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U-HARWARD second dissemination event

Conceptual design and sensitivity analysis for ultra-high aspect ratio wing aircraft

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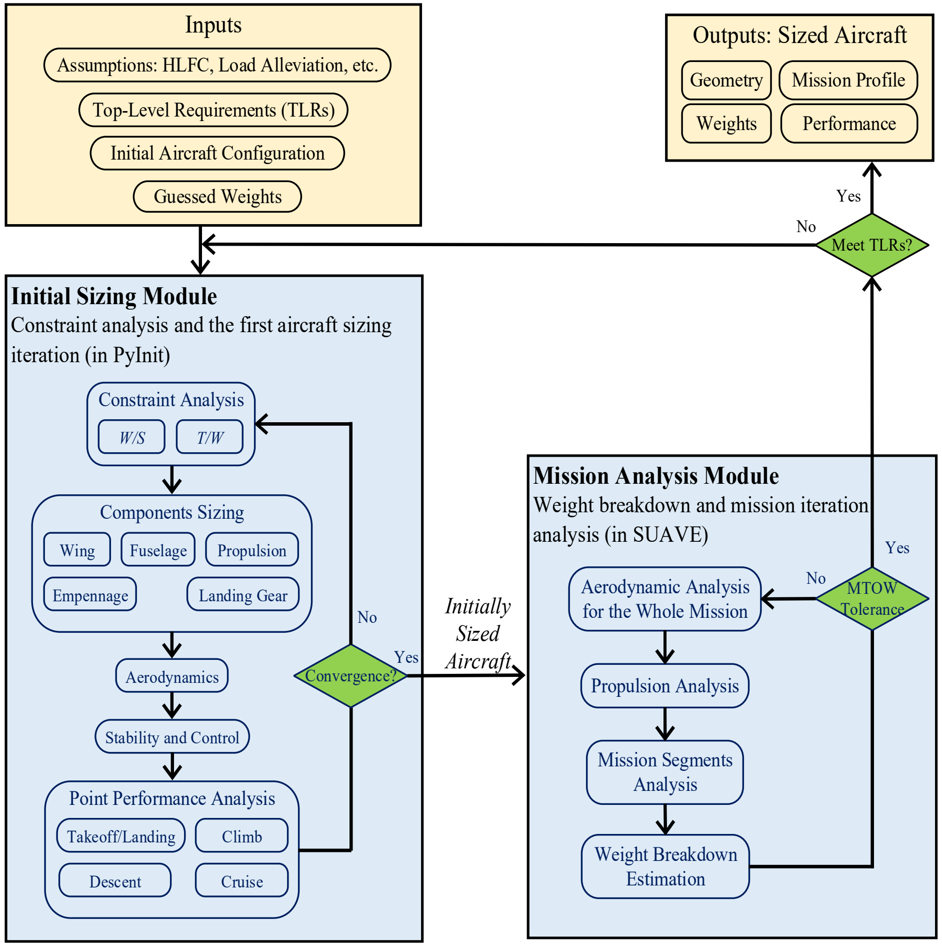
Outline

- UHARW conceptual design
  - Software environment
  - Assumptions and reference aircraft
  - Conceptual designs
  - Outcomes
- UHARW uncertainty/sensitivity analysis
  - Uncertainties
  - Software environment
  - Results
  - Outcomes

Aircraft conceptual design

- In-house aircraft initial sizing tool **Pyinit**
- Aircraft performance assessment tool **SUAVE** is improved for Strut-Braced Wing (SBW) and Twin-Fuselage (TF) configurations



Conceptual design framework

Aircraft conceptual design

Three reference aircraft were selected for the RHEA aircraft conceptual design.

