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# Modelling & Simulation (M&S) – Physics Based and Data Driven (V3)

## *Rotorcraft Structures Workshop*


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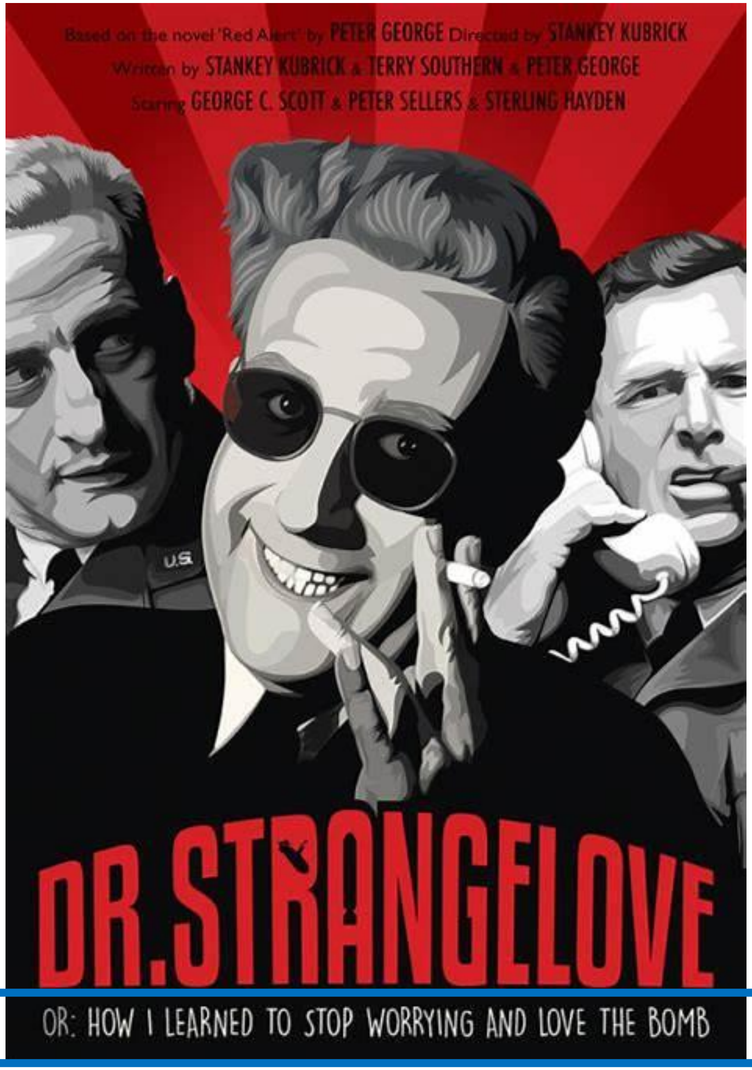
# Disclaimer

# The main inspiration for this presentation….




How to learn to stop worrying
and embrace Modelling & Simulation…

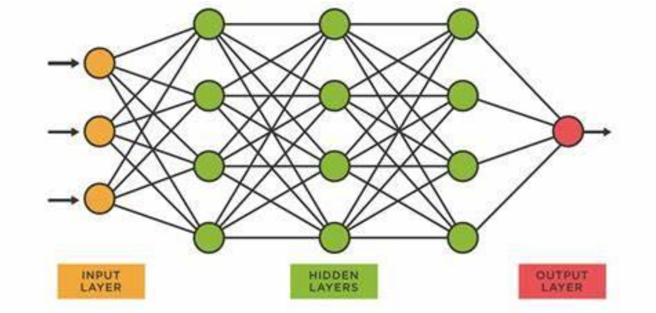
….or: how can I trust computational models
and their results?

