Data Assimilation in a Modelica Framework for Optimizing Battery Longevity in Electric Aircraft

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Introduction

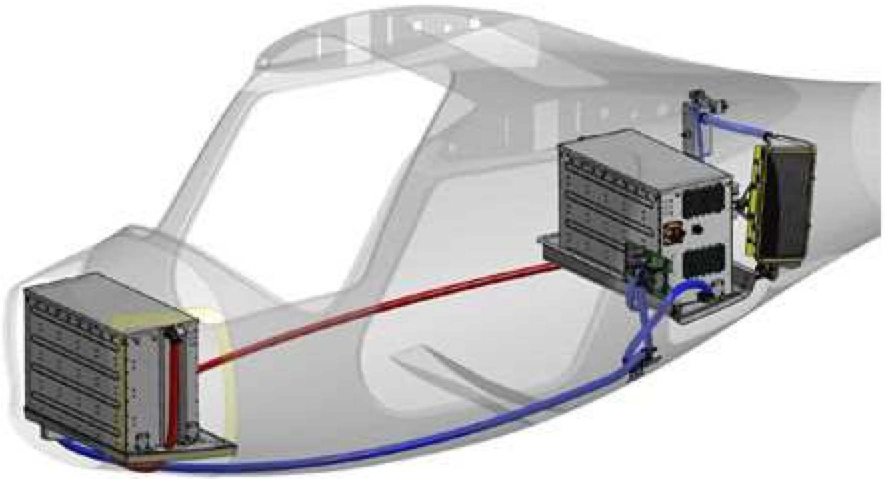


Image credit: https://www.pipistrel-aircraft.com/wp-content/uploads/2023/04/skica-motor-in-baterije.jpg

- Electric aviation offers clear advantages over traditional planes for short distance flights
  - Reduced noise pollution
  - Electric motors require minimal maintenance

The Velis Electro

Image credit: https://www.pipistrel-aircraft.com/wp-content/uploads/2024/07/249A8817-1-2048x1366.jpg

- ➢ Also certified in Mexico and the UK
- ➢ Received light-sport airworthiness exemption from FAA in 2024

- ➢ Manufactured by Slovenia's Pipistrel
- ➢ Short range (50 minute plus reserve) trainer aircraft
- ➢ First (and only) electric aircraft to be certified by the European Union Aviation Safety Agency since 2020

Image credit: Pipistrel Velis Pilot's Manual, June 2020

Velis Electro Powertrain

- Carries two stacks of 1152 Samsung INR 18650-33G cells in a 96S12P configuration
  - ~13.06 kW-hr per stack, or 26.12 kW-hr total; advertised at 20 kW-hr
  - Estimated 500 flight hours between overhauls

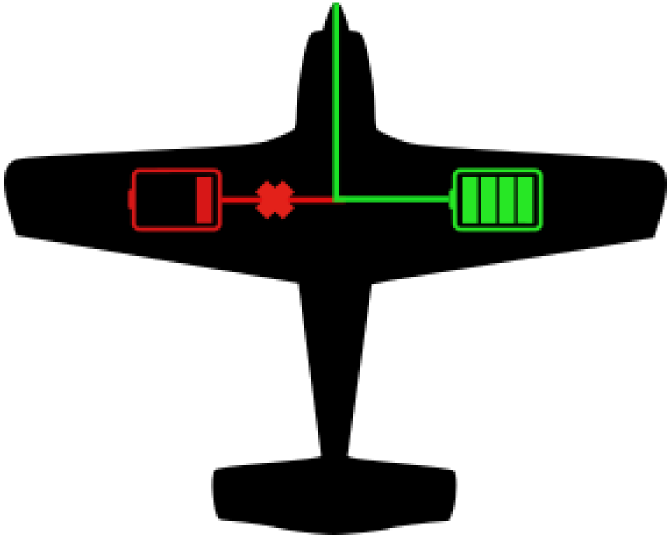
Image credit: https://www.pilotspost.com/articles/200718PipistrelVelisthefirstevercertifiedelectricaircraft/03.jpg

