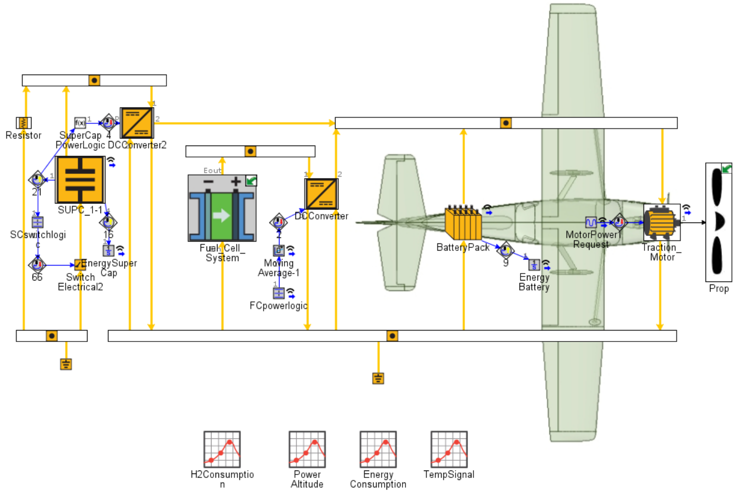
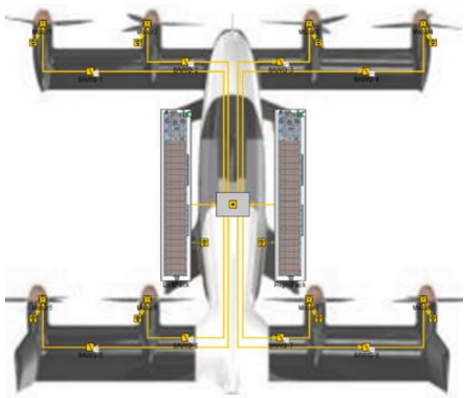




Gamma Technologies Electrified Aircraft Solutions

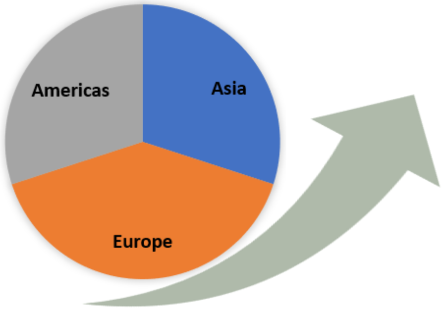
Jon Zenker
Global Aerospace Strategy

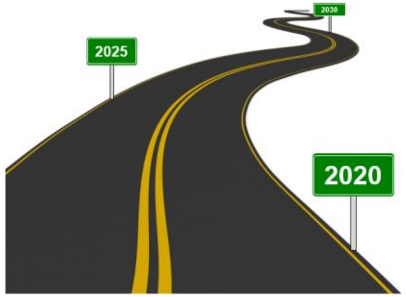
GAMMA TECHNOLOGIES

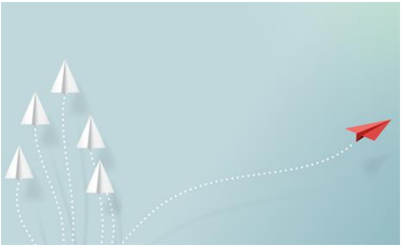
Today's Discussion

- Who is Gamma Technologies?
- Industry Trends
- How GT simulation software can help
  - Complete aircraft
  - Batteries and thermal
- Case Studies
  - VFS Forum 78 paper
  - Airbus A3 Vahana
  - NASA battery thermal runaway
- Next Steps & Open Discussion

About Gamma Technologies







Recognized Innovator
for
Integrated
Multi-Physics
System Simulation
Solutions

Founded in 1994

HQ *Chicago, USA*

Offices *Global*

200+ *Employees*

700+ *Customers*

30+ *Alliance Partners*

Global & Balanced Footprint

Sustainable business momentum based on fundamental principles of innovation and customer success

Market leading growth and profitability

Long-term Outlook

Visionary Board comprised of successful investors and founders

Particular focus on R&D investments

Innovative Technology

Pioneering User Community

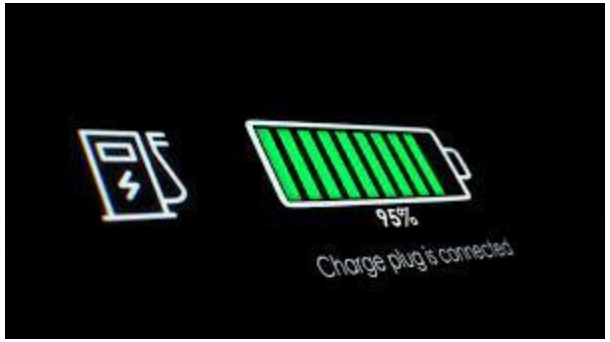
Integrated User Experiences

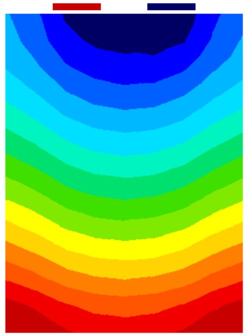
Trusted Advisory Support

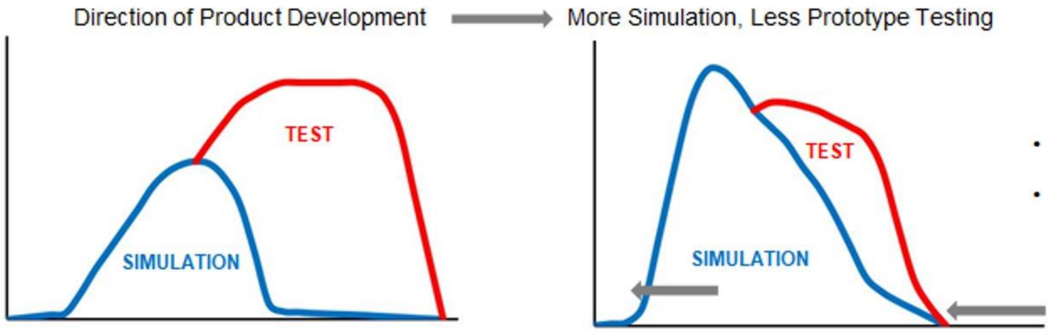
Strong business ethics

Electric Aircraft Trends we see

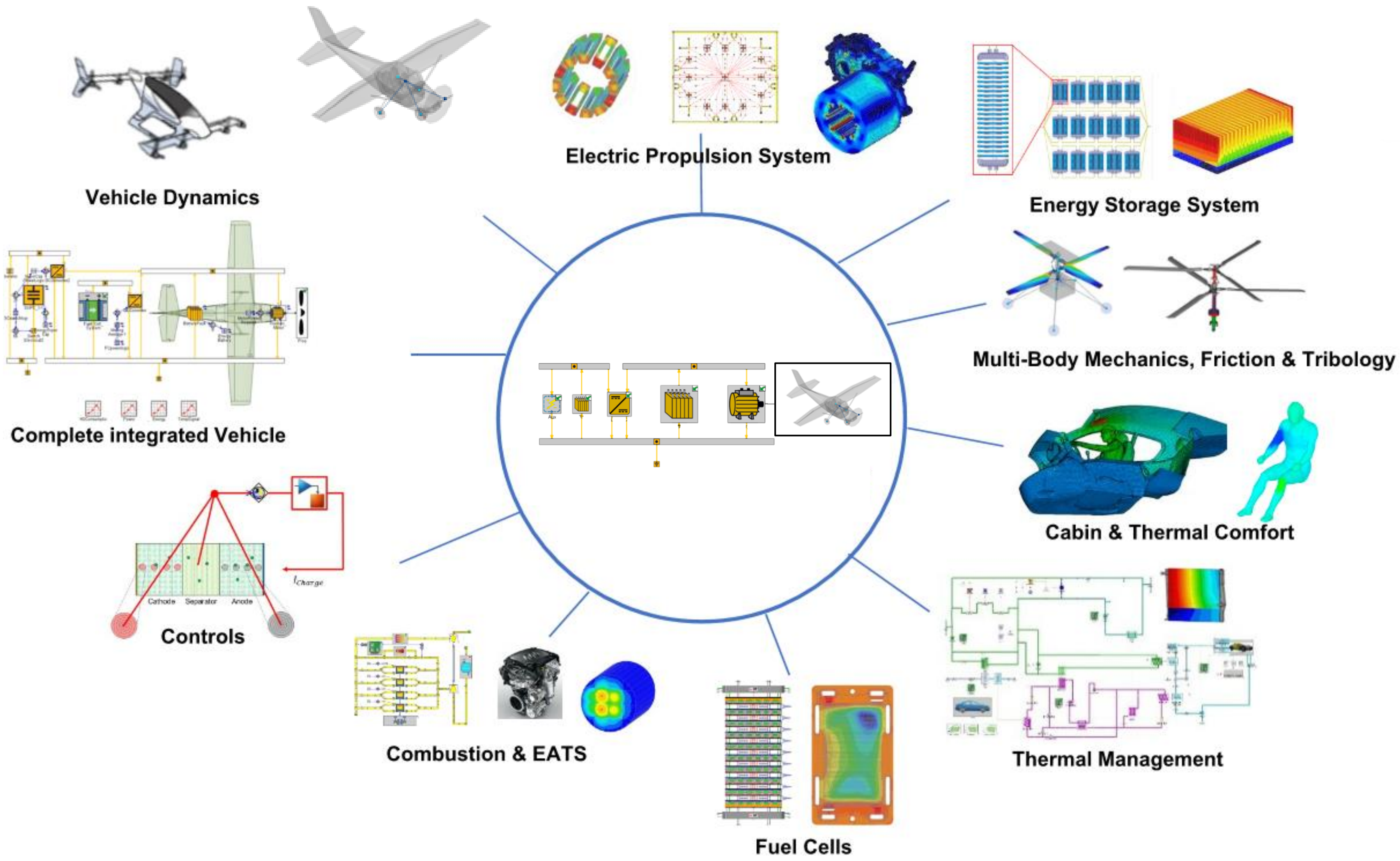
- Higher power density batteries
- Shorter battery re-charge cycles
- Lighter, more efficient electric propulsion system
- Thermal management optimization
- Safety is paramount
- More integrated simulation, earlier in the design cycle





