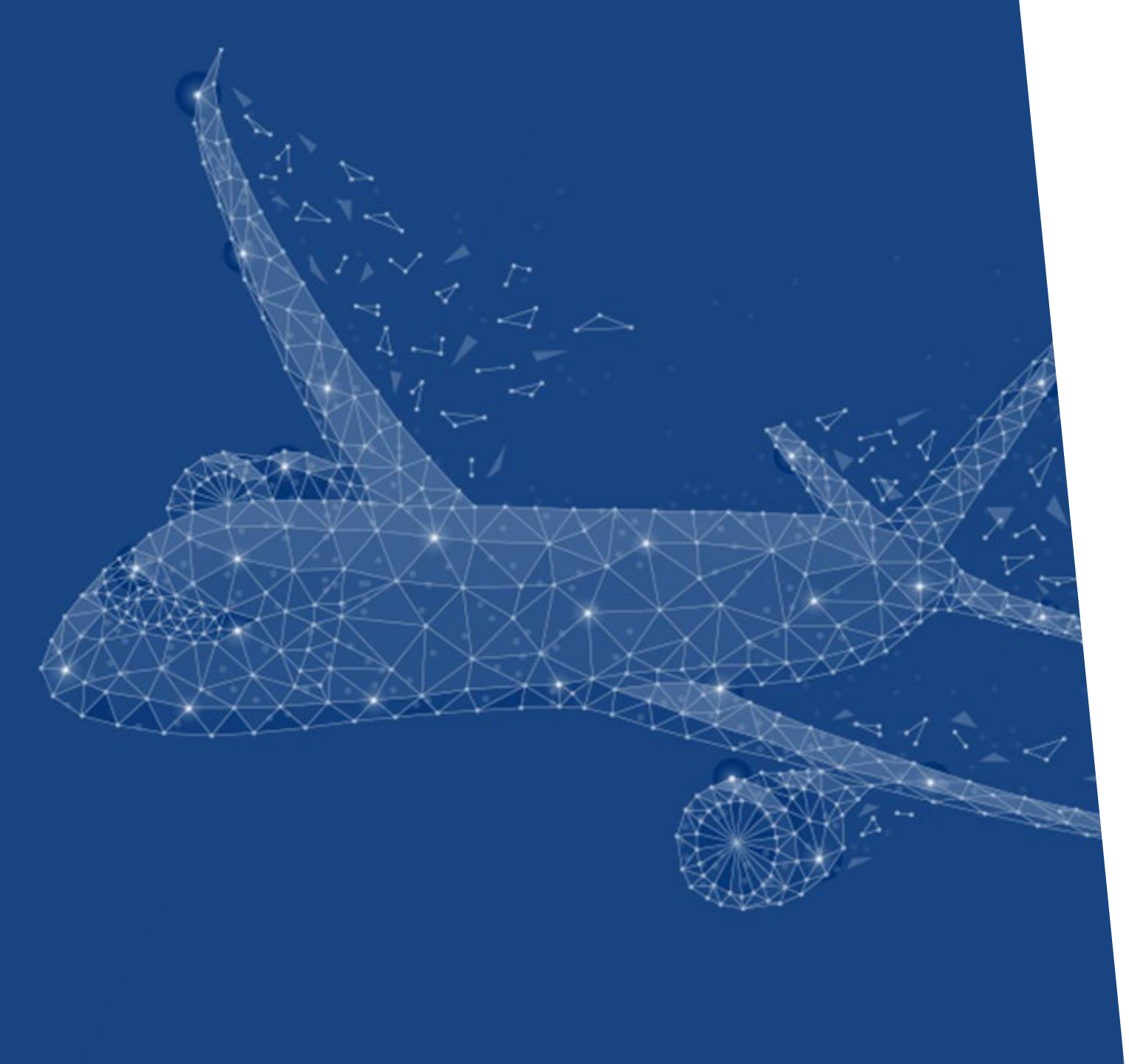


A Guide to Electrified Aircraft Systems Sizing: ePowertrain, TMS, and ECS Analysis

Jonas Verrière
Marek Lehocky

Gamma Technologies & GT-SUITE

Recognized Innovator for Integrated Multi-Physics System Simulation Solutions

Founded in 1994

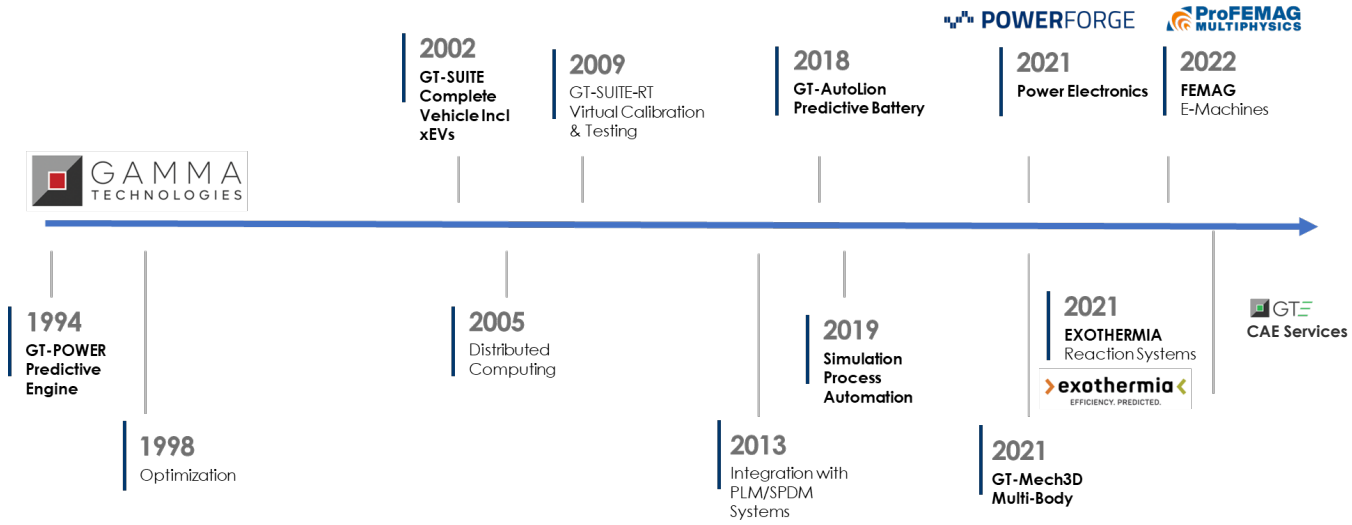
HQ Chicago, USA

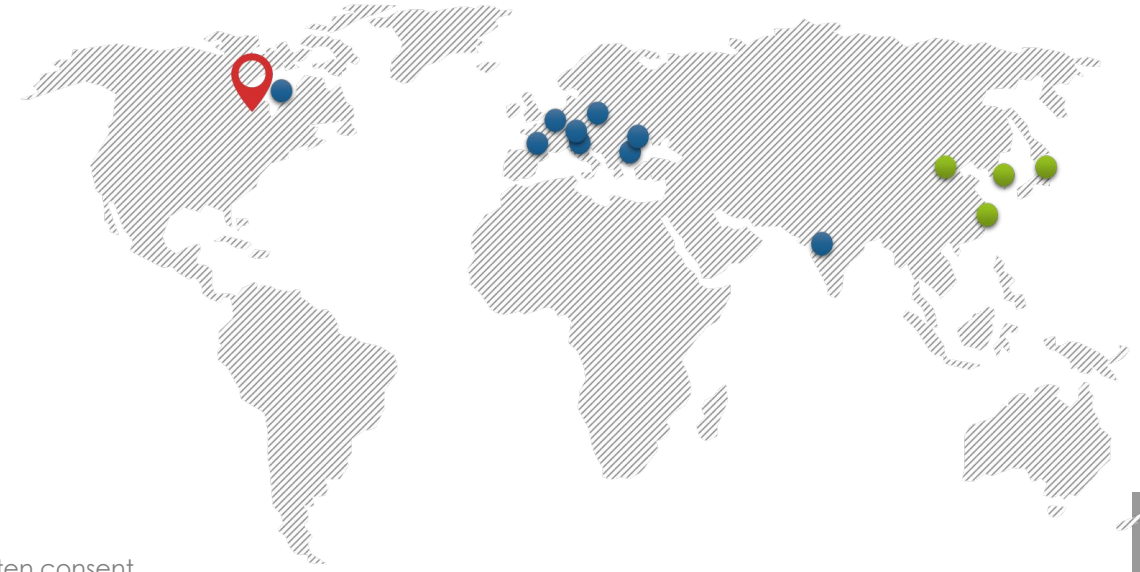
Offices Global

350+ Employees

700+ Customers

30+ Alliance Partners





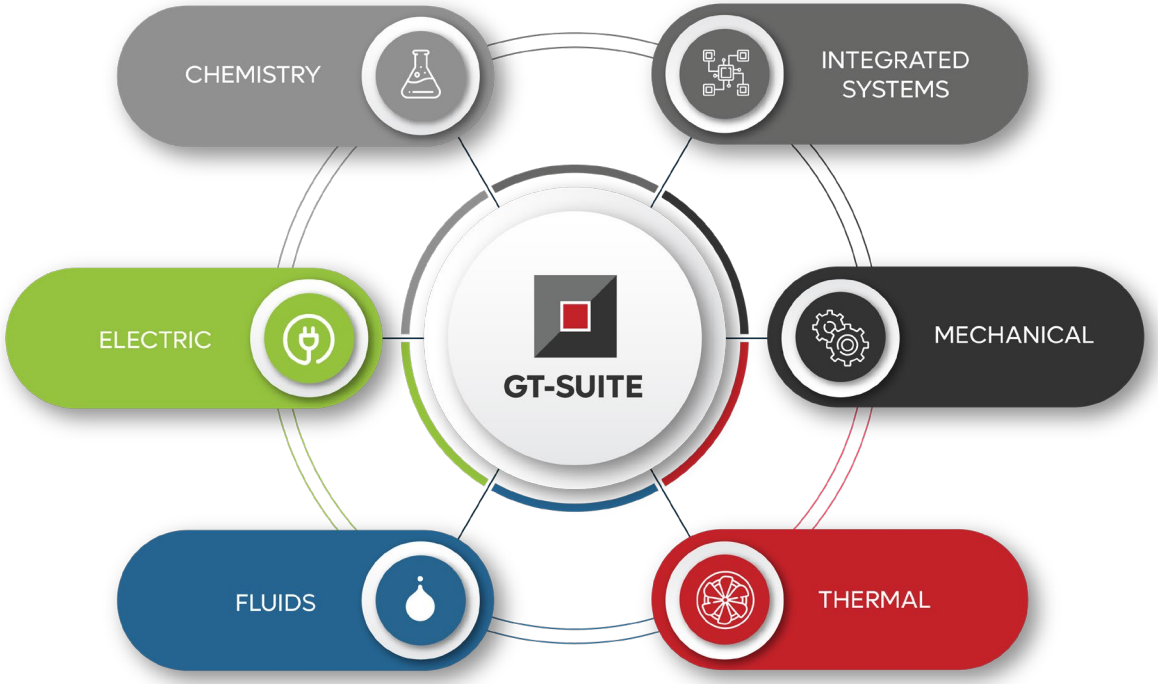
Global Headquarters
Westmont, IL, USA

Regional Offices
Stuttgart, Germany
Pune, India
Thessaloniki, Greece
Glyfada, Greece
Toulouse, France
Troy, MI, USA
Prague, Czech Republic
Basel, Switzerland
Torino, Italy
San Jose, California

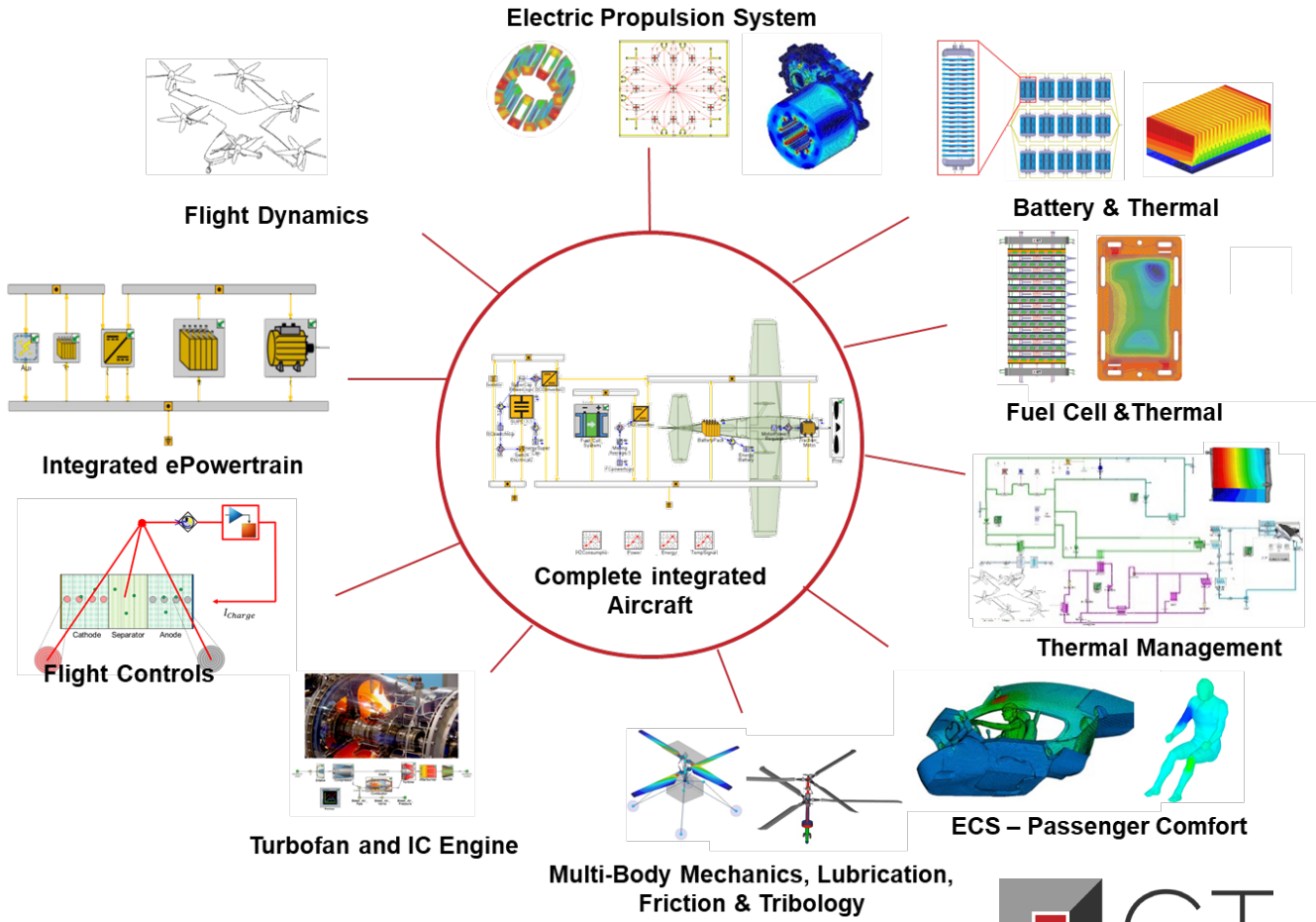
Partners
Yokohama, Japan
Shanghai, China
Gyeonggi-do, S. Korea
Beijing, China
Sao Paulo, Brazil

GT-SUITE System Simulation platform

Physics-based system simulation platform



Multi-physics and Multi-domain integration

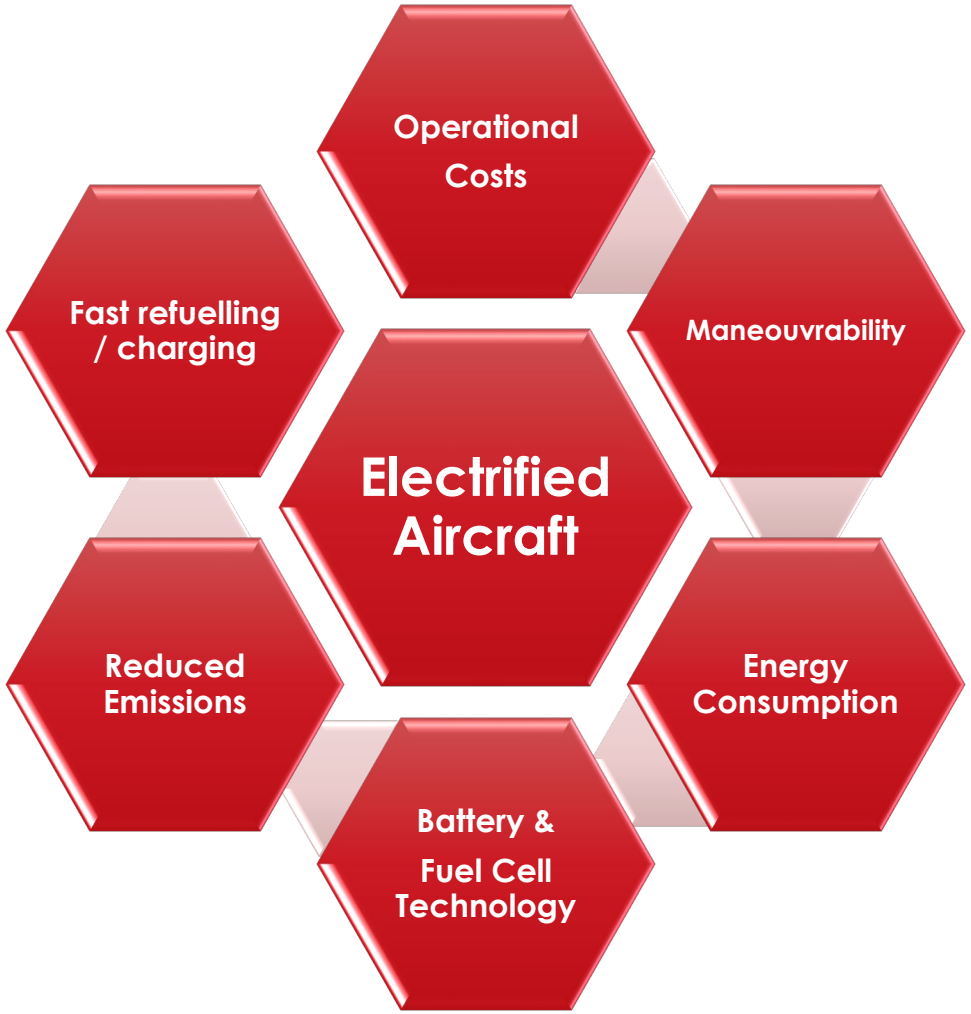


Agenda

- Electrified Aircraft System Development
- Aircraft & Powerplant modeling
- Powerplant optimization
- Cooling system sizing/verification
- ECS integration
- Conclusions

Electrified Aircraft System Development

- Challenges:
  - Safety regulation
  - Environmental regulations
  - Power sources technology
  - Disruptive architectures
  - Development time & costs



