Hydrogen Aircraft Development Applying Co-Simulation with Modelica and FMI

Ludvig Knöös Franzén

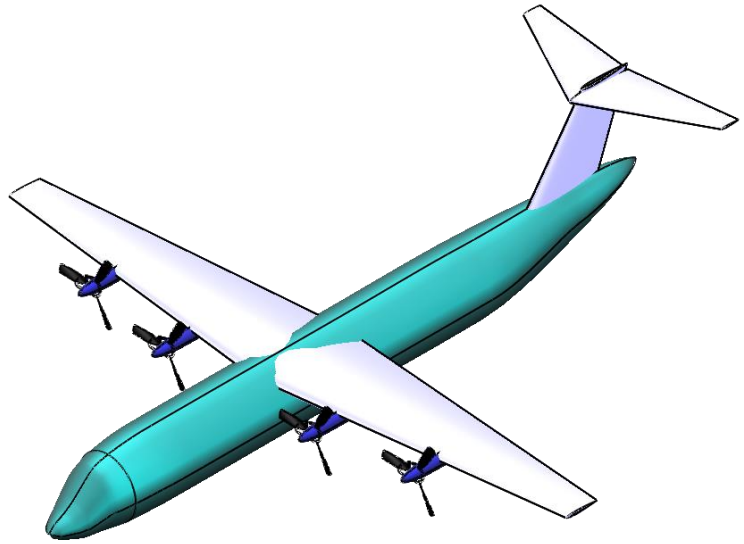
Robert Hällqvist

Presented at the 15th MODPROD Workshop
3-4th February, Linköping, Sweden
www.modprod.org

LINKÖPING UNIVERSITY

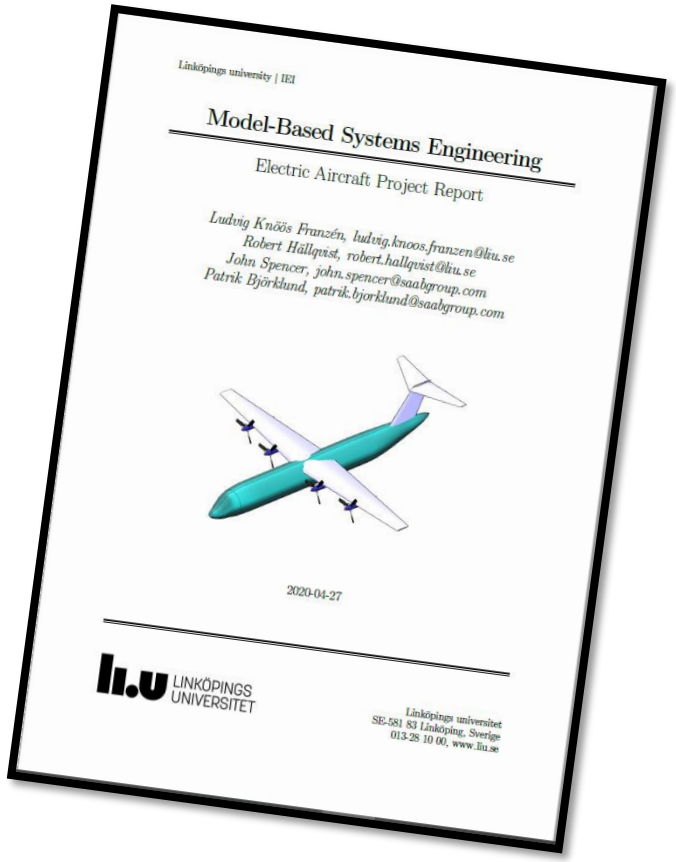
Agenda

- Introduction
- Initial Requirements and Mission Profile
- Approach for Creating the Baseline Aircraft
- Optimization using Co-Simulation
- Baseline Aircraft Results
- Design Space Exploration
- Conclusions and Future Work



Introduction

- Based on an electric aircraft project from an MBSE course given at Linköping University in the spring of 2020
  - Design a medium capacity hydrogen-powered aircraft capable of crossing the Atlantic ocean
- The study shows how a traditional aircraft conceptual design process is enhanced by incorporating Modelica models including dynamics
- Implemented in Modelica and utilizes an FMU for Co-Simulation
- Geometrical model created in OpenVSP


Linköpings university | IEI

Model-Based Systems Engineering

Electric Aircraft Project Report

Ludvig Knöös Franzén, ludvig.knoos.franzen@liu.se
Robert Hällqvist, robert.hallqvist@liu.se
John Spencer, john.spencer@saabgroup.com
Patrik Björklund, patrik.bjorklund@saabgroup.com

2020-04-27

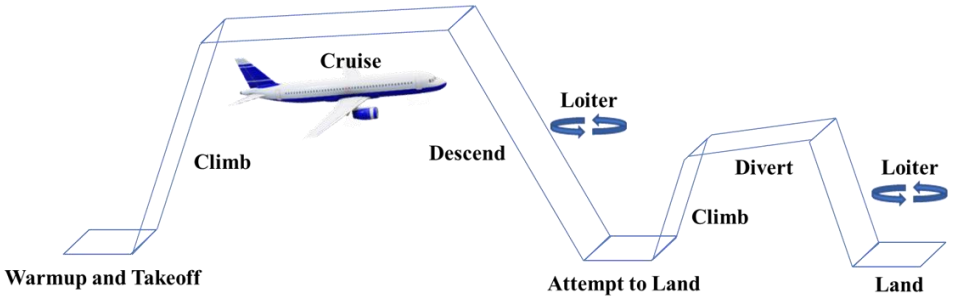
LINKÖPINGS UNIVERSITET

Linköpings universitet
SE-581 83 Linköping, Sverige
013-28 10 00, www.liu.se

Initial Requirements and Mission Profile

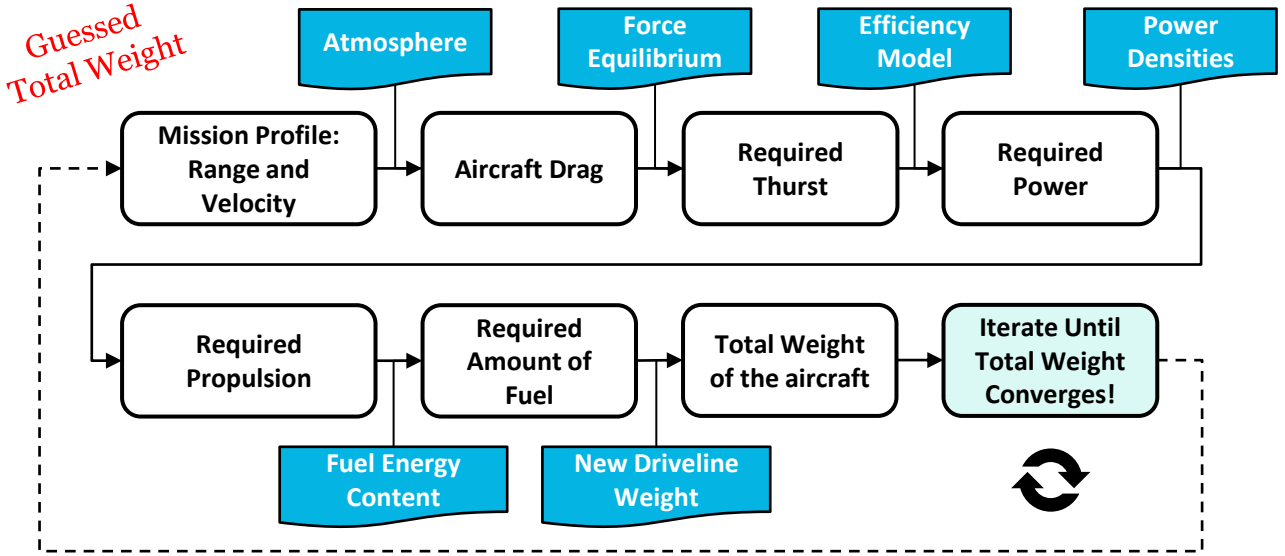
- Electric Aircraft Requirements
  - Desired range: **6288 km** (Arlanda, Sweden to JFK, US)
  - Number of passengers: **200** (excluding crew)
  - Propellant: **Electric** (Hydrogen Fuel Cells)