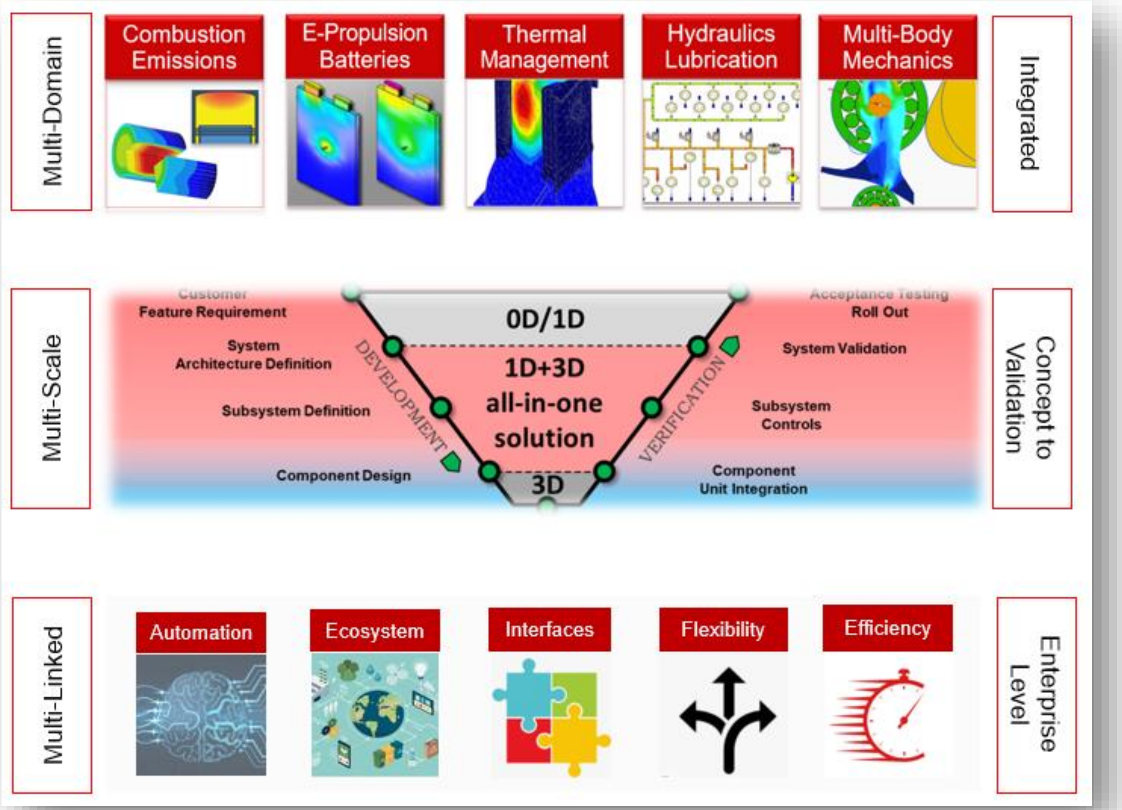


Electrified Aircraft Applications

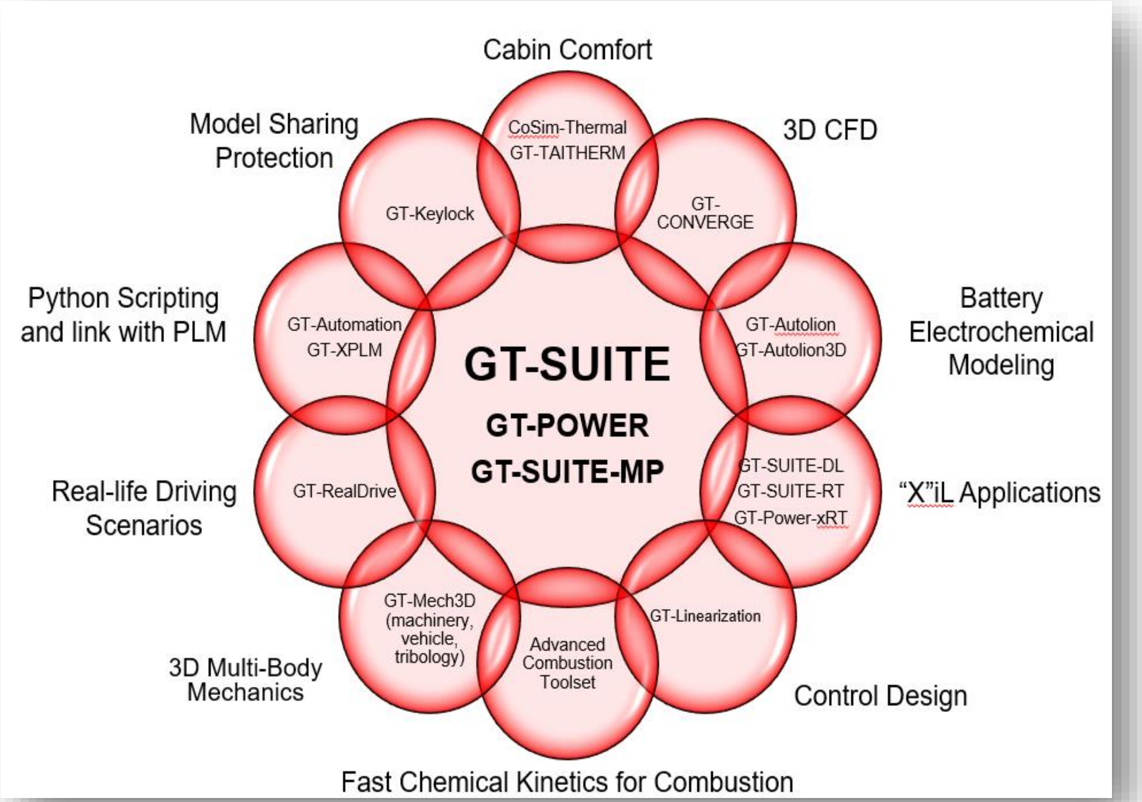


Our Technology & Products

Enterprise-Level Platform with scalable architecture to meet current and emerging industry requirements