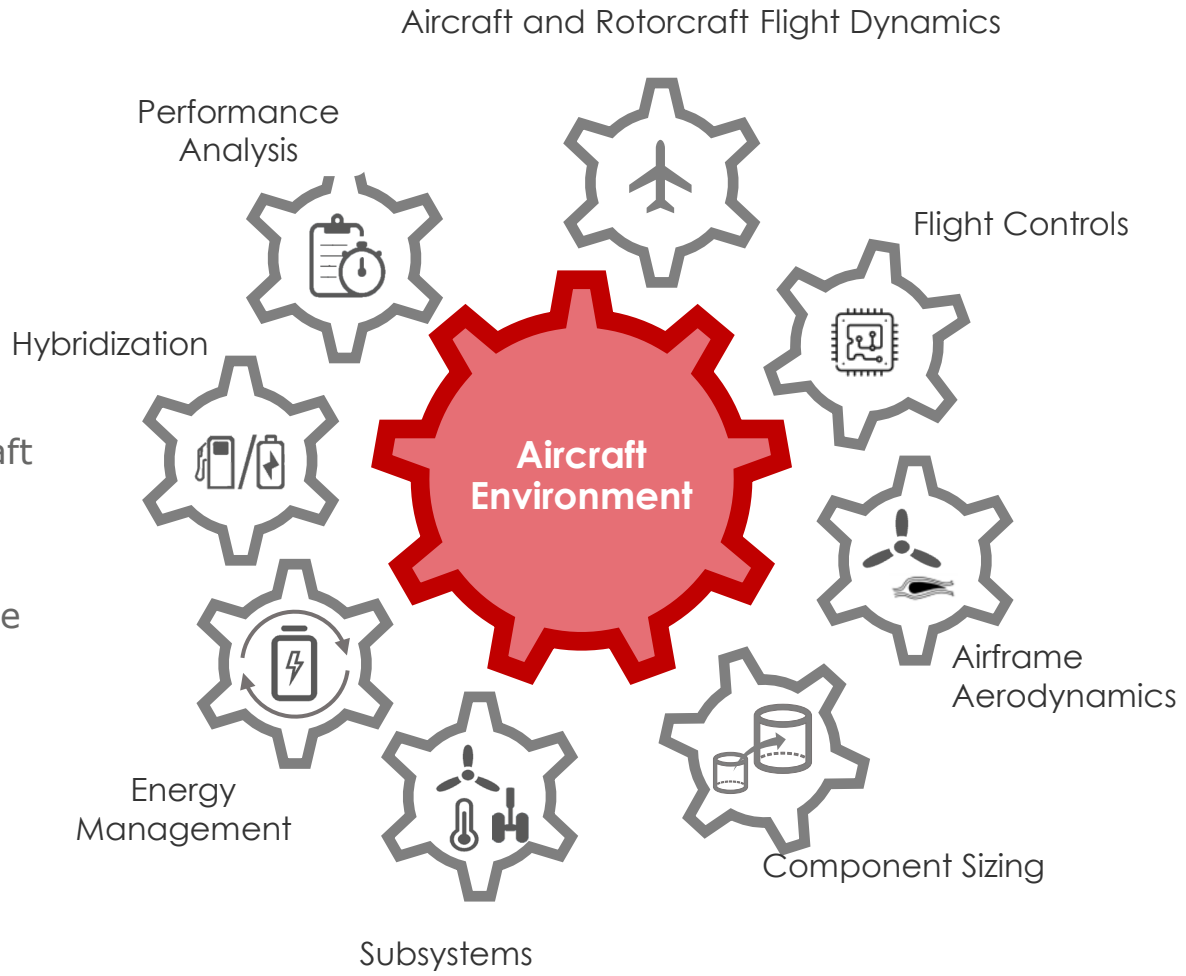
Electric Aircraft System Development

- Why Early Virtualization | Shift Left ?
  - Early stages defines 70% of Product life cycle costs
  - Mitigate risks and avoid late stage failures
  - Prototypes are arriving too late in the design cycle
  - Tests are expensive
- Why Multiphysics System Simulation ?
  - Aircraft is complex assembly of subsystems and Electric aircraft thermal management is even more complex
  - Optimizing the subsystems independently is not an option
  - Need to being more predictive earlier in the development cycle
  - Robust design: multipoint and transient analysis

Holistic approach needed

Physics-based system modeling

From static to dynamic modeling

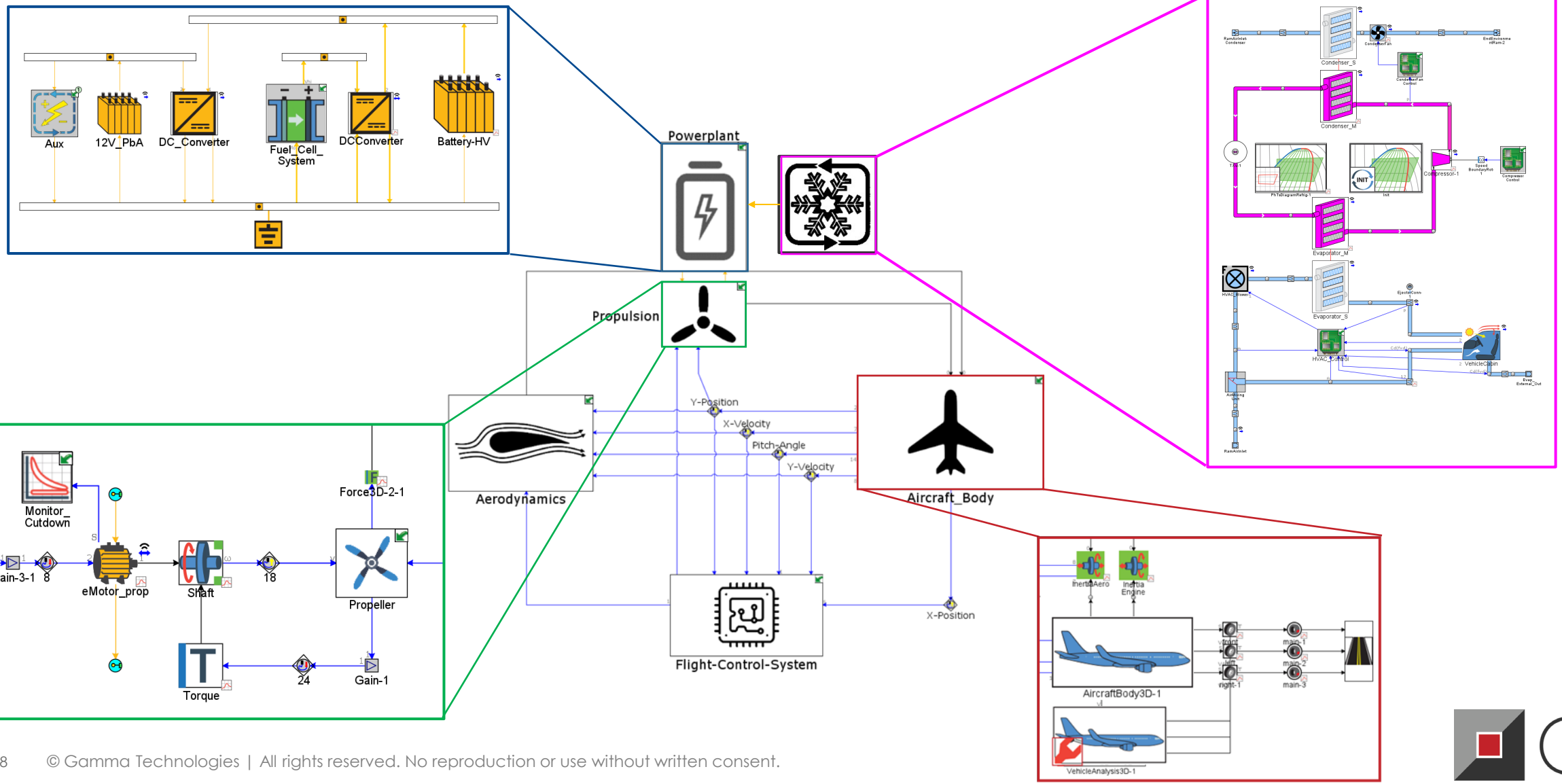


Aircraft model

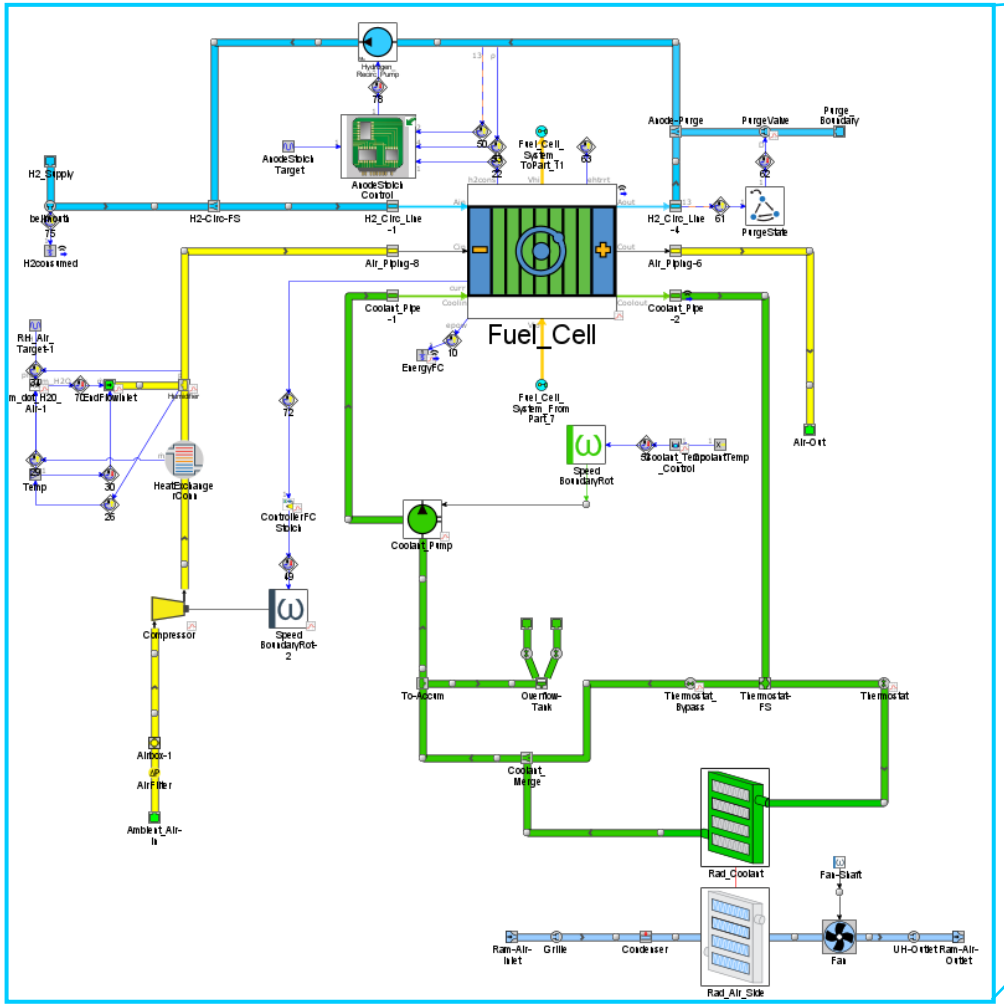
Case study definition

- Small electric aircraft - 2Pax
  - Payload: 200 kg
  - Aircraft Empty Weight : 600 kg
- Single propeller
- Powerplant: Fuel Cell & Battery
- ECS includes Vapor Compression System
- Mission parameters:
  - Climb rate 3 m/s
  - Cruise speed 65 m/s
  - Cruise altitude 1000 m/s
  - 1 kg H2

Electric aircraft modeling in GT-SUITE

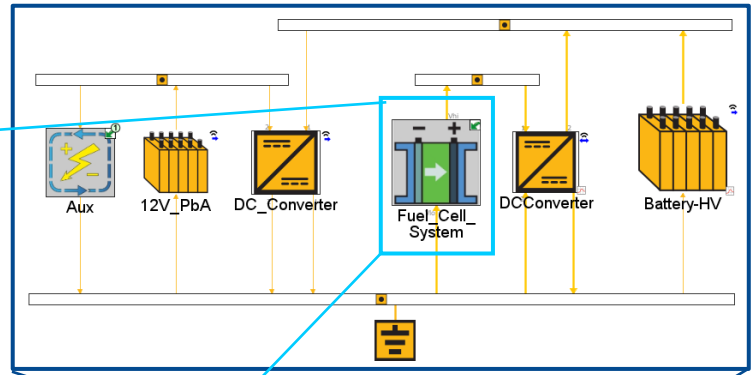


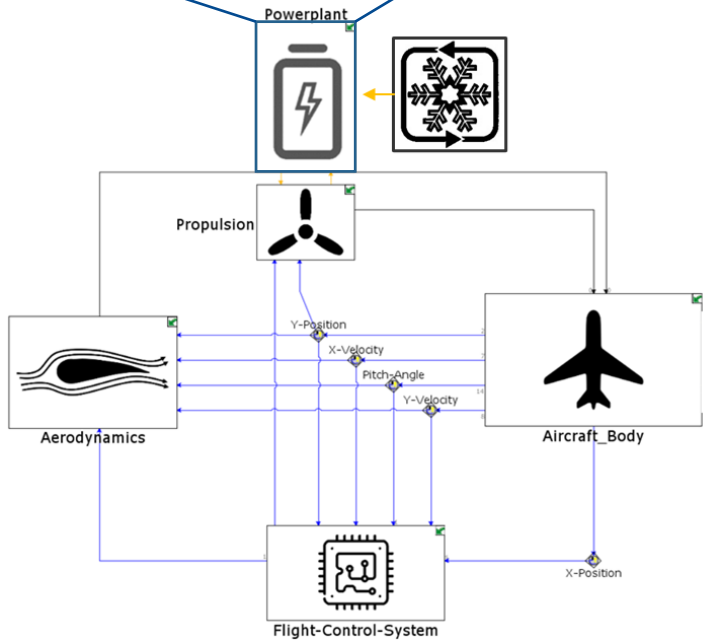
Fuel Cell system modeling



Fuel cell system:

- PEMFC stack
- H2 loop
- Air supply
- Cooling system

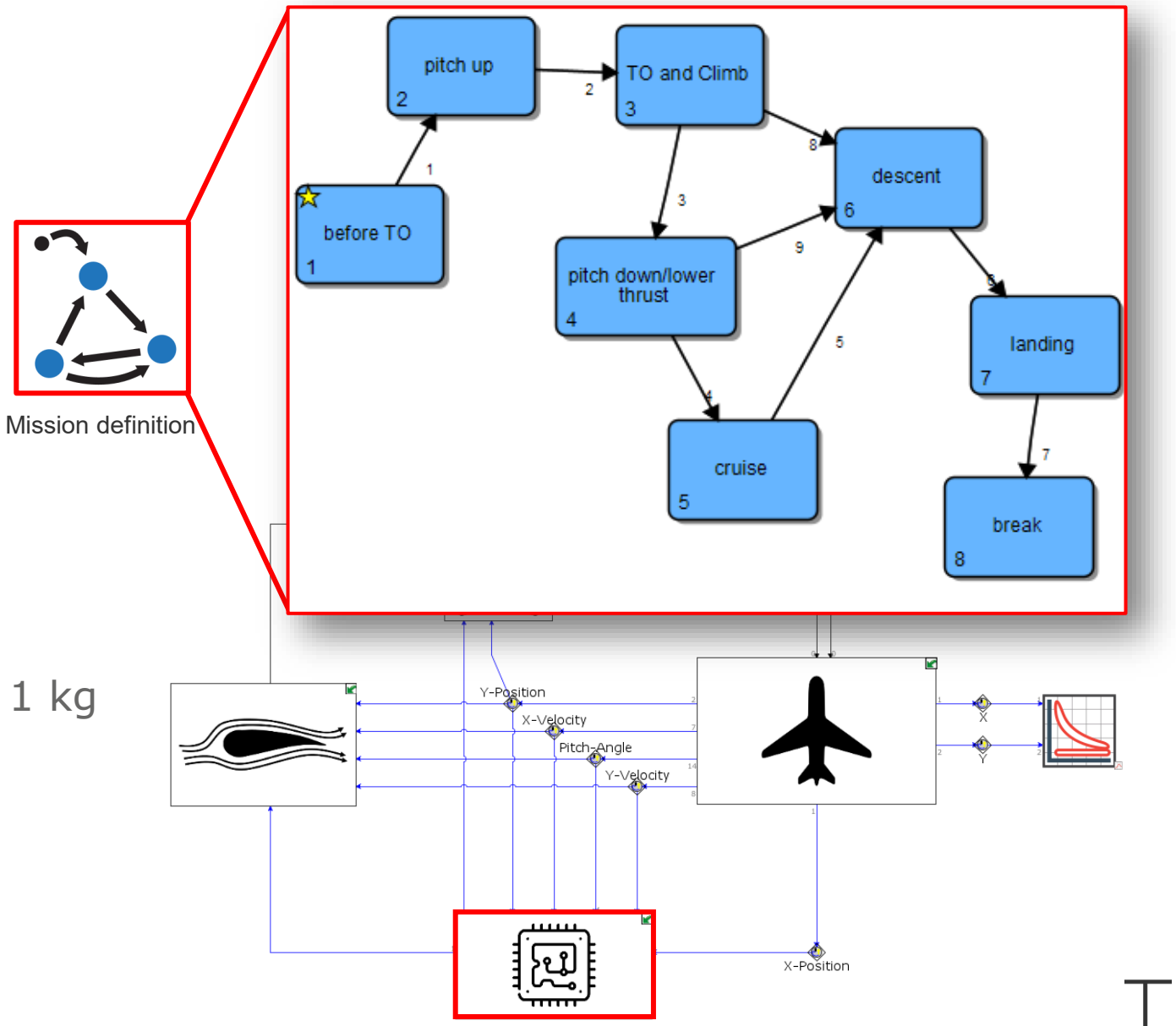




Mission definition

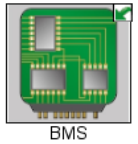
- Finite state manager
- State outputs:
  - Vx target
  - Vy target
  - altitude target

- Transition toward descent:
  - SOC < 0.3 and H2 consumption > 1 kg
  - Emergency descent: SOC < 0.1

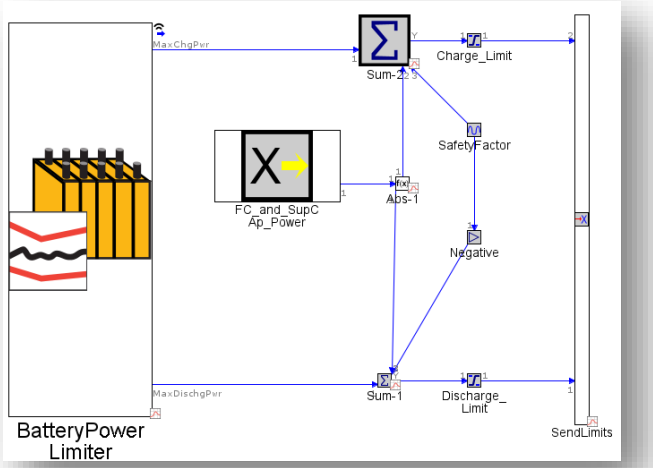


Controls

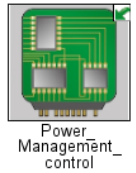
BMS



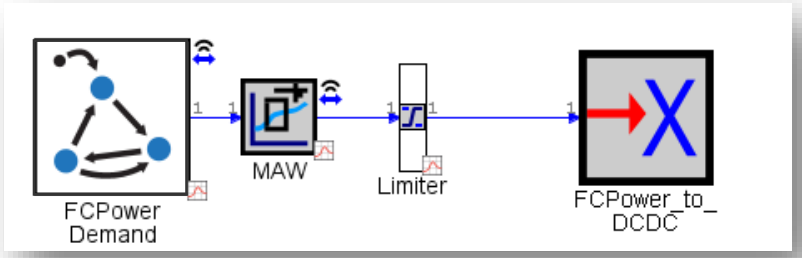
- Determine the maximum available Power:
  - Battery power limiter to protect the battery
  - Fuel Cell Max Power to stay in the safe part of the polarization curve

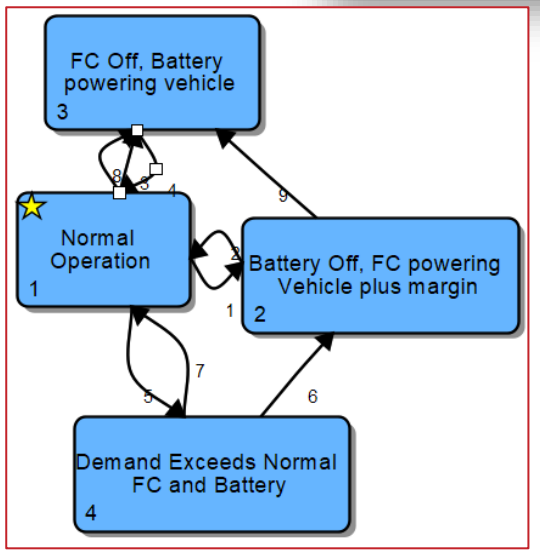


Power management



- Finite State Manager
- Fuel Cell Power request depends on:
  - Motor Power request
  - Battery SOC
  - H2 consumed





ePowertrain Optimization

- Varying Factors
  - Nb Fuel Cell cells
  - Nb Battery cells in parallel
  - Nb Battery cells in series
  - eMotor torque multiplier