# Contents

- Part I: Physics Based M&S
  - Background
  - “Certification by Analysis”
  - ASME VVUQ 90 Committee
  - Summary & Conclusions

Credibility

- Part II: Artificial Intelligence (AI) / Machine Learning (ML) – Data Driven M&S
  - Background
  - Example ML Application to Structures
  - Physics Based Models versus Data Driven ML Models
  - Main Lessons Learned (so far…)
  - Summary & Conclusions




Learning Assurance

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# Part I: Physics Based Modelling & Simulation (M&S)

# Background

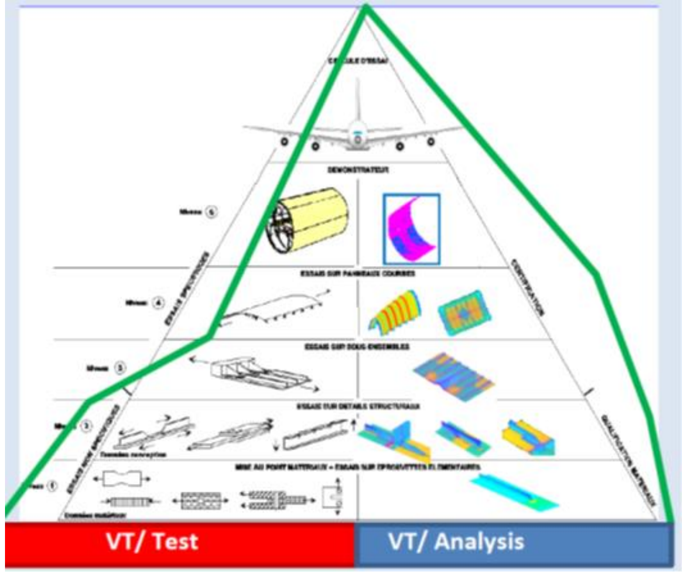
- M&S presentation at Rotorcraft Structures Workshop in 2019:
  - https://www.easa.europa.eu/en/newsroom-and-events/events/rotorcraft-structures-workshop-2019

- What happened since 2019…?
  - Publication of CM-S-014 “Modelling & Simulation – CS-25 Structural Certification Specifications” for public consultation (July 2020)
    - Final version still pending – 2Q2025
  - Publication of Industry White Paper (July 2020) on Modelling & Simulation for (CS-25) Airframe Structures
  - Start of Industry/Authorities WG (September 2020)
  - Creation of ASME VVUQ 90 committee early 2023 – continuation of Industry/Authorities WG
  - Objective to develop VVUQ 90 ASME Standard “Airframe Structures Modeling & Simulation Credibility Assurance Framework”
  - Final version 3Q2025

# Certification by Analysis (1/2)

- "Certification by Analysis" (CbA) or "Virtual Certification" - not very well defined
  - May give wrong impression all (strength, impact…) substantiations can be done by analysis
  - More objective term "Modelling & Simulation" (M&S) is generally preferred to CbA

- General understanding of CbA:
  - An increased reliance on M&S, often in combination with reduction (or re-definition) of the amount of physical testing




E.g. static strength, bird impact, fuel tank crashworthiness,…

↓

M&S to determine critical case(s) to be tested

↓

Perform test(s) and validate M&S model(s)

↓

Substantiation based on validated M&S model(s) (similarity, extrapolation,…)

# Certification by Analysis (2/2)

- The main challenge: the iceberg called Credibility...