Image credit: https://www.planeandpilotmag.com/uploads/2020/08/pipistrel-velis-electro-motor-640x480.jpg?auto=webp&optimize=high&quality=70&width=1920

- Coupled to an Emrax 268 AC motor and emDrive H300C power controller
  - Maximum load 400 A-rms; constant load 190 A-rms
  - Estimated 2000 flight hours between overhauls

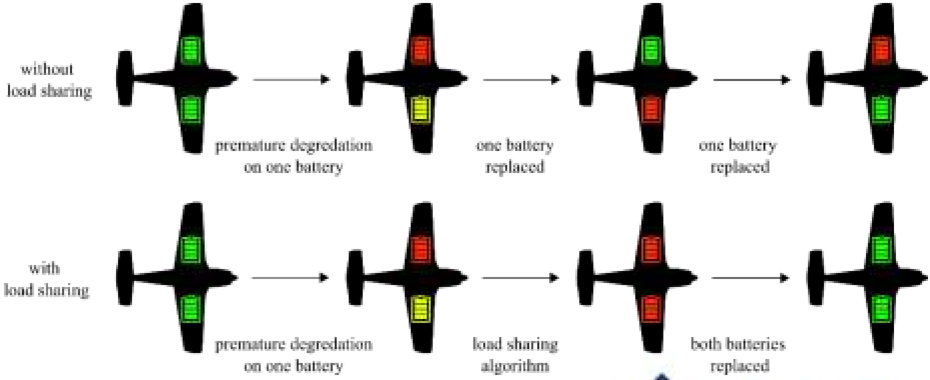
Electric Aviation Economics

- Battery life span key factor in economic viability
  - Fast charge cycles required to maintain availability
  - High power application in-flight
- Furthermore, premature failure of a single stack desynchronizes battery maintenance cycles
- Especially important for Velis Electro; liquid-cooled power train precludes easy replacement