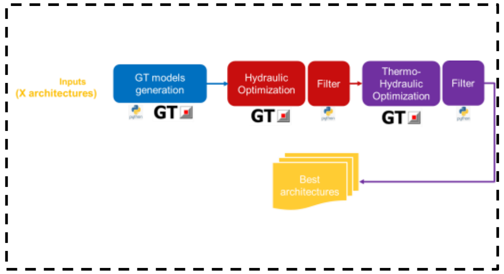


System-level simulation standard for the **full vehicle**

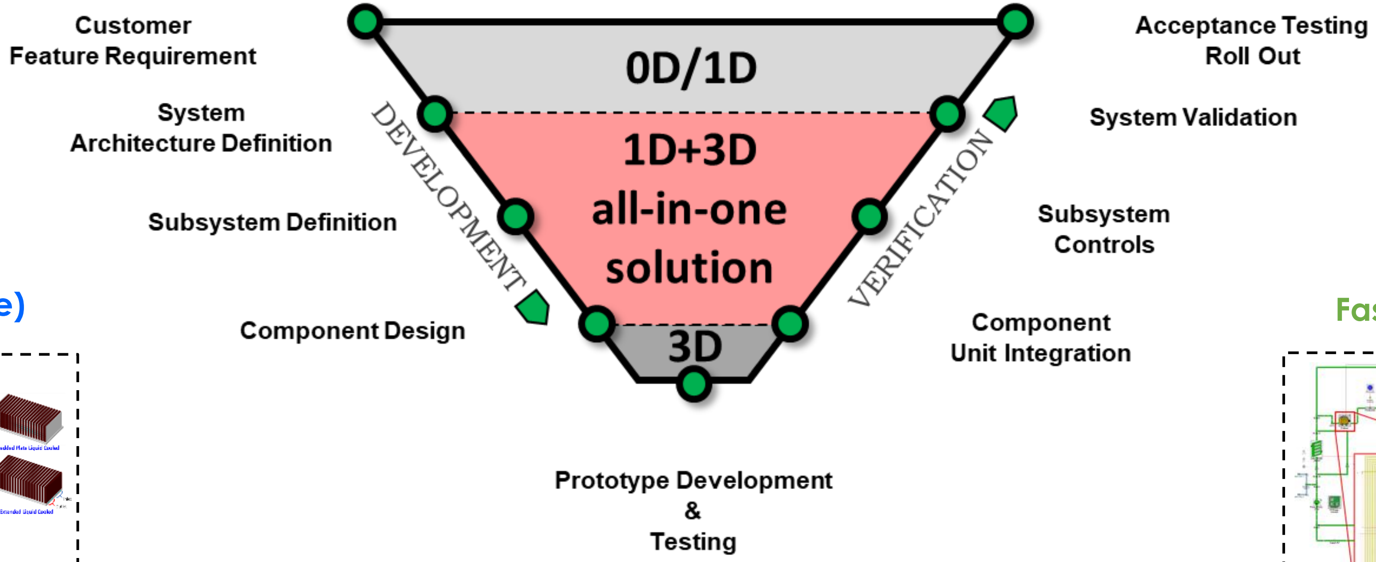


Gamma Technologies – System Simulation
Battery Example

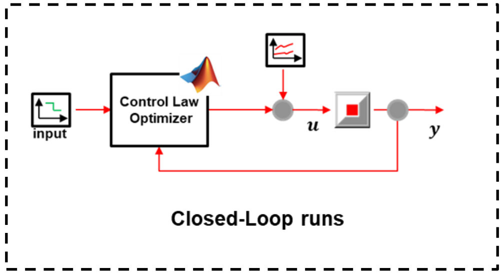
0D-1D System Layout



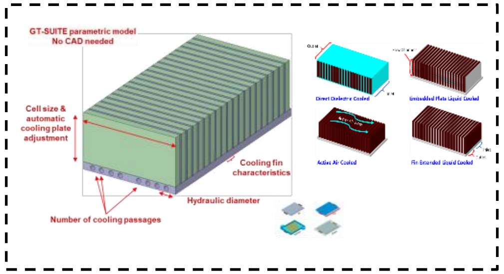
Proposed System Development Cycle



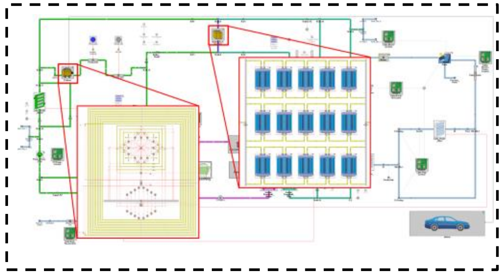
Real-Time Validation (XiL)

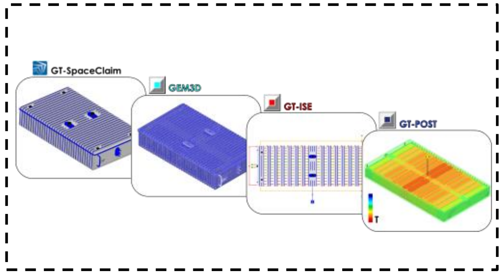


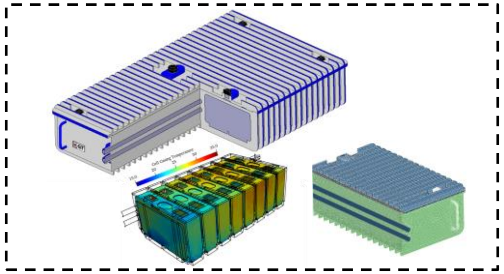
3D FE Parametric (Predictive)

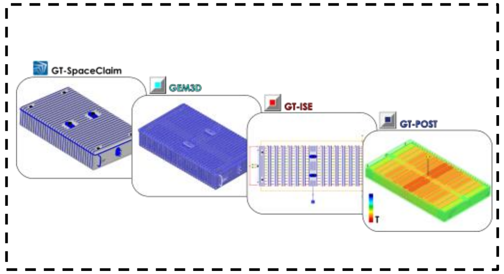


Fast Running Transient Simulations



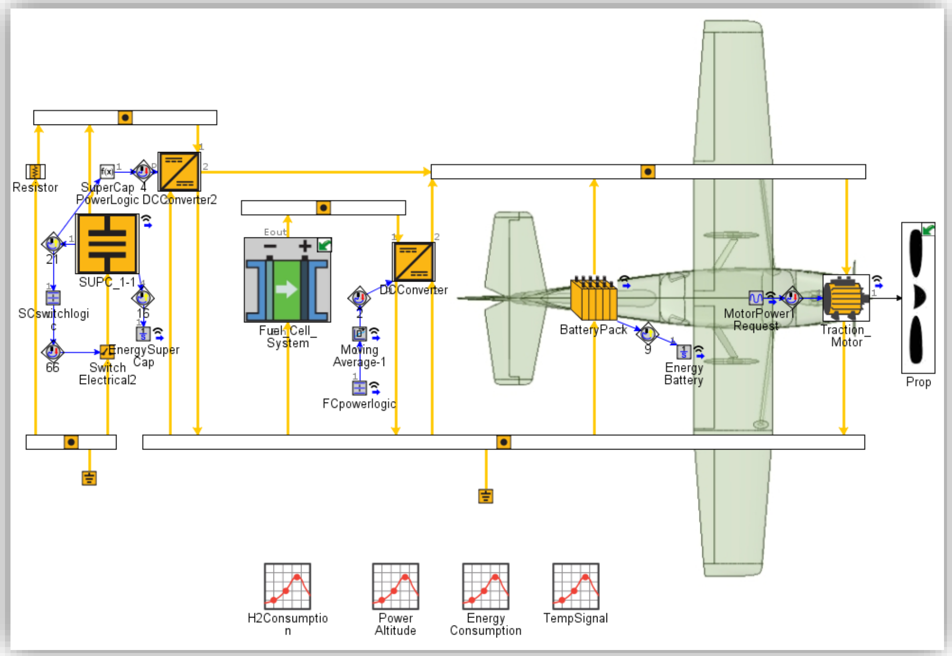


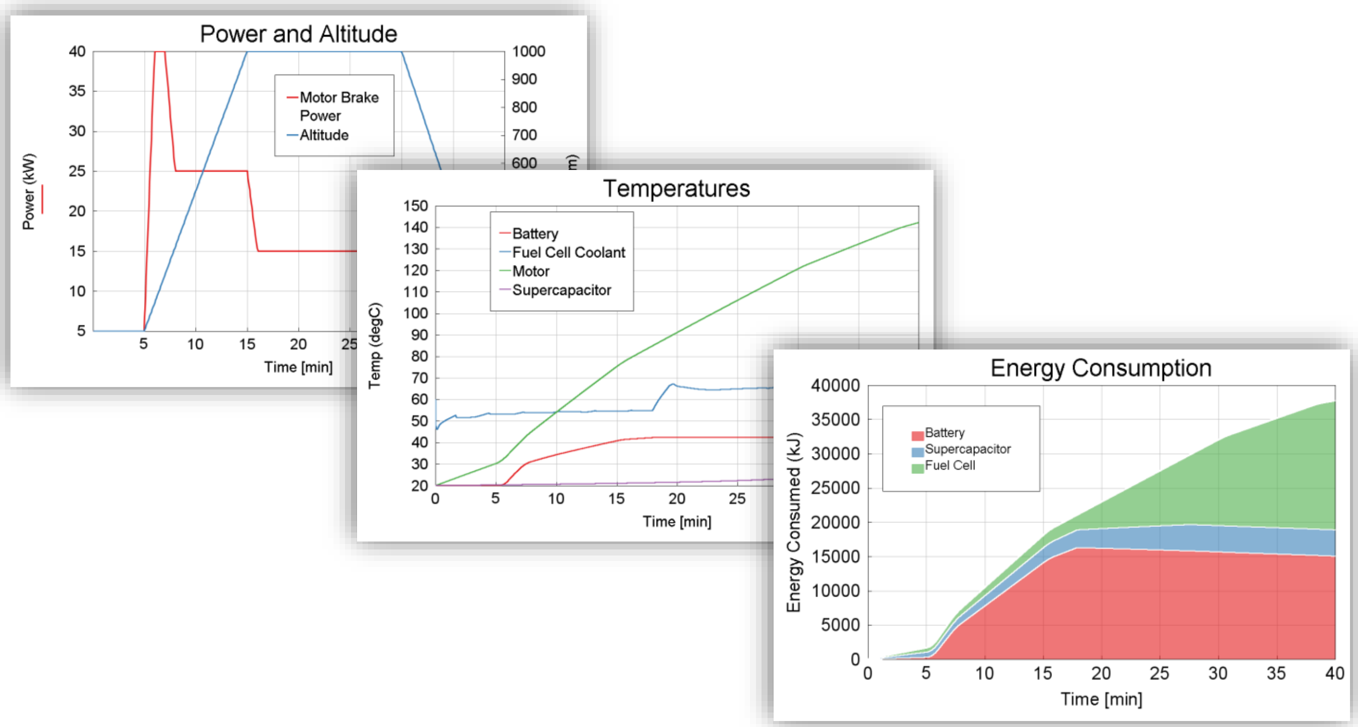




Early Concept Studies

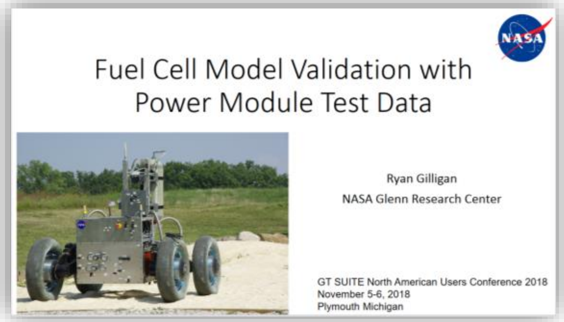
- Evaluate different propulsion architectures
- For hybrid propulsion systems, evaluate different strategies for using the battery, fuel cell, or traditional engine technology