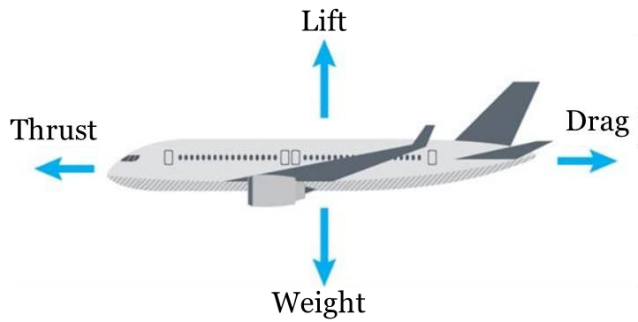
Mission Profile
6288 km range (+ 370 km divert)



Approach for Creating the Baseline Aircraft

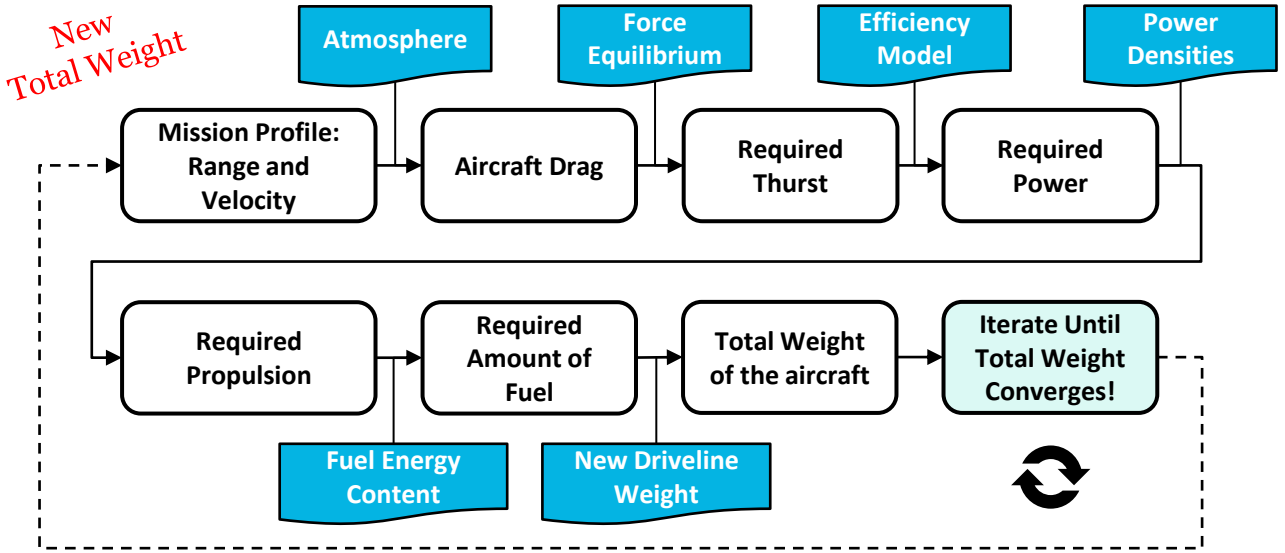
- Overall approach:

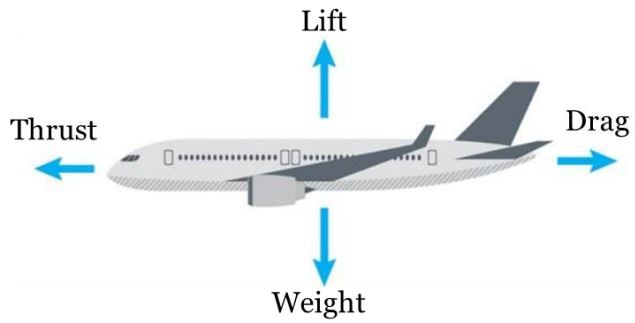




Approach for Creating the Baseline Aircraft

- Overall approach:

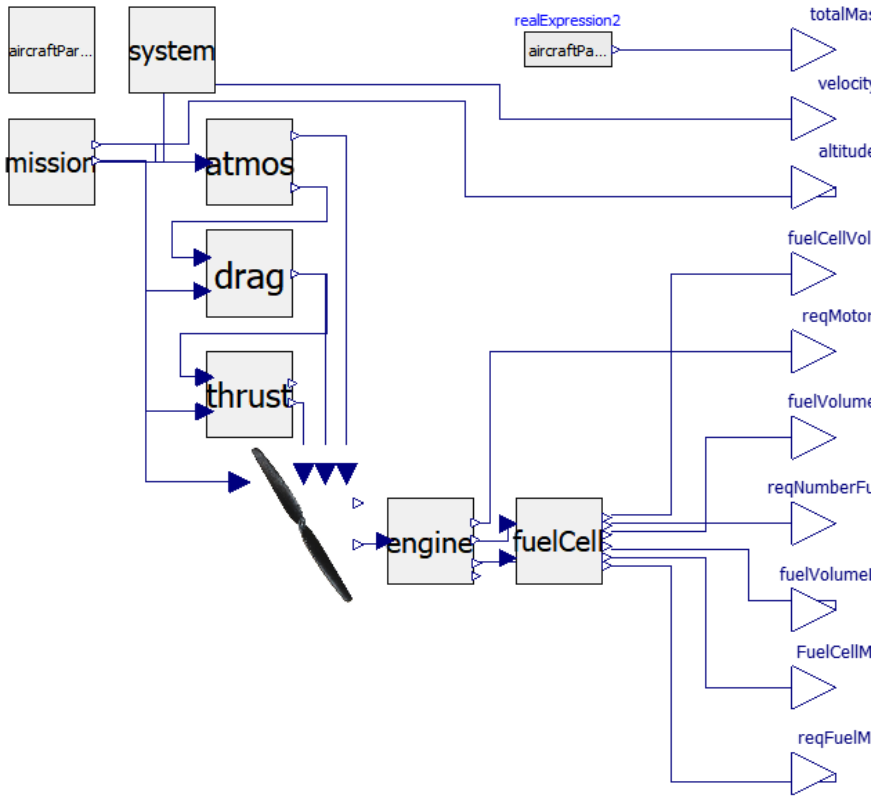




Approach for Creating the Baseline Aircraft

OpenModelica

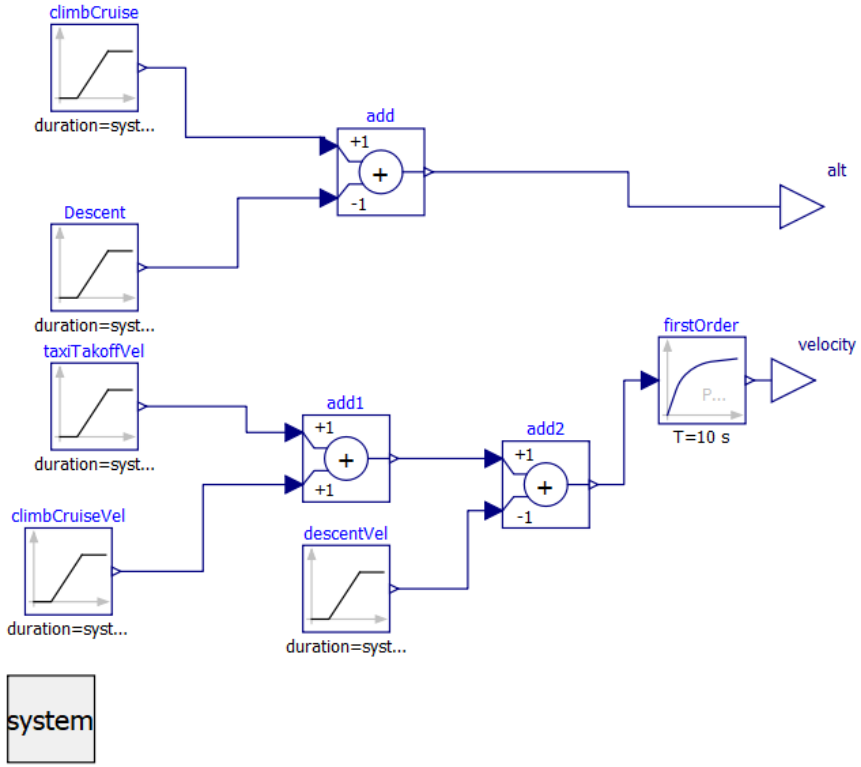
- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications



Approach for Creating the Baseline Aircraft

OpenModelica

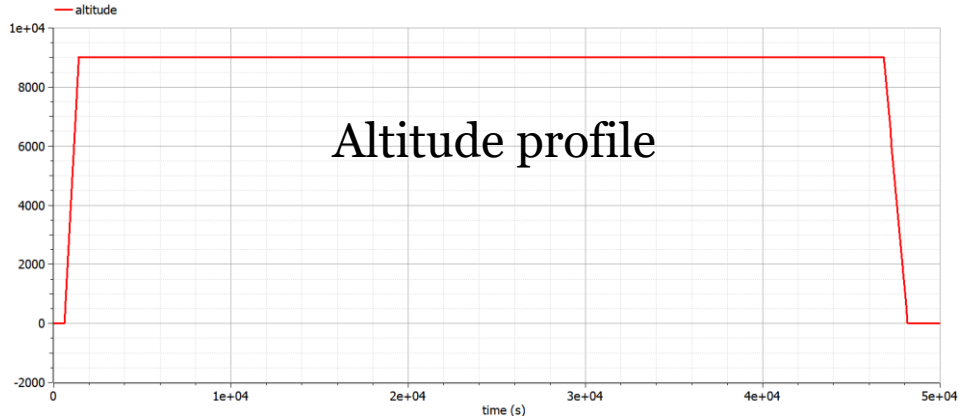
- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications

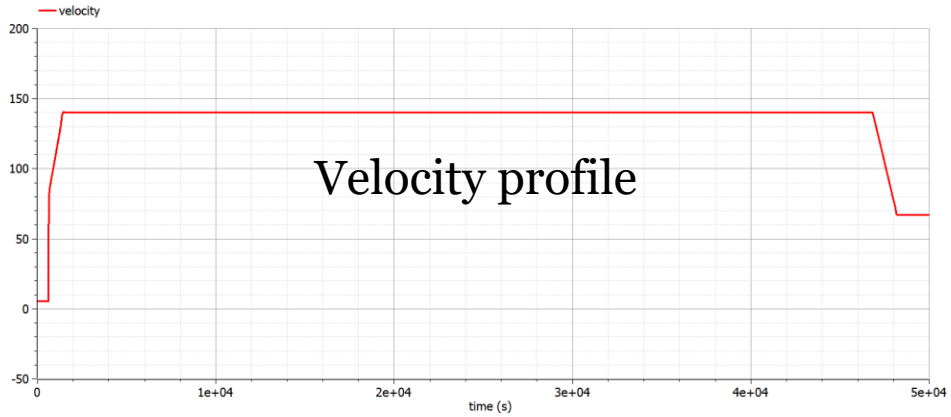


Approach for Creating the Baseline Aircraft

OpenModelica

- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications

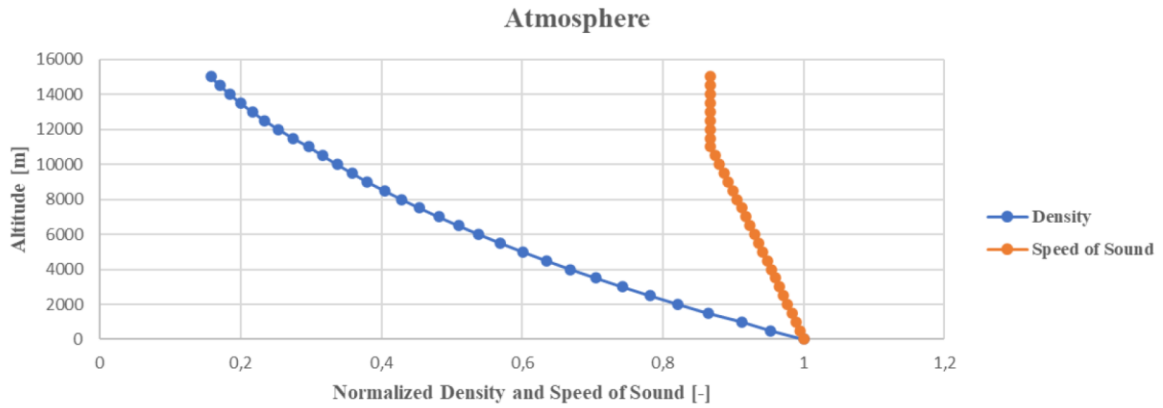




Approach for Creating the Baseline Aircraft

OpenModelica

- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications



Approach for Creating the Baseline Aircraft

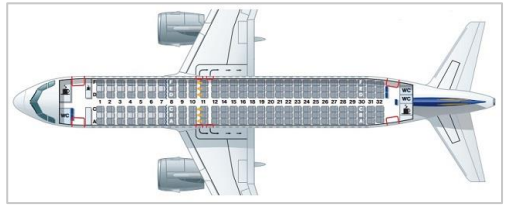
- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications

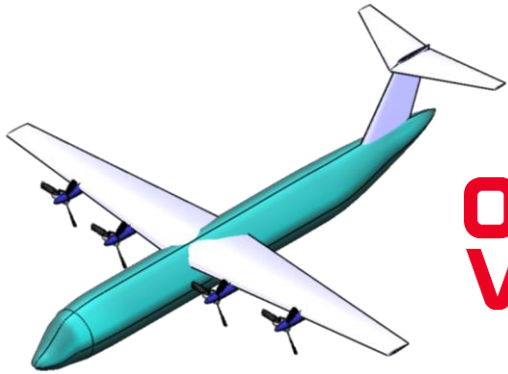
Parameter	Default Value	Description
Cruise Altitude	9000 m	Desired cruise altitude
Taxi Duration	600 s	Assumed time for the taxi segment
Rate of Climb	11.4 m/s	Assumed value, based on Saab 2000
Range	6288 km	Range requirement (Sthlm - NY)
Divert Range	370 km	The divert range for a missed approach
Total Range	6658 km	The total required range
Cruise Speed	184 m/s	Assumed value, based on Saab 2000
Descent Time	1350 s	The average time for a descent
Landing speed	67 m/s	Assumed value, based on A320
Take-off Lift Coefficient	1.8	Assumed lift coefficient for take-off
Taxi speed	5.5 m/s	Assumed taxi speed
Take-off Distance	1500 m	The Arlanda field length

Approach for Creating the Baseline Aircraft

- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications

Parameter	Default Value	Description
Aspect Ratio	10	Default Airbus A320
Wing Span	38 m	Default Airbus A320, with a little extra
Number of Motors	4	Initial guess
Number of Fuel Cells	50 000	Initial guess
Fuel Mass	4000 kg	Initial guess
Fuselage Wetted Area	435.33 m^2	From geometrical model
Wing Ref. Area	154 m^2	From geometrical model
Horizontal Tail Ref. Area	34.57 m^2	From geometrical model
Vertical Tail Ref. Area	57.23 m^2	From geometrical model
Number of Passengers	200	Requirement
Number of Crew Members	2	Pilots and staff





Approach for Creating the Baseline Aircraft

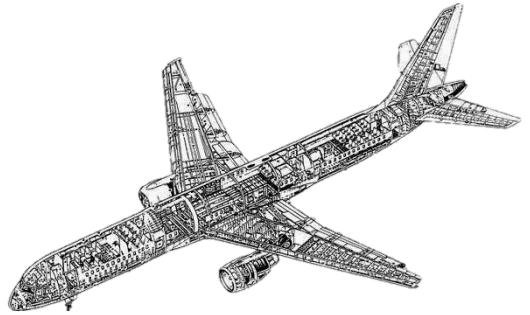
- Overall approach
- Enabling aircraft sizing in OpenModelica
- Implementing the mission
- Implementing the atmosphere
- Specifying aircraft systems information (based on similar aircraft)
- Specifying aircraft parameter values
  - Guessed values
  - OpenVSP model
  - Hydrogen components specifications

Parameter	Default Value	Description
Aspect Ratio	10	Default Airbus A320
Wing Span	38 m	Default Airbus A320, with a little extra
Number of Motors	4	Initial guess
Number of Fuel Cells	50 000	Initial guess
Fuel Mass	4000 kg	Initial guess
Fuselage Wetted Area	435.33 m^2	From geometrical model
Wing Ref. Area	154 m^2	From geometrical model
Horizontal Tail Ref. Area	34.57 m^2	From geometrical model
Vertical Tail Ref. Area	57.23 m^2	From geometrical model
Number of Passengers	200	Requirement
Number of Crew Members	2	Pilots and staff
Motor Mass	120 kg	From MAGNI500 specification
Fuel Cell Efficiency	0.7	Wikipedia, 70% of hydrogen energy is usable
Power per Fuel Cell	274.7 W/cell	From PowerCell S3 specification
Volume per Fuel Cell	$8.179{*}10^{-5} m^3/cell$	From PowerCell S3 specification
Mass per Fuel Cell	0.0945 kg/cell	From PowerCell S3 specification
Drive Train Efficiency	0.938	From MAGNI500 specification
Motor Power	560000 W	From MAGNI500 specification
Propeller Diameter	3.8 m	Based on the Saab2000, with a little extra
Rotational Speed	31.66 rps	From MAGNI500 specification
Propeller Efficiency	0.9	From propeller equations

Approach for Creating the Baseline Aircraft

- Weight calculations
  - Surface area values from OpenVSP
- Implementing the aircraft's aerodynamics
  - Parasitic drag coefficient (C_{Do}) estimation from OpenVSP
- Implementing the propulsion system or "drive line"
- Implementing the Fuel-cells and hydrogen storage
- Iterative process and optimization problem!

***Total Weight* =**
Payload* + *Propulsion* + *Structure* + *Fuel* + *Miscellaneous



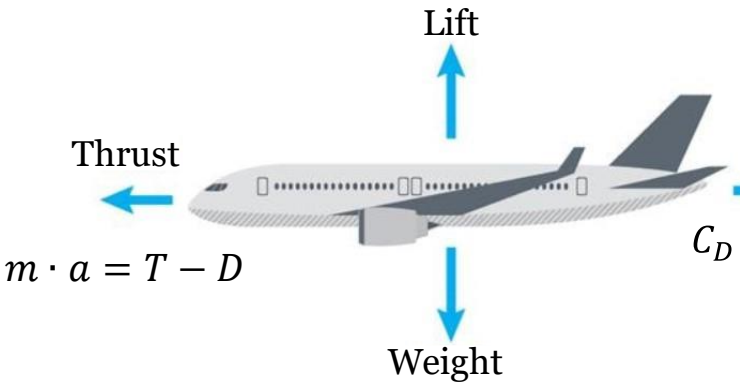
Raymer's Simple and Quick Structural Weight Estimation Table

	Weight per Area [kg/m^2]	Multiplier
Wing	49	Exposed planform area
Horizontal tail	27	Exposed planform area
Vertical Tail	27	Exposed planform area
Fuselage	24	Wetted area

Approach for Creating the Baseline Aircraft

- Weight calculations
  - Surface area values from OpenVSP
- Implementing the aircraft's aerodynamics
  - Parasitic drag coefficient (C_{Do}) estimation from OpenVSP
- Implementing the propulsion system or "drive line"
- Implementing the Fuel-cells and hydrogen storage
- Iterative process and optimization problem!