Factors - Choose from among parameters that already exist in Case Setup					
Factor (OPTIND)		N_Cells_FC	N_CellBat_parallel	N_CellBat_series	torque_multiplier
○	Range (RANGE)	100.0			
◉	Lower Limit (RANGEMIN)	100.0	6.0	10.0	1.0
	Upper Limit (RANGEMAX)	900.0	32.0	200.0	1.6
Integers Only (INTONLY)		☑	☑	☑	☐
Discrete Values (DISCVALUES)		ign	ign	ign	torque_multiplier

- Objective function
  - Aircraft Range

- Weight of the Powerplant system including TMS
  - Fuel Cell system : **0.156 kg per cell**
  - Battery : **0.113 kg per cell**

- Constraints
  - The climb rate cannot differ (more than 1 m/s) from the target more than 200 s
  - eMotor Power limitation < 5 kW

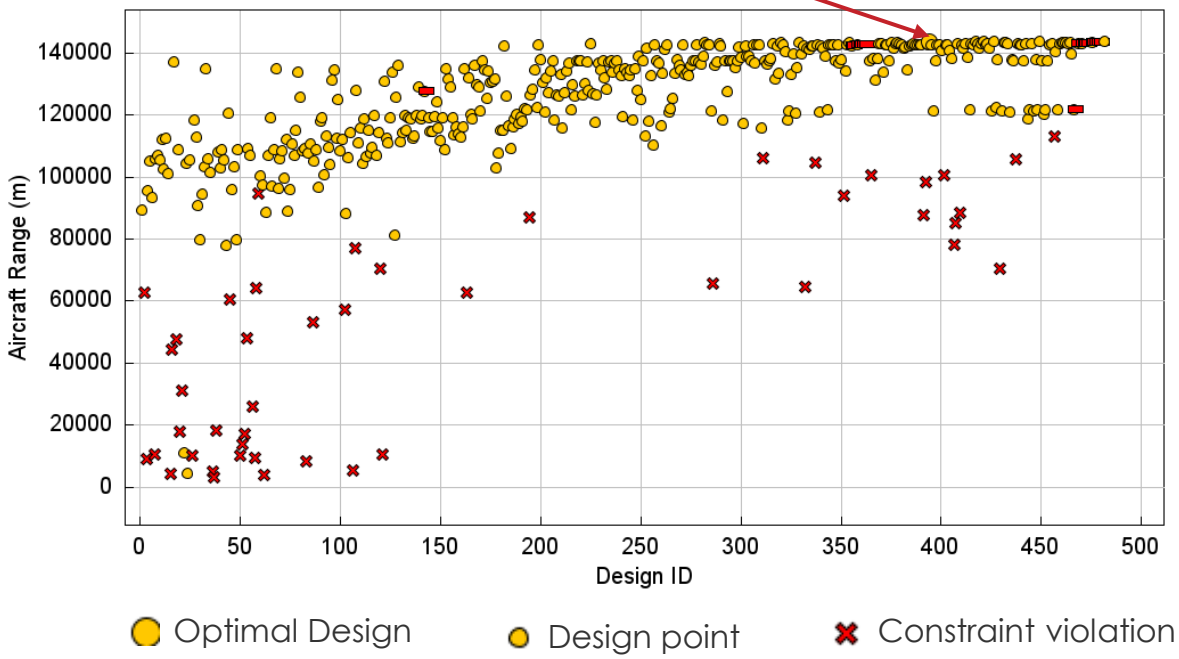
- Evolutionary algorithm
  - Accelerated Genetic Algorithm
    - **NSGA-III coupled with intermediate Kriging steps**
    - **32 designs per generation**
    - **15 generations**

Kadyk, Thomas, et al. "Analysis and design of fuel cell systems for aviation." *Energies* 11.2 (2018): 375.

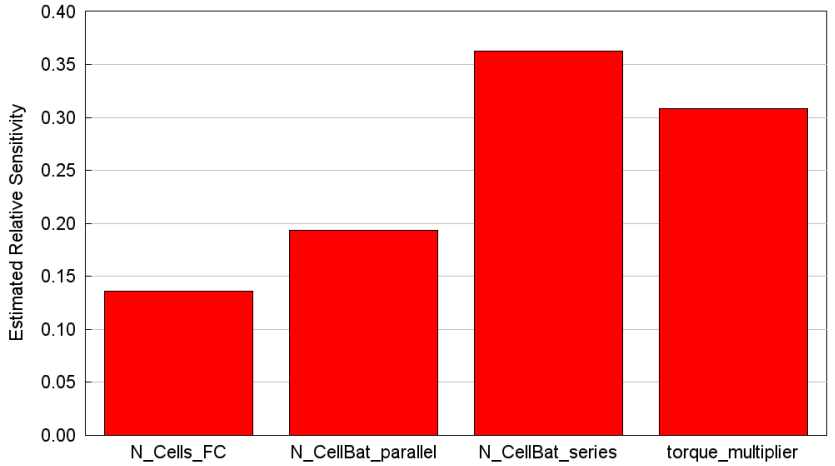
Optimization results

Initial design	Best design
89.34 km	143.89 km

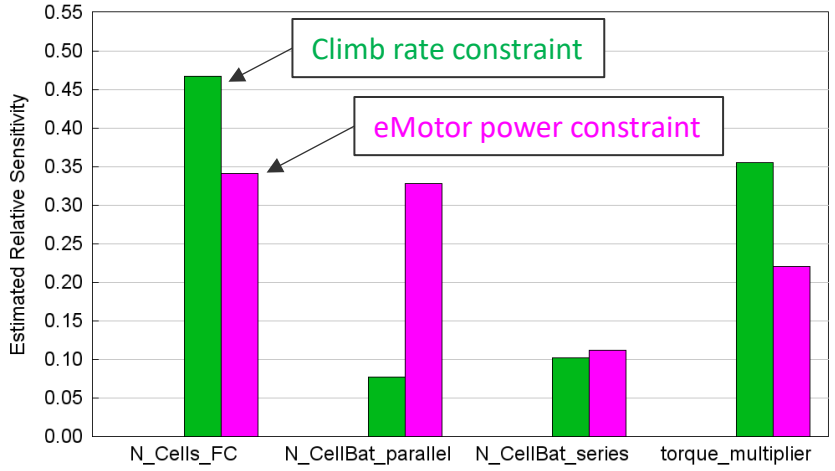
Nb cells FC 345
Nb CellBat parallel 23
Nb CellBat series 165
torque multiplier 1.6



Sensitivity Comparison for Aircraft range vs. Factor

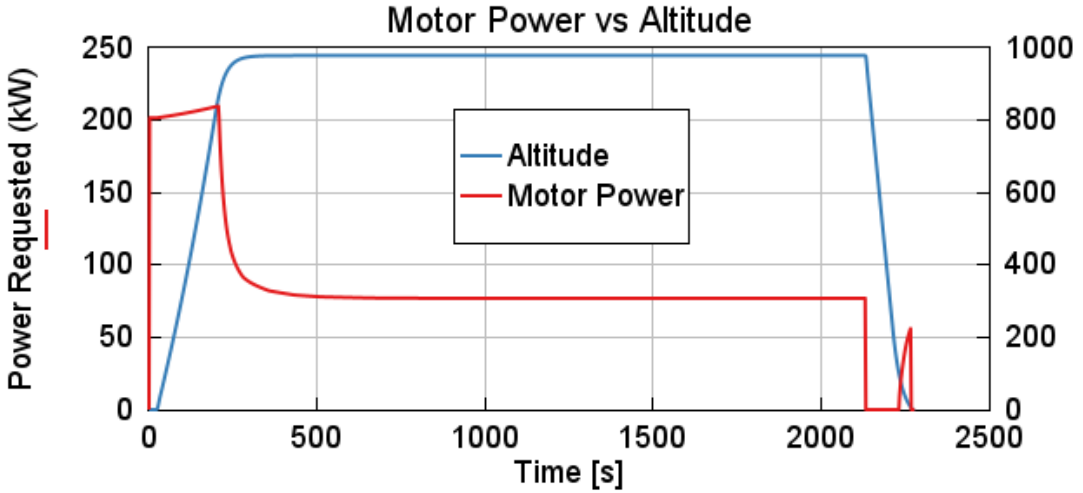


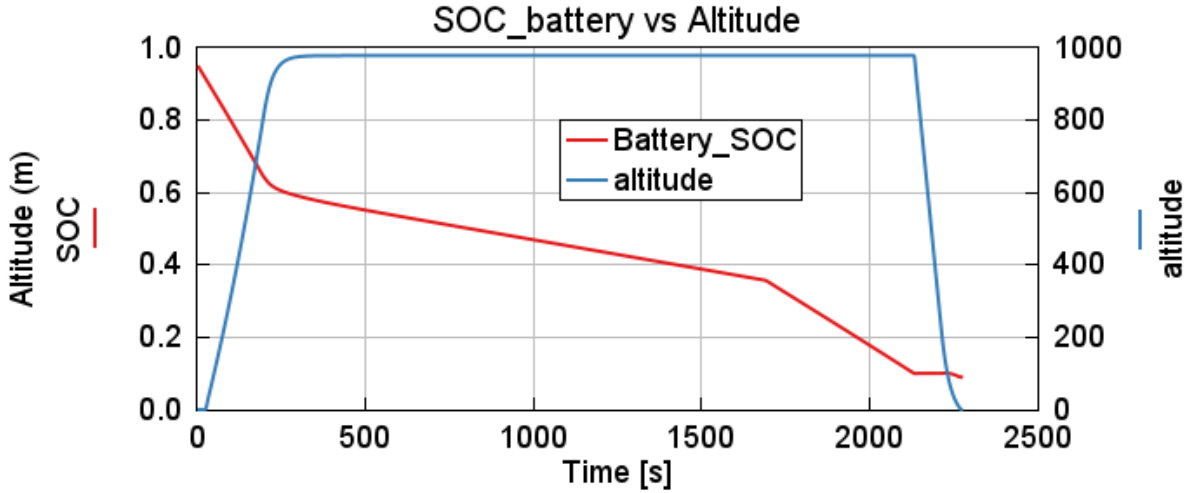
Sensitivity Comparison for Constraints vs. Factor

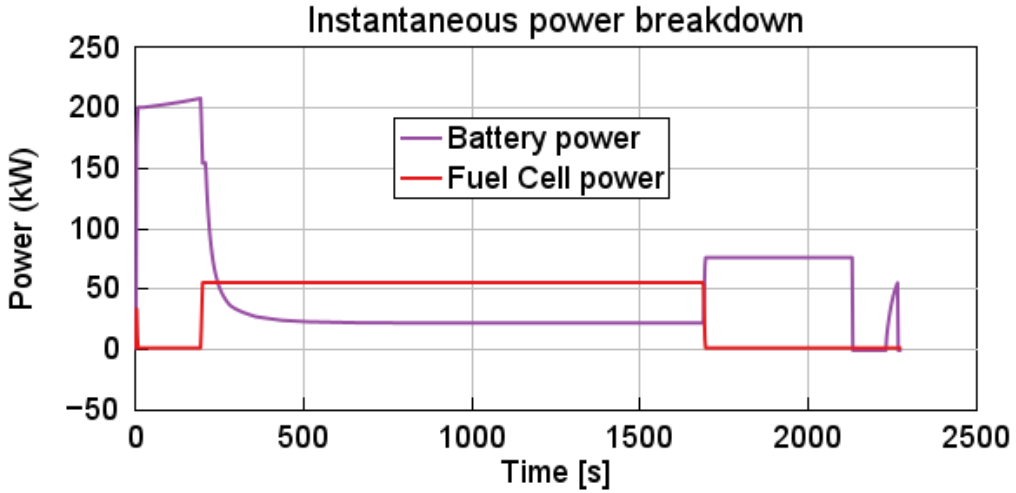


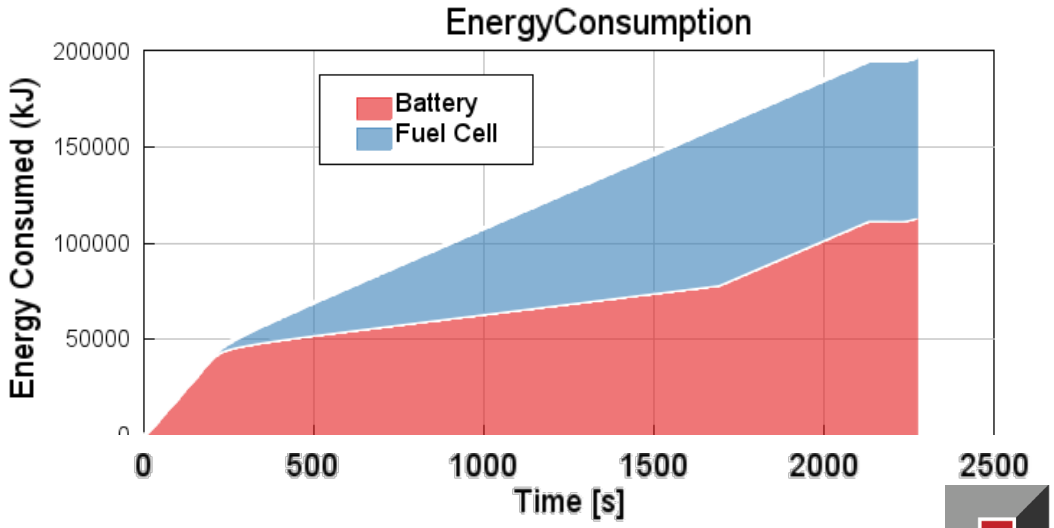
Optimized Design

Power & Energy breakdown



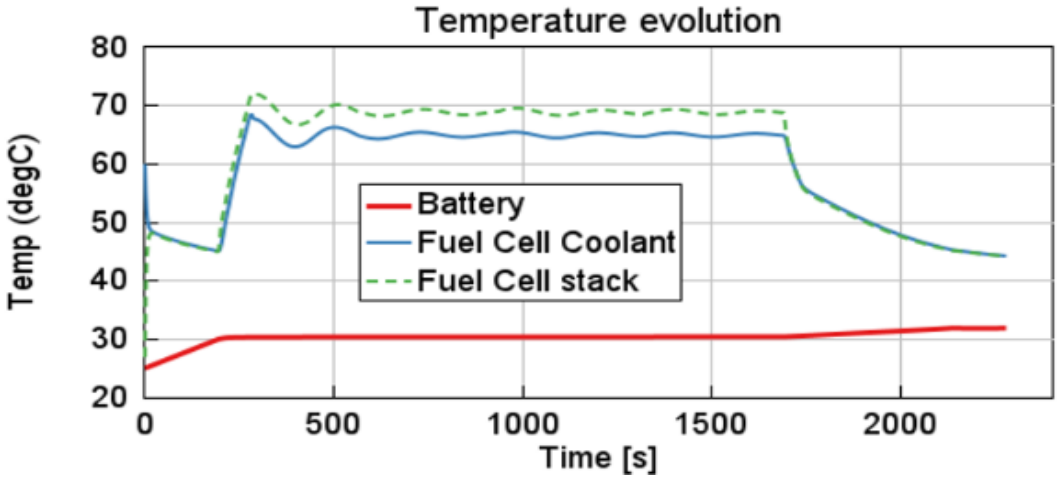




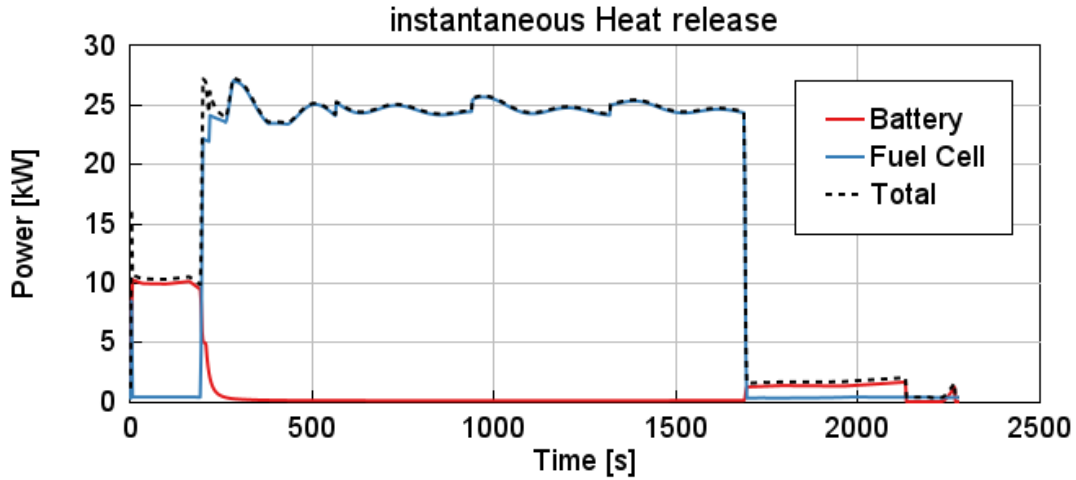


Transient Thermal Analysis

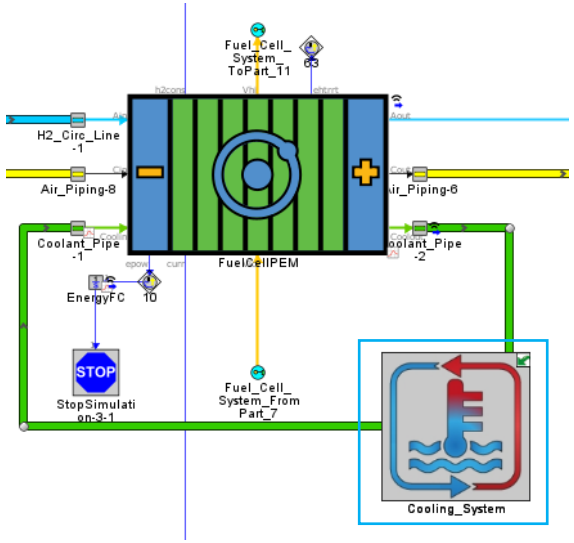
- Evaluate that the cooling system and heat exchangers are sufficient to stabilize the Fuel cell and battery temperatures