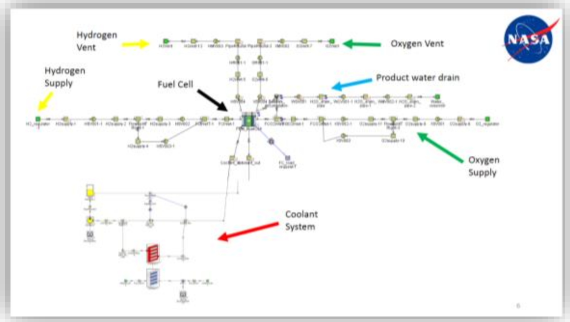




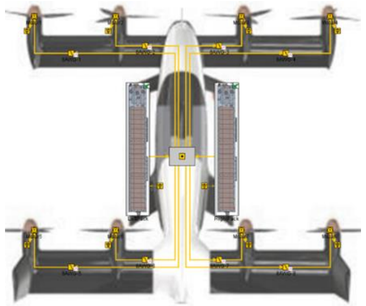
Propulsion Systems Analysis

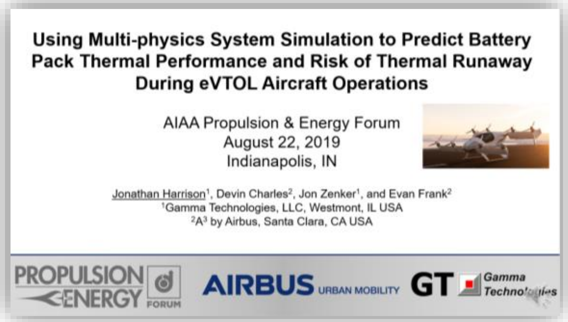
- Fuel Cells

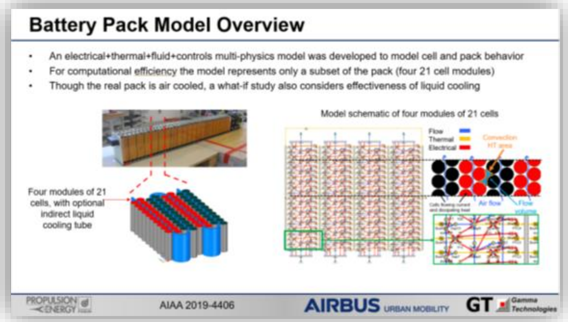




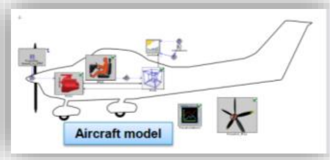
- Battery Packs and Supercapacitors

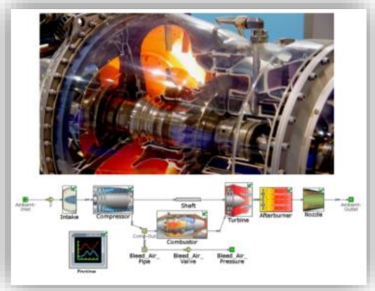






- Traditional IC engine, turboprop, turbojet, turbofan systems

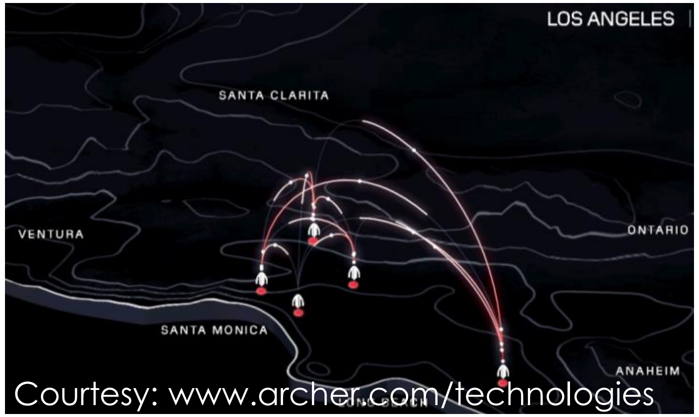




Battery System Analysis

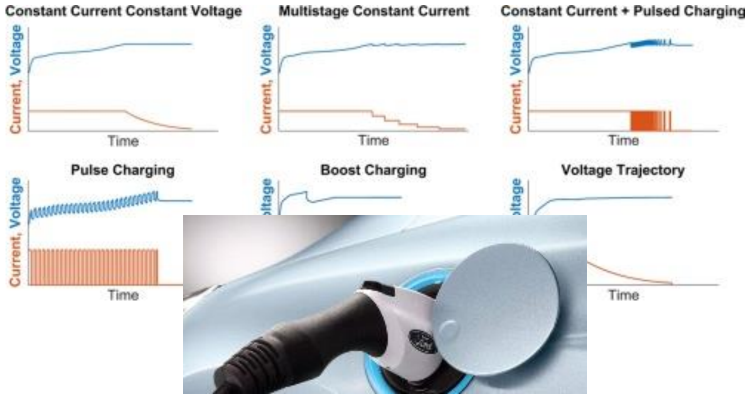
- Predict SOC and SOH over the lifespan of the vehicle, accounting for:
  - Thermal Management Strategies
  - Commuting Behavior
  - Charging Patterns
  - Weather Patterns

Commuting Behavior

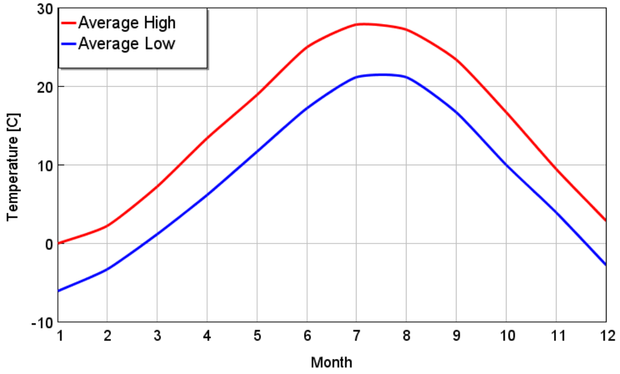


Courtesy: www.archer.com/technologies

Charging Patterns



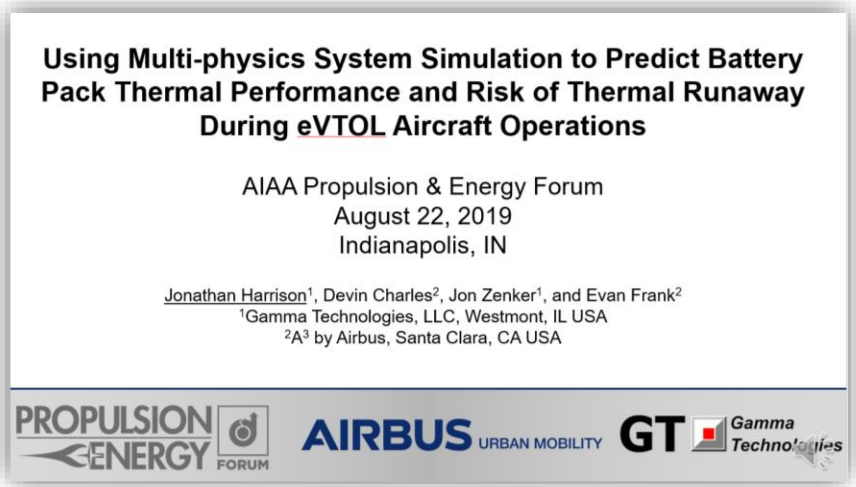
Weather Patterns



Case Studies

eVTOL Battery Pack Thermal, SOC, & SOH

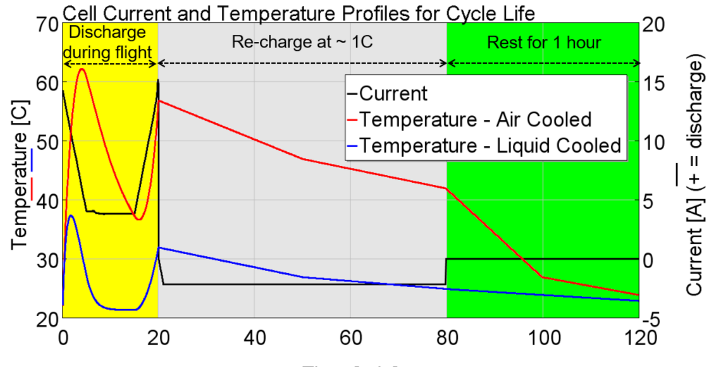
- GT presented a joint paper with Airbus A³ at the 2019 AIAA P&E conference to study:
  - eVTOL pack thermal performance and SOC over real flight missions, compared to test
  - Battery SOH over different mission cycling and thermal management strategies

