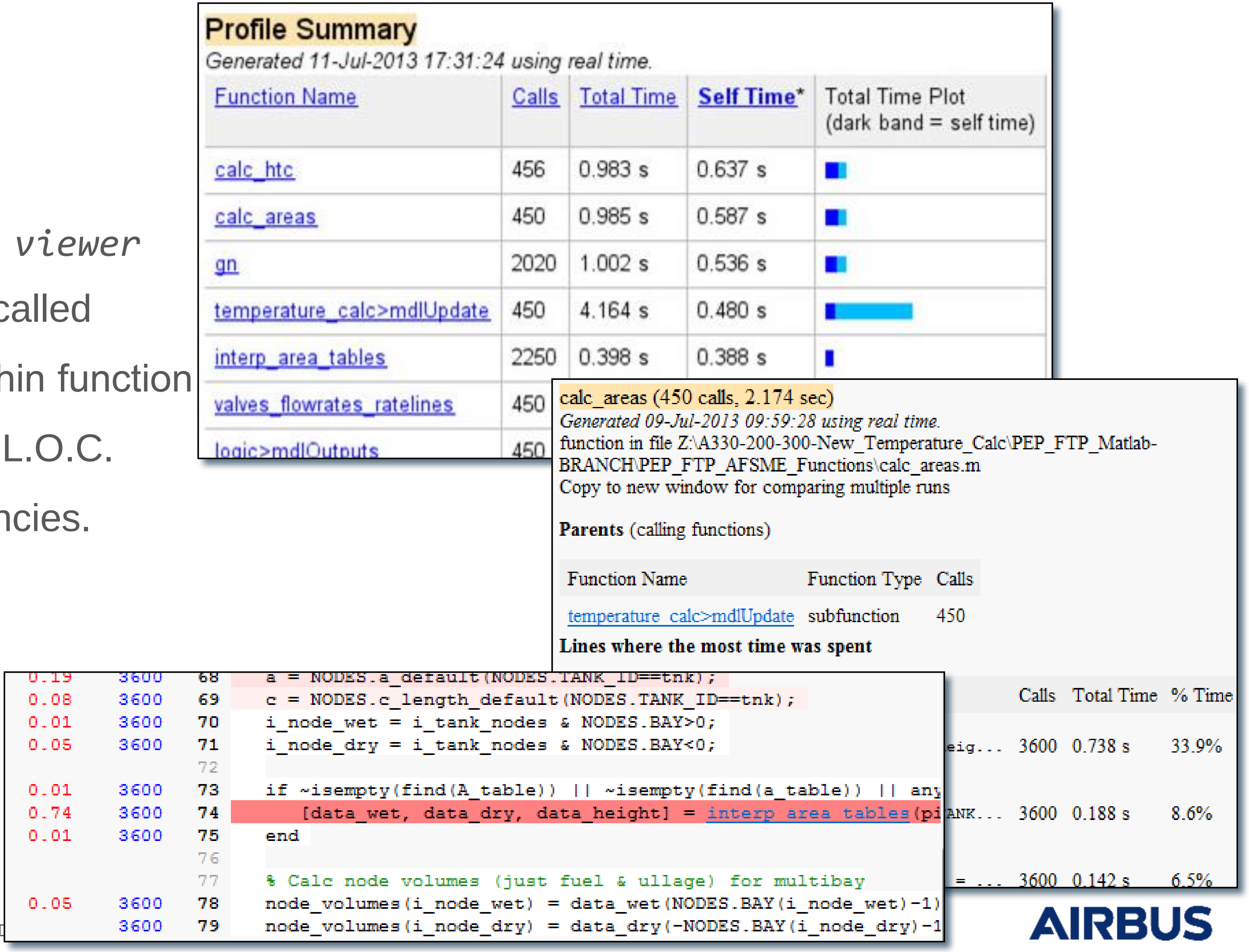
Using MATLAB Profiler to Identify Code Efficiency Bottlenecks

- Exploit MATLAB Profiler
- Built into MATLAB

`profile on ; run program ; profile viewer`

- Creates timing profiles of every function called
- Look at the "Self Time" for time spent within function
- Profile Report highlights most expensive L.O.C.
- Iterative process to increase code efficiencies.