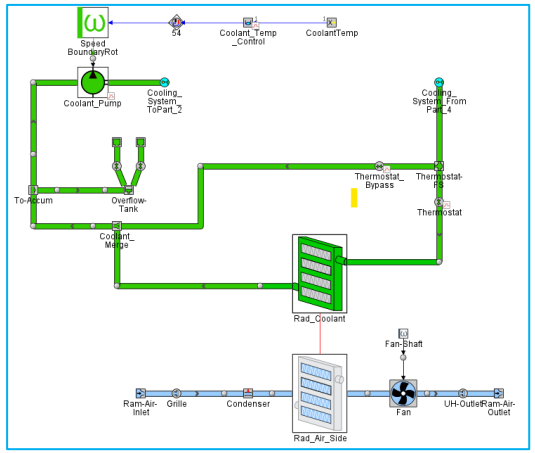


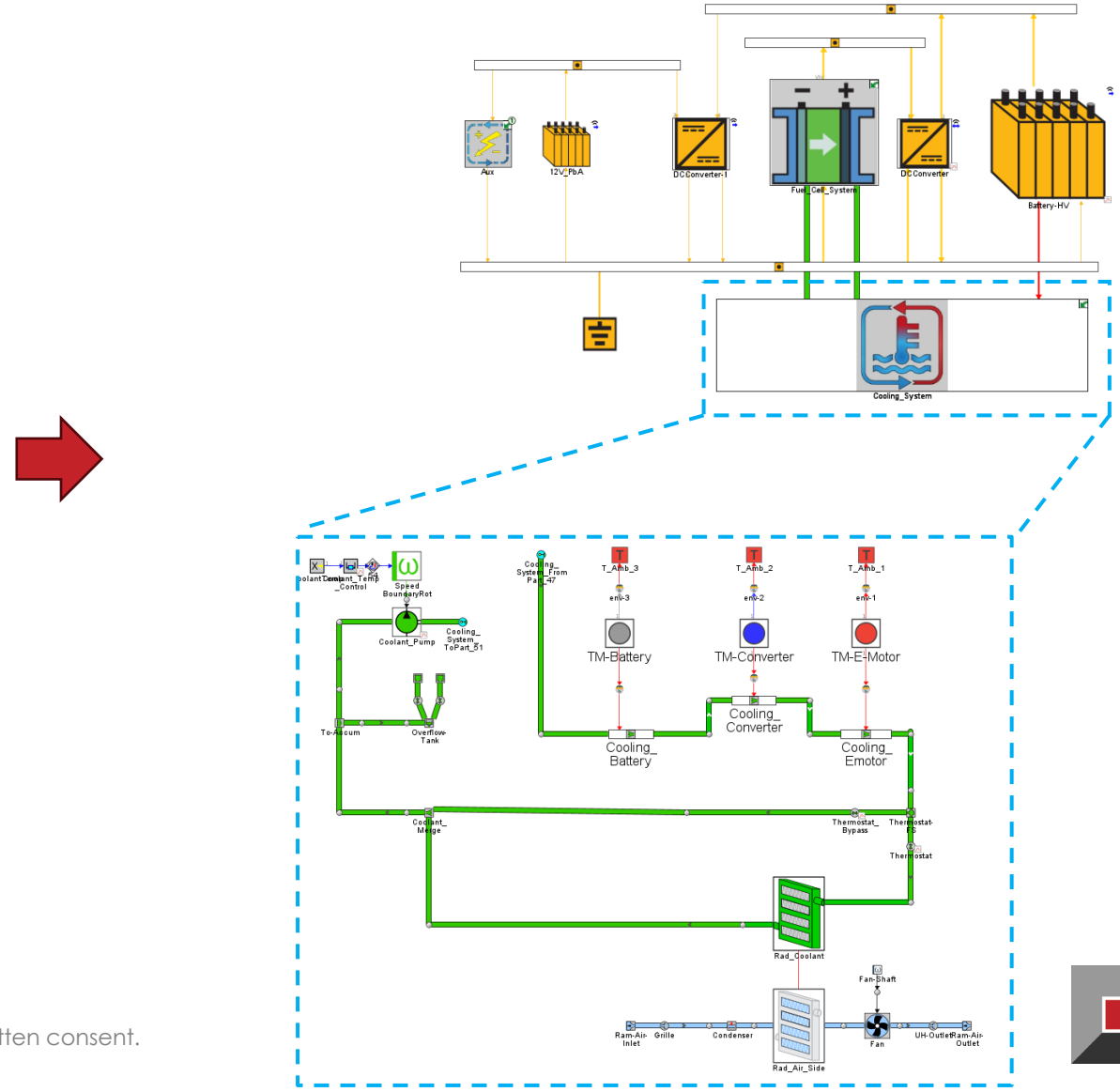
- Assess the instantaneous heat release of your different power sources and High voltage components



Common cooling systems for the powertrain

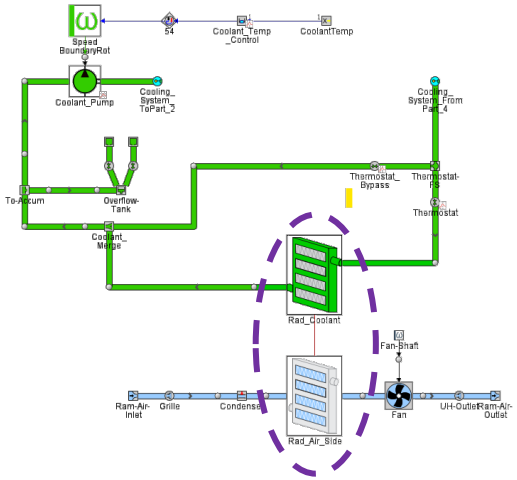


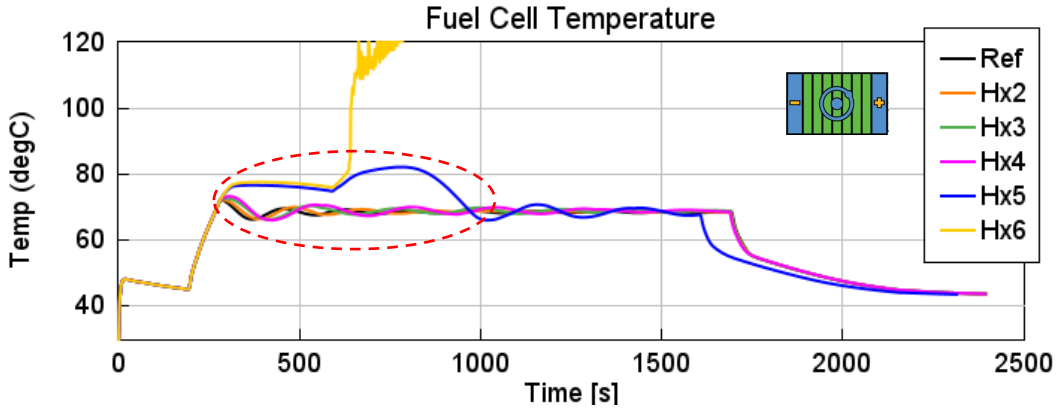


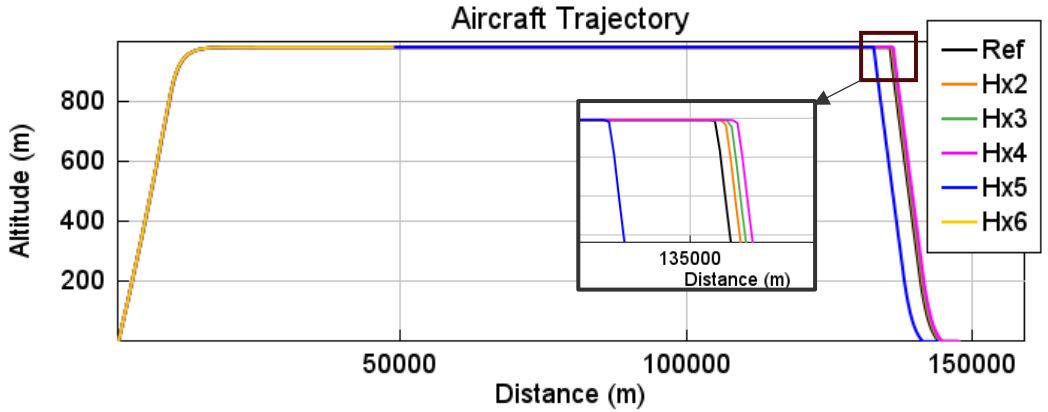


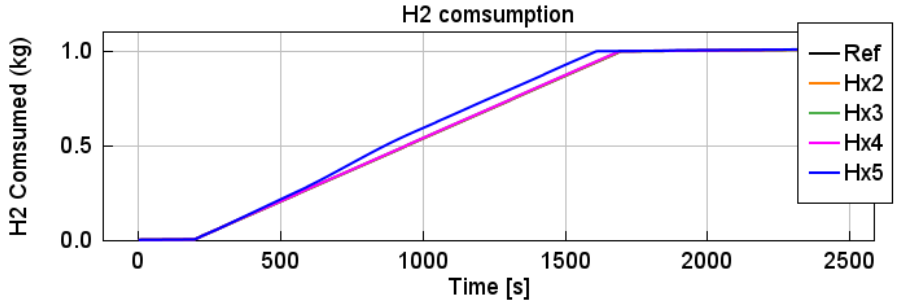
Heat exchanger sizing

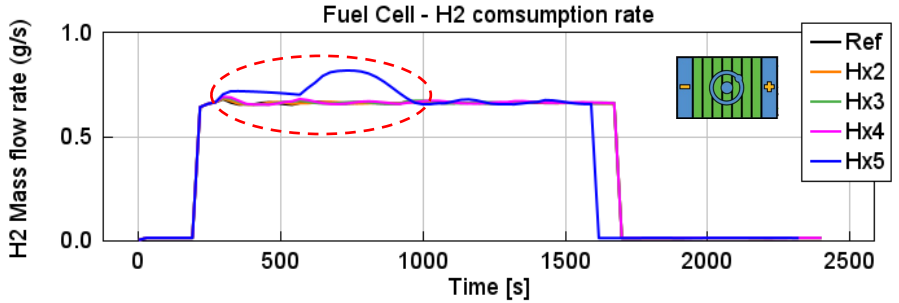
Heat exchanger	Ref	Hx2	Hx3	Hx4	Hx5	Hx6
Dimensions (mm)	600x510x39	500x400x39	400x350x39	300x250x39	300x250x13	250x250x13
$\Delta_{Hx\ mass}$ **(kg)**	0	-1.575	-2.501	-3.675	-5.308	-5.359
Δ_{Range} **(km)**	0	+0,29 (+0.20%)	+0,44 (+0.31%)	**+0,59 (+0.41%)**	**-2,86 (-1.98%)**	-

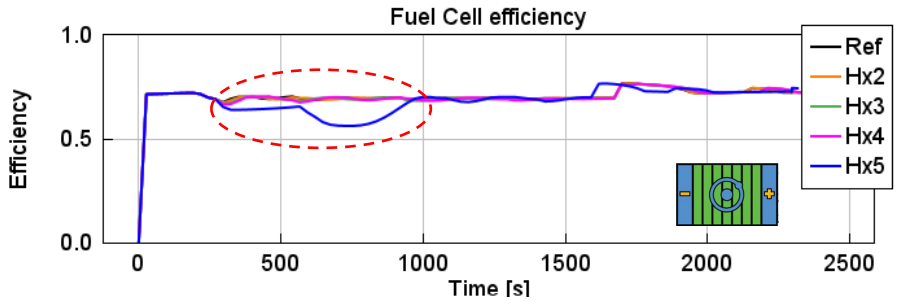












ECS System Analysis - Motivation

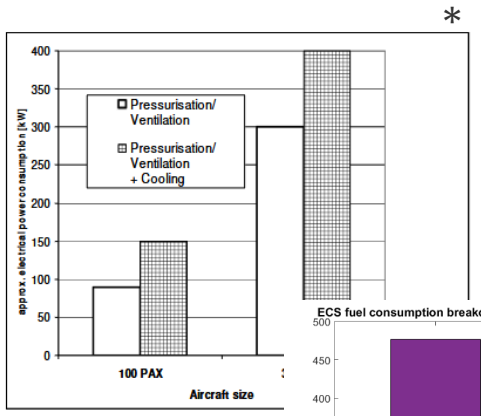


Fig 2: approximate consumption of an ful depending on the aircraft siz

*

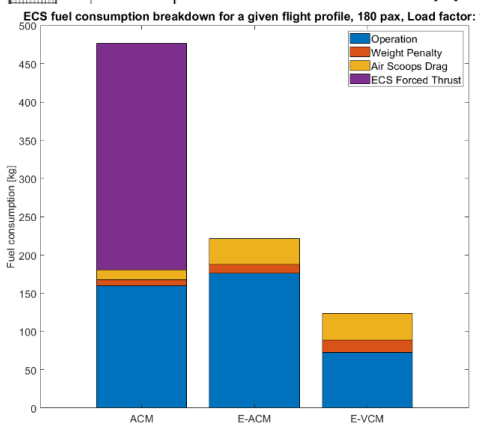
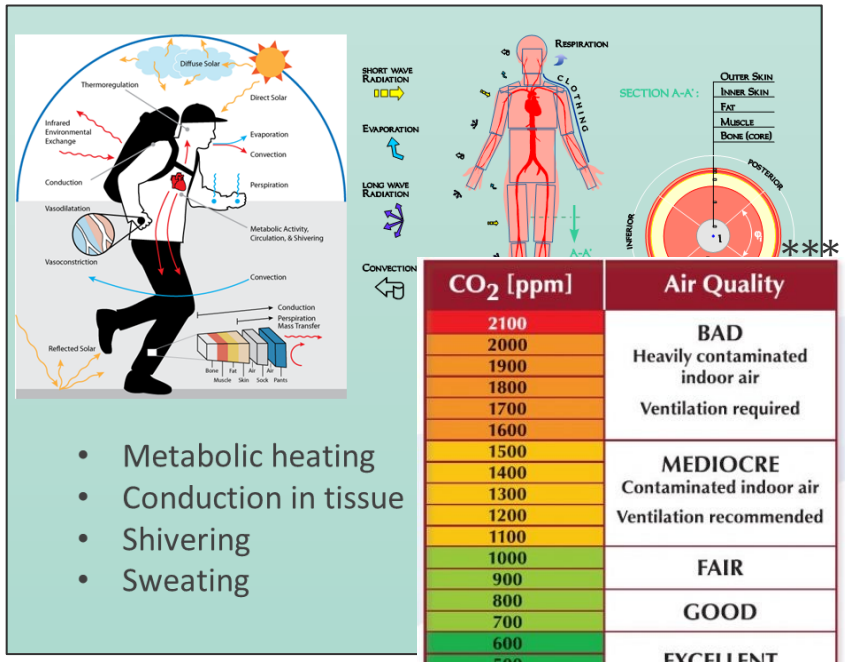


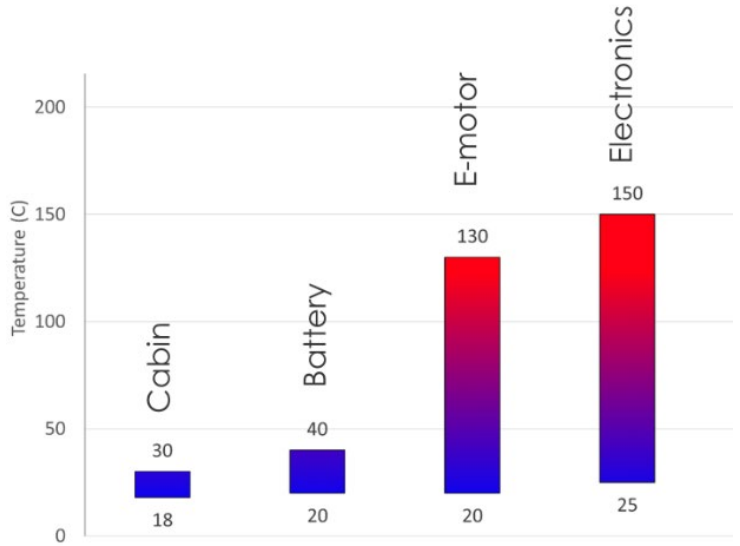
Figure 4 – ECS fuel consumption breakdown for a round trip flight, Copenhagen-Stockholm-Copenhagen, with a modelled A320 and 180 pax.

**



- Metabolic heating
- Conduction in tissue
- Shivering
- Sweating

***



ECS power consumption

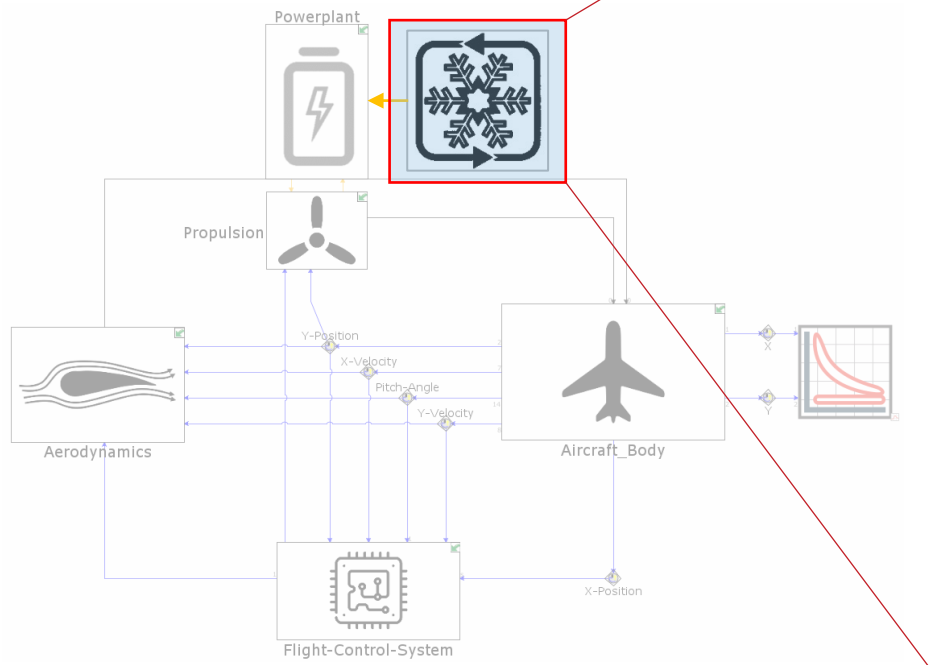
Passenger comfort

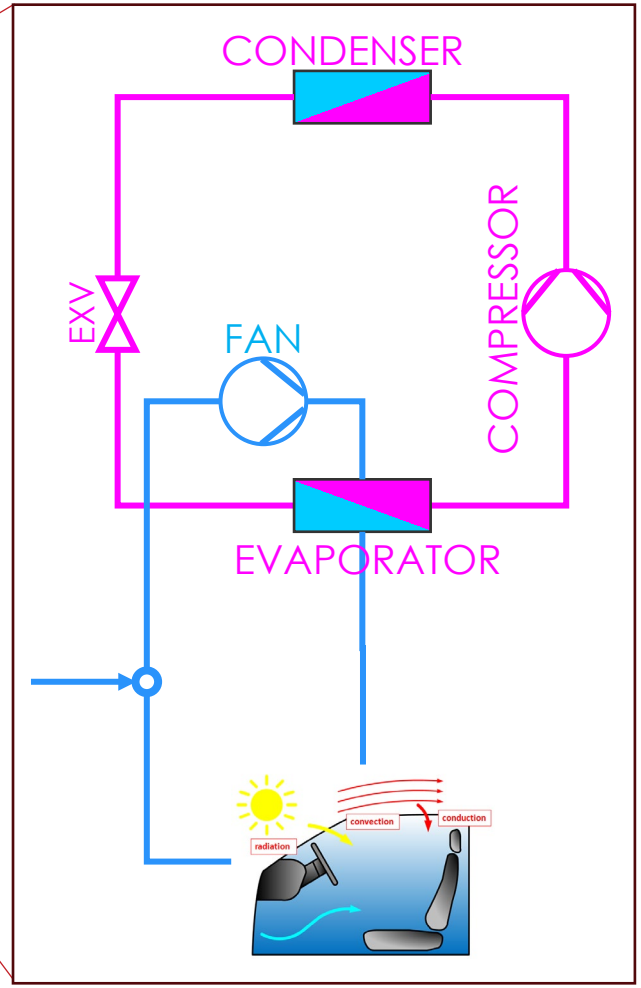
Thermal security

* https://www.icas.org/icas_archive/ICAS2006/PAPERS/344.PDF
** https://icas.org/icas_archive/ICAS2022/data/papers/ICAS2022_0369_paper.pdf
*** https://safecility.com/indoor-co2-levels-are-making-us-stupid/