Typical focus during certification

Validation

Verification

Errors & Uncertainty Quantification

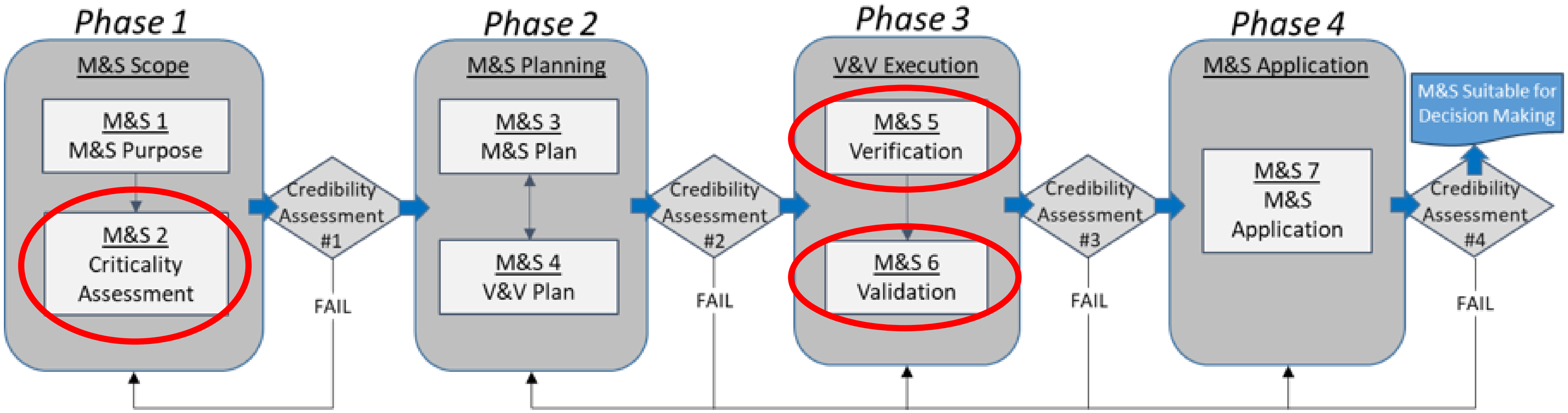
Hardware & Software Qualification

Data Governance

Experience

# VVUQ 90: Airframe Structures M&S Credibility Assurance Framework (CAF)

- Credibility Assurance Framework (CAF):




- Main CAF elements discussed:
  - Criticality Assessment
  - Verification
  - Validation (including Errors & Uncertainty Quantification)

# VVUQ 90: Airframe Structures M&S Credibility Assurance Framework (CAF)

- Criticality Assessment

| | | Criticality Level | | | |
|---|---|---|---|---|---|
| M&S Influence Level | 1 | LOW | MEDIUM | HIGH | HIGH |
| | 2 | LOW | MEDIUM | MEDIUM | HIGH |
| | 3 | LOW | LOW | MEDIUM | MEDIUM |
| | 4 | LOW | LOW | LOW | MEDIUM |
| | | D | C | B | A |
| | | Design Influence Level | | | |

- Low criticality M&S applications do not require application of the CAF process, but applicants might benefit from applying it. Industry M&S best practices for V&V activities supported by applicant´s demonstrated capabilities are sufficient to provide credibility to low criticality M&S applications.
- Medium criticality M&S applications are typically expected to apply the CAF process, but with commensurate levels of effort.
- High criticality applications are expected to apply the CAF process with significant levels of effort.