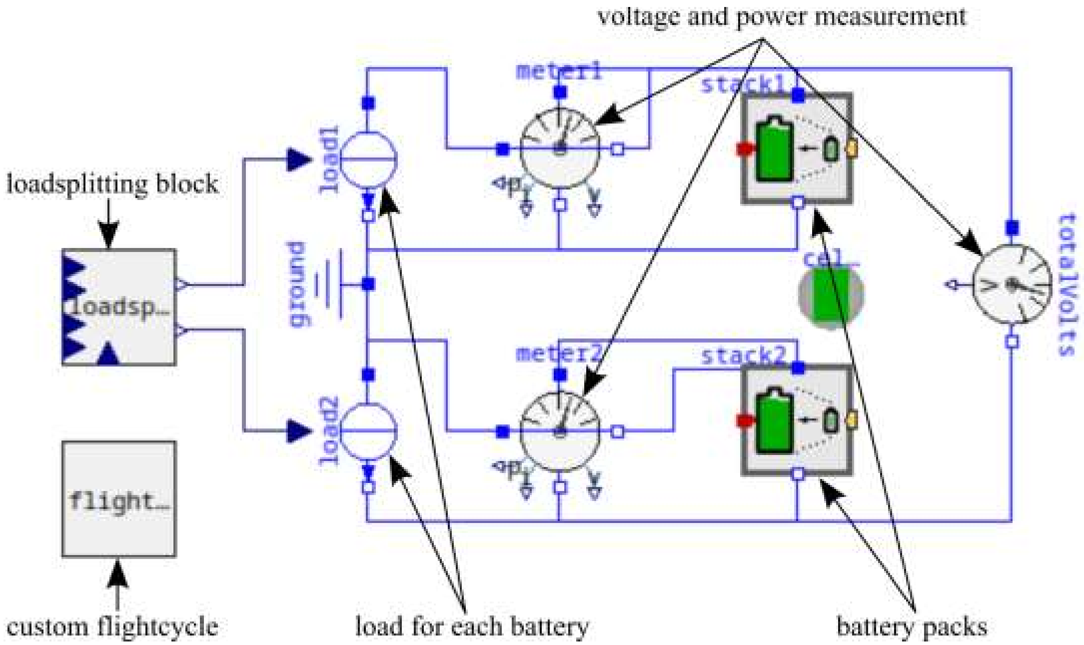


Objectives

- ➢ Digital twins and load sharing agents represent a possible way to track and manage battery health
- ➢ Ex: algorithm developed by Anthony et al. splits the load to equalize the RUL over time
- ➢ Goals:
  - ➢ Model the battery system of an electric aircraft in OpenModelica
  - ➢ Apply a simple load sharing agent to a generic flight path to demonstrate the flight hours recovered



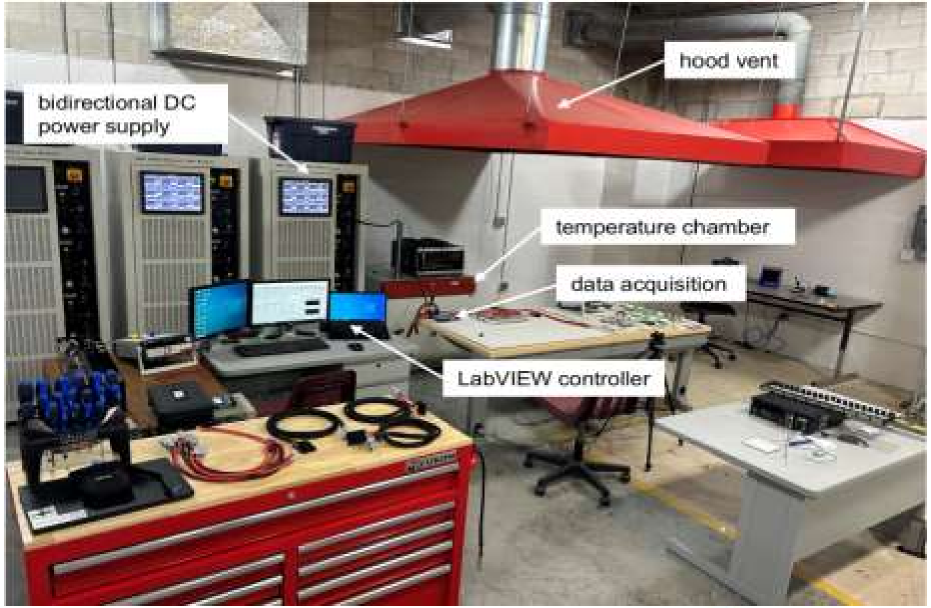
OpenModelica Modeling



- Open-source multi-physics package based on the Modelica language
- Four main components
  - Two battery stacks, “stack1” and “stack2”
  - “loadsplitter” block
  - “flight_cycle” block

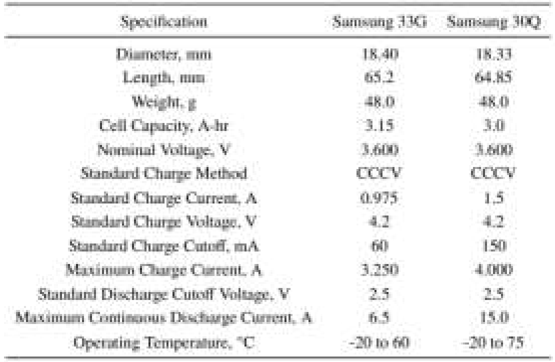
Experimental Setup for Battery Characterization

- Batteries characterized based on discharge test data provided by the University of South Carolina Adaptive Real-Time Systems (ARTS) Laboratory
- Tested via NHR 9200 Battery Test system controlled by LabView
- Cells kept in temperature chamber; maintained constant 20C ambient

