European Aerospace Science Network (EASN) 2025: Session LCA in Aviation

Uncertainty Quantification in Life Cycle Assessment for Aviation

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DLR

Life Cycle Assessment
according to DIN EN ISO 14040/14044

Goal and Scope

Defining the system boundaries and functional unit

Life Cycle Inventory

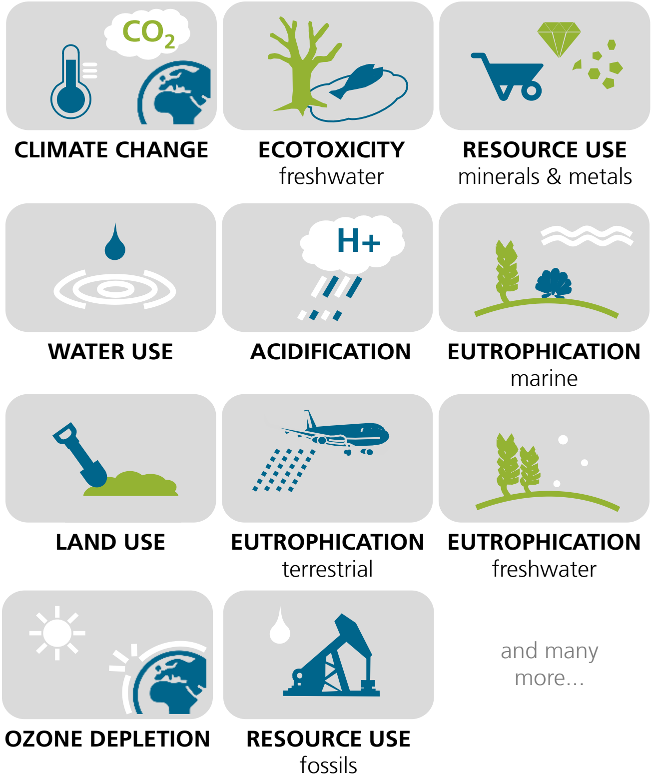
Modelling the inventory: materials, energy, emissions and waste

Life Cycle Impact Assessment

Translating the inventory to environmental impacts

Interpretation

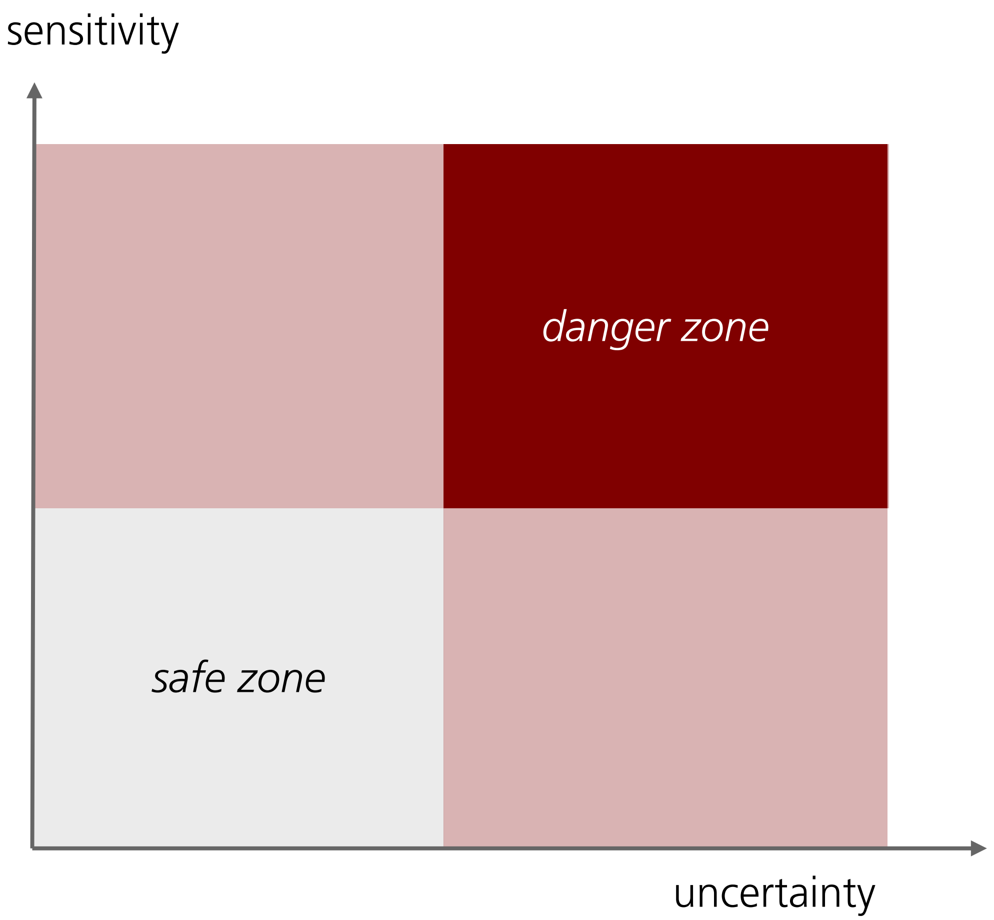
Drawing conclusions and analysing of results
(→ includes uncertainty and sensitivity assessment)



