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Health monitoring for highly reusable launch vehicles using Machine Learning

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Introduction

- Sweden has many assets and capabilities, linked to strong knowledge and experience, that let it profit from the growing (commercial) space market
- Independent EU access to space is of strategic importance, and Sweden is uniquely positioned to provide many parts of the value chain
- Reusability can support both economic and strategic aspects
  - Reduced launch service costs
  - Rapid response capabilities

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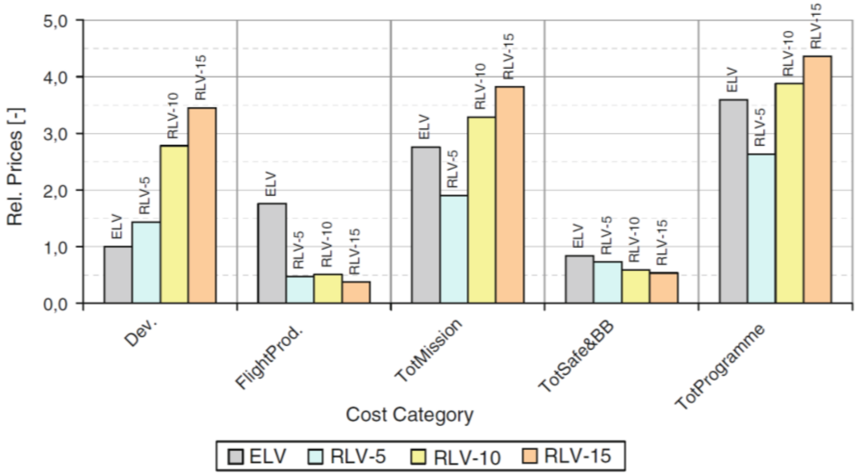
Reusability & Financial sustainability



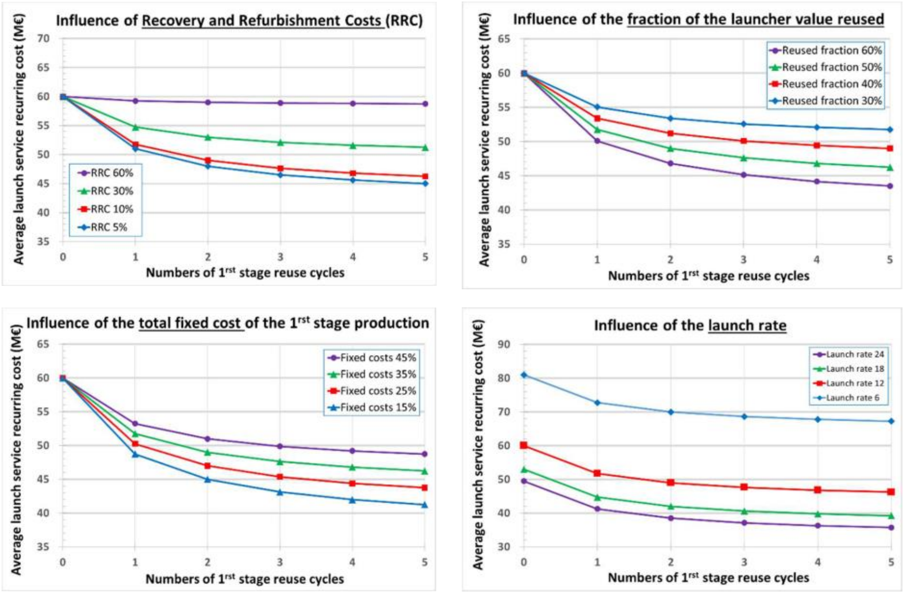
From: Preclik, D. et al, 2011 [1]

- The key financial feature of reusable launch vehicles is the reduction in vehicle costs per flight.
- Development costs will rise due to increased design and analysis efforts, as well as the need for more testing due to more difficult validation requirements
- Further cost increases occur due to new inspection and maintenance tasks
- Due to this there may be a minimum in costs, which reflects the current state of technology
- Technical solutions to the above issues will therefore become increasingly valuable