# VVUQ 90: Airframe Structures M&S Credibility Assurance Framework (CAF)

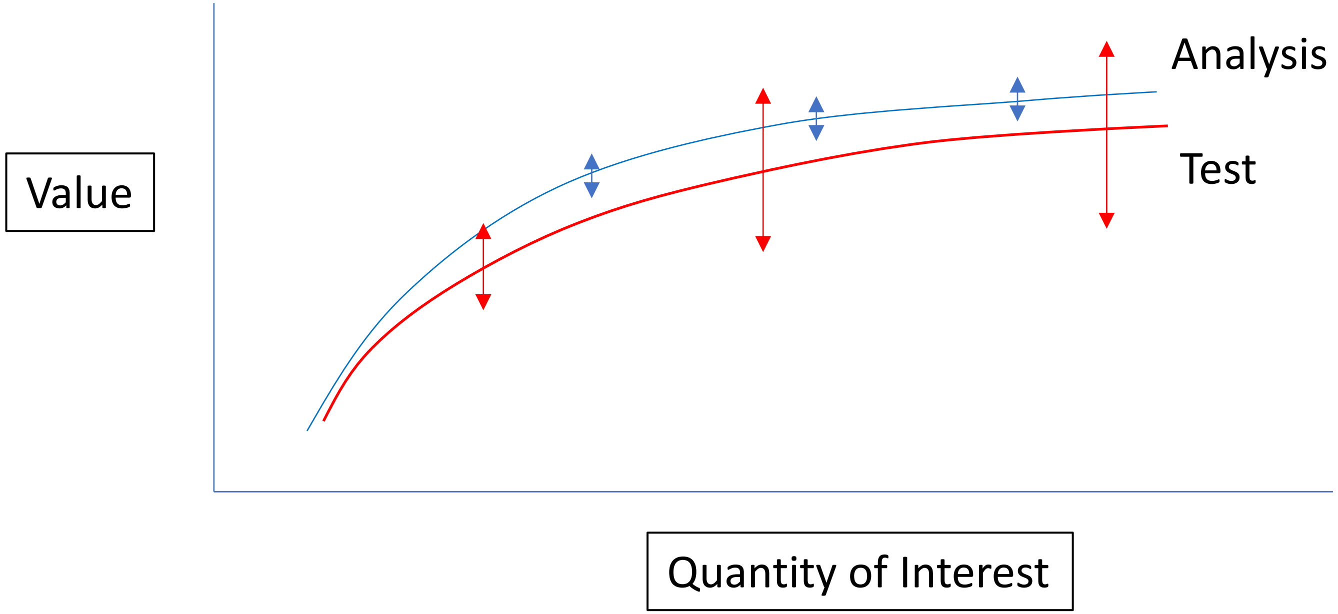
- Verification
  - Verification is the process that establishes the mathematical correctness of the model ("did I build the model correctly?")

- Main verification checks:
  - *Code verification (Hardware & Software Qualification)*
    - Software Quality Assurance (SQA): software errors and bugs
    - Numerical Algorithm Verification: correct implementation of the discretization and solution algorithms
  - Verify that all *model input data* are correctly defined, used and applied to the model
    - Geometry, materials, loads, boundary conditions,….
  - *Verification of the model*
    - Model quality checks (coordinate systems, units, mesh quality,..)
    - Numerical plausibility checks (unit gravity, strain energy,…)
  - *Calculation verification*
    - To assess compliance with the calculation accuracy requirements (mesh convergence,..)

# VVUQ 90: Airframe Structures M&S Credibility Assurance Framework (CAF)

- Validation
  - Validation is the process of determining the degree to which a model represents the referent (test) data ("did I build the correct model?")

  - Well established practice of comparing analysis results with test data
    - Except for Uncertainty Quantification, see next slide



# VVUQ 90: Airframe Structures M&S Credibility Assurance Framework (CAF)

- Errors & Uncertainty Quantification
  - M&S process and referent (test) data are subject to errors and uncertainties
  - These affect the accuracy of the analysis and test results, as well as the comparison (validation)
  - Identification, minimization and quantification process is called Uncertainty Quantification (UQ)

  - Various UQ methods exist, see e.g. ASME VVUQ 10 & 20 documents
  - Require multiple simulation runs (from dozens to thousands) - prohibitive in industrial context
  - Current practice mostly based on safety factors, conservative data and assumptions and “high quality” test data and simulations

  - Today, UQ is one of the weak links in the credibility chain
    - Subject to on-going research activities

# Summary & Conclusions (for Physics Based M&S)

- Interest from Industry to re-define balance between test data and M&S efforts
  - To reduce cost, development & certification time and test failure mitigation
- Requires more attention to all Credibility aspects
  - Historically focus on Validation aspects
- CM-S-014 & VVUQ 90 Standard are both providing guidance on the Credibility process for airframe (CS-25) applications
  - Principles applicable to other Products as well
  - Software Verification and Uncertainty Quantification remain weak links in VVUQ chain
  - Concern with new or less experienced applicants, or new M&S applications

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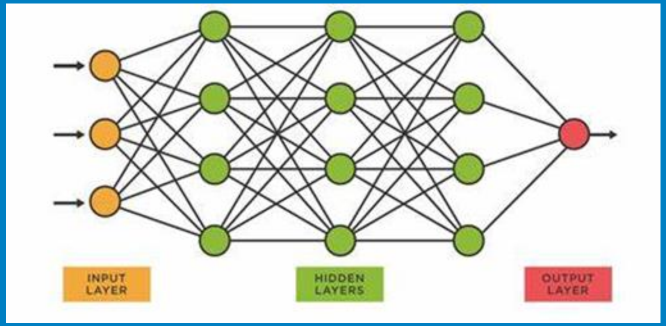
# Artificial Intelligence (AI) / Machine Learning (ML) - Data Driven Modelling & Simulation (M&S)