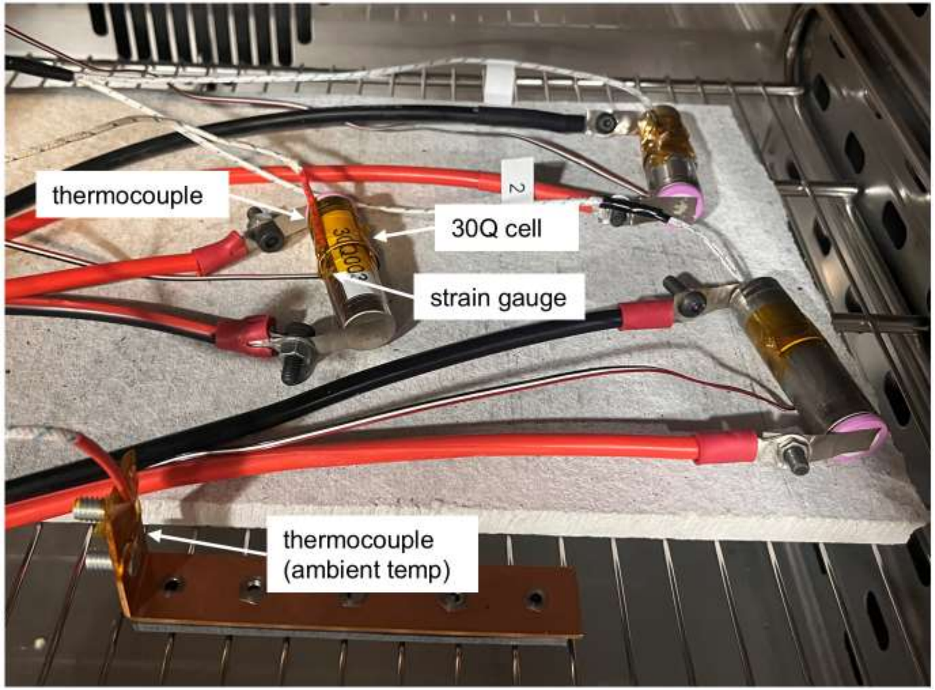


Thermal and Mechanical Analysis of Battery Cells

- Samsung INR 18650-30Q cells the lab’s current standard
  - Similar specifications and chemistry to the 33G
  - Primary difference is higher charge/discharge currents
- Tested in temperature control chamber maintained at 20ºC



Specification	Samsung 33G	Samsung 30Q
Diameter, mm	18.40	18.33
Length, mm	65.2	64.85
Weight, g	48.0	48.0
Cell Capacity, A-hr	3.15	3.0
Nominal Voltage, V	3.600	3.600
Standard Charge Method	CCCV	CCCV
Standard Charge Current, A	0.975	1.5
Standard Charge Voltage, V	4.2	4.2
Standard Charge Cutoff, mA	60	150
Maximum Charge Current, A	3.250	4.000
Standard Discharge Cutoff Voltage, V	2.5	2.5
Maximum Continuous Discharge Current, A	6.5	15.0
Operating Temperature, °C	-20 to 60	-20 to 75