Short-range

ATR 72-600

MTOW (kg)	22800
Passengers	72
Range (nm)	825
Cruise Mach	0.415

Mid-range

A320-NEO

MTOW (kg)	79000
Passengers	180
Range (nm)	3400
Cruise Mach	0.78

Long-range

B777-300ER

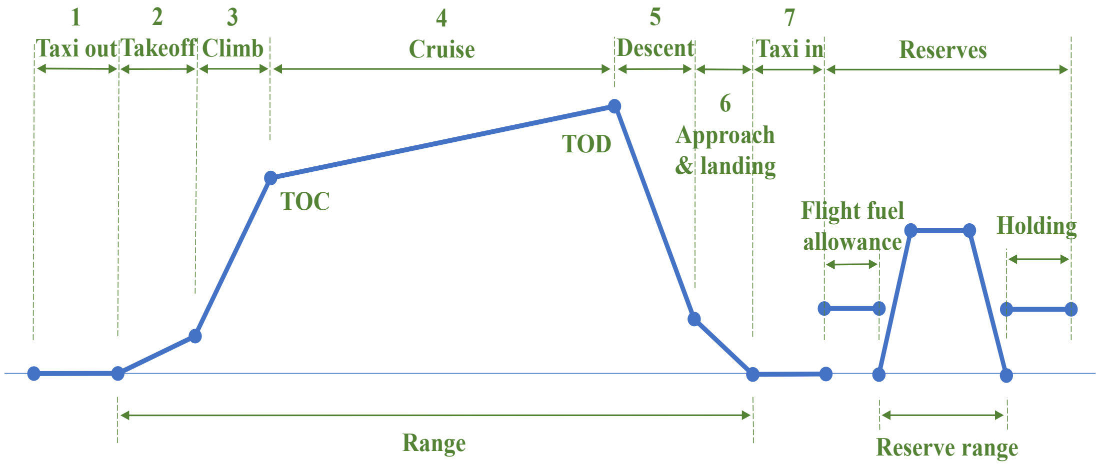
MTOW (kg)	351535
Passengers	378
Range (nm)	7370
Cruise Mach	0.84

Overview of Design Requirements and Assumptions

- Entry-into-service year: 2040.
- CS-25 certificate regulations.
- Wing aspect ratio: 25.

Several advanced airframe technologies of the next-generation passenger aircraft need to be considered in this research.

Mission profile

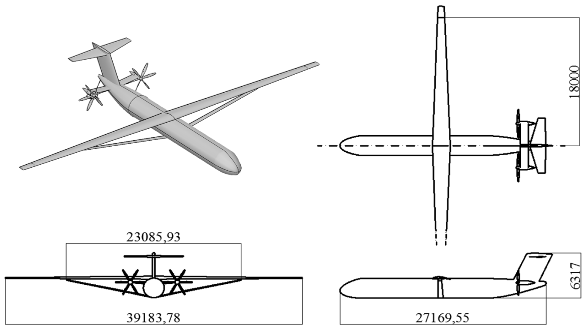


Assumptions of novel airframe technologies

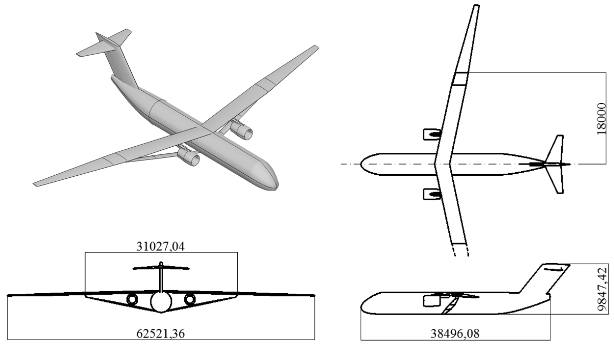
Configuration		HLFC	Load alleviation	Advanced materials & structures
Short-range	SBW	65%	+1.5g and -0.5g	20% structural weight reduction
	TF	70%		
Mid-range	SBW	50%	+1.5g and -0.5g	20% structural weight reduction
	TF	55%		
Long-range	SBW	50%	+1.5g and -0.5g	20% structural weight reduction
	TF	55%		

