FUTure PRopulsion and INTegration
towards a hybrid-electric 50-seat regional aircraft

An interactive framework to facilitate probabilistic set-based multidisciplinary design optimisation studies

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FutPrInt50

Cranfield Aerospace

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European Commission

Content Overview

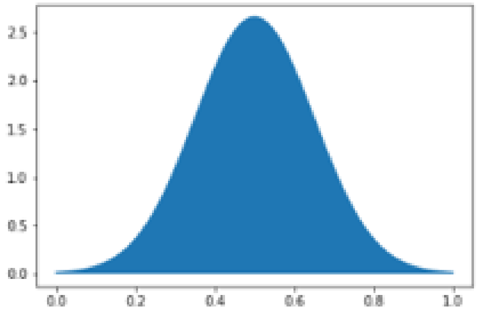
FutPrInt50

- Introduction
- Context and Motivation
- Visualisation tool for decision-making
- Probabilistic set-based multidisciplinary design optimisation
- Interactive Parallel Coordinates and Scatter Plots
- Illustrative use case
- Future Work
- Conclusion/take-aways

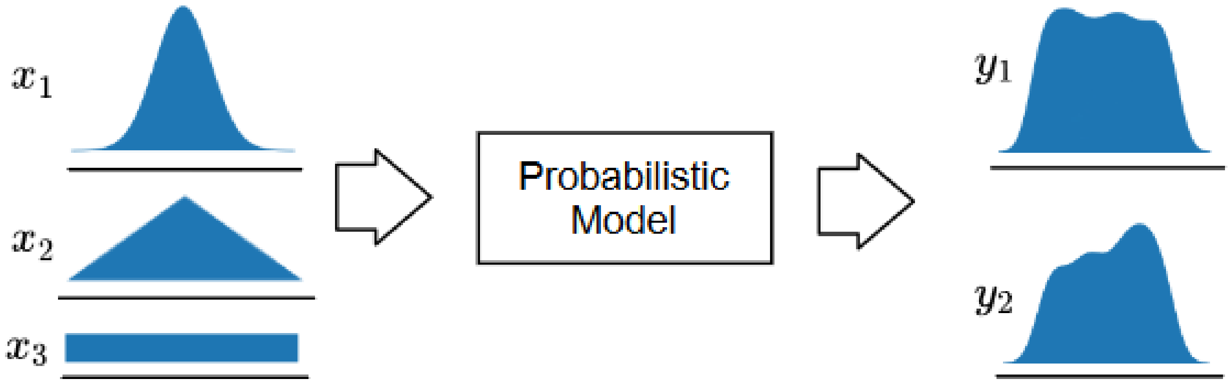
Introduction

Why **probabilities**?

- The concept of probability has been formalized (in Measure Theory) in 1930s by Kolmogorov.
- This means that it can be modelled by a **random variable**. Therefore, **we are not thinking** about situations akin to the toss of a coin (frequentist approach).
- We are thinking about "**states or degrees of belief**".
- **This allows one to deal mathematically with uncertainty and risk associated with future engineering systems.**



Normal or Gaussian distribution $N(\mu, \sigma^2)$



Context and Motivation

- Decision-making and analysis can benefit from this probabilistic perspective provided that the complex mathematics is “hidden” from the user.

- A recent development of a probabilistic set-based multidisciplinary optimisation methodology has demonstrated the ability to explore trade-offs when the requirements are uncertain.

- Based on this methodology, we developed a web application tool to facilitate probabilistic set-based multidisciplinary design optimisation studies.

- This tool allows the user to interactively visualise high-dimensional results using a combination of parallel coordinates and scatter plots.

- This tool is also extendable to facilitate the studies performed by different research codes, by providing a GUI and visualisation interactivity.

Visualisation tool for decision-making

- Provide **interactive multi-dimensional visualisation capability**
- Easy access to **Uncertainty Quantification and Propagation and Sensitivity analysis methods**
- Web and desktop application.
- Offers a easy way to integrate research and engineering codes. (Black-box)
- It will be released as **open-source** after the ending of the FUTPRINT50 project.