Reusability & Financial sustainability

- The impact of recovery and refurbishment activities on launch service costs is on the same order as
  - that of the fixed costs and
  - the fraction of the launcher value that can be reused

- Optimization of recovery and maintenance processes will therefore likely become an important source of competitive advantage



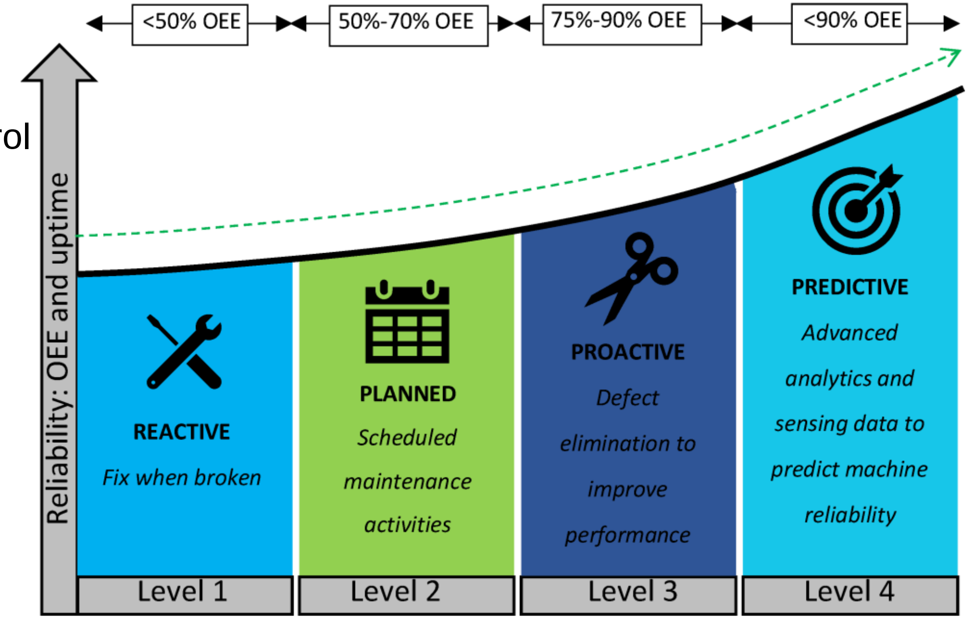
From: Oswald et al., 2020 [2]

Space Shuttle Main Engine – Lessons Learned [3-4]

- High costs related to maintenance processes due to:
  - Up to 120h of maintenance work with large team
    - > Suboptimal accessibility makes maintenance difficult and slow, increases reassembly time and risk
    - > Large inspection burden due to limited health monitoring
- Lessons for second generation reusable engines
  - Design for
    - > Reuse: trade-off between performance and part/system life time
    - > Inspection and maintenance: critical parts need to be accessible
  - Monitor
    - > Provide necessary information for maintenance planning
    - > minimize inspection and maintenance burden

How to decrease cost and increase reliability?

- Use advanced sensor data and intelligent on-board processing to:
  - Detect faults quickly
  - Implement Damage Limiting Control
  - Asses maintenance needs
  - Report system reliability status



From: Carvalho et al., 2019 [5]

Approach and challenges

Understand known failure modes

- Bolt torque relaxation
- Coolant passage leakage/restriction
- Cracked turbine blade
- Turbopump seal leakage
- Valve failure
- Small tube failure
- Loose electrical connectors
- Etc.

Discover new failure modes

- In current designs, engines operate at a high percentage of their physical limits. If operated at lower percentages, parts will have longer life, but new failure modes could occurre
- Lessons could be learned from related systems with long life, e.g. commercial and military jet engines

Where practical, address by design

- Turbine blade fracture => Use electric pumps
- Loose electrical connector => Use e.g. screw connector

Find measurands for each failure mode and lifing parameter

- Pressure
- Temperature
- Vibration
- Strain
- Fluid composition
- Thermal radiation
- Fluid contaminations
- Etc.