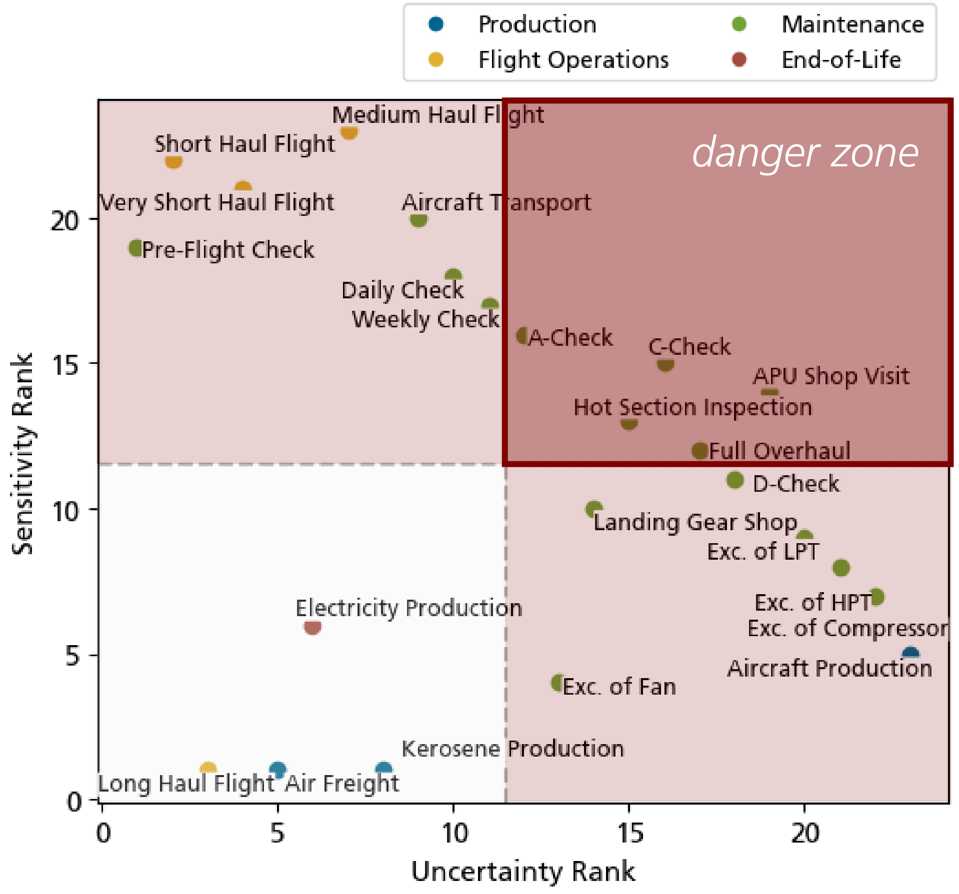
Why should we care about uncertainties?