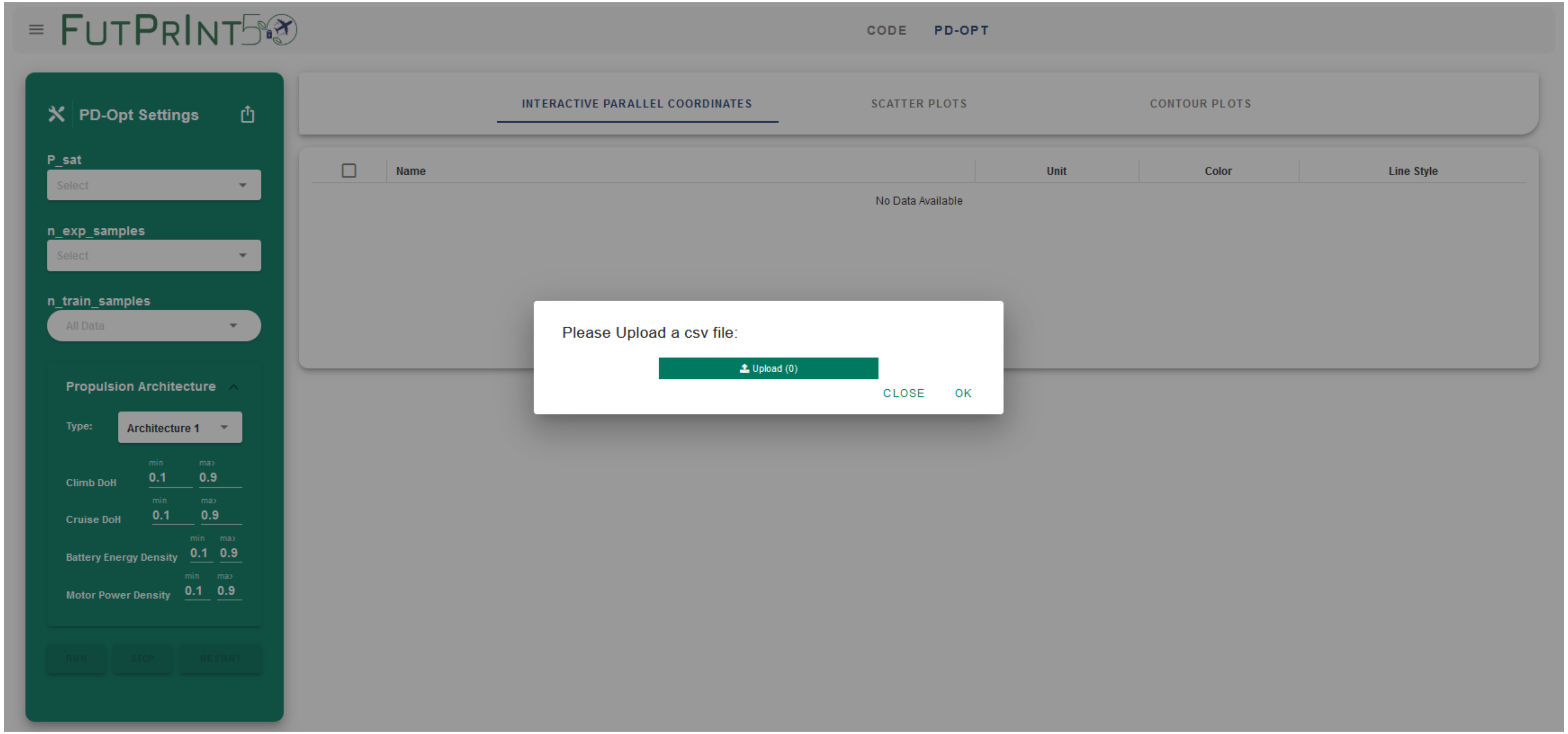
Layer 1 – Given Research Code

Layer 2 – Data-Driven Analytics (UQ)