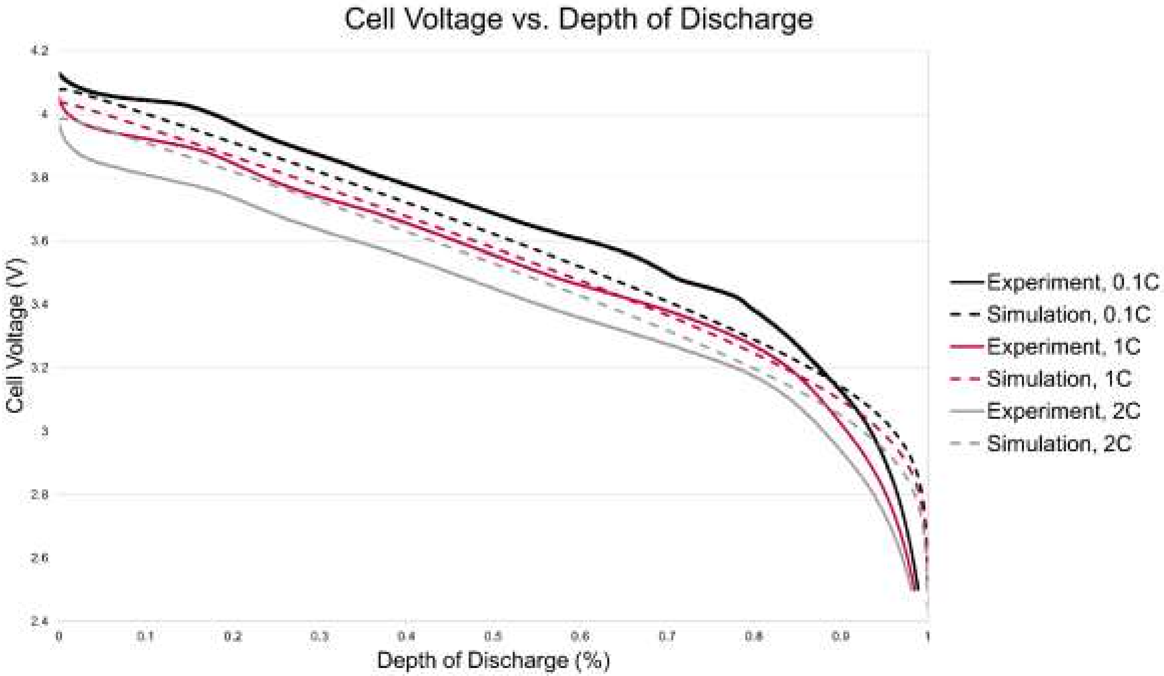
Voltage-Discharge Profiles for Model Validation

- Each cell discharged in increments of 10% SOC using 6 A pulses

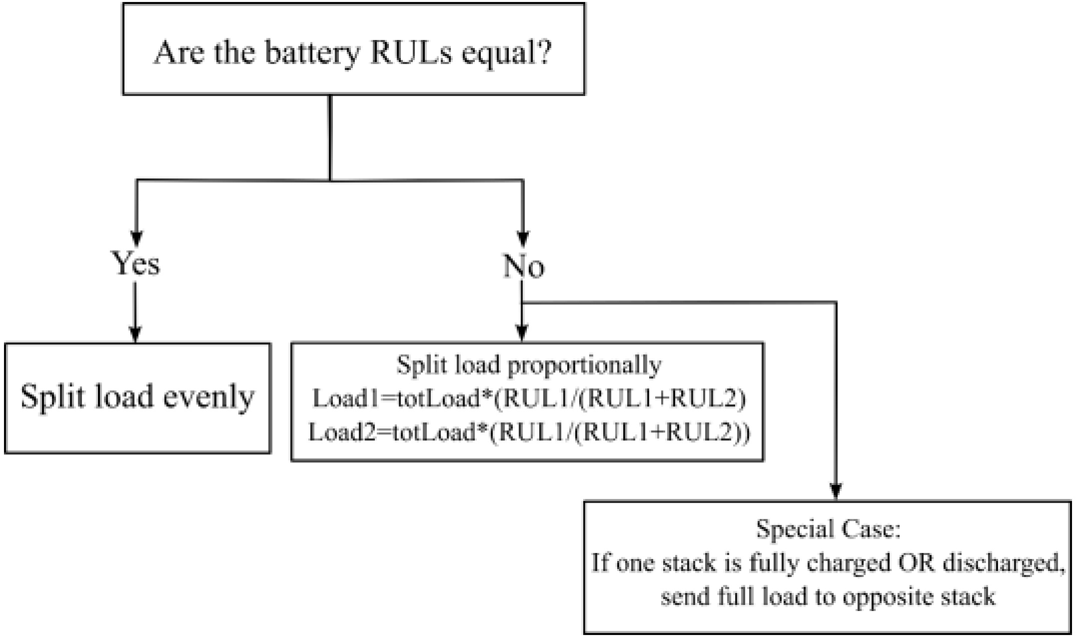
- Resulting data curve-fitted to find the coefficients of the empirical relation:

$$OCV = K_0 + K_1 SOC + K_2 \ln(SOC) + K_3 \ln(1 - SOC)$$

- Internal resistance calculated from Ohm's Law: ~0.162 Ω



Load Splitting Agent



Are the battery RULs equal?

Yes

No

Split load evenly

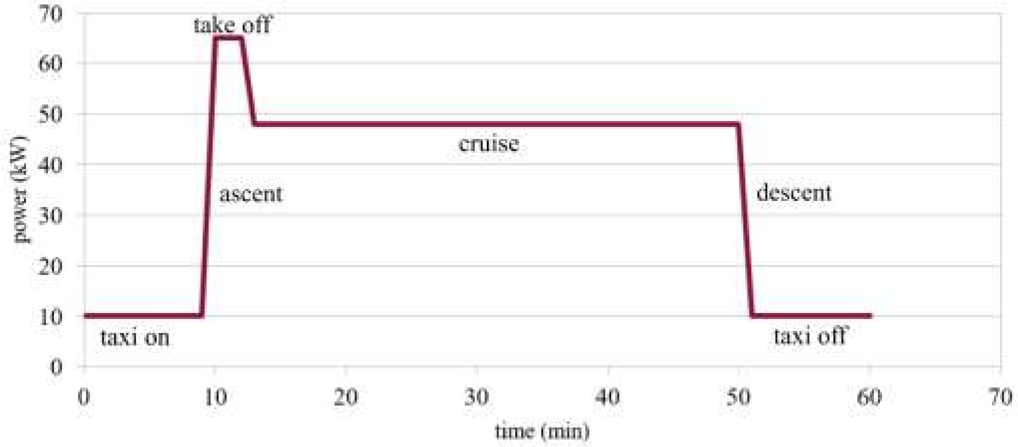
Split load proportionally
Load1=totLoad*(RUL1/(RUL1+RUL2)
Load2=totLoad*(RUL1/(RUL1+RUL2))

Special Case:
If one stack is fully charged OR discharged,
send full load to opposite stack

- ➢ Splits total current load proportionately based on each cell’s remaining useful life
- ➢ Limited to initial RUL’s of greater than 50%

The Generic Flight Cycle

- Discharged via a generic flight profile
  - 65 kW peak power (~80 A), 40 kW (~60 A) cruising power
- Charged at a constant 10 A per stack (0.265C) until both stacks reach 90% SOC