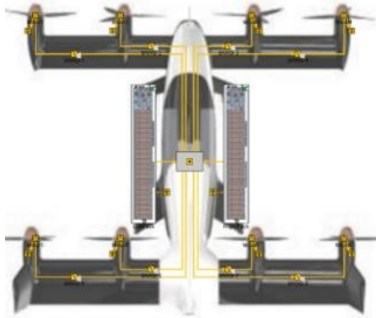

Using Multi-physics System Simulation to Predict Battery Pack Thermal Performance and Risk of Thermal Runaway During eVTOL Aircraft Operations

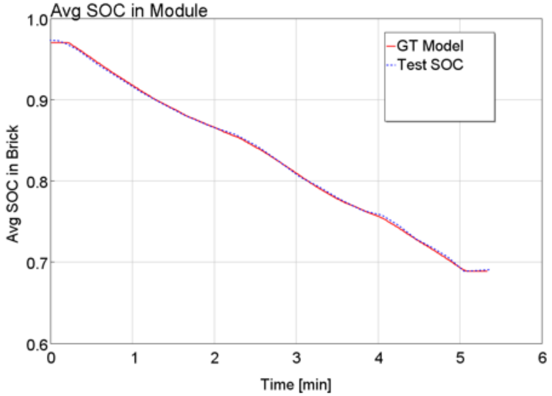
AIAA Propulsion & Energy Forum
August 22, 2019
Indianapolis, IN

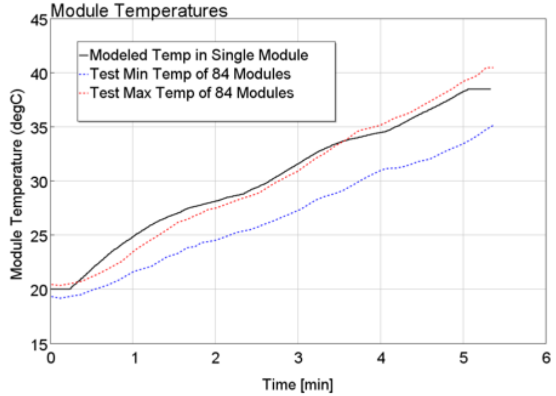
Jonathan Harrison[1], Devin Charles[2], Jon Zenker[1], and Evan Frank[2]
[1]Gamma Technologies, LLC, Westmont, IL USA
[2]A³ by Airbus, Santa Clara, CA USA

PROPULSION ENERGY FORUM
AIRBUS URBAN MOBILITY
GT Gamma Technologies



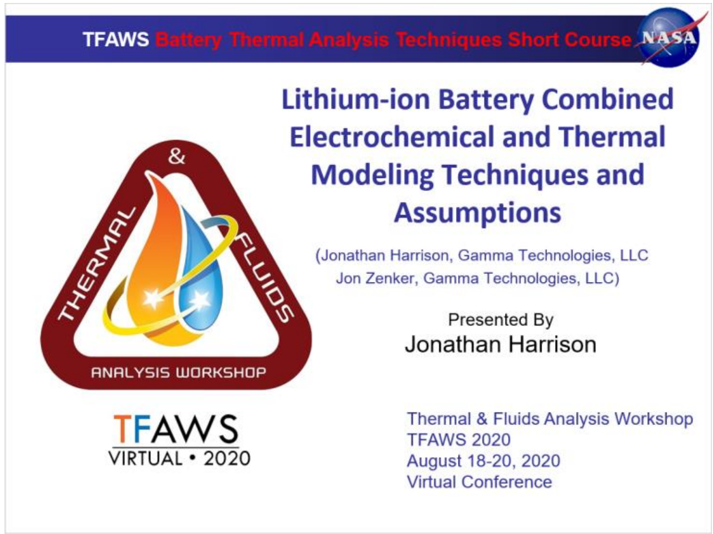




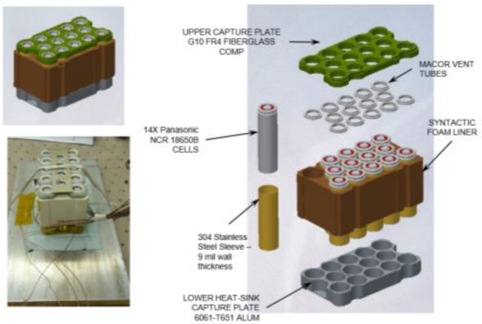


Battery Pack Thermal Runaway

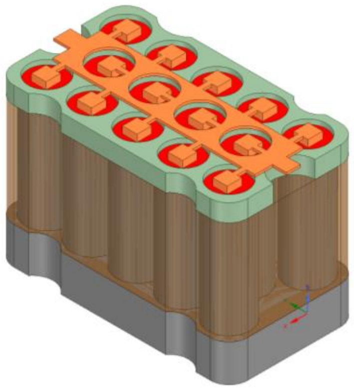
Comparison to Orion Module Battery Pack when corner cell triggered to thermal runaway