Layer 3 – High-Dimensional visualisation

Application overview

Visualisation tool for decision-making



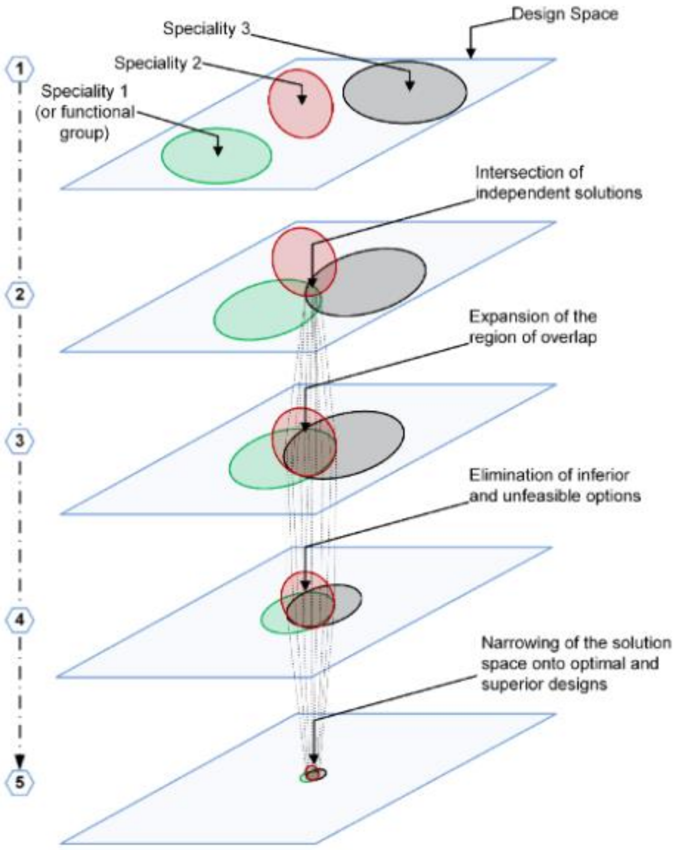
Set-based design

- Contrasted to point-based design.

- Design decisions are delayed until a better understanding of overall relations are identified.

- Disadvantage of the non-probabilistic set-based: it requires expert rules based on domain knowledge.

- Probabilistic set-based replaces the expert rules with a **Statistical Model and Probabilistic Evaluation**



Probabilistic Set-based multidisciplinary design optimization

Design Parameters
Discretized into levels

Requirements
Expressed as Probabilistic Constraints

Step 1

1. Generate "Sets" (Hypercube of levels)
2. Evaluate Sets **by calculating the probability to satisfy requirements**, discard undesirable and infeasible ones.

Step 2

1. Run MOO in surviving sets
2. Discard more sets from MOO results

Visualization and Post-processing

Interactive Parallel Coordinates and Scatter Plots

- In the late 80s, researchers in computer graphics recognized a specific stream of applications as an emerging field and called it **visualisation**[1].
- Designers explore and synthesize multiple alternative solutions in a problem space (**system + subsystems**).
- Parallel coordinates is a widely used visualization technique for multivariate data and high-dimensional geometry.
- Parallel coordinates allows the mapping of subsets of R^n to R^2.
- Parallel coordinates also allows users to interact with the data in many ways. (colour sets and scatter plots).

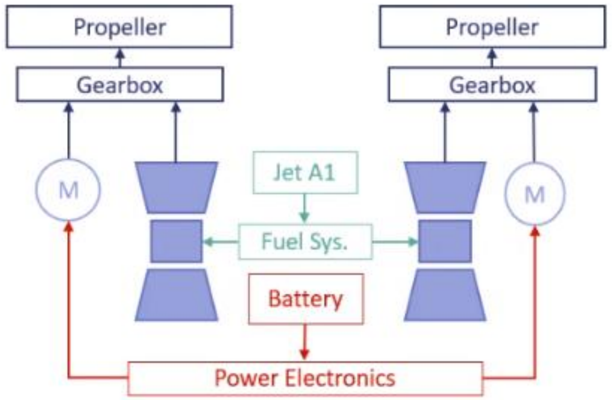
[1]: Parallel Coordinates: Visual multidimensional geometry and its applications by Alfred Inselberg

Problem formulation and results

$$\min_{X} M_{fuel}, M_{NO_x}$$

$s.t:$

$$M_{takeoff} \leq \ 20{,}000\ kg\ (P_{sat} \geq 0.5)$$



we can potentially solve this problem for different configurations and architectures and construct tables such as:

Sets	Optimisation Input x_i				Optimisation Output y_n						Constant Parameter
Set ID	Climb h0	Climb h1	Cruise h0	Cruise h1	Take-off Mass [kg]	Burned ful mass [kg]	Emitted Nox [kg]	Battery Mass [kg]	Emitted CO [kg]	Emitted CO2 [kg]	Battery Energy density [Wh/kg]
0	0.019019	0.042392	0.176987	0.136356	18488.12	1053.11484	6.390926	885.000801	11.29786	3159.345	**500**
0	0.248721	0.247232	0.248985	0.246306	19570.91	1019.602066	6.012993	2001.31695	11.58773	3058.806	**500**
1	0.188485	0.022992	0.109803	0.252109	18830.09	1042.594753	6.223893	1237.48971	11.76279	3127.784	**500**
1	0.241412	0.108446	0.216049	0.453849	19924.61	1009.550187	5.852417	2365.06638	14.62732	3028.651	**500**
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	**500**
4	0.245803	0.211336	0.40778	0.24737	19992.22	1007.329279	5.831765	2434.90193	14.0391	3021.988	**500**
4	0.245178	0.201692	0.413797	0.008595	19258.76	1030.272815	6.050613	1678.48368	12.76141	3090.818	**500**
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	**500**
208	0.773123	0.41146	0.108772	0.10428	19701.79	1017.944584	5.820675	2133.85199	13.47194	3053.834	**500**
208	0.75259	0.252407	0.005897	0.001813	18873.93	1044.221176	6.062478	1279.70633	13.03581	3132.664	**500**

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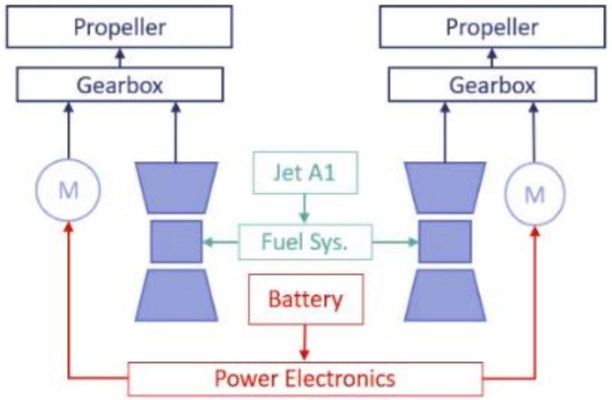