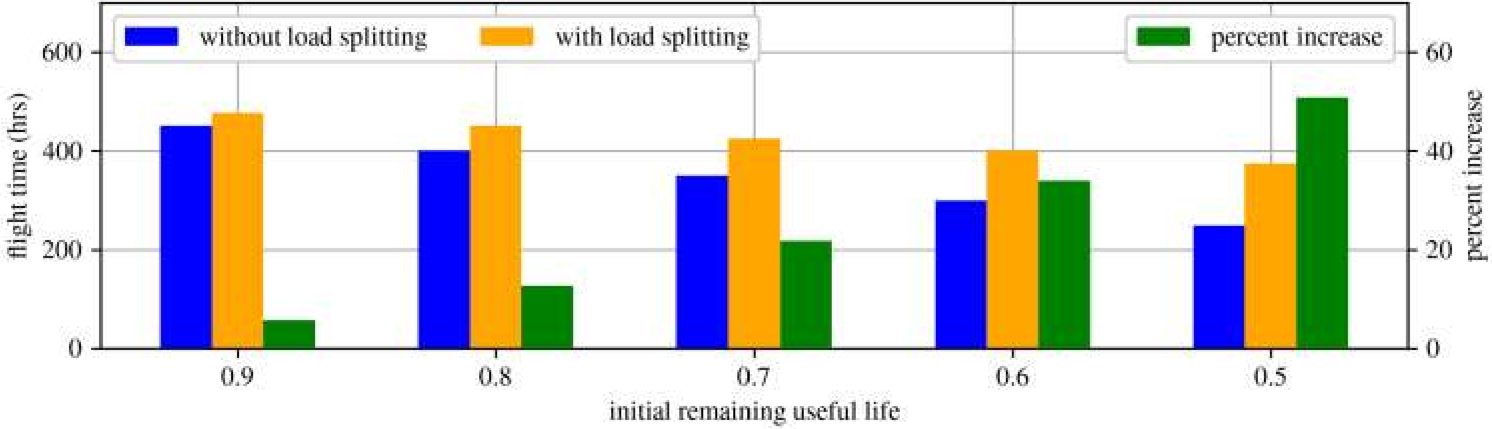
- Taxi, takeoff, and cruise times all user-defined
  - Neglected taxi periods in simulation
  - Take off limited to 90 sec. per manual
- Cycled until one or both stacks reach their end of life

Simulation Scheme

- 33 total simulation cases
  - Five initial RULs for partially degraded stack, from 90% to 50%; opposite stack always begins at 100% RUL
  - Three different discharge times: 10, 30, and 50 minutes
  - Each RUL/discharge time combination simulated with and without load sharing
    - Sum total flight time and compare
  - Three special cases: each stack begins at 100% RUL for comparison with manufacturer

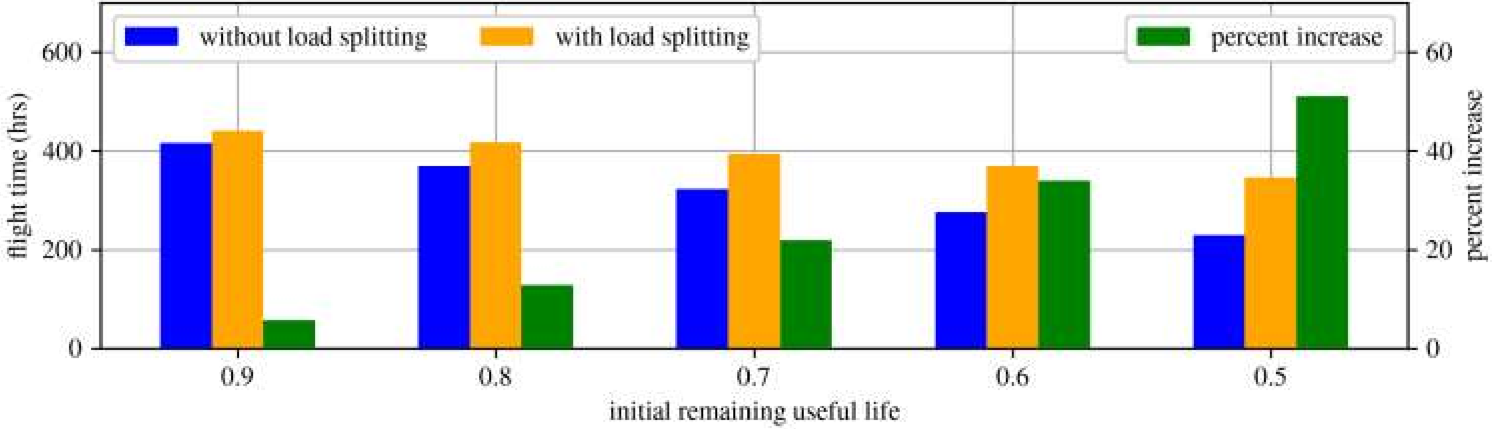
Results (10-minute test)

- **Base Case:** ~500 flight hours for 10-minute flights.
- **With Load Splitting:**
  - Flight time recovered by ~50% of losses.
  - Gains increase with greater initial degradation of the secondary battery.
- **Observation:** Recovery improves as battery RUL decreases, showing consistent algorithm performance.