$$m \cdot a|_{a=0} = q \cdot S_{ref} \cdot C_L - m \cdot g$$

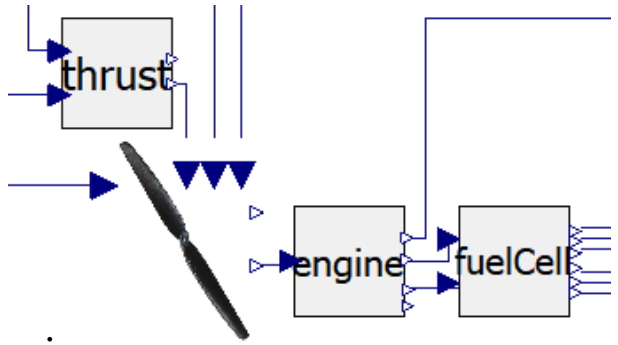


$$m \cdot a = T - D$$

$$C_D = C_{D0} + \frac{C_L^2}{AR \cdot e \cdot \pi}$$

Approach for Creating the Baseline Aircraft

- Weight calculations
  - Surface area values from OpenVSP
- Implementing the aircraft's aerodynamics
  - Parasitic drag coefficient (C_{Do}) estimation from OpenVSP
- Implementing the propulsion system or "drive line"
- Implementing the Fuel-cells and hydrogen storage
- Iterative process and optimization problem!



Required Power gives:
- Total number of required motors
- Total number of required fuel cells

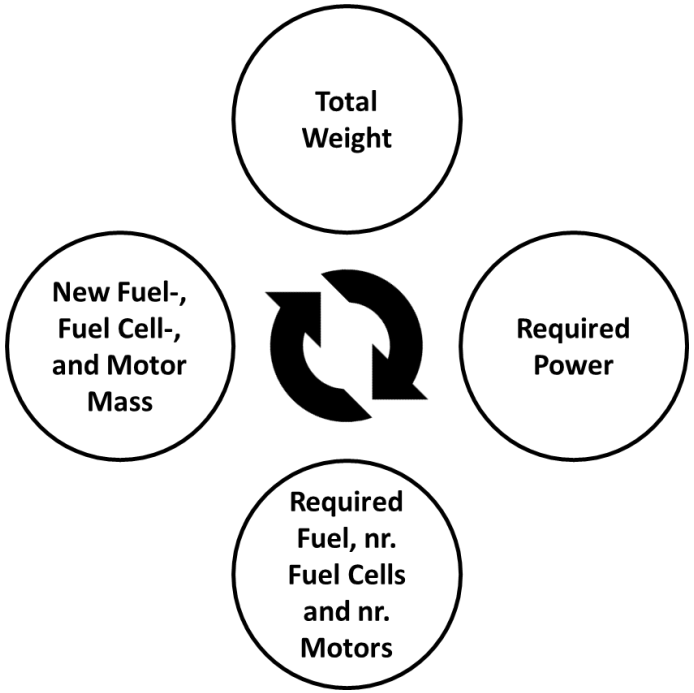
Duration of flight gives:
- Total required energy
- Total required amount of hydrogen

This results in three weights:
- Total weight of Motors + installation
- Total weight of stored hydrogen
- Total weight of Fuelcells + installation and cooling

- Hydrogen is here assumed to be an ideal gas
- Stored at 80MPa in room temperature

Approach for Creating the Baseline Aircraft

- Weight calculations
  - Surface area values from OpenVSP
- Implementing the aircraft's aerodynamics
  - Parasitic drag coefficient (C_{Do}) estimation from OpenVSP
- Implementing the propulsion system or "drive line"
- Implementing the Fuel-cells and hydrogen storage
- Iterative process and optimization problem!



Optimization using Co-Simulation

- Sizing Optimization
  - Optimization problem example

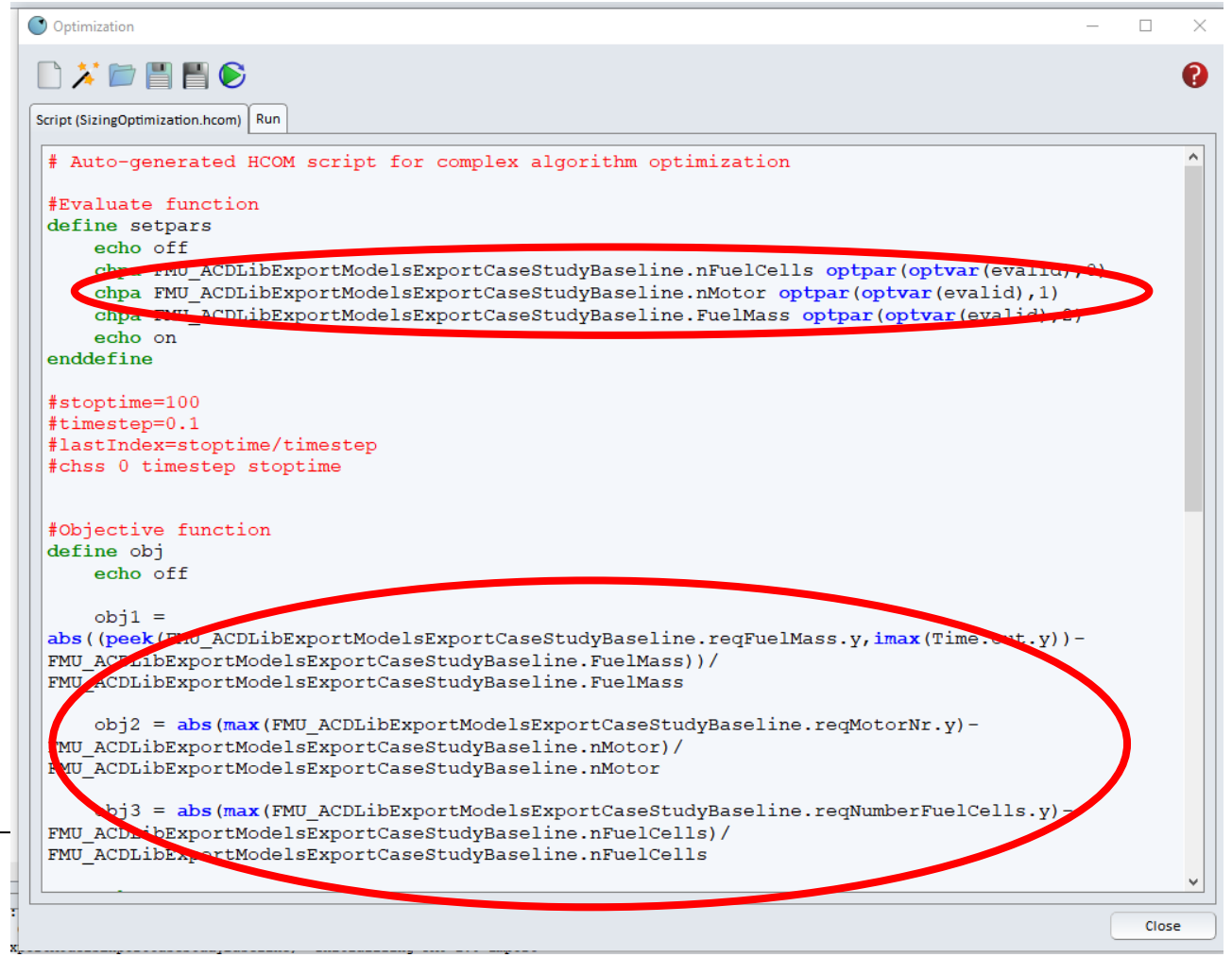
    $\min(\lambda_1 f_1(X) + \lambda_2 f_2(X) + \lambda_3 f_3(X))$