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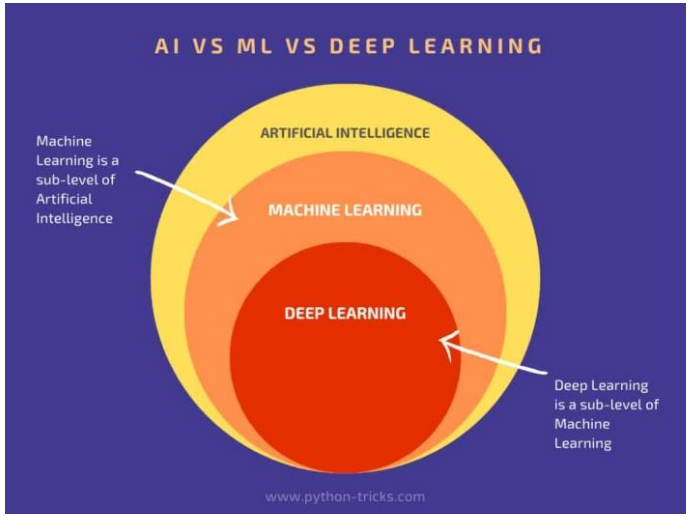
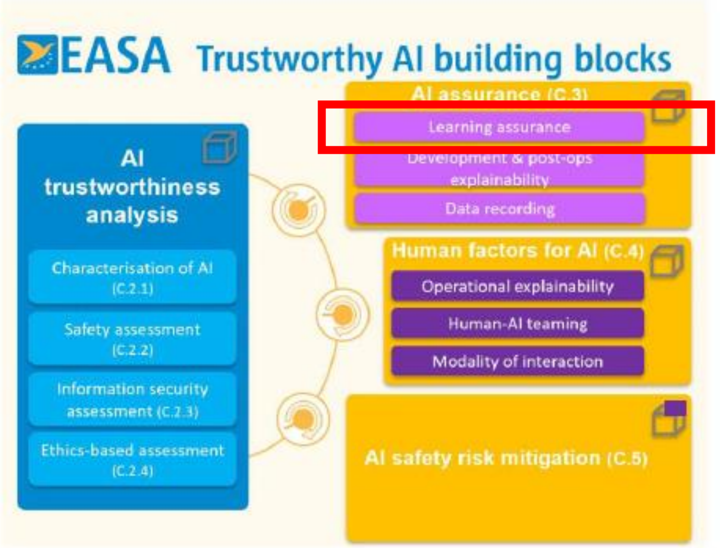
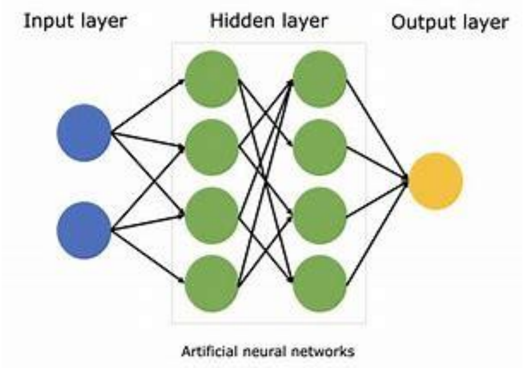
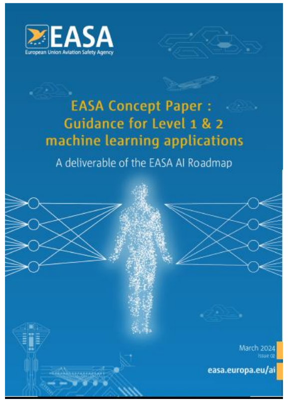
# Background (1/2)