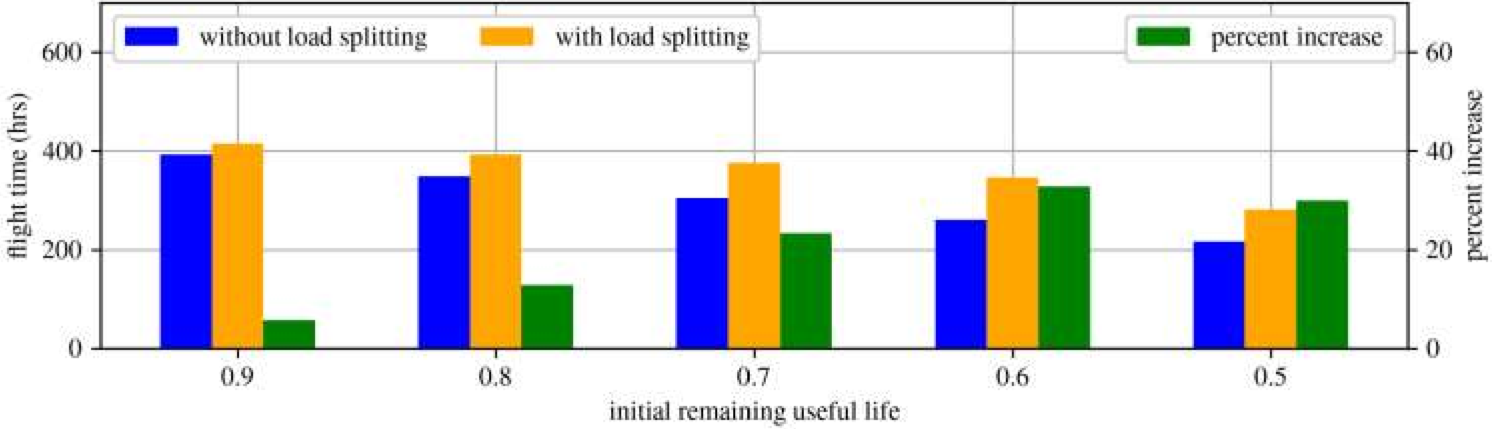
Results (30-minute test)

- **Base Case:** Flight hours reduced by 7.6% compared to 10-minute flights due to higher discharge.
- **With Load Splitting:** ~40% of lost flight time recovered, consistent across RUL values.
- **Observation:** Gains are slightly lower than for 10-minute flights but still effective under moderate discharge.



Results (50-minute test)

- **Base Case:** Further reduction in flight hours by 5.75% compared to 30-minute flights and significantly lower than 10-minute flights.
- **With Load Splitting:** Recovery effective but reduced, ~30% gain for highly degraded batteries (0.5 RUL).
- **Observation:** Gains diminish under high discharge, highlighting algorithm limitations with highly degraded batteries.



Conclusions

- Algorithm Benefits:
  - Extended battery life, up to 50% more flight hours for 10-minute flights.
  - Reduced battery replacement frequency, lowering costs and downtime.
- Performance Insights:
  - 30-minute flights showed moderate reductions with strong recovery.
  - 50-minute flights had larger reductions and diminishing gains, revealing algorithm limits under high discharge.
- Future Work:
  - Improve algorithm for degraded batteries and high-discharge cases.
  - Explore partial recharges, varied charge rates, and operational irregularities.

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