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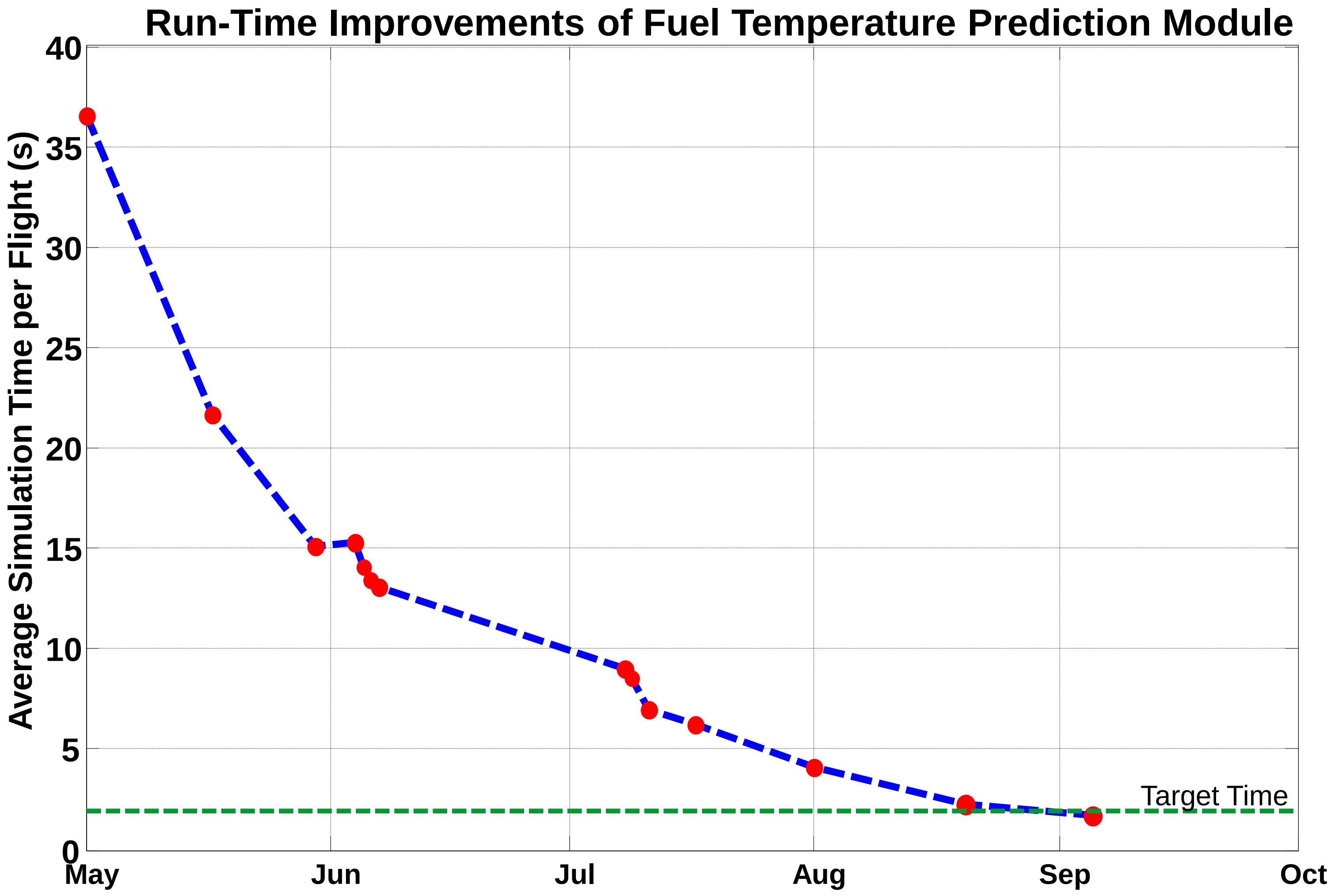
Code Optimisation Strategies

- Equation Vectorisation
- Loop Unrolling
- Switch…case statements
  – Reduce volume of code inside each “case”
- Use c-mex for time-critical functions
  – Check target platforms
- Minimise Globals
  – Very slow in MATLAB
- Reduce calculations inside for loops
  – Pre-calculate invariant parts of equations



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Keeping Track of Mathworks Release Cycles