GT

ECS System Analysis



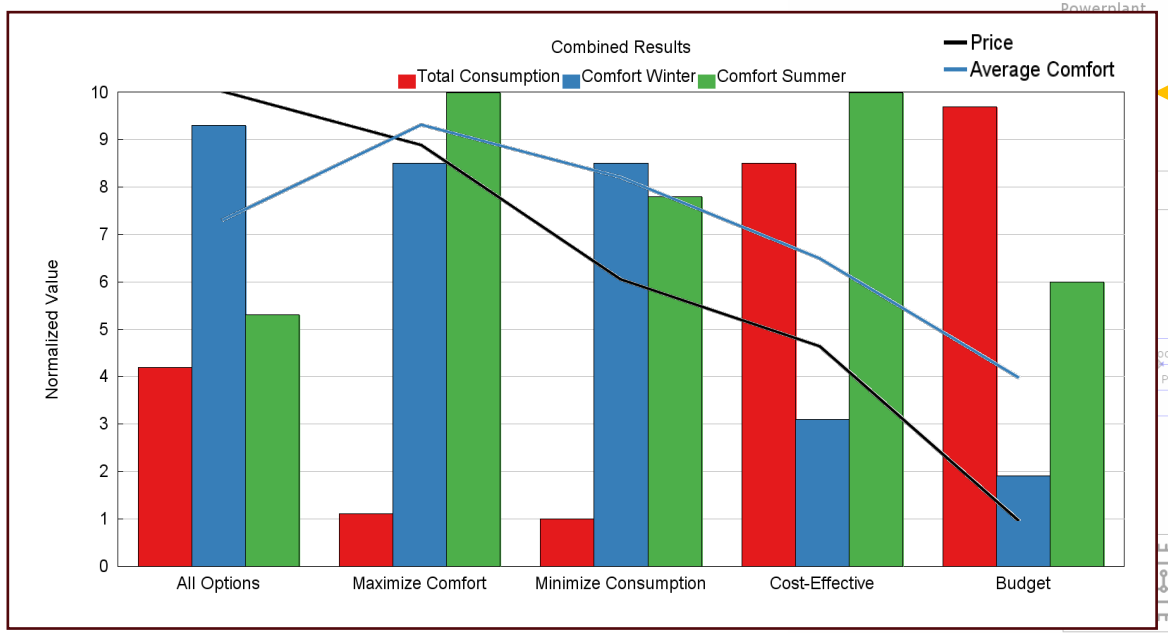


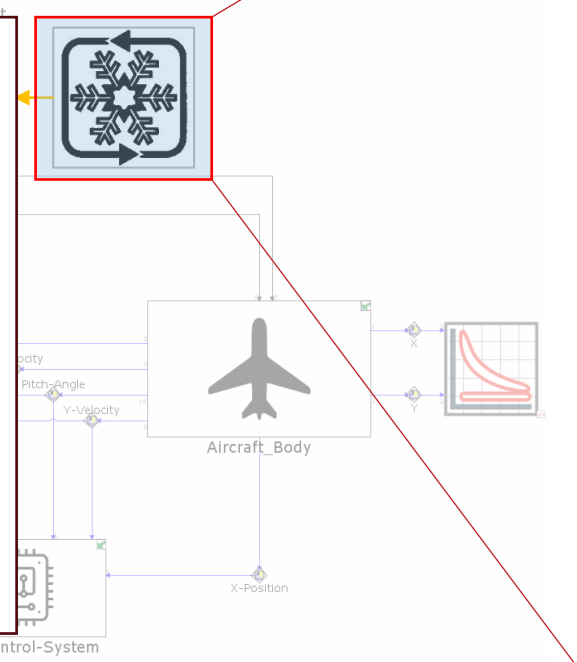
Optimize ECS system for efficiency, cost or comfort

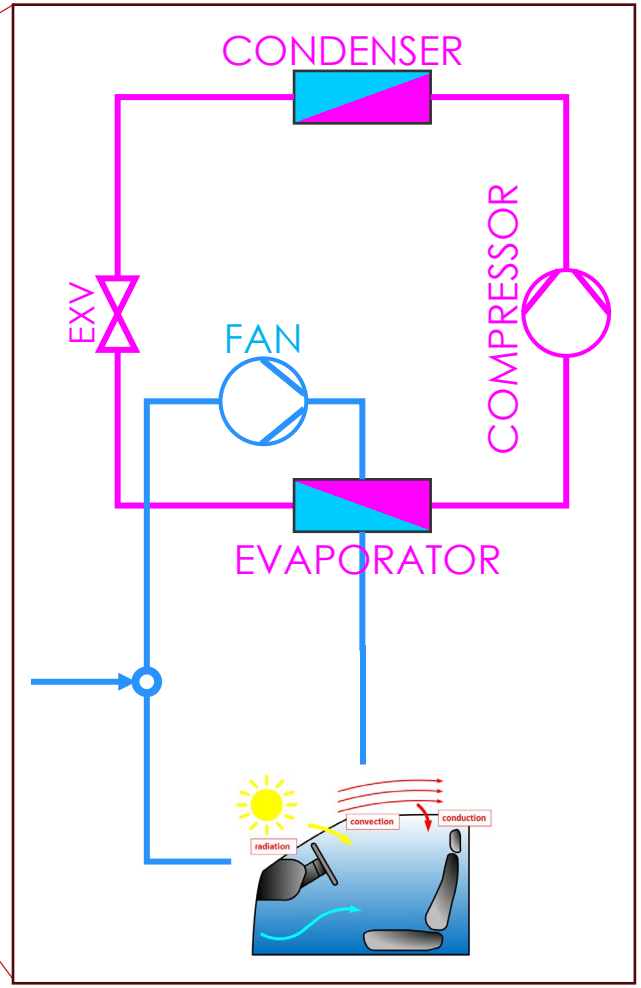
Estimate performance under varying scenarios

Investigate different system layouts and configurations

ECS System Analysis







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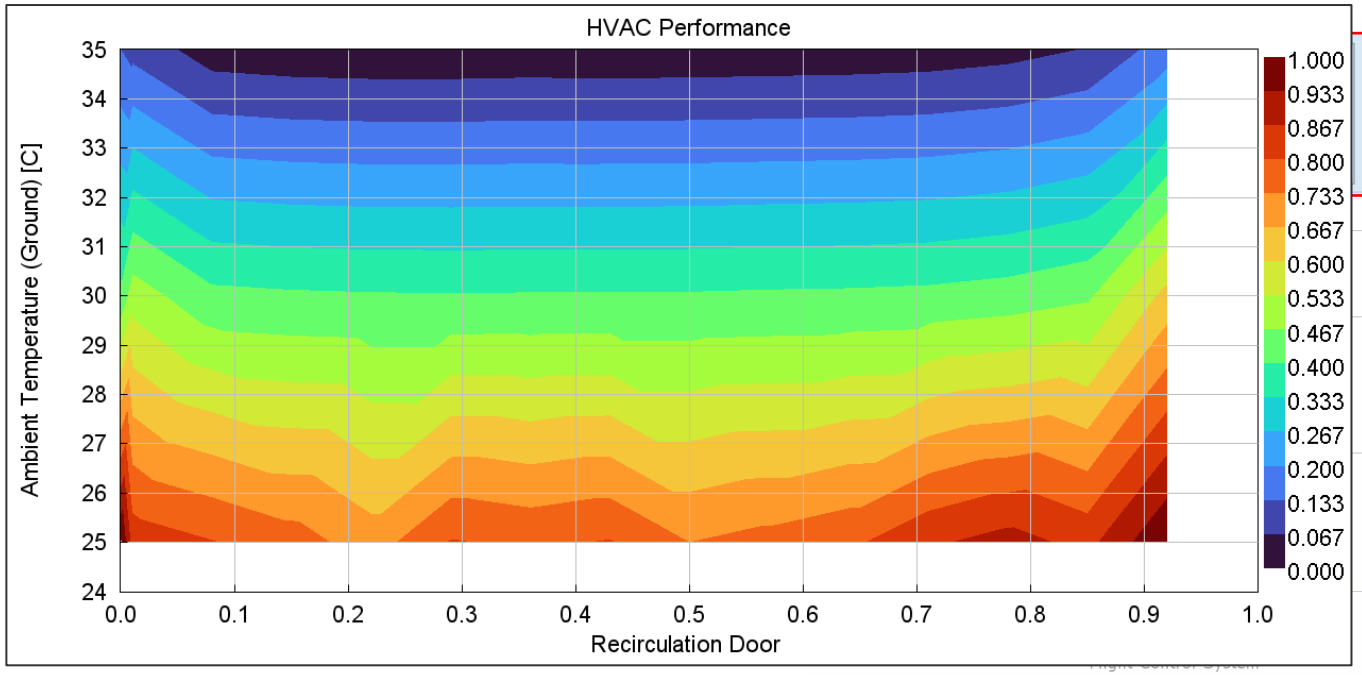
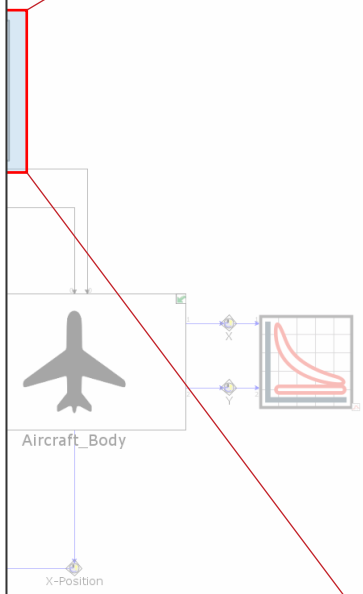
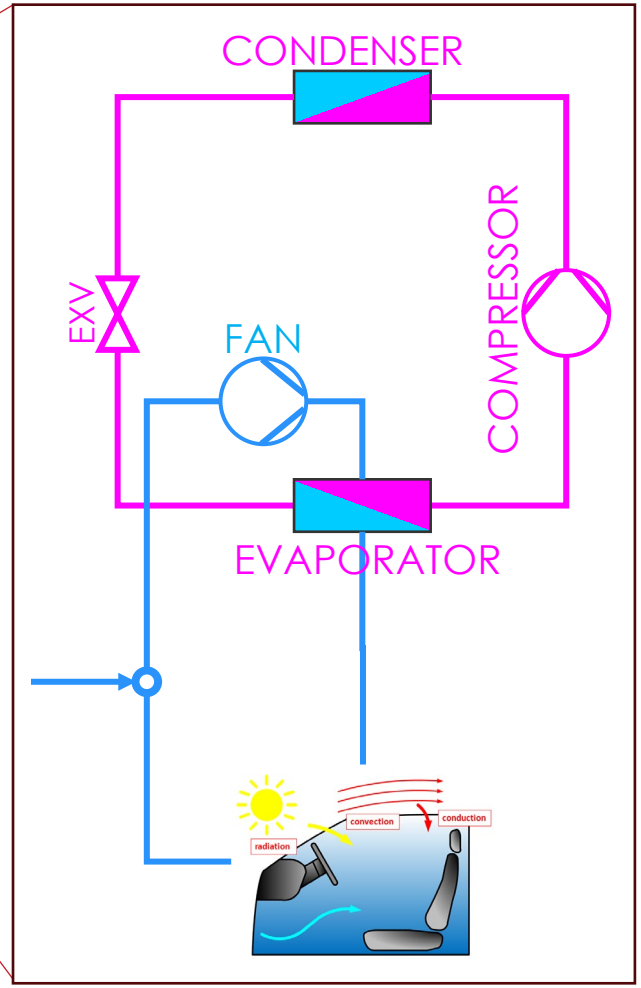




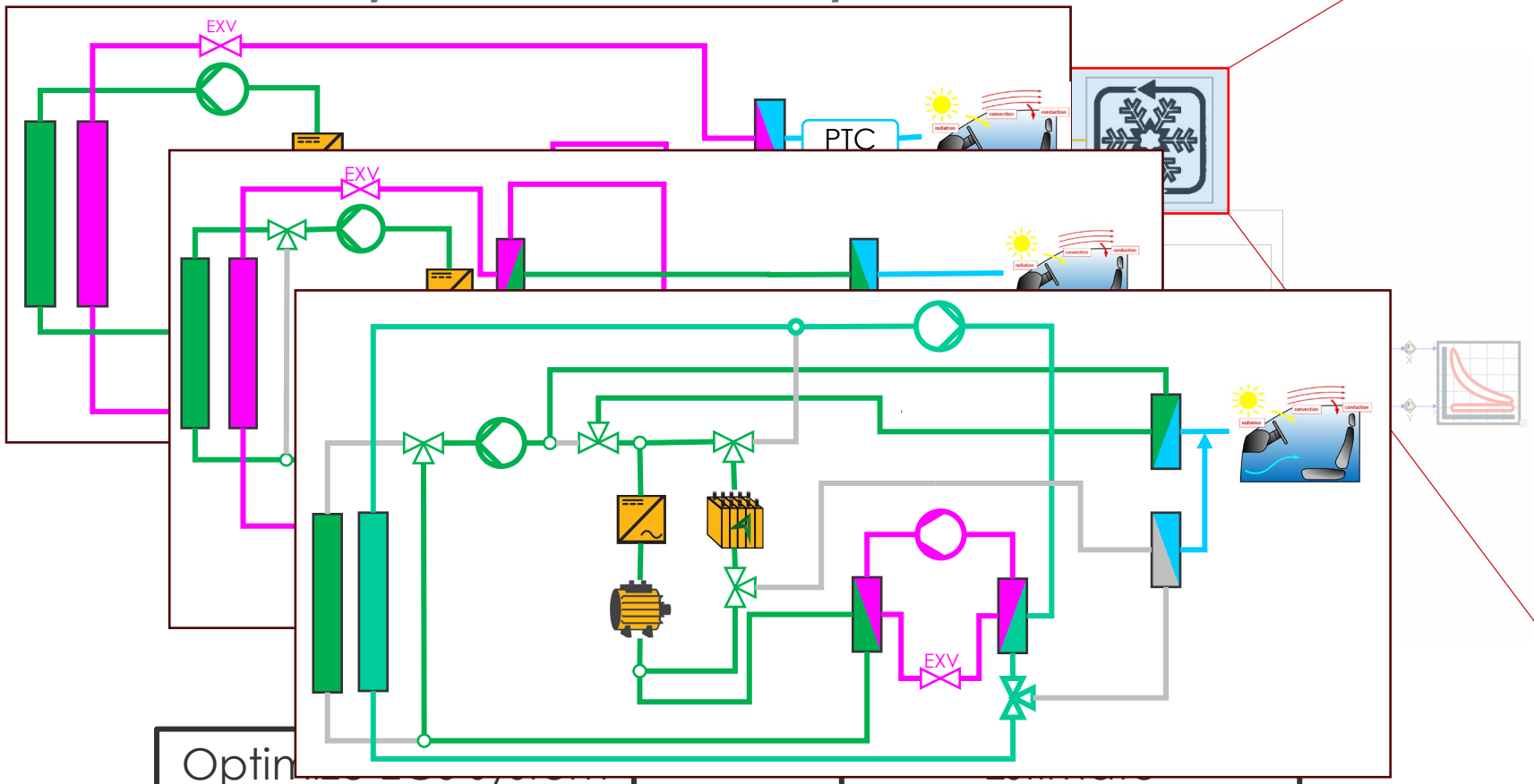


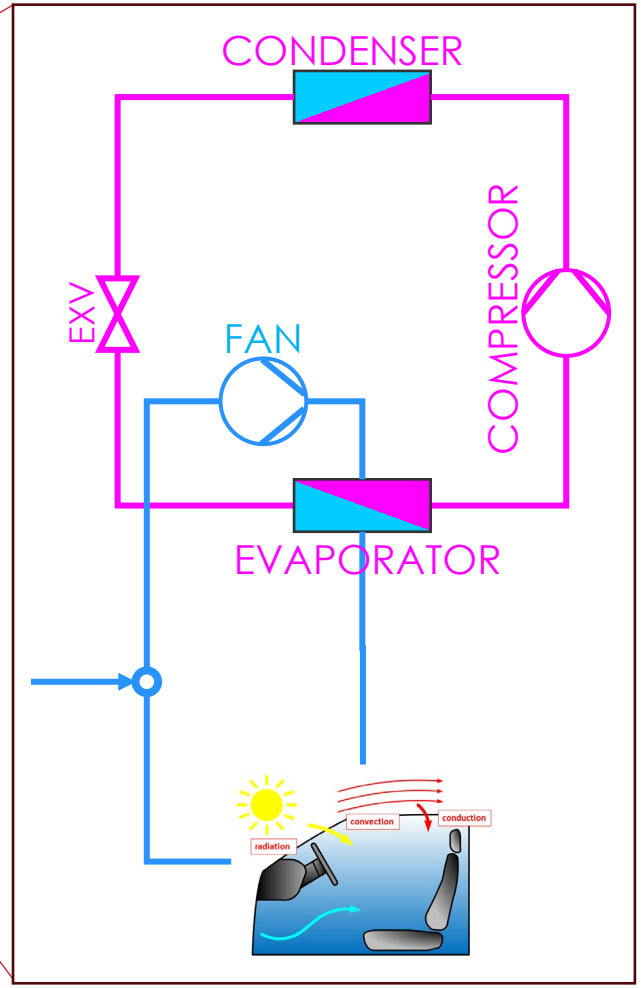
Optimize ECS system for efficiency, cost or comfort

Estimate performance under varying scenarios

Investigate different system layouts and configurations

ECS System Analysis





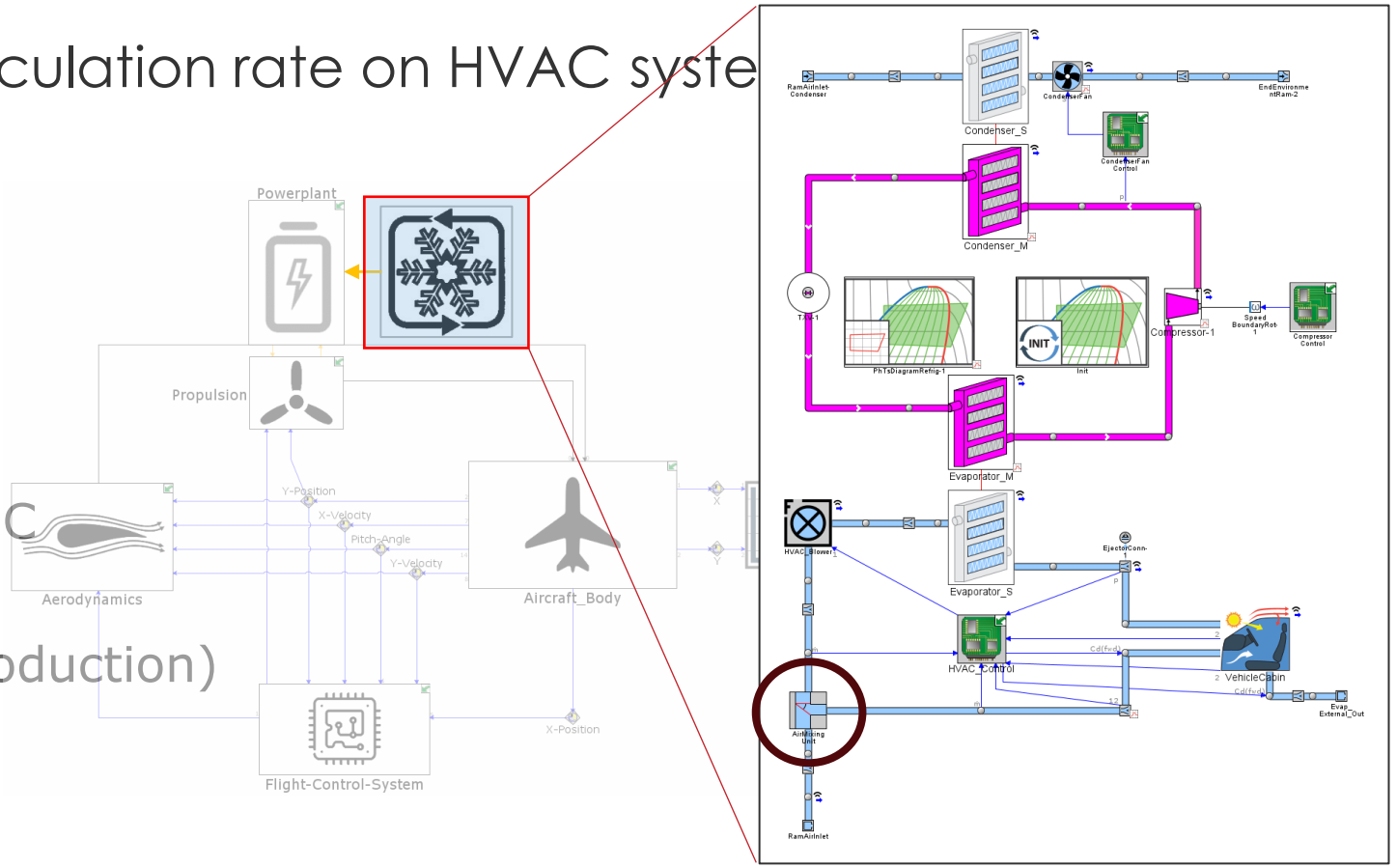
Optim for efficiency, cost or comfort

performance under varying scenarios

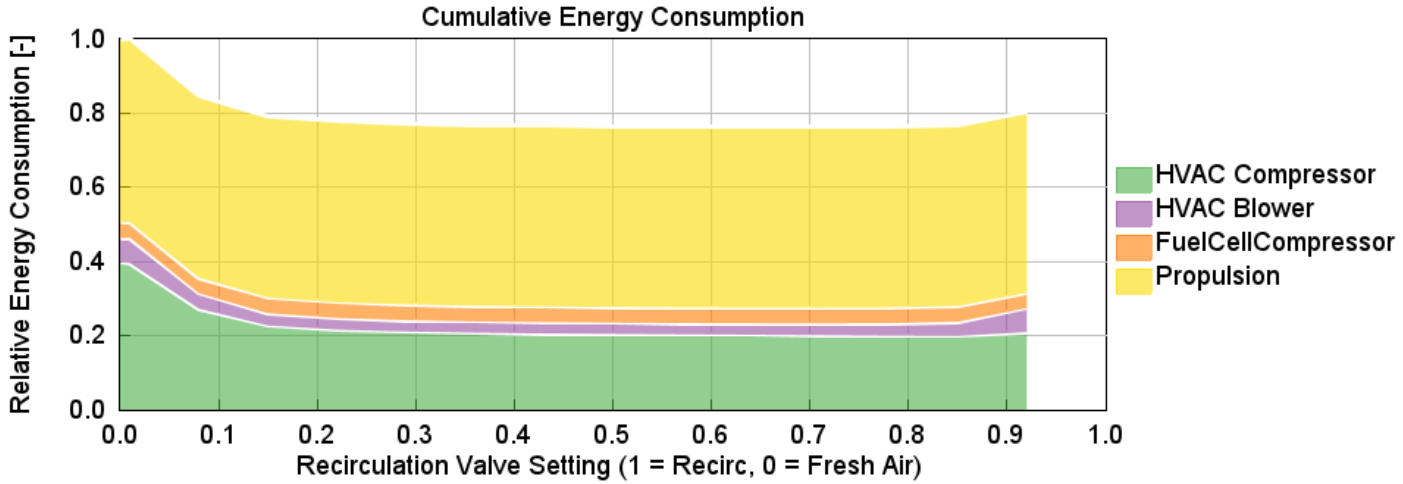
Investigate different system layouts and configurations