- LCA is a model that assesses *potential* environmental impacts
- Transparency regarding uncertainties enables trustworthiness
- Uncertainty analysis can help direct efforts for model improvement

Finding Critical Parameters: Diagnostic Diagrams



Diagnostic Diagram for a Case Study



- D250-TF-2040 from DLR's digital hangar
  - Short-haul aircraft with Entry into Service 2040
  - Turbofan with kerosene combustion
- Data from the projects EXACT and ALICIA

Methodological Framework

Discrete-Event Life Cycle Assessment

Lifecycle Analysis Framework for Environment and Economics (LYFE²)
DLR‘s in-house discrete-event simulation framework

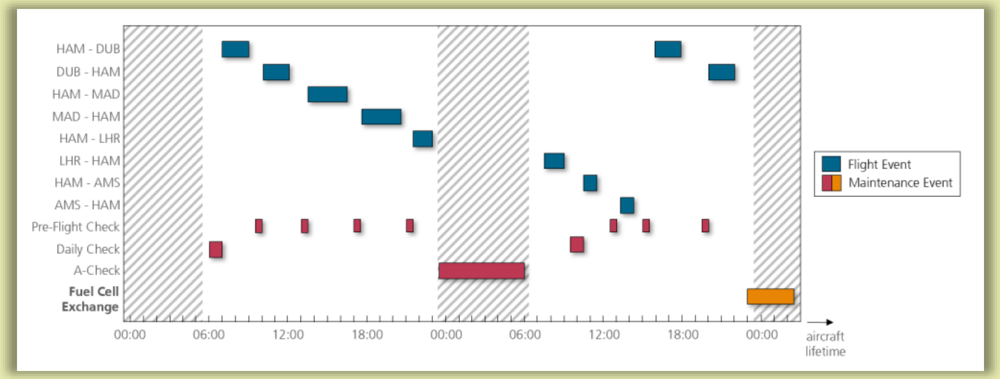


Figure 1: Event calendar from LYFE²

Institute of Maintenance, Repair and Overhaul

Lifecycle Analysis Framework for Environment and Economics (LYFE²)

Life Cycle Assessment (LCA) using Brightway2
Defined by DIN EN ISO 14040 & 14044

- Goal and Scope Definition
- Life Cycle Inventory
- Life Cycle Impact Assessment
- Interpretation

Connection of LCA and Discrete-Event Simulation

input parameters for cradle-to-gate LCAs

LCA Databases

Cradle-to-Gate LCAs

A-Check

- Aircraft Towing
- Engine Oil Replacement
- Kerosene for Test Run
- Engine Wash Fluid
- Filter Exchange
- GPU Operation
- Hangar Operation
- Heat Exchanger
- Transport to/from Shop
- Tyre Production

Aircraft Production

Daily Check

C-Check

…

cradle-to-gate LCA results = LYFE² input parameters

AirLYFE Lifecycle Analysis Framework for Environment and Economics (LYFE²)

Life Cycle Inventory of an A-Check

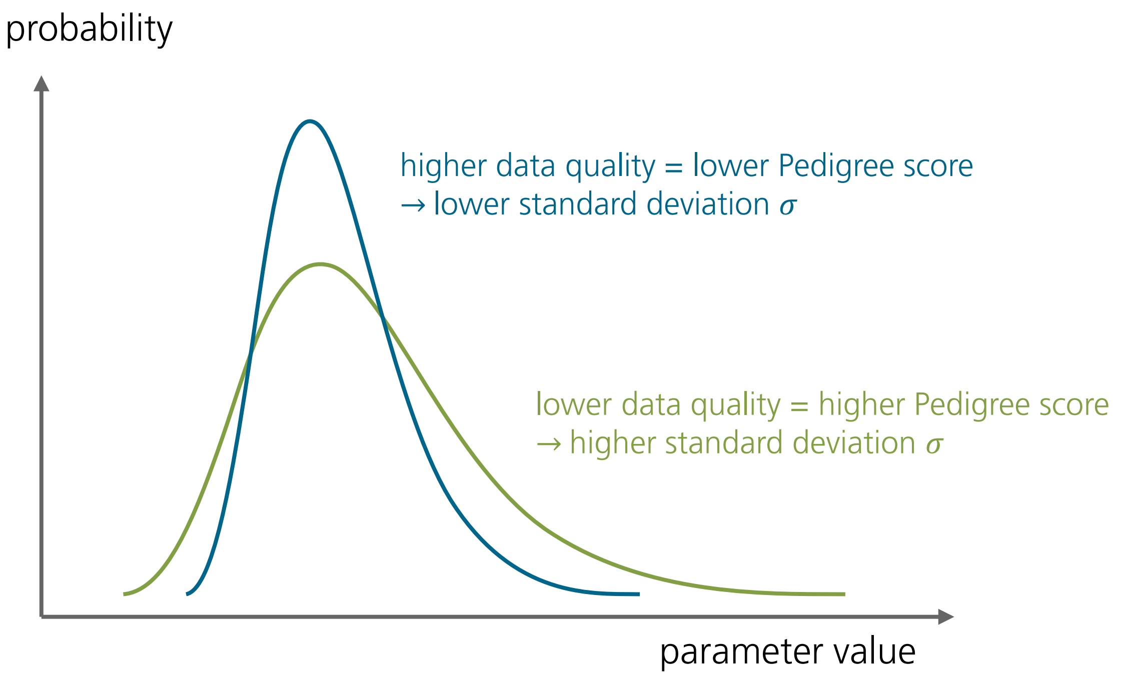
Input Activity	Deterministic Amount	Unit
Aircraft Towing	1.0	–
Engine Oil Replacement	3.2	kg
Kerosene for Test Run	578.4	kg
Engine Wash Fluid	140.0	kg
Filter Exchange	1.5	kg
GPU Operation	10.0	h
Hangar Operation	10.0	h
Heat Exchanger	1.0	h
Transport to/from Shop	664.0	tkm
Tyre Production	109.4	kg