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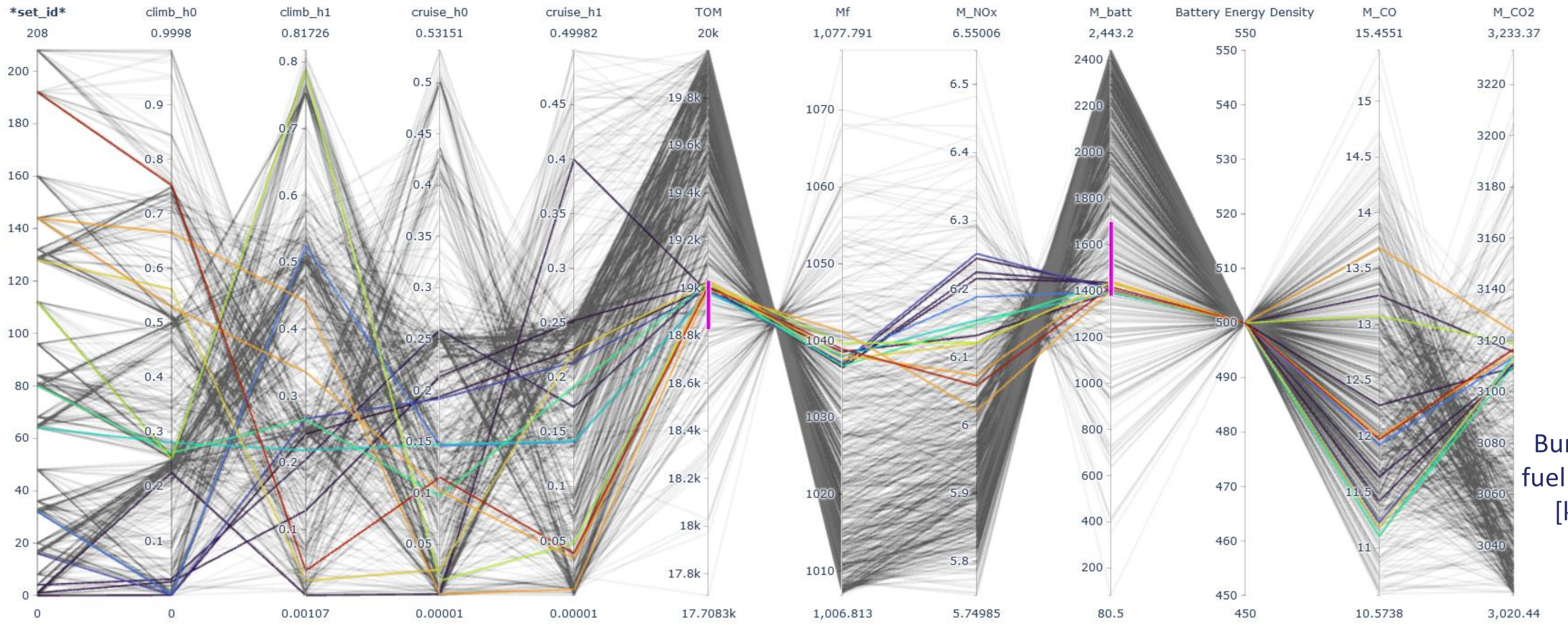
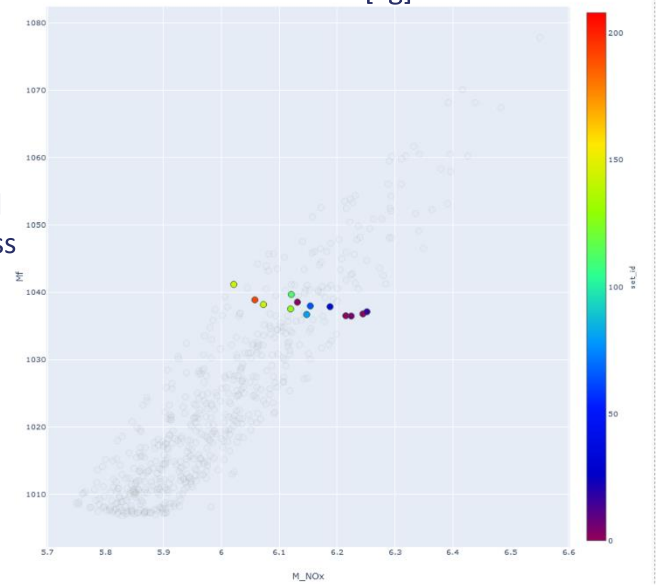
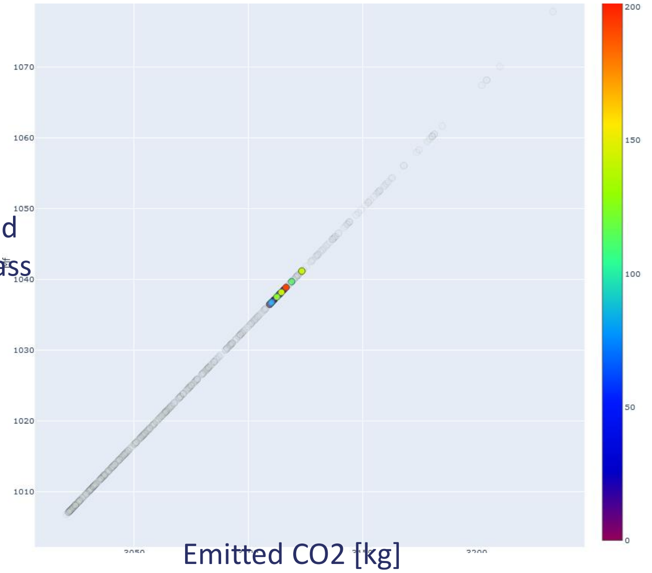
Use Case – identifying sets under MTOW 19000 kg

$$\min_{X} M_{fuel}, M_{NO_x} \quad s.t{:}$$
$$M_{takeoff} \leq \ 20{,}000\ kg\ (P_{sat} \geq 0.5)$$