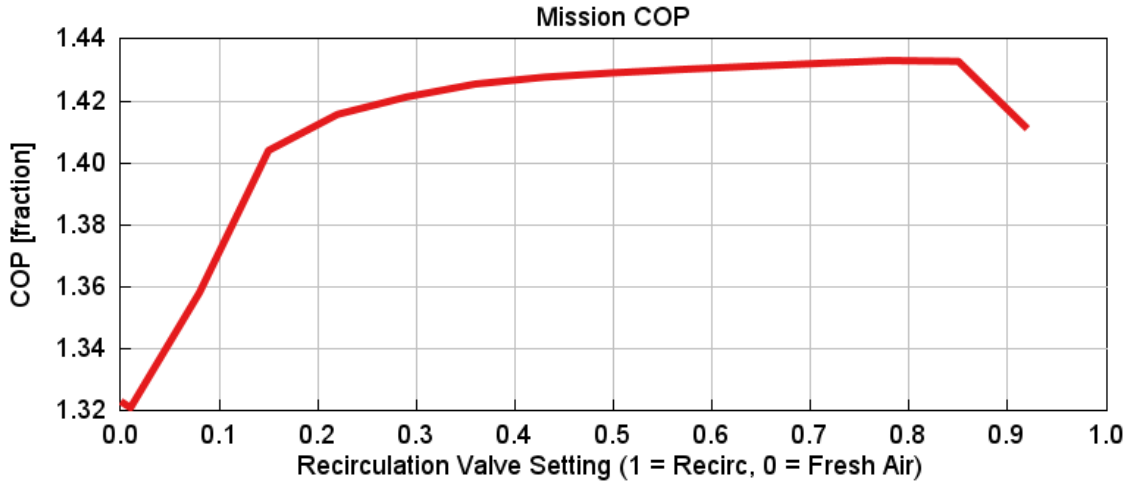
ECS Case Study – HVAC recirculation rate

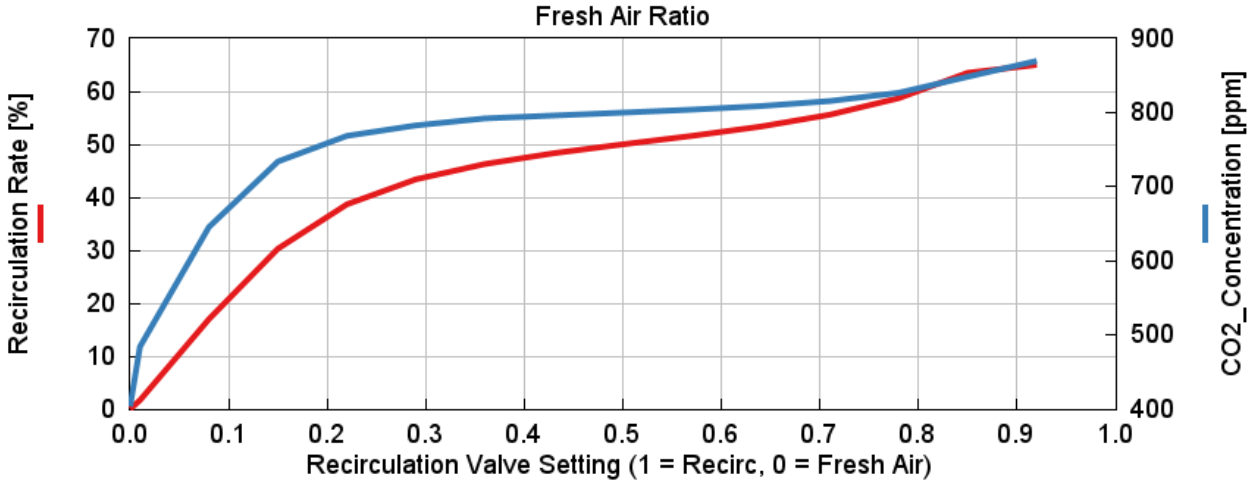
- Investigate impact of recirculation rate on HVAC syste
  - Energy consumption
  - Passenger comfort
    - Thermal
    - CO_2 concentration
- Boundary conditions
  - Ground Temperature = 33°C
  - Solar Load 1000W/m^2
  - 2 passengers (CO_2, H_2O production)
  - Standard mission

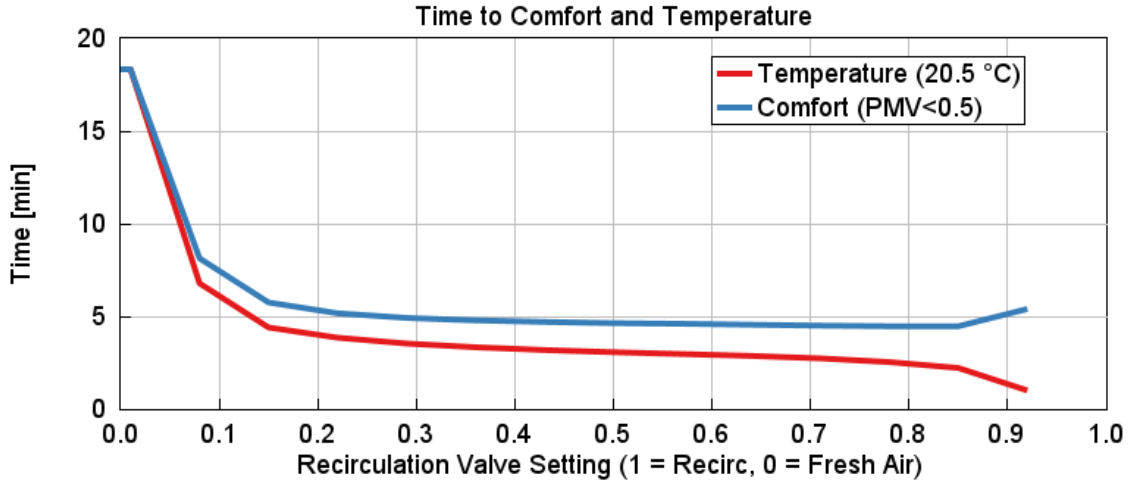


ECS Case Study – HVAC recirculation rate

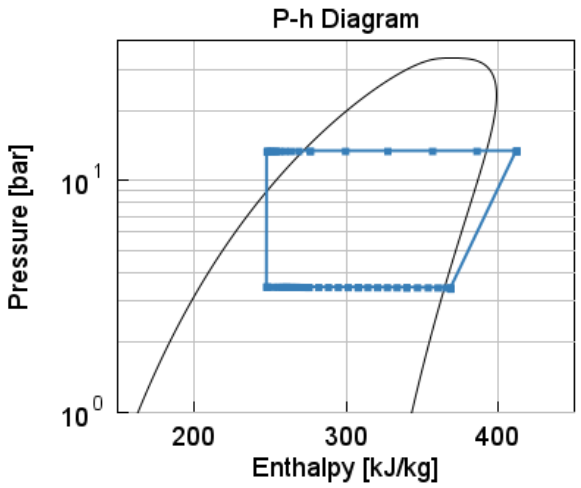


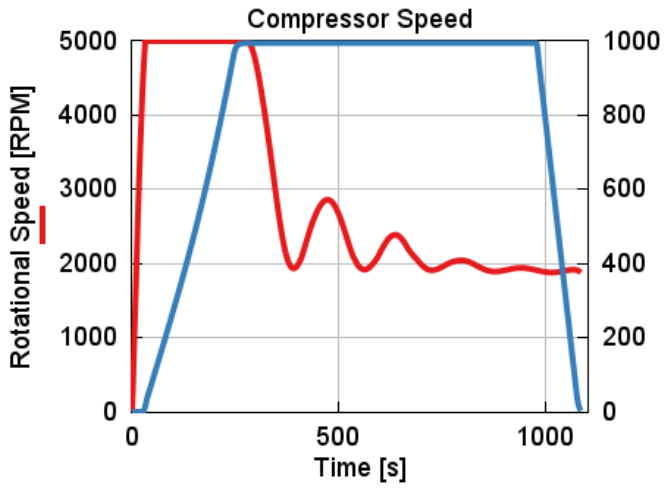


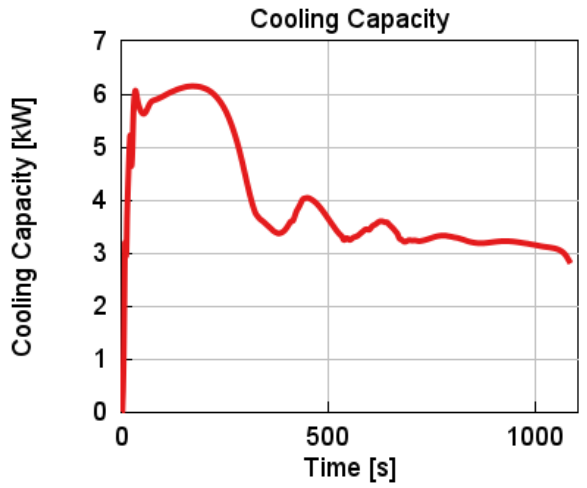


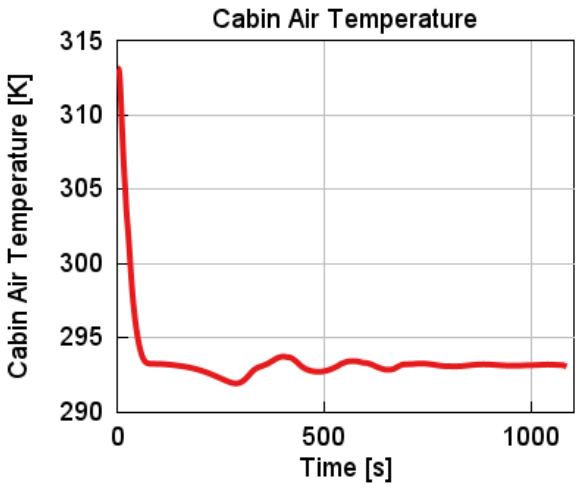


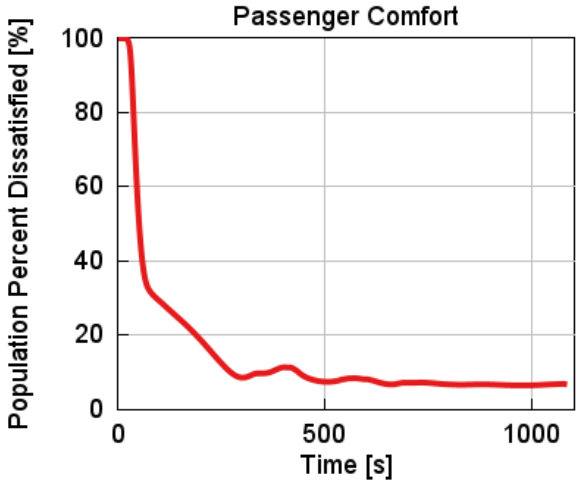
ECS Case Study – HVAC recirculation rate

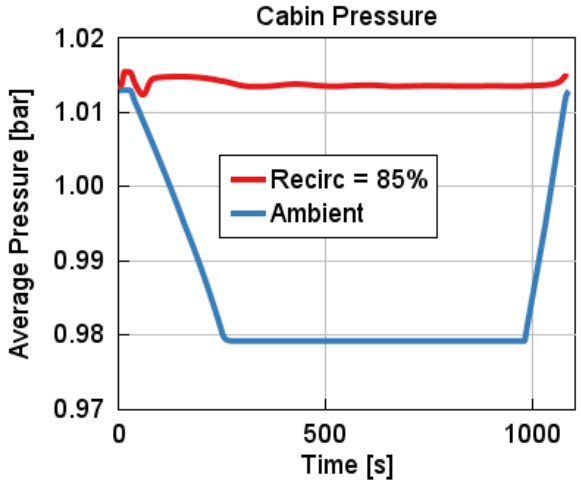


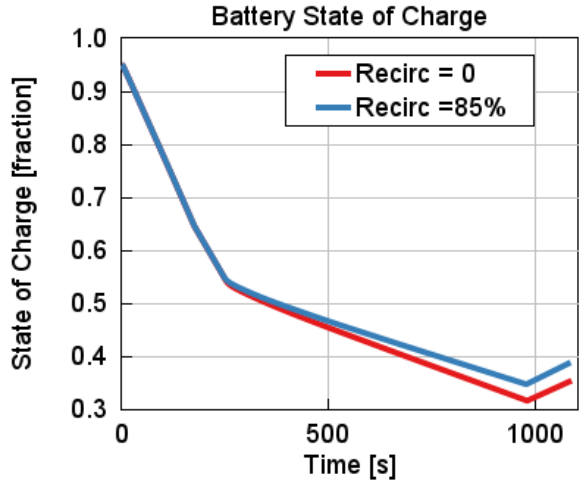


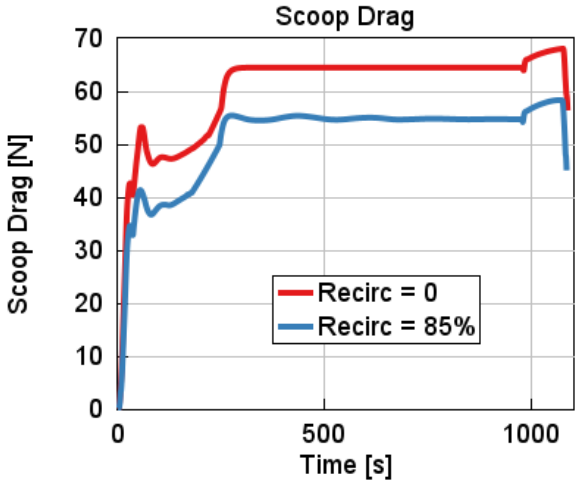






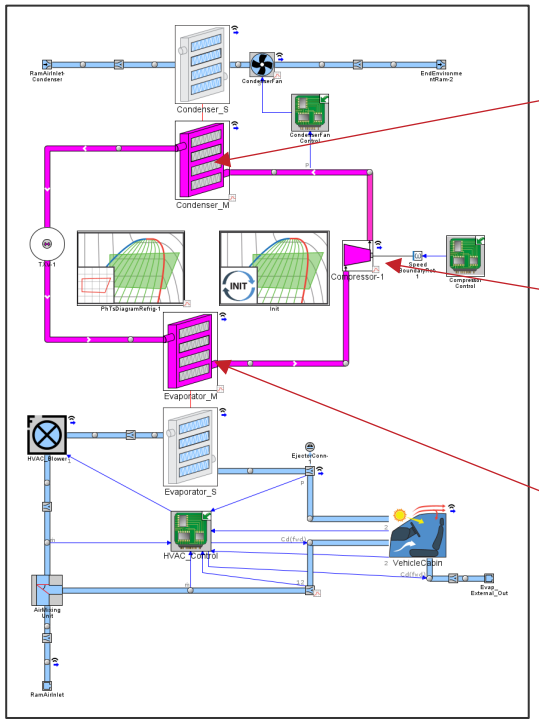






ECS Case Study – Component Selection

- Select optimal components for given system layout
  - Various optimization criteria (consumption, comfort, weight)



Condenser_350x840x16
Condenser_370x480x12
Condenser_380x530x16
Condenser_390x660x16

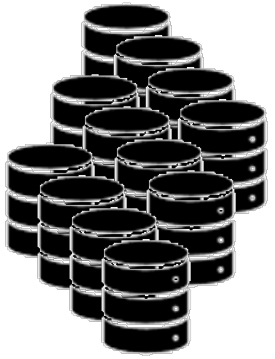
AC_Compressor_30cc
AC_Compressor_60cc
AC_Compressor_115cc
AC_Compressor_170cc

Evaporator_160x275x40
Evaporator_195x290x40
Evaporator_220x310x50
Evaporator_220x320x50

DOE consisting of
64 configurations

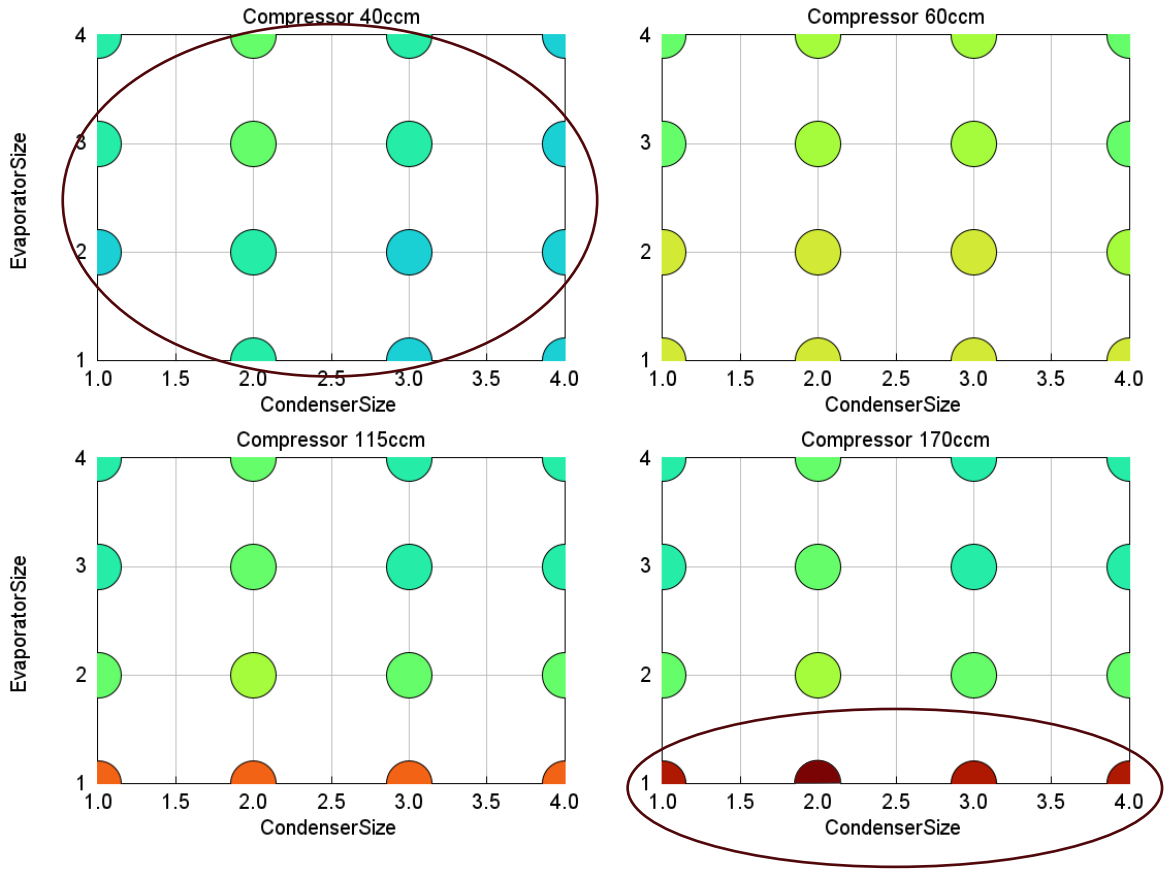
Parameter	Active	Condenser	Evaporator	Compressor
Units (Units)				
Label (Label)		Heat Exchanger Specifications Object	Heat Exchanger Specifications Object	Compressor Specification Object
1 (1)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_160x275x40	AC_Compressor_30cc
2 (2)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_160x275x40	AC_Compressor_60cc
3 (3)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_160x275x40	AC_Compressor_115cc
4 (4)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_160x275x40	AC_Compressor_170cc
5 (5)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_195x290x40	AC_Compressor_30cc
6 (6)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_195x290x40	AC_Compressor_60cc
7 (7)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_195x290x40	AC_Compressor_115cc
8 (8)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_195x290x40	AC_Compressor_170cc
9 (9)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_220x310x50	AC_Compressor_30cc
10 (10)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_220x310x50	AC_Compressor_60cc
11 (11)	☑	TubeFin_HVAC_Condenser_350x840x16	TubeFin_HVAC_Evaporator_220x310x50	AC_Compressor_115cc