Industry Model Testing

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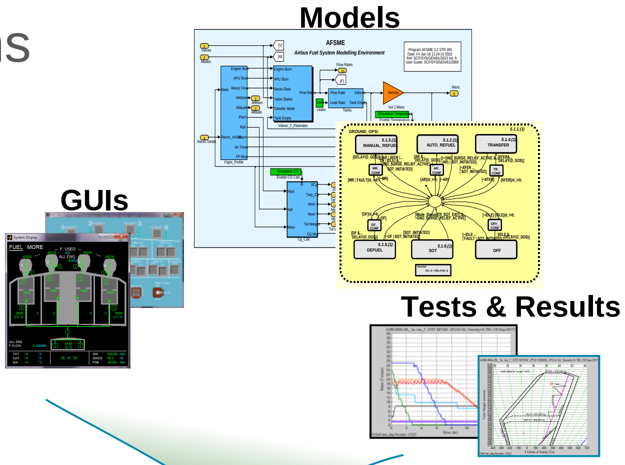
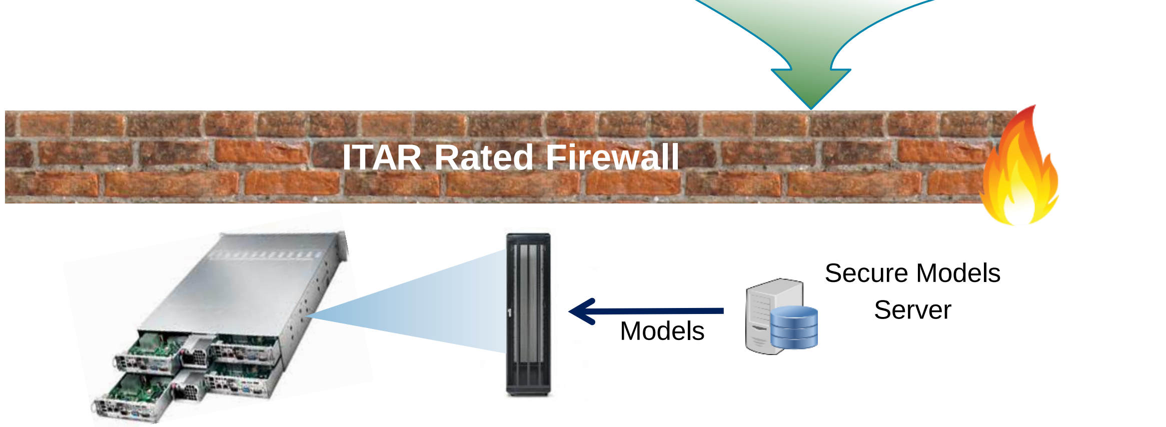
Industry Model & Code Testing

- Aircraft Development 3-5 years, Mathworks upgrades every 6 months
  - One solution to reduce cost of (continuing) upgrade cycles
- Testing infrastructure utilising customer models and MATLAB scripts
  - Release Compatibility
  - Performance

Win-Win Situation:

- **Value to Customers**
  - Reduced product upgrade cost
  - Increased productivity
  - Early knowledge of regression
- **Value to Mathworks**
  - Compatibility testing
  - Performance testing
  - Increased tool adoption





Simple 4-step process

Establish NDA → **Package Models/Scripts** → **Send Package** → **Review and Act on Results**

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Summaries and Lessons Learnt

Lessons Learnt

- Deployment of MBSE
  - As much about Competences as Technologies
    - Skillsets & Mindsets
  - Integration of Functional & Non-Functional models
- Model Build Reveals Emergent Properties
  - Validation for free
  - System difficult to model will be difficult to build/test
- Validation/Verification Testing
  - A test that is more complex than that being tested is probably wrong
  - Easy to be caught in the trap of “Test for Success”
    - Testing for intentional but not unintentional behaviour
  - Automated Test/Analysis allows regression testing
  - Formal Proof more thorough than test scripts
- System Designers Focus on Designing the System
  - The System Model is the System Requirements
    - Extra functionality required to exercise the model are not requirements
    - Need to clearly identify what are requirements and what are the extras
- Model Architecture
  - Must match System Architecture
  - Also conducive to multi-team development
- Easy for Designers can be Difficult for Simulators
  - Engineers can be very “ingenious”
  - Break downstream processes
    - Model exchange with suppliers
    - Automatic code generators
  - Require adherence to Style Guidelines and Design Patterns

Thank you

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