- EASA Concept Paper on Machine Learning Applications (issue 2)
  - Level 1 and Level 2 AI applications, but not covering Level 3 AI applications;
  - Supervised learning, but not other types of learning such as unsupervised or reinforcement learning;
  - Off-line learning processes where the model is ‘frozen’ at the time of approval, but not adaptive or online learning processes
  - Focus on Decision Trees and Neural Networks




| Level 1 AI : assistance to human | Level 2 AI : human-AI teaming | Level 3 AI : advanced automation |
|---|---|---|
| •Level 1A: Human augmentation<br><br>•Level 1B: Human cognitive assistance in decision and action selection | •Level 2A: Human and AI-based system cooperation<br><br>•Level 2B: Human and AI-based system collaboration | • Level 3A: The AI-based system makes decisions and performs actions, safeguarded by the human.<br><br>•Level 3B: The AI-based system makes non-supervised decisions and performs non-supervised actions. |

# Background (2/2)

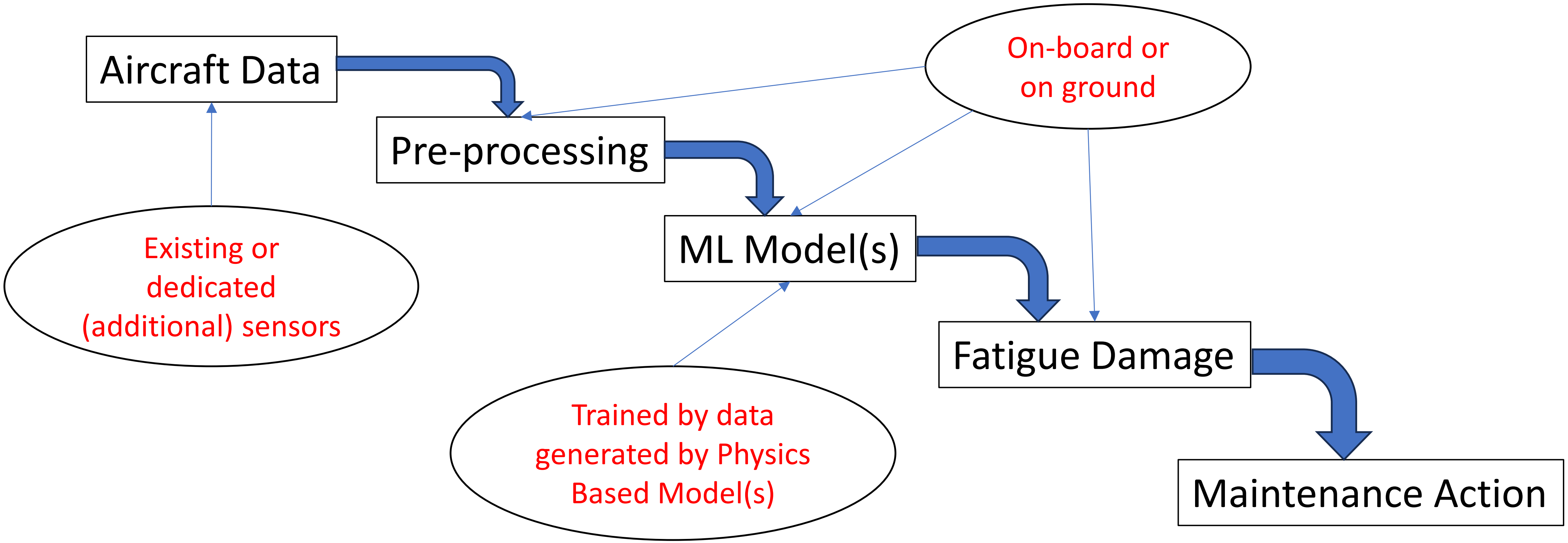
- Most aerospace activities on AI/ML tend to focus on systems assisting (or perhaps in the future replacing…) the flight crew in the performance of their tasks

- So far, application of AI/ML to Structures is relative limited
- EASA is involved in a number of projects with a number of applicants
  - Through Research & Innovation, Technical Advice Contract (TAC), DOA Extension of Scope,….