Aircraft conceptual design

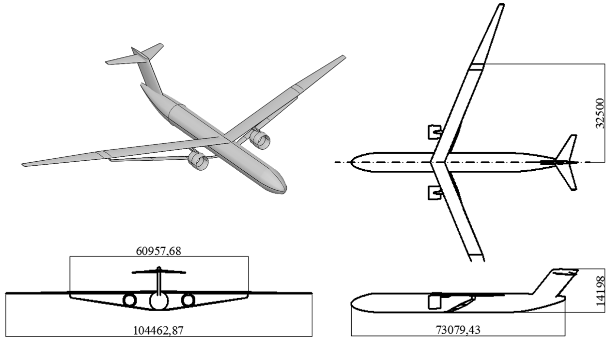
A strut-braced wing configuration and a twin-fuselage configuration with UHARW are initially designed for each mission.



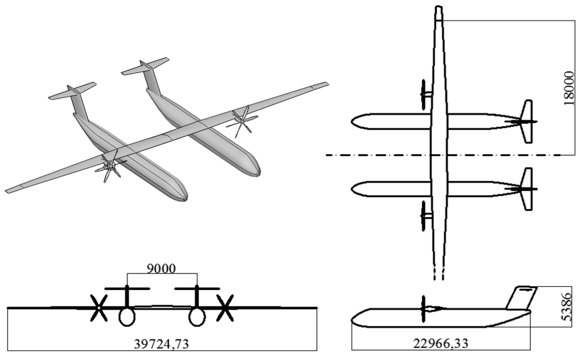
Short-range SBW



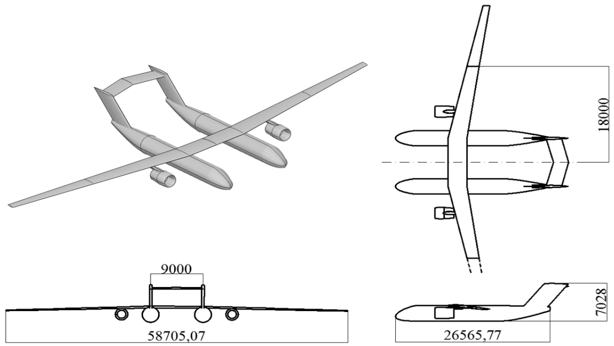
Mid-range SBW



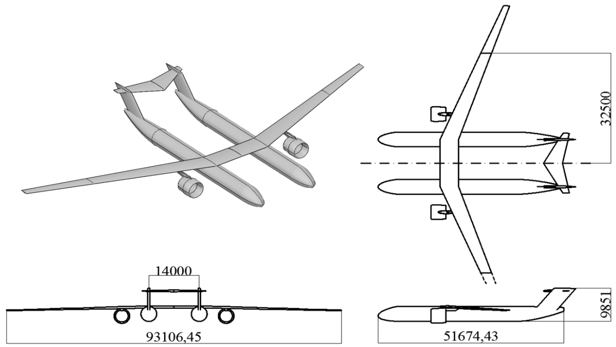