    Where the weights are specified as

    $$\lambda_i = \frac{1}{X_{guess}}$$

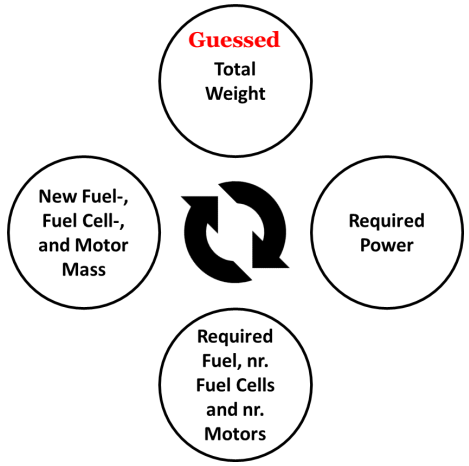
    and X are the parameters to be optimized

Hopsan example optimization specification script



Optimization using Co-Simulation

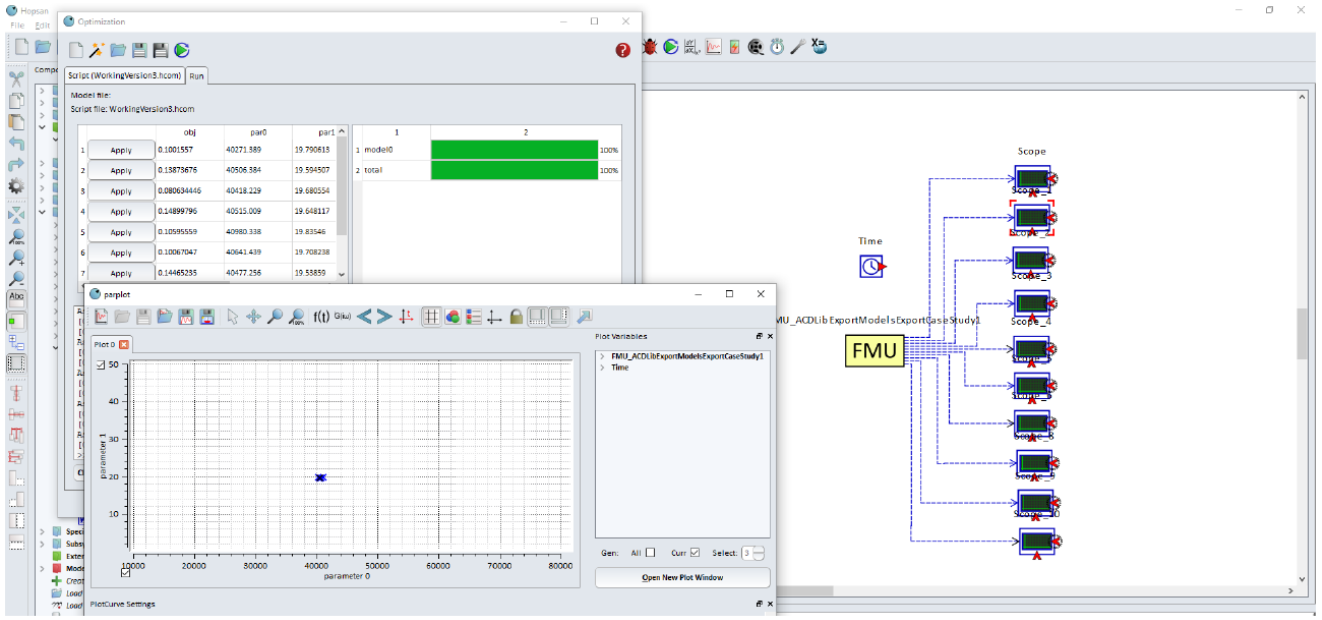
- Running exported FMU in HOPSAN
- Optimizing with Complex-RF until the weights have converged
- Arriving at the baseline aircraft design!



Continue until weight difference between iterations is insignificant

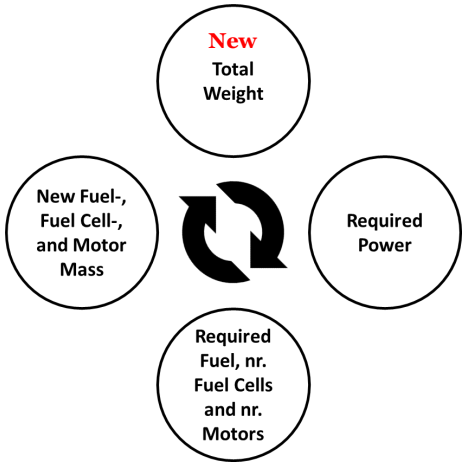
HOPSAN

fmi Functional Mock-Up Interface



Optimization using Co-Simulation

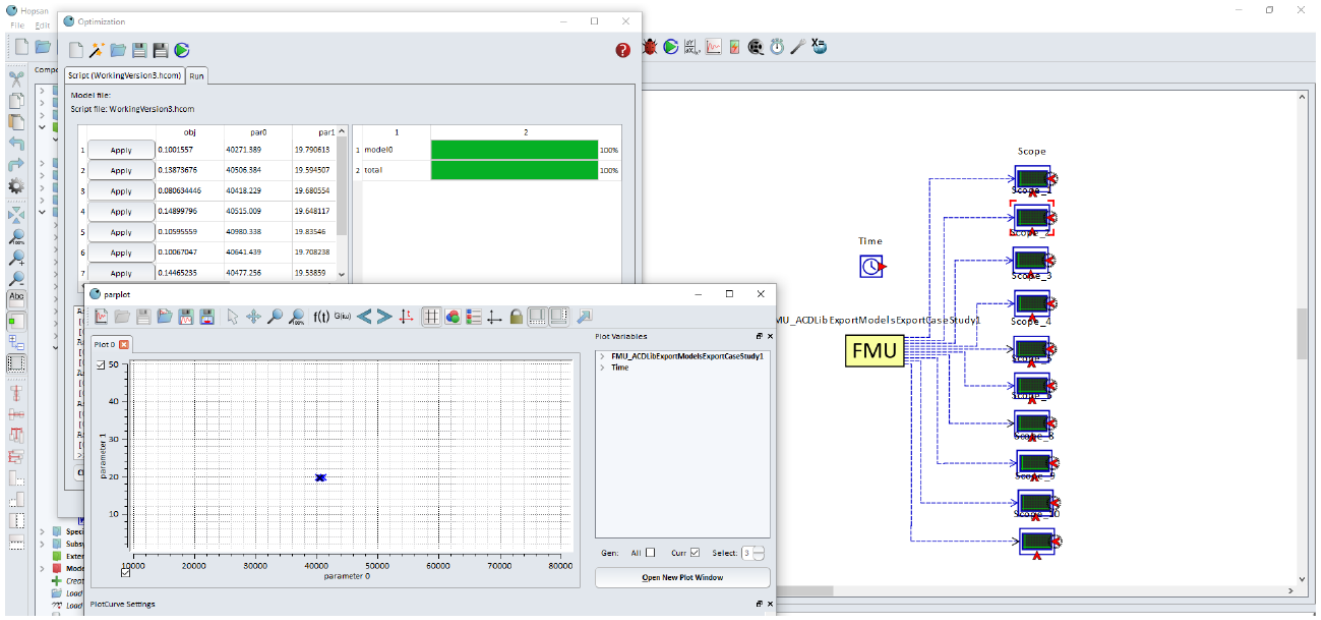
- Running exported FMU in HOPSAN
- Optimizing with Complex-RF until the weights have converged
- Arriving at the baseline aircraft design!