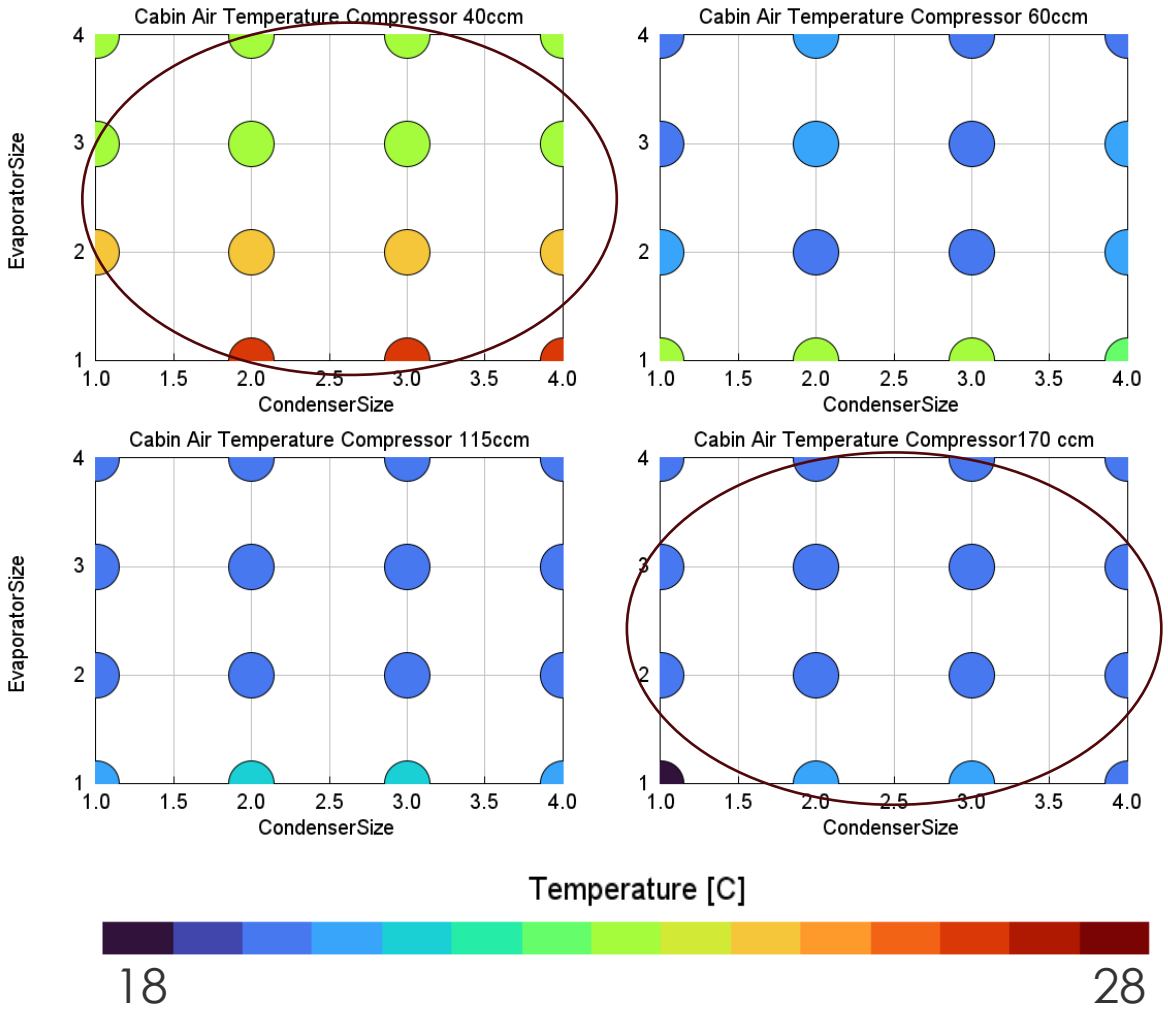
Distributed Parallel
Simulation



Mission duration ~20 minutes
Simulation run ~0.6*RT
Results can be generated in ~12 minutes