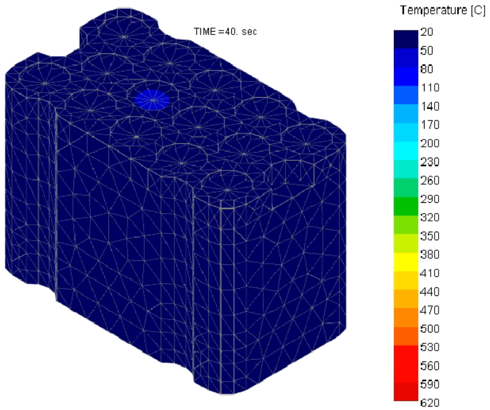
Physical Pack



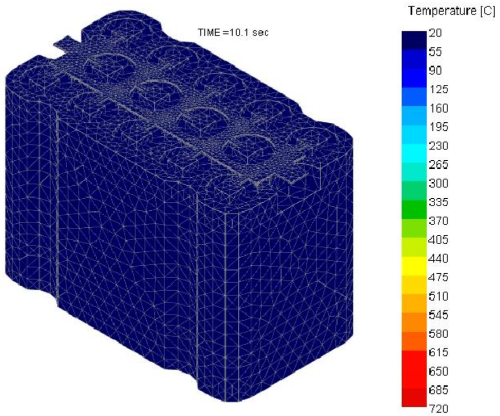
GT-SUITE Model



Passing Test

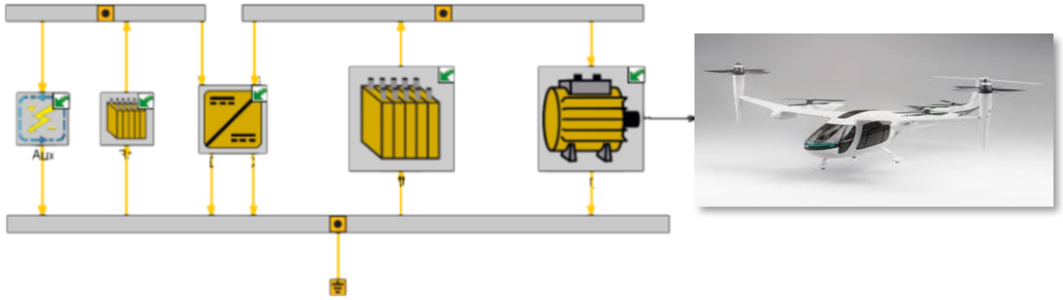


Failing Test

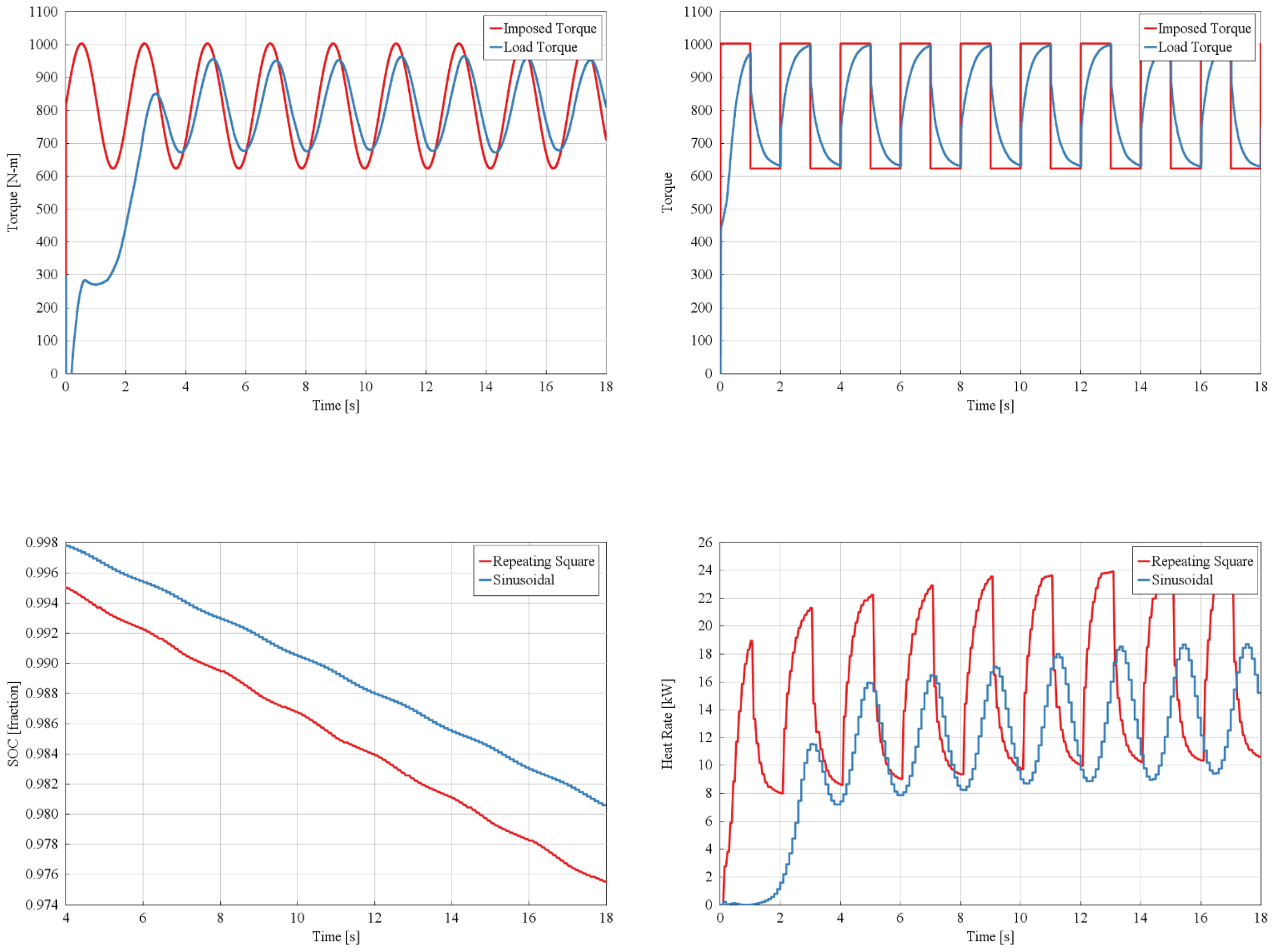


Complete eVTOL: rotor to battery

- GT presented paper at 2022 VFS Forum 78 last week
- Complete 'rotor to battery cell' solution:
  - Is my electric powertrain sized properly to my eVTOL and mission?
  - Predicting battery SoC in different wind/turbulence
  - How does different battery types/chemistry affect performance?
  - How does temperature effect range?



Torque Variations and SOC Effects



Sinusoidal and repeating square torque excitations of lift propeller

Deviations and delay between applied torque and rotor hub torque due to propeller moment of inertia

Effects on Battery Performance

Physics-based powertrain model allows for detailed investigations of powertrain performance.

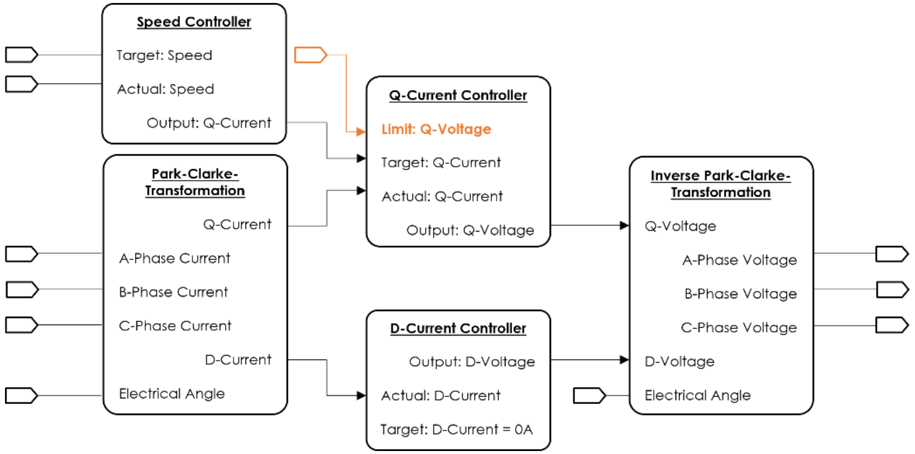
→ Higher SOC gradients and heat generation rate at repeating square excitation

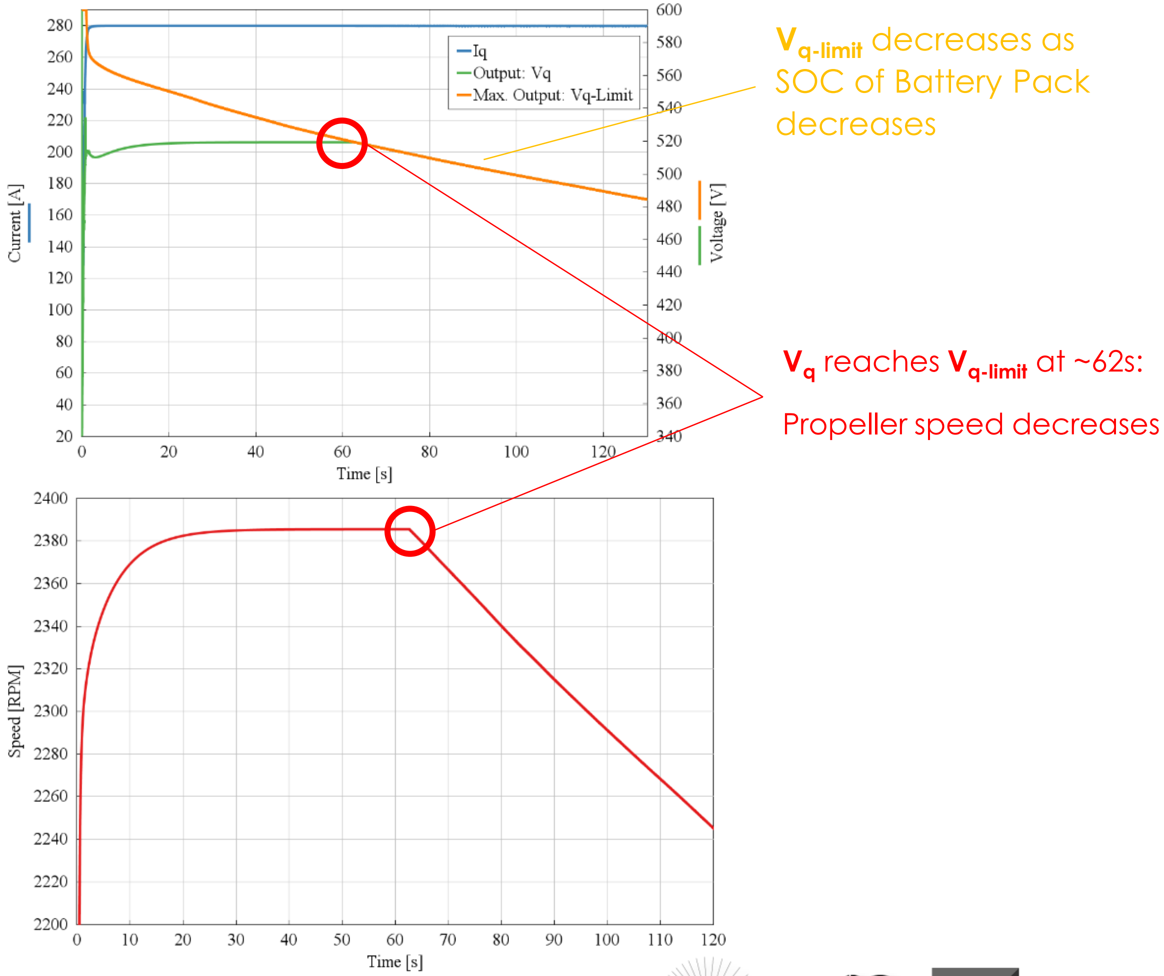
Effect of Battery SOC on Propeller Speed

Additions to motor controls allow to visualize battery limiting effects on propeller performance

Limiting the battery current load to 6C which equals a DC current of I_{limit}=780A.