Pedigree Approach by Ciroth et al. (2016)[1]

Assessing data quality based on five criteria:

- Reliability
- Completeness
- Temporal Correlation
- Geographical Correlation
- Technological Correlation

→ Modelling of a log-normal probability distribution



1 Ciroth, Andreas et al. "Empirically based uncertainty factors for the pedigree matrix in ecoinvent". In: The international journal of life cycle assessment 21.9 (Jan. 2016), pp. 1338–1348. ISSN: 0948-3349. DOI: 10.1007/s11367-013-0670-5

Modelling of probability distributions for an A-Check

Using the Pedigree Approach

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Input Activity	Deterministic Amount (= Mean μ)	Pedigree Scores	Standard Deviation σ	Unit
Aircraft Towing	1.0	(4,5,1,1,2)	0.29	–
Engine Oil Replacement	3.2	(4,4,1,1,2)	0.92	kg
Kerosene for Test Run	578.4	(4,5,1,1,2)	169.2	kg
Engine Wash Fluid	140.0	(4,5,1,2,2)	41.3	kg
Filter Exchange	1.5	(4,5,1,2,5)	0.74	kg
GPU Operation	10.0	(4,5,1,1,2)	2.9	h
Hangar Operation	10.0	(4,5,1,1,2)	2.9	h
Heat Exchanger	1.0	(4,5,1,1,2)	0.29	h
Transport to/from Shop	664.0	(4,5,4,2,2)	200.0	tkm
Tyre Production	109.4	(4,5,1,2,2)	32.3	kg

Individual Events: Uncertainty and Sensitivity Scores

Pedigree Approach and Local Sensitivity Analysis

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Uncertainty quantification

Qualitative assessment of data quality using scores between 1 and 5

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Deterministic amount becomes mean μ

↓

Scores are translated into standard deviation σ

↓

Calculating uncertainty score σ / μ

Sensitivity quantification

Setting each parameter to $x_0 = \mu$ and $x_1 = 1.1\mu$

↓

Calculating LCA results y_0 for x_0 and y_1 for x_1

↓

Calculating sensitivity score $(y_1 - y_0)$ / $(x_1 - x_0)$

Uncertainty and Sensitivity Scores for an A-Check

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Input Activity	Deterministic Amount (= Mean μ)	Pedigree Scores	Standard Deviation σ	Unit	Uncertainty Score σ / μ	Sensitivity Score $(y_1 - y_0) / (x_1 - x_0)$
Aircraft Towing	1.0	(4,5,1,1,2)	0.29	–	0.292	8.64
Engine Oil Replacement	3.2	(4,4,1,1,2)	0.92	kg	0.288	6.34
Kerosene for Test Run	578.4	(4,5,1,1,2)	169.2	kg	0.292	5.33
Engine Wash Fluid	140.0	(4,5,1,2,2)	41.3	kg	0.295	2.00
Filter Exchange	1.5	(4,5,1,2,5)	0.74	kg	0.493	39.1
GPU Operation	10.0	(4,5,1,1,2)	2.9	h	0.292	134.0
Hangar Operation	10.0	(4,5,1,1,2)	2.9	h	0.292	66.3
Heat Exchanger	1.0	(4,5,1,1,2)	0.29	h	0.292	7.78
Transport to/from Shop	664.0	(4,5,4,2,2)	200.0	tkm	0.301	0.426
Tyre Production	109.4	(4,5,1,2,2)	32.3	kg	0.295	301