- These Structures applications are mostly characterized by:
  - Focus on stress, fatigue and loads
  - Use of Surrogate ML Models (NN/regression) to replace Physics Based Models
    - ML Models trained on data generated by Physics Based Models
  - Use of recorded aircraft data to support assessment of in-service events or to determine fatigue damage

# Example ML Application to Structures

- Use of aircraft data to derive fatigue damage
  - Aircraft Health / Usage / Vibration Monitoring “with a ML twist”



# Physics Based Models versus Data Driven ML Models

| Physics Based M&S | Data Driven M&S |
|---|---|
| Credibility | Learning Assurance |
| Criticality assessment | Proportionality |
| Validation based on physical tests | Validation based on validation / test data |
| Verification<br><br>- Hardware & Software<br>- Input Data<br>- Model<br>- Calculation / Solution | Verification<br><br>- Hardware & Software<br>- Data Management<br>- Validation based on validation / test data<br>- (not so much) |
| UQ – deterministic<br><br>(conservative methods and assumptions, high quality test data, safety factors,…) | UQ – probabilistic<br><br>(bandwidth of results with probability of 99.5% with a confidence level of 95%) |

# Main Lessons Learned (so far…) with ML Models for Structures

- Data management
  - Crucial for credibility of final results
  - Requires “end-to-end” approach (from data acquisition to final result)

- Verification, Validation and Uncertainty Quantification (VVUQ)
  - Covered through application of EASA Concept Paper
  - Challenge to establish equivalent level of VVUQ between ML Surrogate models and Physics Based models
    - Lack of rigorous UQ process for Physics Based models
    - Different definition of accuracy (deterministic vs. probabilistic)
    - Errors and Uncertainties in ML models largely subject to research (methods and criteria)

- Assurance Level (hardware, software, ML model)
  - Challenge to assign appropriate assurance level and standards to be applied
    - Failure of ground-based ML model: Minor? Catastrophic? Determines assurance objectives to be met in EASA Concept Paper

# Summary & Conclusions (for Data Driven M&S)

- Emerging applications of (Surrogate) ML models in structural applications

- Application of EASA Concept Paper on AI/ML
  - Issue 2 explicitly covers Surrogate ML models
  - Also covers Verification, Validation, Errors & Uncertainty Quantification
    - Note: For Maintenance Domain no safety assessment is required => but Instructions for Continued Airworthiness (ICA) is considered to be part of Initial Airworthiness

- Main challenges identified in:
  - Data management
  - Addressing VVUQ (methods and pass-fail criteria)
  - Defining appropriate Assurance Level(s) (in particular for ground based equipment)

# The Future is Made Today…

### Machine Learning

$$u^\star = \operatorname{argmin}_{\mathbf{u}} \quad \frac{1}{N}\sum_{i=1}^{N} L\left(\nu_i, y_i, \mathbf{u}\right)$$

### Differential Equation

$$\begin{cases} \dfrac{\partial v}{\partial t}(t,x) + \mathcal{N}[v](t,x) = 0, & (t,x) \in [0,T)\times\Omega, \\ v(\cdot,x)|_{x\in\partial\Omega} = v_{\partial\Omega}, \\ v(0,\cdot) = v_0. \end{cases}$$

Optimization

### Physics-Informed Neural Networks

$$\theta^\star = \operatorname{argmin}_{\boldsymbol{\theta}} \quad \frac{1}{N}\sum_{i=1}^{N}\left(u_{\boldsymbol{\theta}}(t_i,x_i) - y_i\right)^2$$

Measurement error

Constraint

$$\text{s. t.} \quad \frac{\partial u_{\boldsymbol{\theta}}}{\partial t}(t,x) + \mathcal{N}[u_{\boldsymbol{\theta}}](t,x) = 0, \quad (t,x) \in [0,T)\times\Omega.$$

$\Rightarrow$ Learning under constraint problem

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