Use Case Future Work

- For a reconstructed probabilistic model *f:*

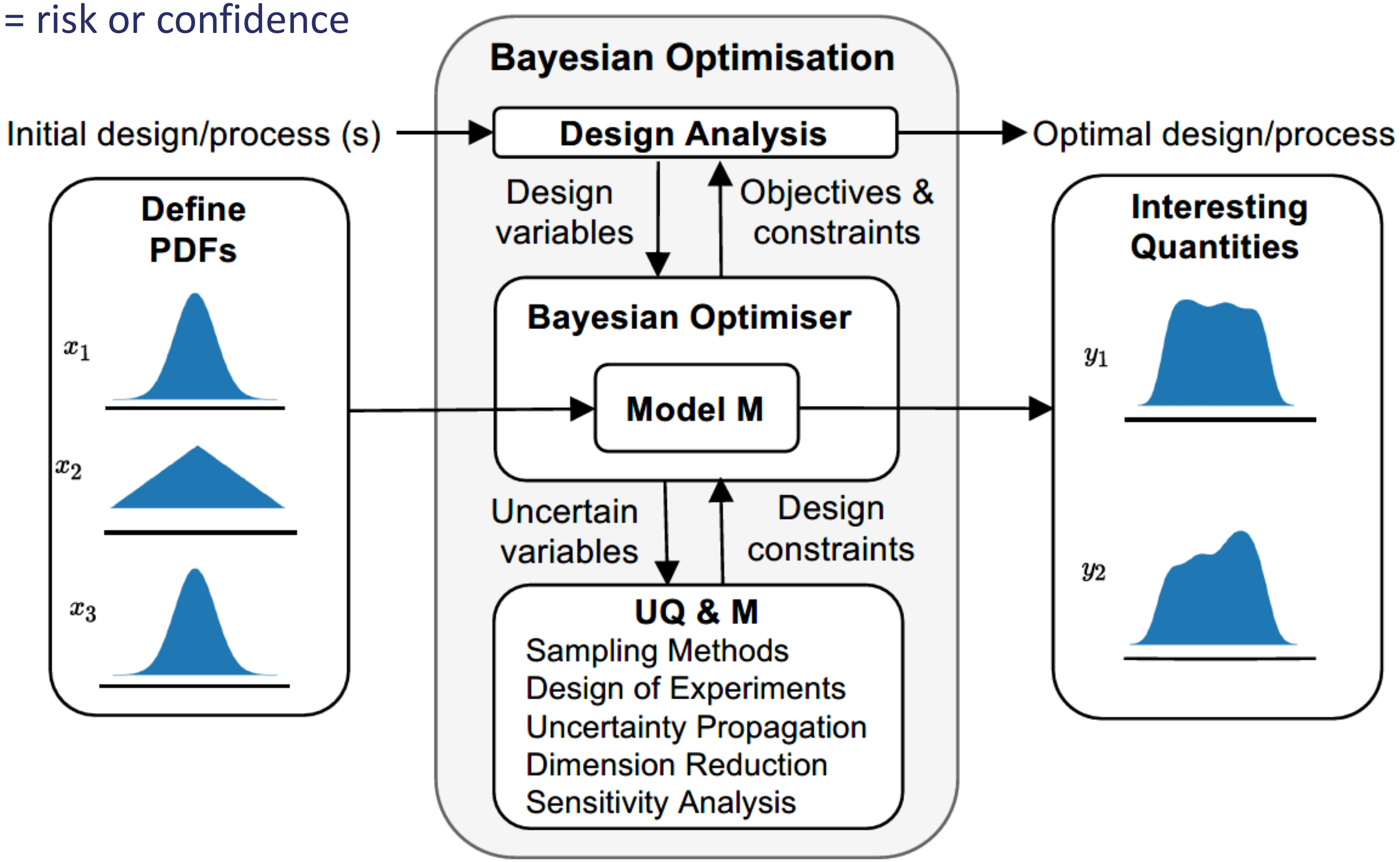
$$\tilde{y}_1, \cdots, \tilde{y}_n = f(\tilde{x}_1, \cdots, \tilde{x}_i)$$