Match Measurands with suitable sensors

- Pressure gauge
- RTD / Thermocouple
- Accelerometer
- Strain gauge
- ?
- IR sensor
- ?
- Etc.

Design data processing

- In-flight fault detection
- Control feedback
- Part life assessment
- Maintenance indicator generation
- Etc.

Verification & Validation

- Testing

Key challenges:

- New failure modes
- Lacking sensors
- Lacking data to test algorithms

Sensors

- Sensors will be necessary for
  - In-flight, onboard and real-time diagnostics
    - Selected based on performance metrics and failure modes
  - On-ground inspection and maintenance
    - Select sensing capabilities that cannot be placed onboard but are highly value adding to inspection and maintenance.

- Many ‘commercial of the shelf’ sensors could be used
- New sensor technologies may enable advance predictive capabilities
  - Example: Online detection of fuel decomposition in engine cooling channels, which may lead to elevated wall temperature due to solid carbon depositions.
    - Currently under development at KTH

Machine Learning (ML) using neural networks (NN)

- Machine Learning has been successfully applied to [5]:
  - Heat transfer predictions in rocket cooling channels
  - Fatigue life estimations
  - Discovery of suitable precursors to combustion instability
  - Optimized engine control
- Advantages
  - Similar accuracy as high-fidelity CFD or FEM simulations
  - Low prediction time (a NN only has to multiply the input vector with its weight matrices to generate the output)
  - NN can scale to large data sets and capture the behavior of complicated functions with high-dimensional inputs and outputs
  - Data fusion and assimilation techniques allow to integrate multiple data sources and combine simulations and experimental data in a systematic way
- Disadvantages
  - Depending on the complexity of the problem, the construction of a precise approximation model can require a huge number of data samples
  - NNs are not able to extrapolate, but only provide reliable predictions within the region of the input space that is populated with “training points”

Proposed Idea

- The development of advanced health monitoring and health management technologies are proposed.
- This development is foreseen to have two focal points:
  - First, the continued development of **new sensing methods** for currently unmonitored health indicators, e.g. the thermal decomposition of propellants in cooling channels. This point goes hand-in-hand with the investigation of **failure modes in reusable launch vehicles**;
  - Second, the analysis of health monitoring data through **sensor fusion** and **machine learning** techniques. The developed machine learning algorithms are to be applied to assess the cyclic damage and degradation of system performance of reusable rockets in real-time. This capability supports **in-flight fault detection** and **predictive maintenance**.
- Furthermore, inspection and maintenance techniques will need to be developed to support the process of technology demonstration through sub-scale tests.

Possible implementation formats

Commercial development

- Commercialization of technology by existing industry
- Commercialization by start-up company

Industrial-Academic Research coop.

- National level
- 1 or more Academic partners
- 1 or more industrial partners
- Industrial/Academic research leader
- Several PhD students / researchers
- Several technicians

Academic Research

- Local level
- 1 University
- 1 Research leader
- 1-2 PhD students
- 1-2Technicians

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References:

[1] D. Preclik, R. Strunz, G.Hagemann and G. Langel, Reusability aspects for space transportation rocket engines: programmatic status and outlook, CAES Space Journal, 2011, 1, 71:82

[2] J. Oswald, K. Kheng, L. Pineau, J.M. Bahu, Economic analysis of a semi reusable launcher for Europe, 71st International Astronautical Congress 2020, IAC-20-D-2.2.4, October 2020

[3] C.A. MacGregor, Reusable rocket engine maintenance study, Rockwell International for NASA, CR-165569, 1982

[4] I. Cannon, A. Norman and M. Olsaky, Application of SSME launch processing lessons learned to second generation reusable rocket engines including condition monitoring, Rockwell International, AIAA/ASME/SAE/ASEE 24th Joint Propulsion Conference, July 1988

[5] G. Waxenegger-Wilfing, K. Dresia, J. Deeken, M. Oschwald, Machine Learning Methods for the Design and Operation of Liquid Rocket Engines – Research Activities at the DLR Institute of Space Propulsion, Space Propulsion 2020+1 Conference, 2021