Continue until weight difference between iterations is insignificant

HOPSAN

fmi Functional Mock-Up Interface



Baseline Aircraft Results

- Aircraft Sizing results:
  - Nr. Motors ≈ **20**
  - Nr. Fuel cells ≈ **41000**
  - Amount of hydrogen ≈ **3800 kg**
- Fuel cell and hydrogen storage
  - Fuel cells occupy (in total) ≈ **3.35 m^3**
  - Required hydrogen storage ≈ **71 m^3**
  - Possible storage locations:
    - Wings (about **55 m^3** available between wing spars)
    - Rear part of fuselage or pods the wing (would require **16 m^3** of space)

Number of motors
(Determined by peak in power)

Baseline Aircraft Results

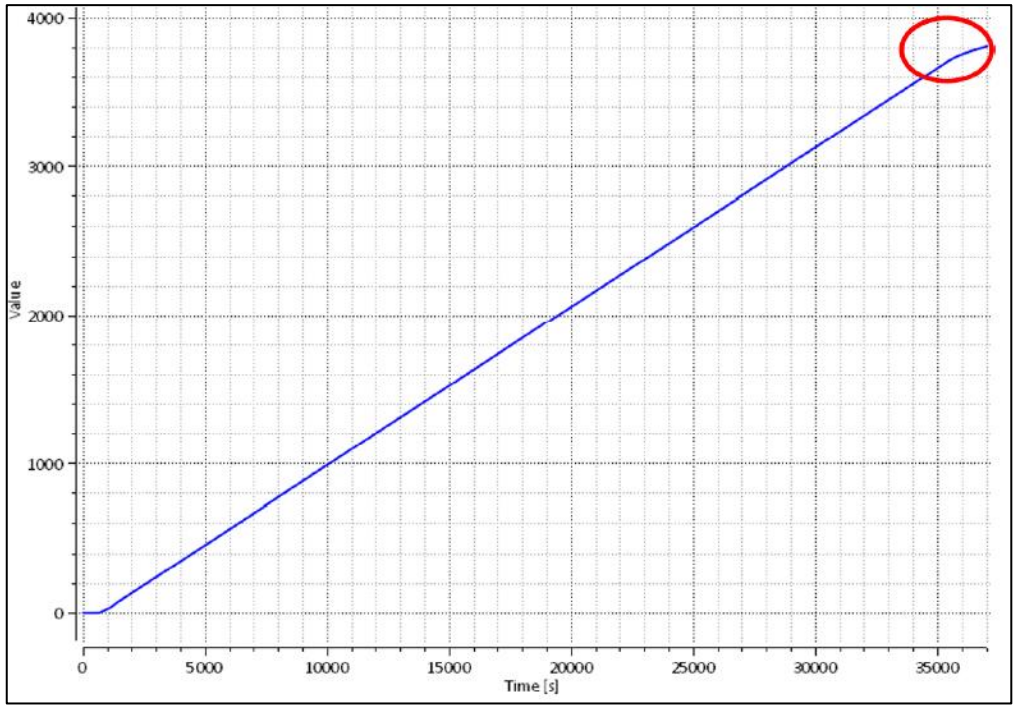
- Aircraft Sizing results:
  - Nr. Motors ≈ **20**
  - Nr. Fuel cells ≈ **41000**
  - Amount of hydrogen ≈ **3800 kg**
- Fuel cell and hydrogen storage
  - Fuel cells occupy (in total) ≈ **3.35 m^3**
  - Required hydrogen storage ≈ **71 m^3**
  - Possible storage locations:
    - Wings (about **55 m^3** available between wing spars)
    - Rear part of fuselage or pods the wing (would require **16 m^3** of space)

Number of fuel cells
(Determined by peak in power)

Baseline Aircraft Results

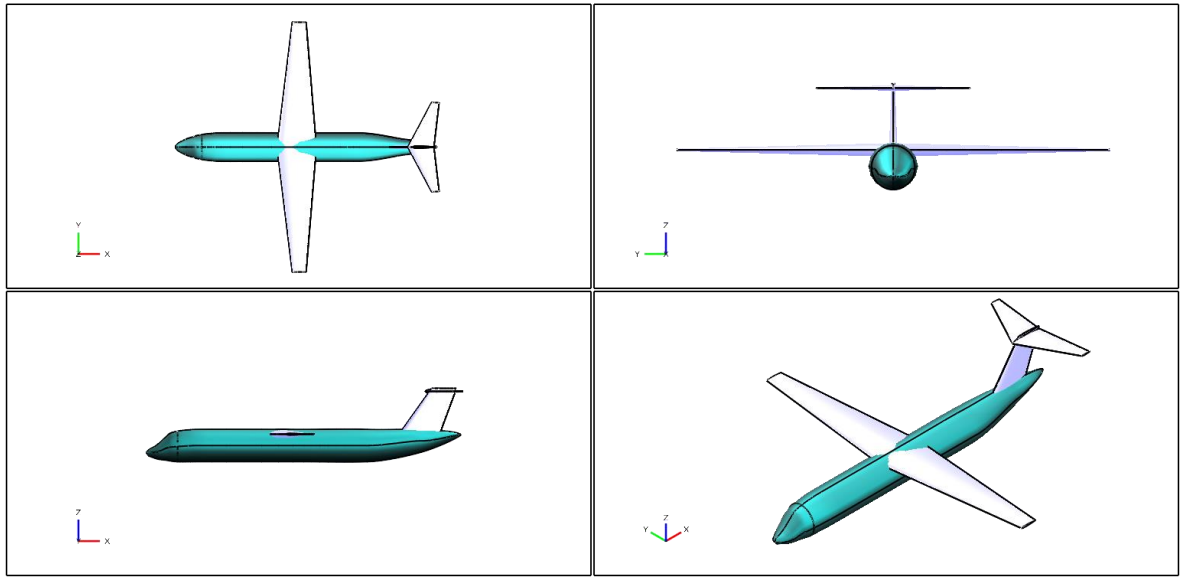
- Aircraft Sizing results:
  - Nr. Motors ≈ **20**
  - Nr. Fuel cells ≈ **41000**
  - Amount of hydrogen ≈ **3800 kg**
- Fuel cell and hydrogen storage
  - Fuel cells occupy (in total) ≈ **3.35 m^3**
  - Required hydrogen storage ≈ **71 m^3**
  - Possible storage locations:
    - Wings (about **55 m^3** available between wing spars)
    - Rear part of fuselage or pods the wing (would require **16 m^3** of space)