- We would like to answer questions, such as:
  - How the technology **uncertainties** modelled by parameters $\tilde{x}_1, \cdots, \tilde{x}_i$ affect the outputs $\tilde{y}_1, \cdots, \tilde{y}_n$? (uncertainty propagation problem)
  - What is the sensitivity of the outputs $\tilde{y}_1, \cdots, \tilde{y}_n$ and its **uncertainties** to a given input, for instance, the battery power density? (technology forecasting problem)
- Also, we may be interested in the inverse problem:

$$\tilde{x}_1, \cdots, \tilde{x}_i = F(\tilde{y}_1, \cdots, \tilde{y}_n)$$

Use Case Future Work

- Probability = uncertainty = risk or confidence



Conclusion/take-aways

- Research codes integrated in an easy-to-use web visualisation tool can assist top-management to make decisions, without the need for specialized computational and mathematical knowledge.
- The interactive interface developed guides the user through the steps of the design methodology and the produced data is visualised to aid an informative decision-making process.
- In our illustrative case study, decision-makers are enabled to interactively explore the hybrid-electric propulsion design space while considering the impact to the figures of merit from expected improvements in the coming years of key enabling technologies.
- In this way, the feasibility of hybrid-electric aircraft can be studied from a systems perspective but maintaining the connection with more detailed trade-off studies of components of the sub-systems.

THANK YOU!

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Definitions

Degree of Hybridisation (DOH) is defined with a combination of two parameters: the degree of hybridisation itself h and its relative distance position x across the mission phase.

These two quantities are defined as follows:

$$h_i = \frac{p_{re}}{p_{rt}} \in [0,1]$$

$$x_i = \frac{d}{L} \in [0,1]$$

where P_{rt} is the total power (in Watts) required to sustain flight across the mission phase, of which P_{re} is the amount to be provided by electric propulsion, d is the length of the phase spanned over the total phase length L (in kilometers).

References

1. Singer, D. J., Doerry, N., and Buckley, M. E. (2009). What is set-based design? Naval Engineers Journal, 121(4):31–43
2. Georgiades A., Sharma S., Kipouros T., & Savill M. (2019). ADOPT: An augmented set-based design framework with optimisation. Design Science, 5, E4. https://doi.org/10.1017/dsj.2019.1
3. Spinelli, Andrea, Luchien Anderson, and Hossein Balaghi Enalou. "Application of Probabilistic principles to Set-Based Design for the optimisation of a hybrid-electric propulsion system." *IOP Conference Series: Materials Science and Engineering*. Vol. 1226. No. 1. IOP Publishing, 2022. https://doi.org/10.1088/1757-899X/1226/1/012064
4. Spinelli, A.; Enalou, H.B.; Zaghari, B.; Kipouros, T.; Laskaridis, P. Application of Probabilistic Set-Based Design Exploration on the Energy Management of a Hybrid-Electric Aircraft. *Aerospace* **2022**, *9*, 147. https://doi.org/10.3390/aerospace9030147
5. Eisenhut, D.; Moebs, N.; Windels, E.; Bergmann, D.; Geiß, I.; Reis, R.; Strohmayer, A. Aircraft Requirements for Sustainable Regional Aviation. *Aerospace* **2021**, *8*, 61. https://doi.org/10.3390/aerospace8030061

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Probabilistic set-based multidisciplinary design optimization

i-th Set

Sampling

X^i

Experimental Data

Look-up Tables

Data sampled from numerical model

Build

Statistical Surrogate Model

$\mu_{QoI}, \sigma_{QoI} = F(X)$

Where QoI is either objectives or constraints

Probabilistic Requirements
P(F(X) > g) > 10%

$$P_k^i(F(X) > g) = \Phi\left(\frac{\mu_k^i - g}{\sigma_k^i}\right)$$

$$P(Req.\,|i\text{–}th\ Set) = \frac{n_{samples}\ such\ that\ \sum P(F(X) > g) > 0.1}{N_{samples}}$$

Multiple requirements are combined by assuming conditional independence:

$$P(i\text{–}th\ Set) = \prod P(j\text{–}th\ Req.\,|i\text{–}th\ Set)$$