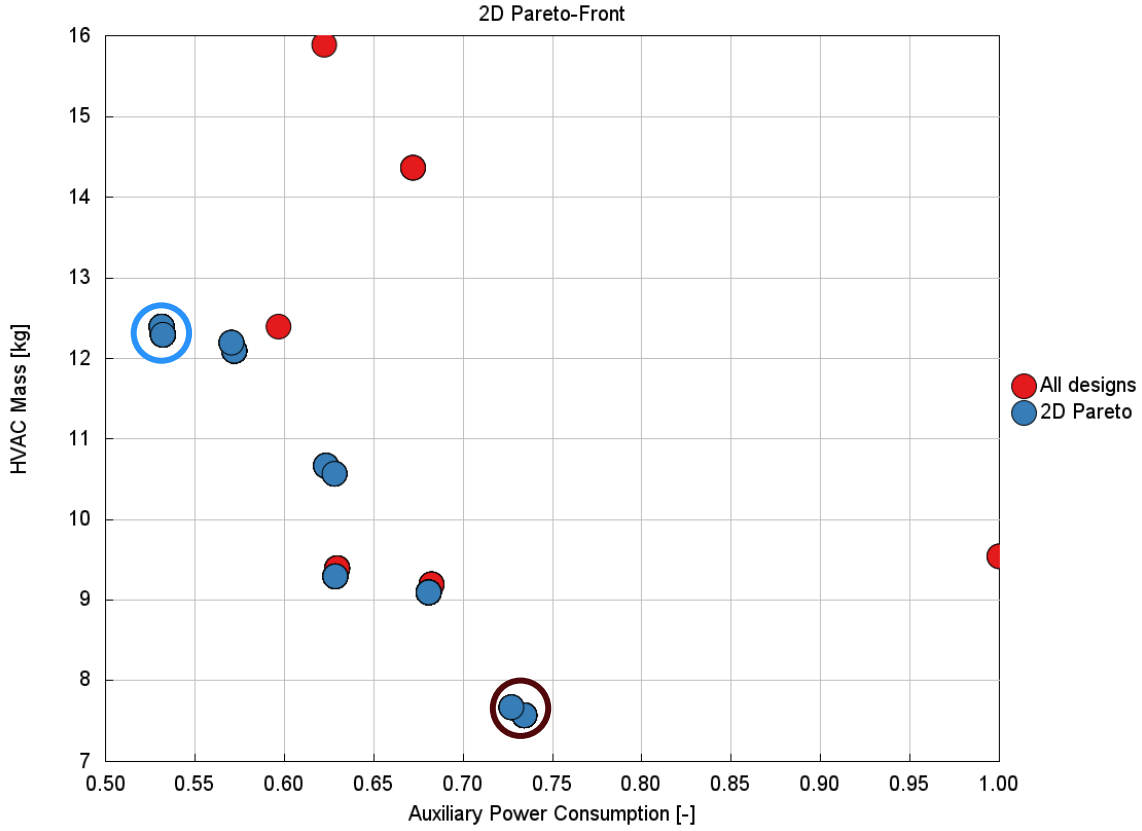
ECS Case Study – Component Selection

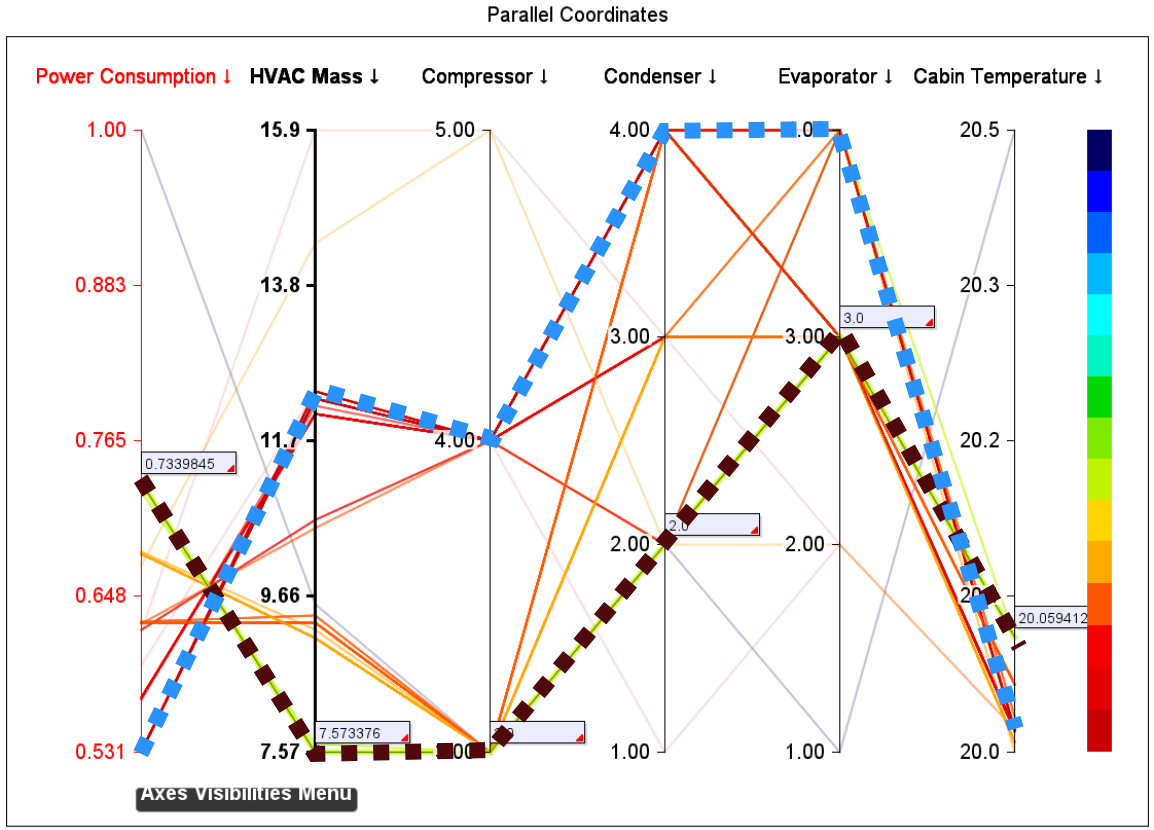




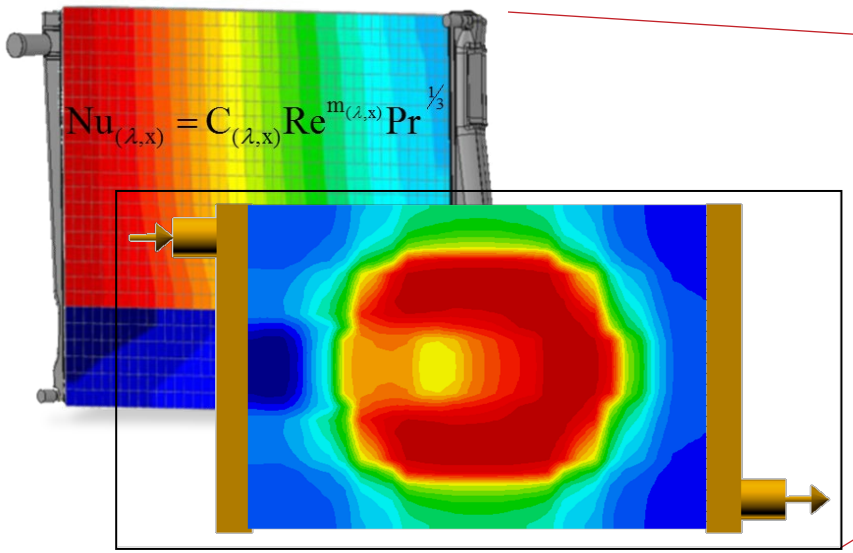
ECS Case Study – Component Selection

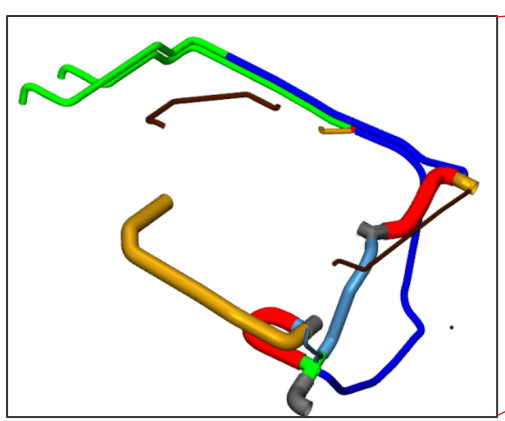
- Results post-processing

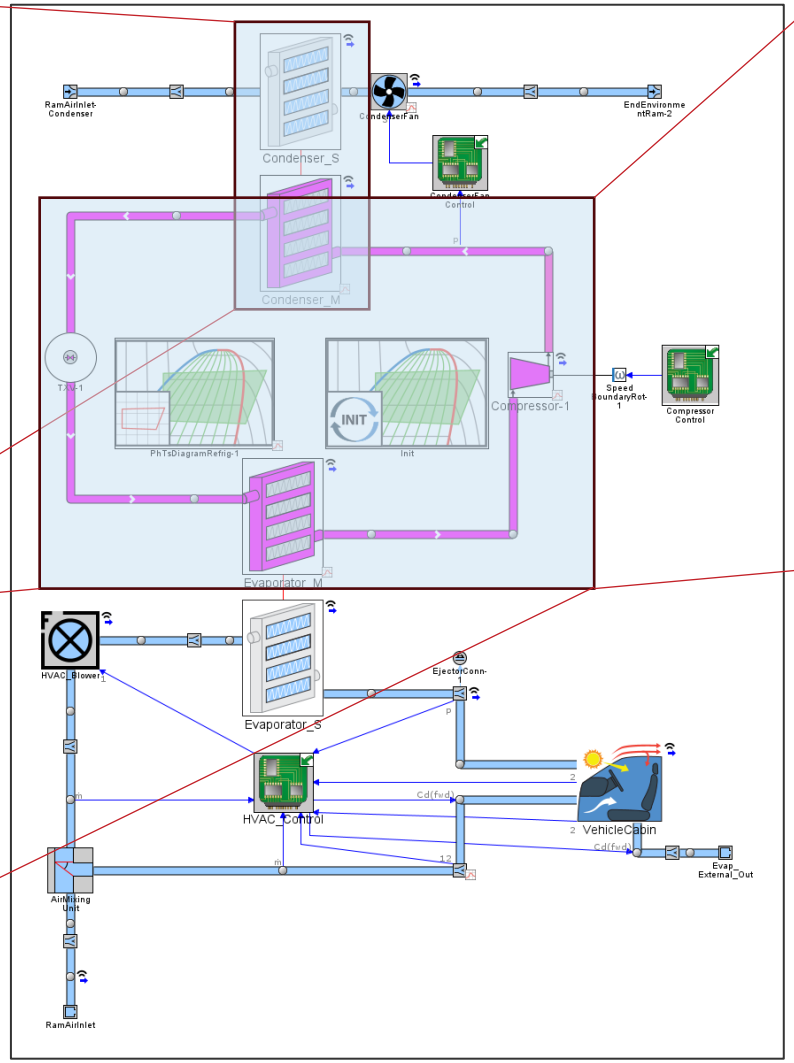


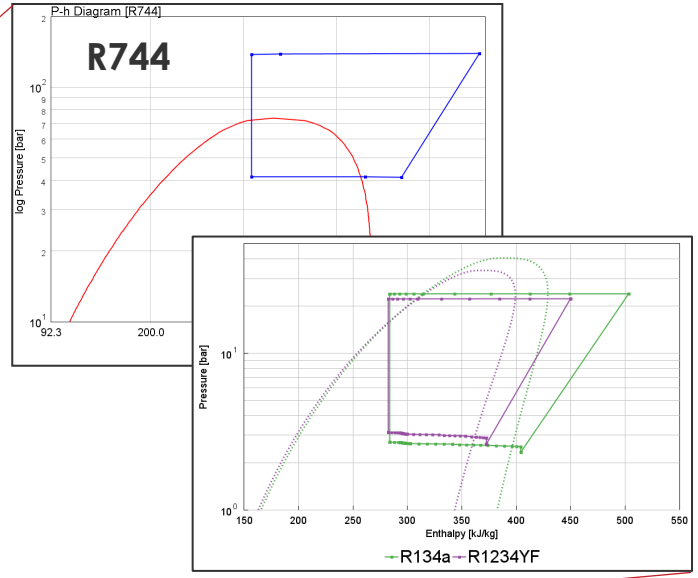


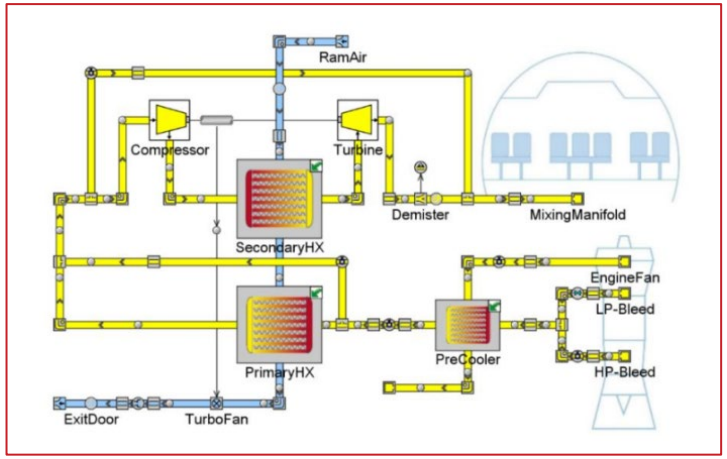
ECS Fidelity Options



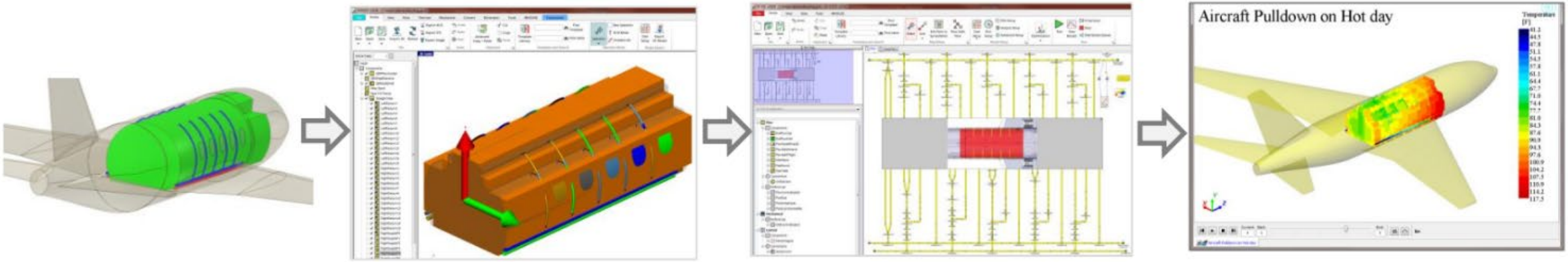


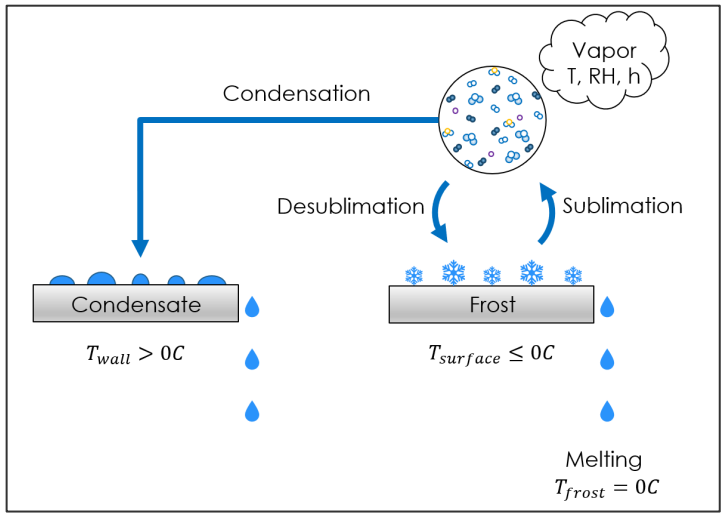


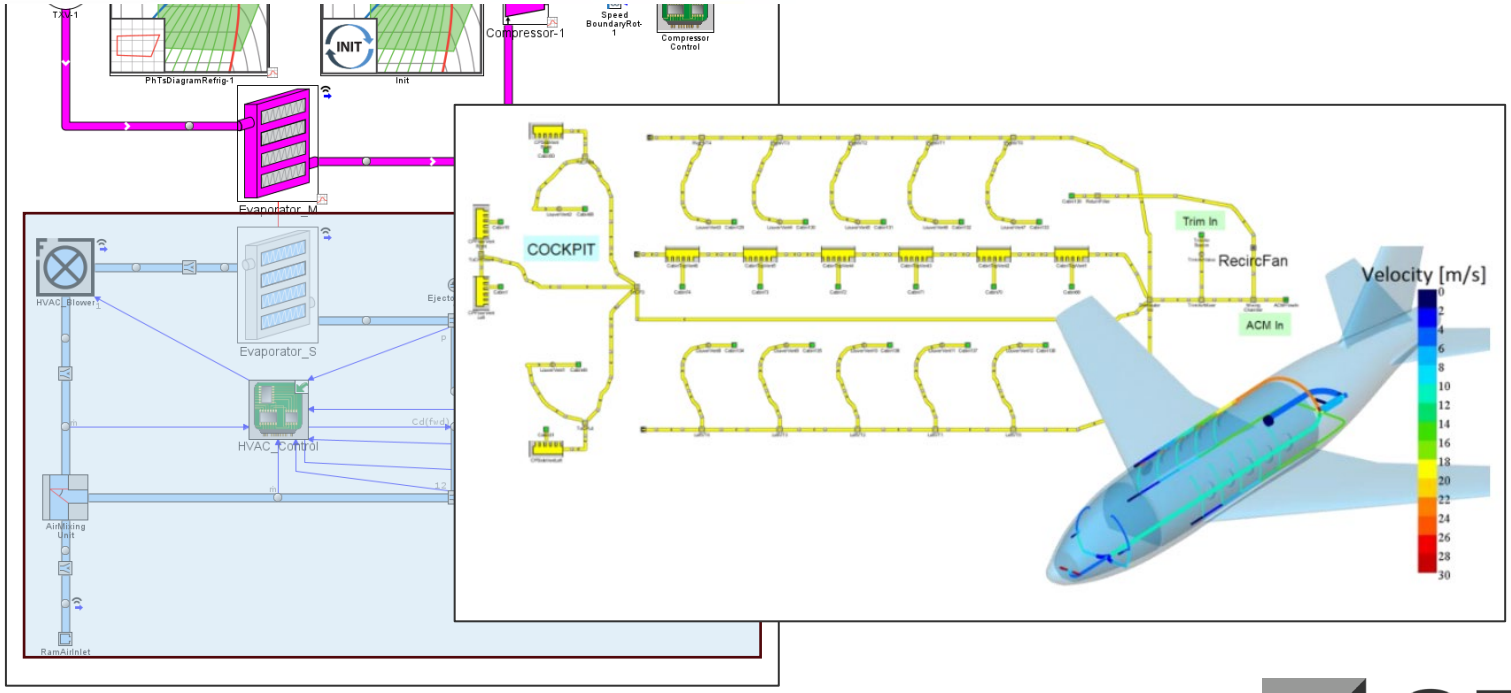




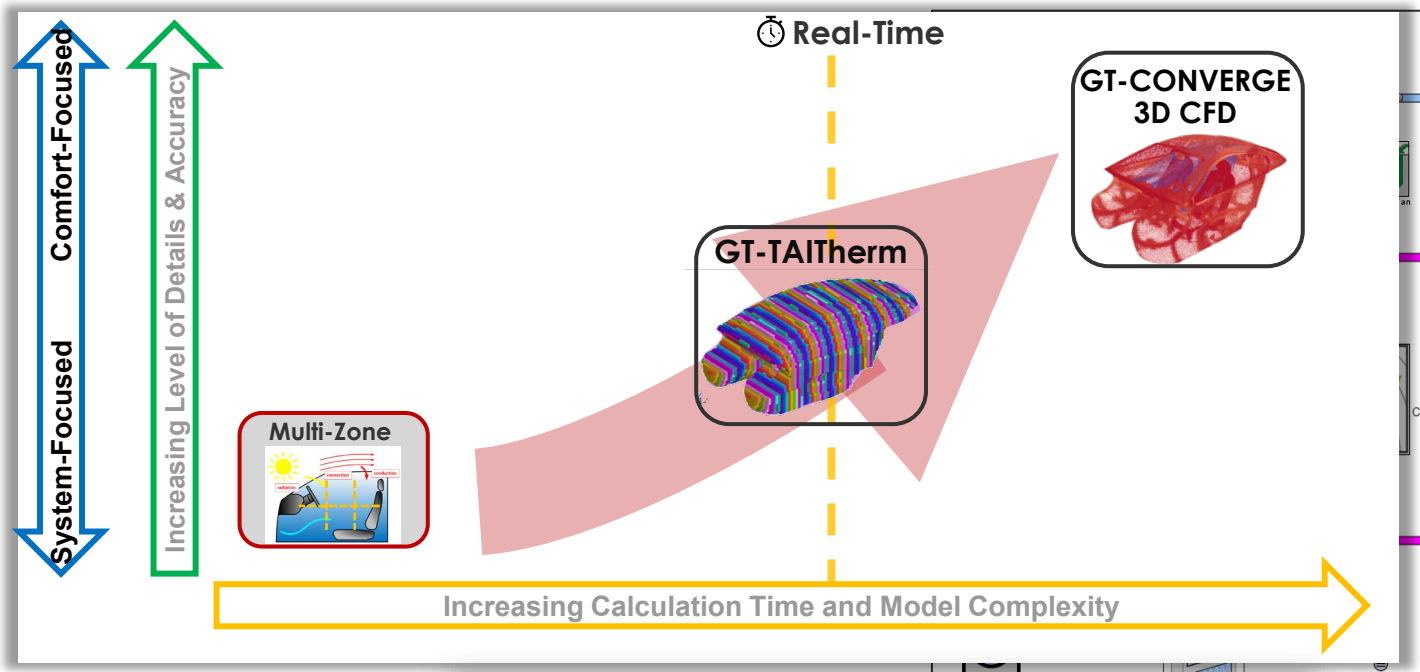
ECS Fidelity Options

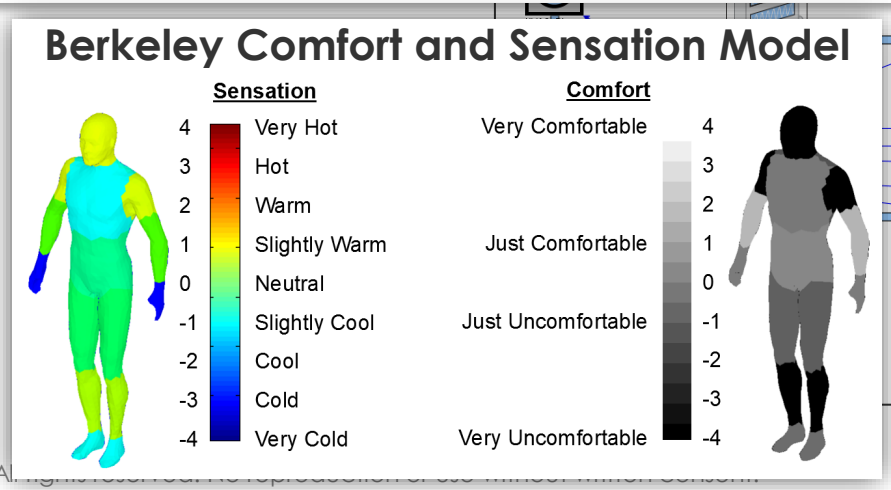






ECS Fidelity Options





Conclusion & Way Forward

- GT-SUITE **predictive** simulation framework of Aircraft model including:
  - Fuel cell stack and BoP, Batteries
  - Cooling & Environmental Control Systems
- Optimizing Powerplant layouts and Component sizing requires **dynamic modeling** over transient scenarios
- This study showed that a substantial **Range increase** can be achieved by applying simulation and keeping realistic parameters
- ECS System is a significant **power consumer** with large **optimization potential**
- Including **passenger comfort** predictions can help improving the design for wide range of boundary conditions

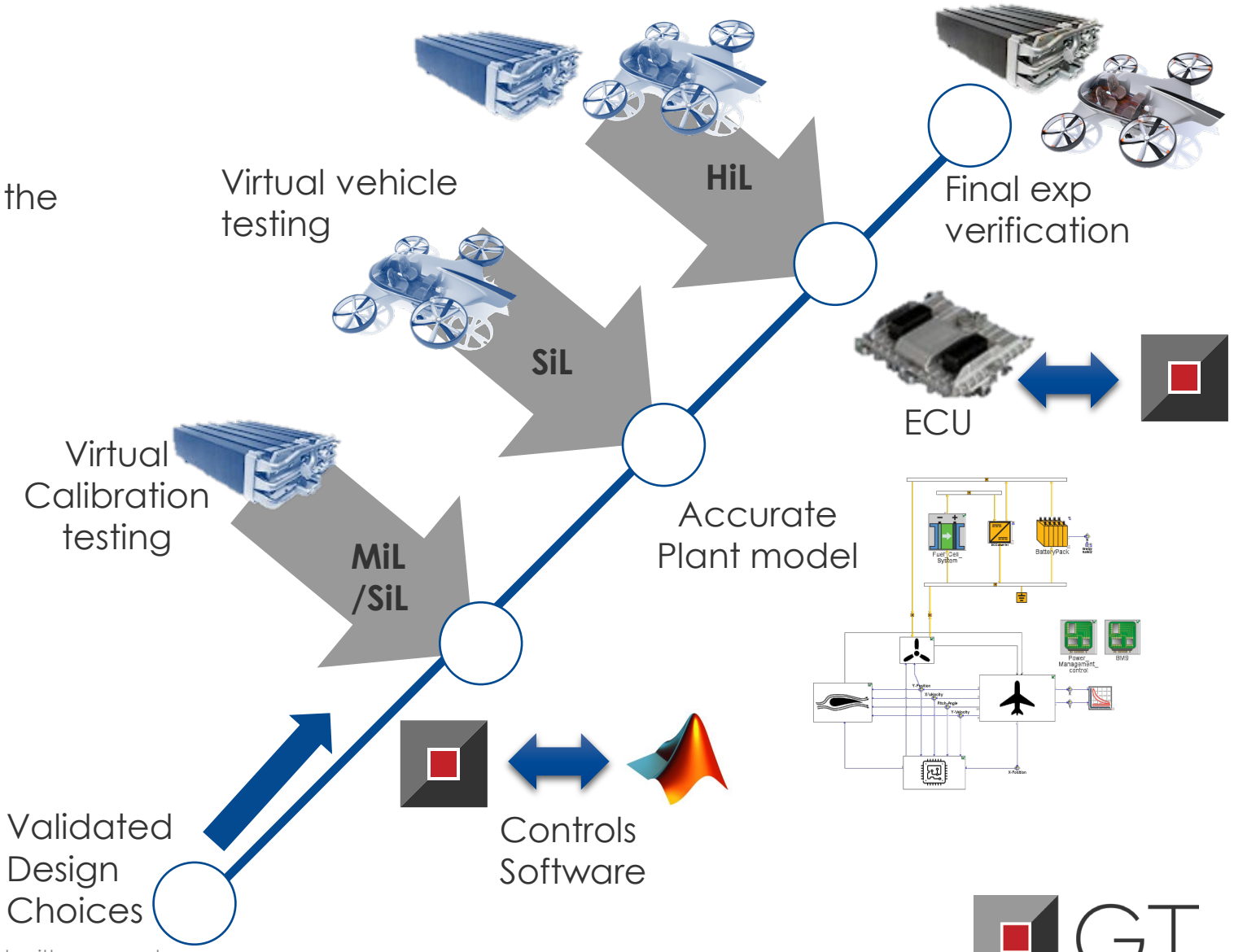
Conclusion & Way Forward

Real Time System Simulation

- Use GT model as a virtual plant for all the verification side of the V-cycle
  - Model in the Loop
  - Software in the Loop
  - Hardware in the Loop

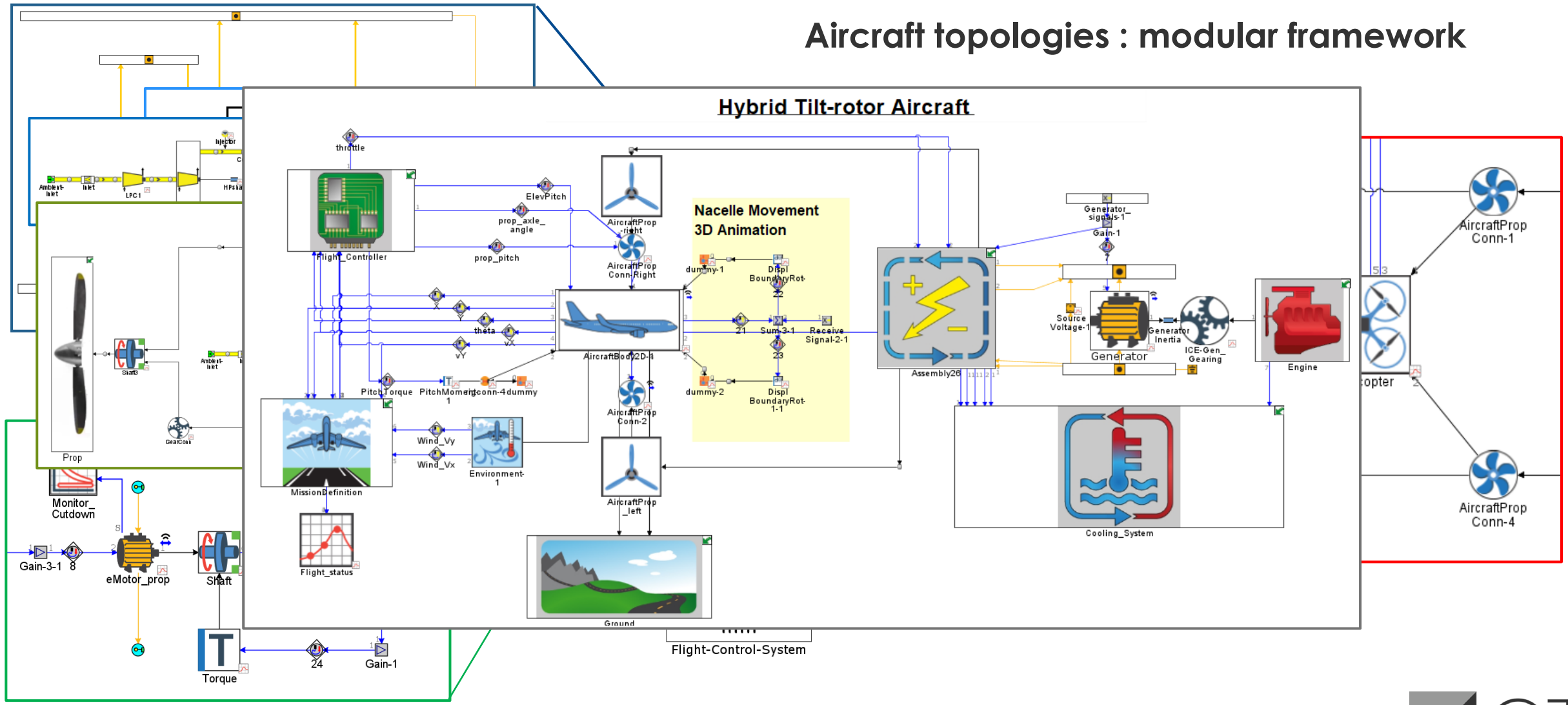
Simulation speed full model	0.61 real-time

Real Time capable



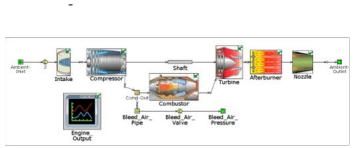
Conclusion & Way Forward

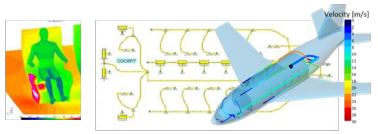
Aircraft topologies : modular framework

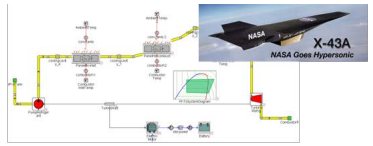


Conclusion & Way Forward

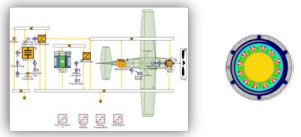
- With GT-SUITE's Predictive and Multi-Physics 1D capabilities, various studies, topologies and component can be taken into account :
  - Hybrid Fuel/Electric Aircraft
  - ECS with advanced Cabin simulation capabilities
  - Cryogenic and Fuel Systems
  - Advanced Thermal Management
  - Virtual Calibration and Controls Validation
  - Multi-Body Mechanics and Landing Gears

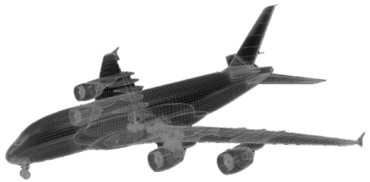

Gas Turbine Systems

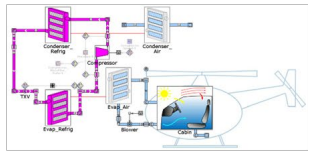

Environmental Control Systems

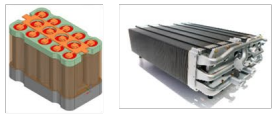


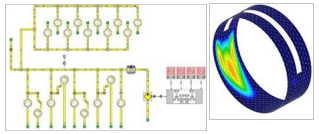
Thermal Management Systems

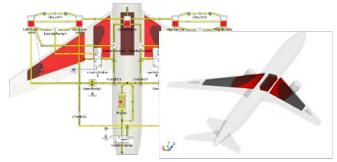

Electric Propulsion Systems




Vapor Compression Systems


Energy Storage Systems


Fuel, Hydraulic and Oil Systems


Airframe Fuel Systems

- Component and System Design can be shortened with GT-SUITE and fast 1D Predictive simulation

Thank you

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GAMMA TECHNOLOGIES