$V_{q\text{-}limit}$ is calculated at every timestep and imposed on the motor controls:





Battery Chemistry Variation and Effect on System Performance

Comparison of cell chemistries

NCM811: Lithium-Nickel-Manganese-Cobalt-Oxide

LFPO: Lithium-Iron-Phosphate

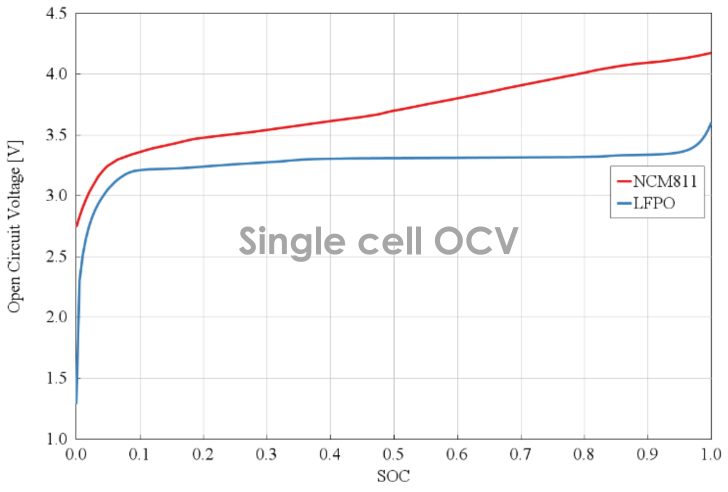
Battery pack sizing

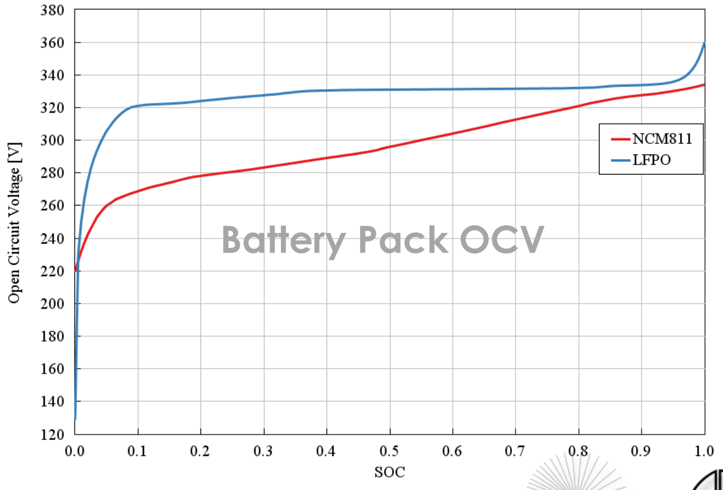
Comparing single cell OCV (Open-Circuit-Voltage) curves to find battery pack configurations with matching maximum OCV values

NCM811: 80 series, 40 parallel cells - total: 3200

LFPO: 100 series, 33 parallel cells – total: 3300*

*Increased LFPO pack-size to match battery pack mass





Battery Chemistry Variation and Effect on System Performance

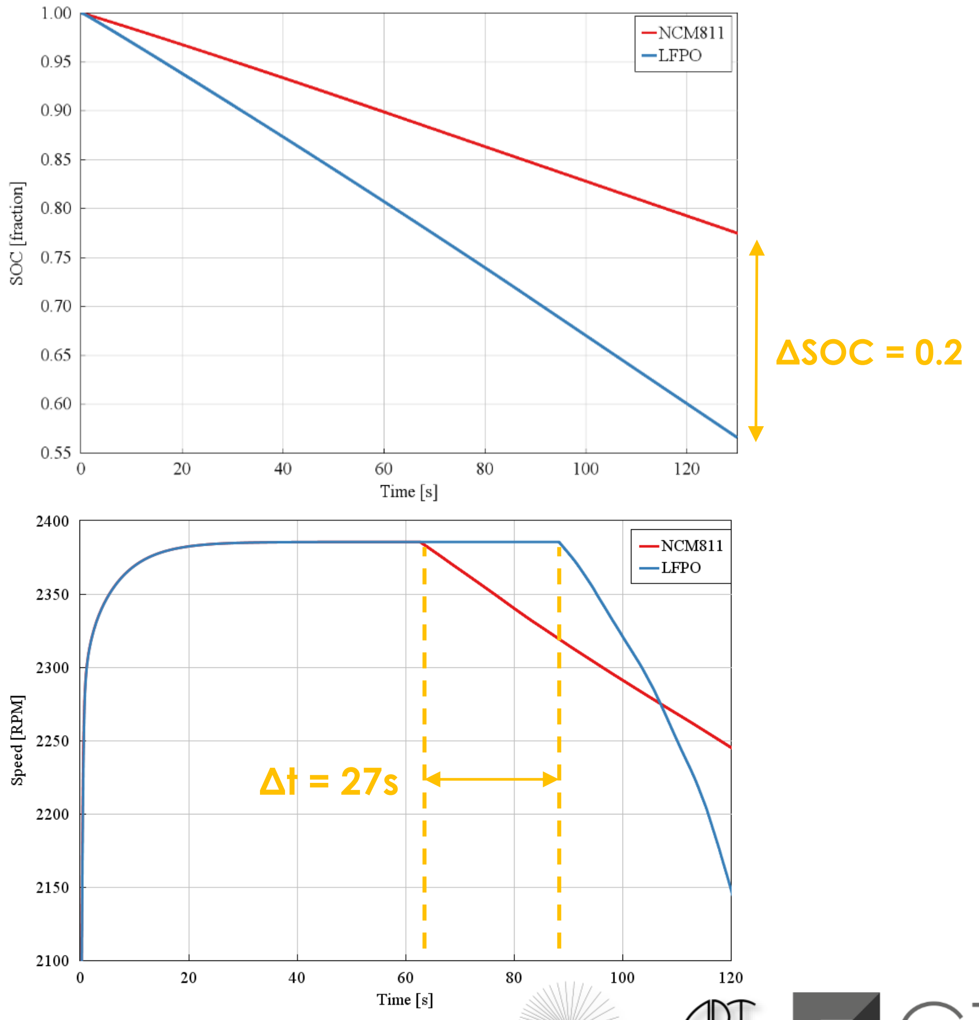
Battery pack performance

LFPO shows significant higher SOC gradients – due to chemistry and lower number of series cells

Propeller performance

Propeller speed decrease occurs earlier when using NCM811 cell but propeller speed shows higher gradients for LFPO

→ Speed decrease correlates with shape of battery pack OCV curves and battery pack capacity of the two chemistries



Aircraft Range: Effect of Battery Chemistry and Temperature

Operating conditions

Hover propeller at constant speed

Constant temperatures are imposed on the Battery Pack: T_{pack}=[0,10,20]°C

Battery performance

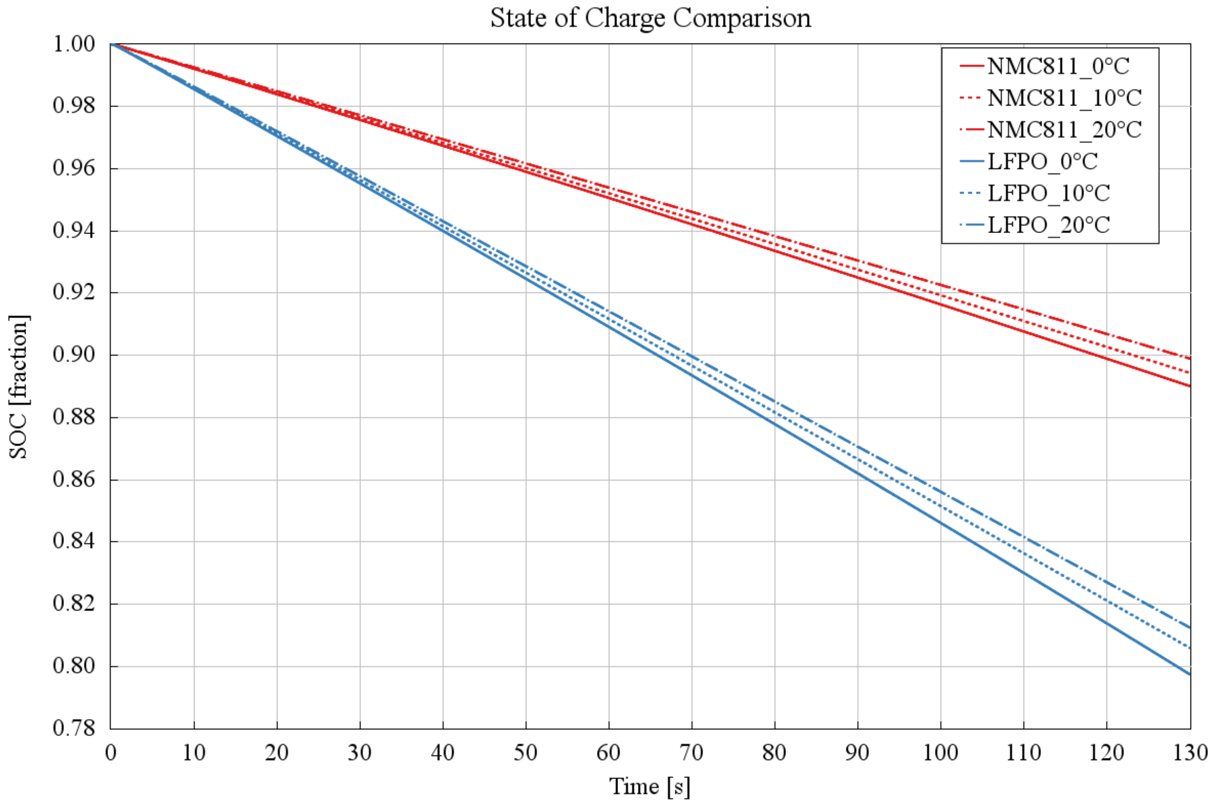
NMC811 pack shows lower SOC gradients compared to LFPO

Performance reduced at lower temperatures

Extending the thermal model

Internal thermal solution to calculate an accuare temperature based on electrochemical reactions, resistive losses and entropic heating