Amount of hydrogen
(Determined by flight duration)



Baseline Aircraft Results

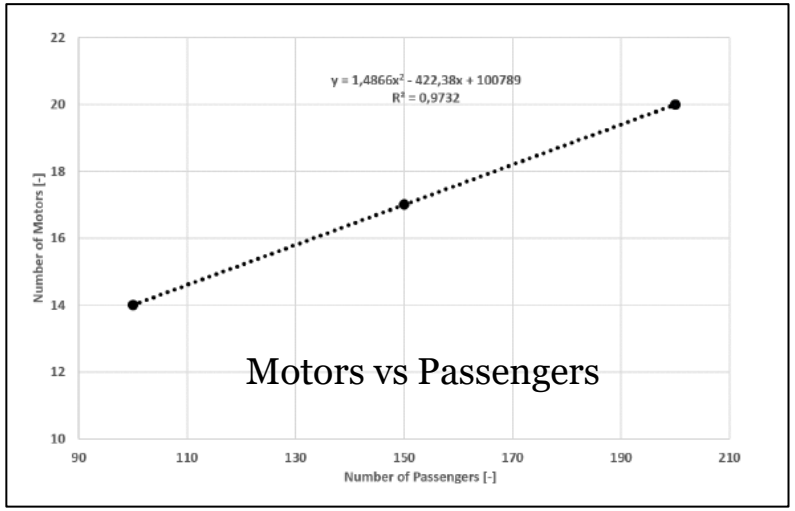
- VSP illustration of the baseline aircraft!
- Summary of baseline aircraft parameters
- Where to fit **20** motors??

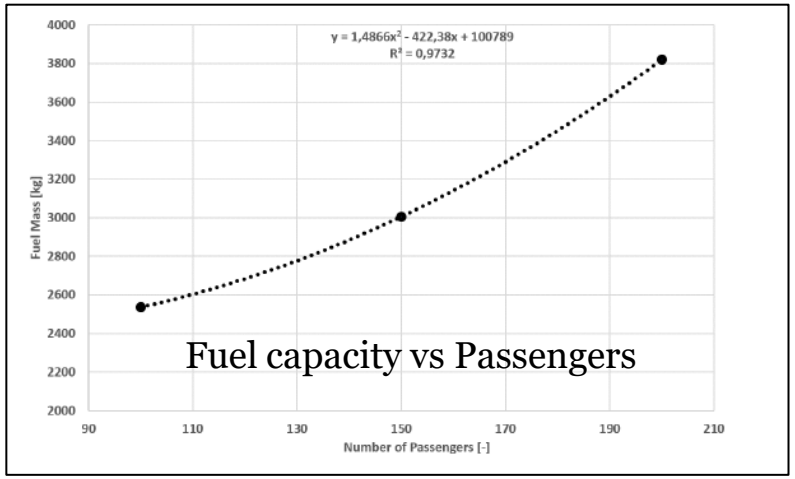


Baseline Aircraft Parameters		
Parameter	**Value**	**Comment**
Fuselage Length	40 m	
Fuselage Diameter	4.3 m	
Wing Area	153.9 m^2	
Wing span	38 m	
Wing Root Chord Length	4 m	
Wing Tip Chord Length	2 m	
Thickness to Chord Ratio	0.15	Based on Airbus A320
Parasitic Drag Coefficient	0.02	From VSP Aerodynamic Analysis
Take-Off Weight	73294 kg	
Operational Empty Weight	51074 kg	
Cruise Speed	Mach 0.59 (180 m/s; 648 km/h)	At cruise altitude
Range	6658 km	
Cruise Altitude	9000 m	
Propeller Diameter	3.8 m	
Number of Motors	20	MAGNI500
Number of Fuel Cells	40912	Powercell S3
Fuel Capacity	71 m^3	
Take-off Lift Coefficient	1.8	With high-lift devices
Cruise Lift Coefficient	0.59	
Passenger Capacity	200	
Mission Time	10.4 h	

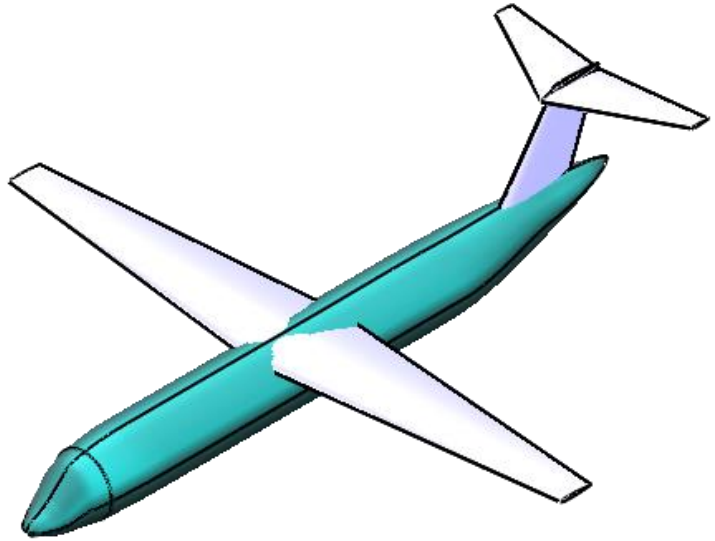
Trade Studies

- Trying to reach a reasonable number of required motors!
- Framework and methodology allows for design space explorations and trade studies
- Investigating sensitivity of changing initial requirements and assumed values
- Several case studies were run to give suggestions for a future Dash-2 aircraft
- General considerations to make it realistic:
  - **Lower passenger capacity (smaller aircraft)**
  - **Lower cruise and climb speed**





Conclusions and Future Work



- Conclusions:
  - An initial attempt to design an aircraft using Modelica and FMU
  - Quite simple project so far, but can be expanded
  - Not just for hydrogen powered aircraft!
- Future work:
  - Implement a geometrical model and increase overall model details
  - Expand library with components for “conventional” aircraft design
  - Case study accounting for one or more aircraft subsystems in the conceptual phase
- Acknowledgements:
  - **John Spencer, Patrik Björklund, Peter Fritzon and Ingo Staack who also contributed to this project**

Thank you for listening!

Questions?

Ludvig.knoos.franzen@liu.se

Robert.hallqvist@liu.se

LINKÖPING UNIVERSITY