Connection of LCA and Discrete-Event Simulation

✓

input parameters for cradle-to-gate LCAs

LCA Databases

Cradle-to-Gate LCAs

A-Check

- Aircraft Towing
- Engine Oil Replacement
- Kerosene for Test Run
- Engine Wash Fluid
- Filter Exchange
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Aircraft Production

Daily Check

C-Check

…

?

cradle-to-gate LCA results = LYFE² input parameters

AirLYFE Lifecycle Analysis Framework for Environment and Economics (LYFE²)

Discrete-Event LCA: Uncertainty and Sensitivity Scores

Monte Carlo Simulation and Local Sensitivity Analysis

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Uncertainty quantification

Probability distributions from before for each cradle-to-gate input parameter

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Sampling 10,000 sets of parameters from their probability distributions

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Performing 10,000 cradle-to-gate LCA calculations

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Statistical evaluation of mean μ and standard deviation σ of LCA results

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Calculating uncertainty score σ / μ

Sensitivity quantification

Setting each cradle-to-gate LCA result to $x_0 = \mu$ and $x_1 = 1.1\mu$

↓

Calculating LYFE² results y_0 for x_0 and y_1 for x_1

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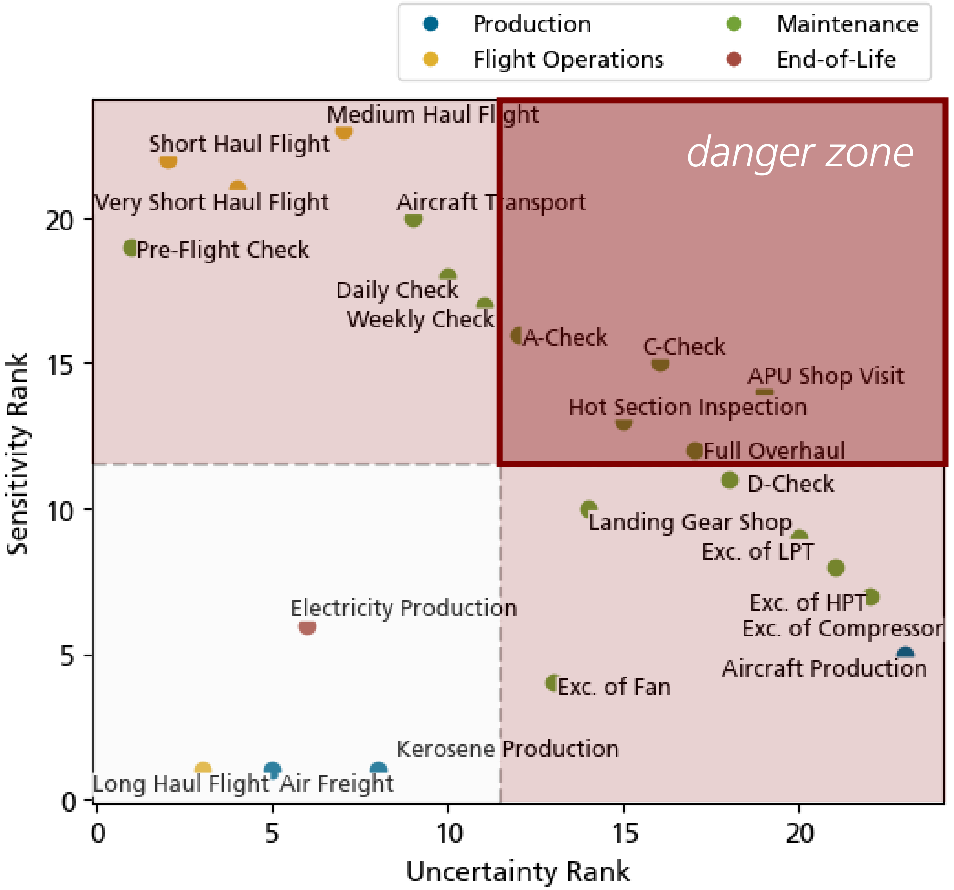
Calculating sensitivity score $(y_1 - y_0)$ / $(x_1 - x_0)$