Modeling of heat transfer to surrounding parts or cooling



Next Steps

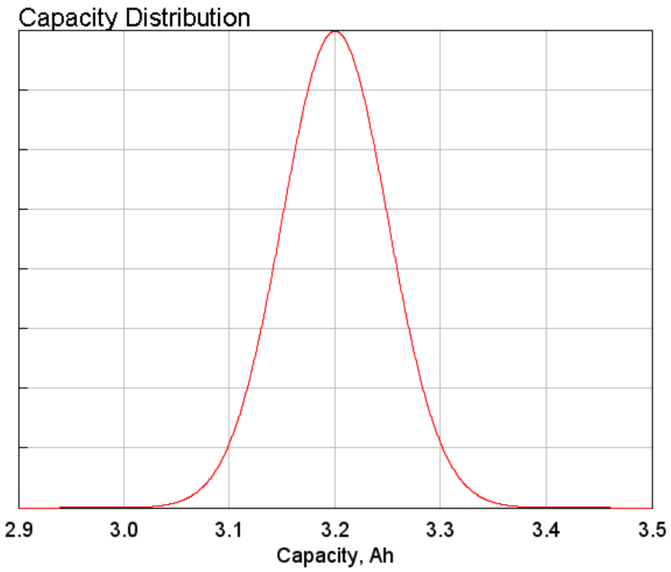
- Gamma Technologies offers simulation software with industry-leading engineering support included
- We are happy to discuss how GT can help your organization
- Please contact us to arrange a call or web meeting

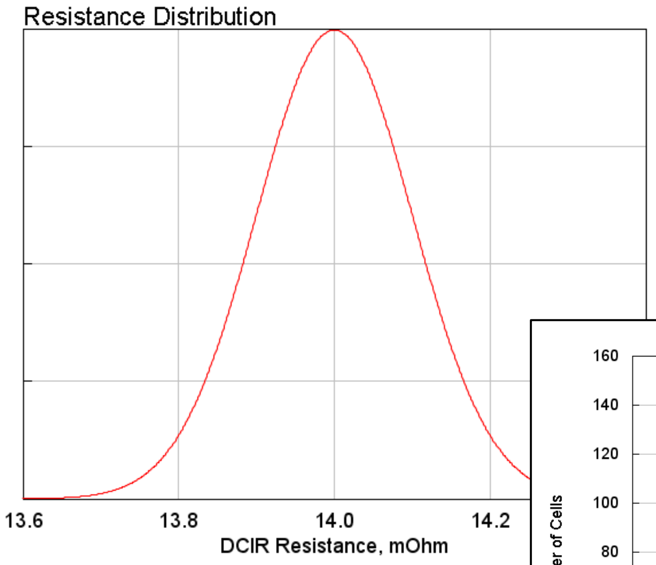
Contact: Jon Zenker, j.zenker@gtisoft.com

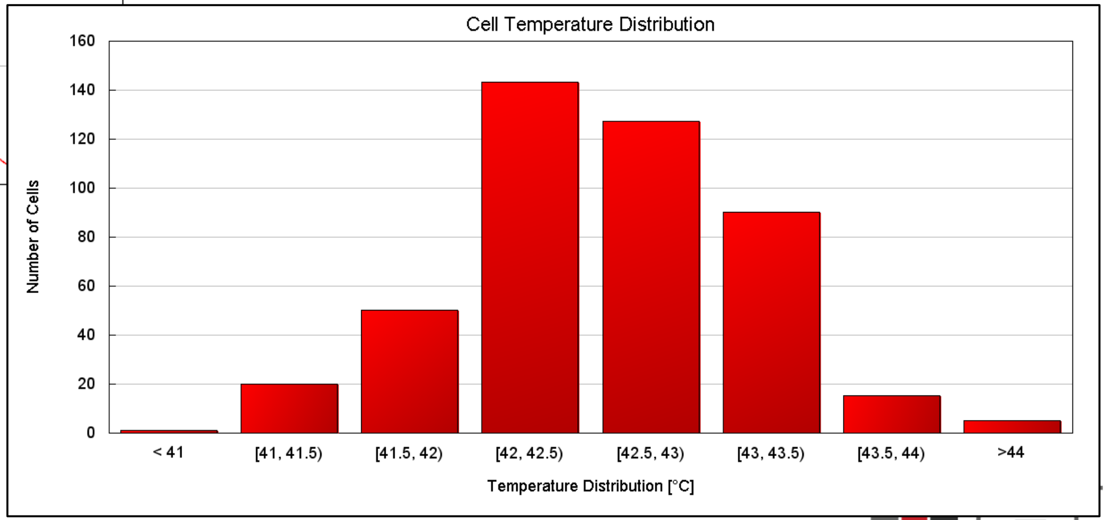
GT-SUITE additional capabilities

Analyze Statistical Variability Analysis Example: Battery Thermal

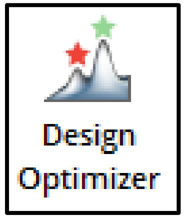
With GT's statistical variance and Monte Carlo abilities, analyze how variance in cells affects module behavior

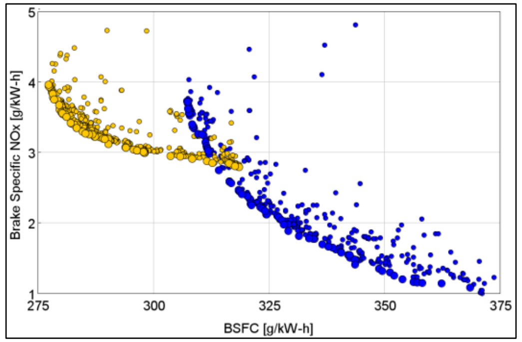






Design Optimization



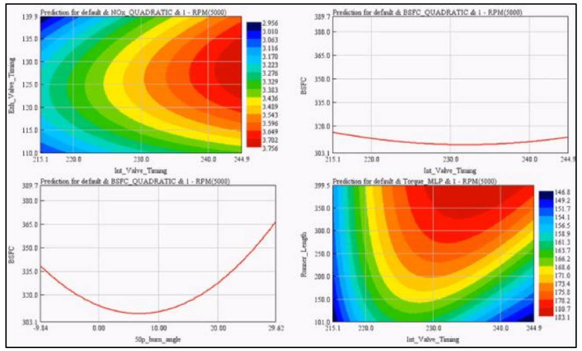


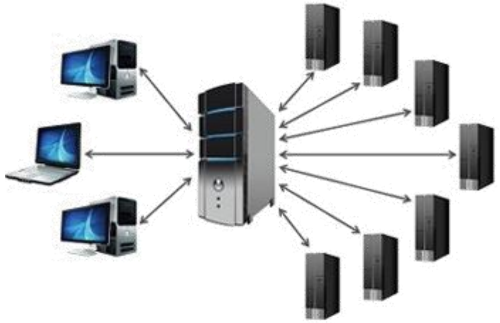
Integrated Design Optimizer

- Fast and easy setup and execution
- Vary Parameters to match experimental results

DOE Analysis

- Visual, interactive design exploration
- Fast optimization through metamodeling





Distributed Computing

- Exploit High Performance Computing
- Run many cases simultaneously

Multi-Physics Requires Flexible and Open Platforms

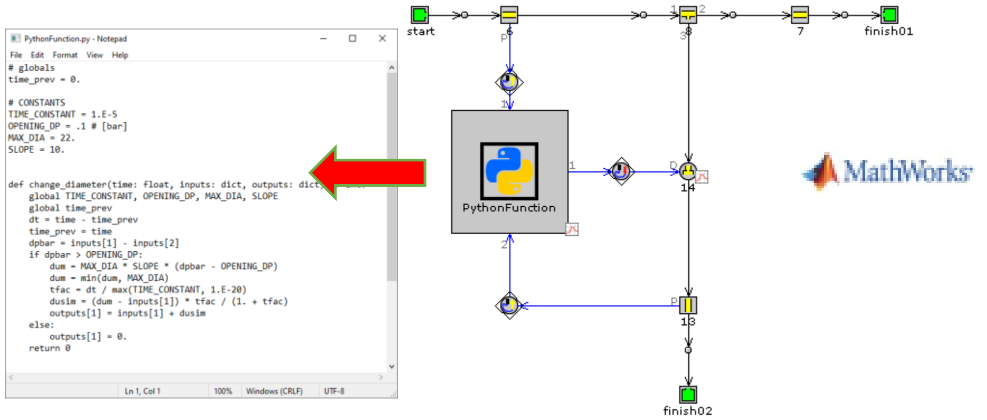
No single tool can complete all the simulation related tasks on its own, requires collaborating with an ecosystem of tools

- Co-simulation with many commercial tools

Controls & MiL/SiL/HiL	MathWorks, ETAS, dSPACE, National Instruments, A&D Technology Inc., Realtime technologies inc, OPAL-RT, concurrent
Co-sim	MathWorks, fmi Functional Mock-up Interface, D2T, National Instruments, TLK-Thermo GmbH, COSATEQ
MBD and FE	MSC Software, ANSYS, Altair, JMAG, Romax Technology
CFD & Thermal	Convergent Science, TAI, OpenFOAM, Exa, ANSYS, Siemens STAR-CCM+, Simerics
Design Exploration	modeFRONTIER, Dassault Systemes, noesis, optiSLang, MathWorks, SMARTUQ
Turbomachinery	npss, SoftInWay, SCORG™

- Open API to link to any tool

- Write your own user code in Python, C, Matlab (via C or Simulink), or Fortran



- Configure models for MiL, SiL, or HiL