(same as before)

How to Create a Diagnostic Diagram



Steps to Uncertainty Quantification:

1. Quantifying input uncertainties
   → Pedigree Approach
2. Propagation to cradle-to-gate LCA results
   → Monte Carlo Simulation
3. Sensitivity analysis
4. Communication → Diagnostic diagrams

Different Types of Uncertainties in LCA for aviation

Parameters: amount of required material, fuel burn rates, maintenance frequency, …

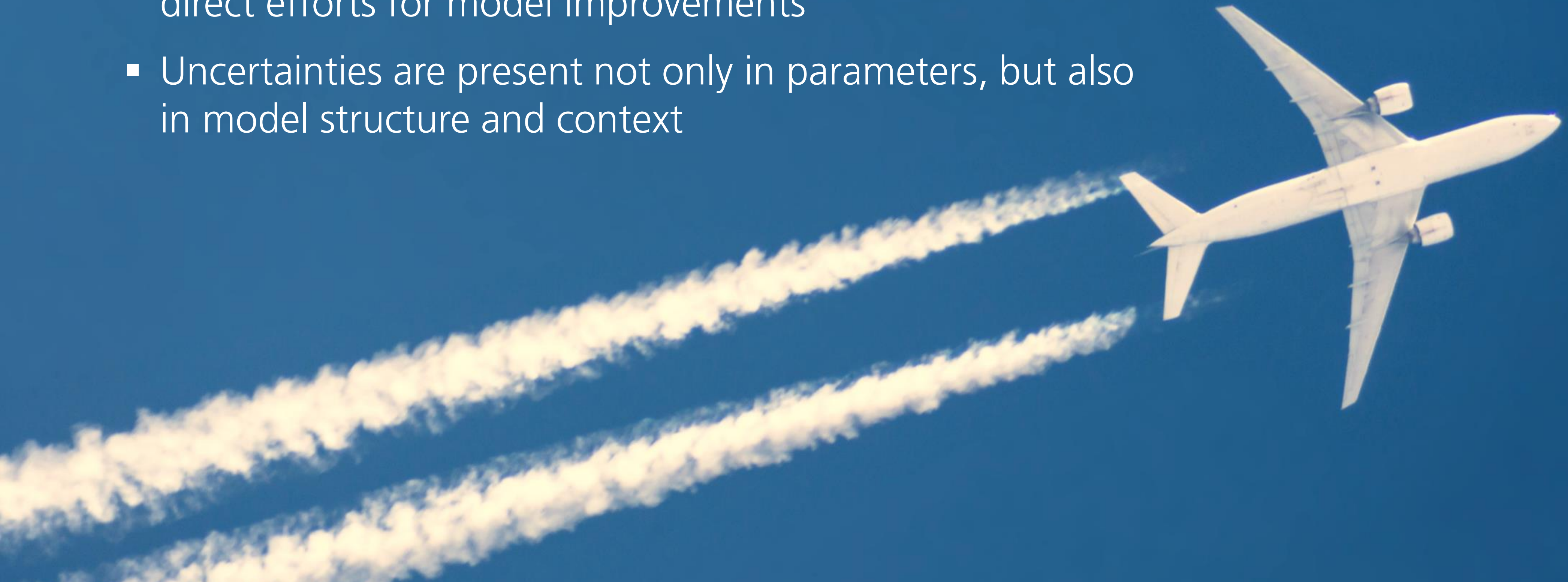
Model structure: simplified modelling of operation and maintenance, allocation models, …

Impact assessment at altitude: contrail formation, non-CO_2 effects, …

Context: fuel pathways, regulations, end-of-life practices, …

Takeaways

- Uncertainty quantification helps ensure trustworthiness in Life Cycle Assessment results
- Diagnostic diagrams can help find critical parameters and direct efforts for model improvements
- Uncertainties are present not only in parameters, but also in model structure and context



Thank you for your attention!

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