Long-range SBW



Short-range TF



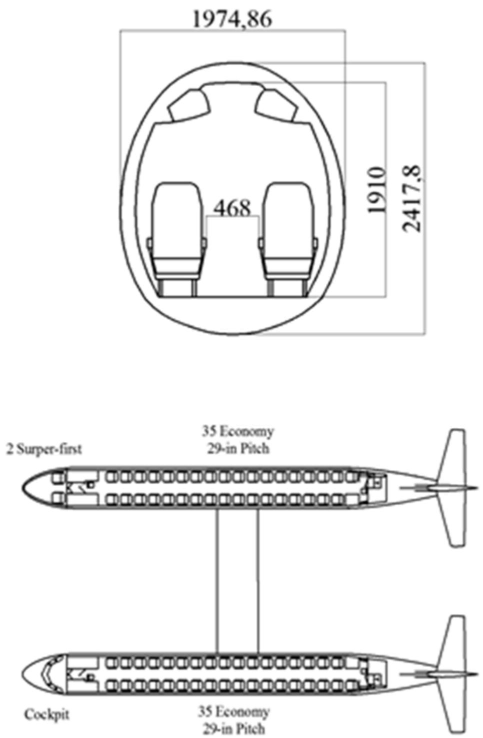
Mid-range TF



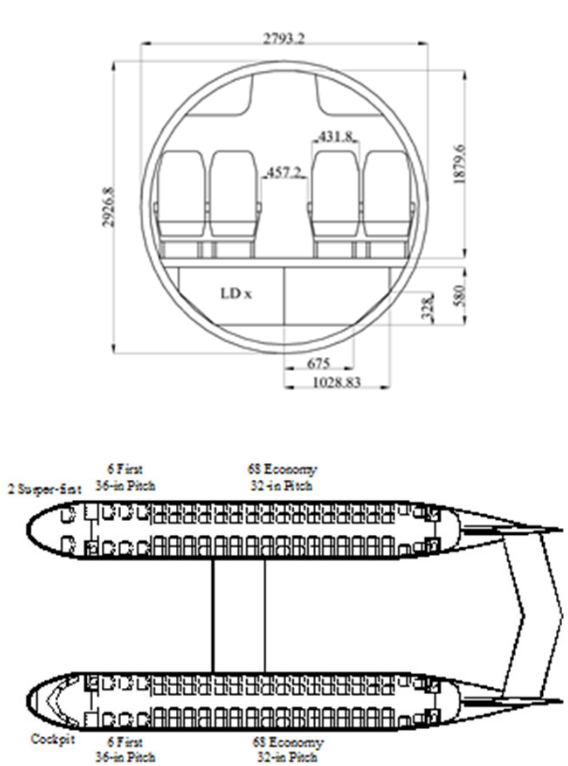
Long-range TF

Aircraft conceptual design

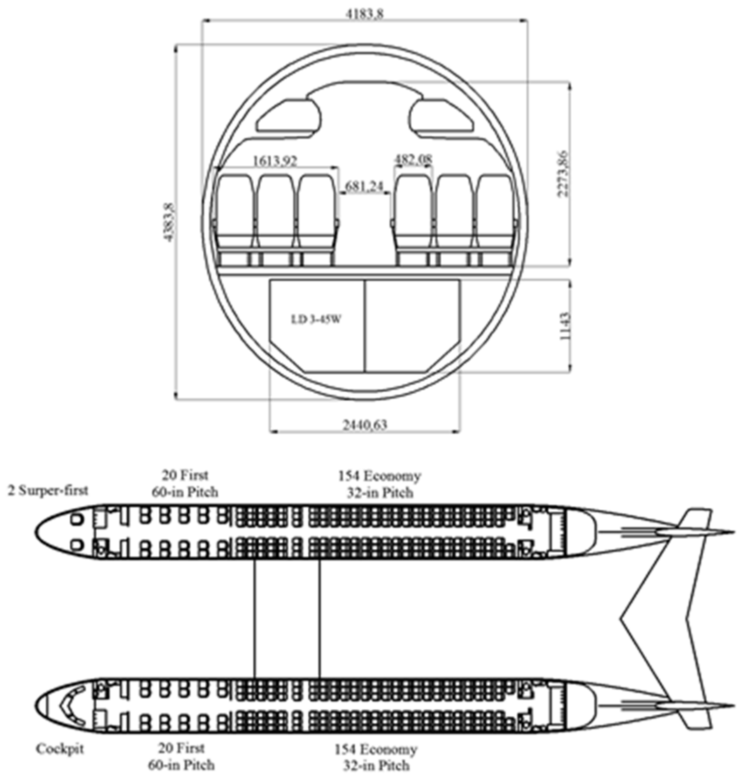
In particular, the cabin interior arrangement of twin-fuselage aircraft has been researched in detail.



Short-range



Mid-range

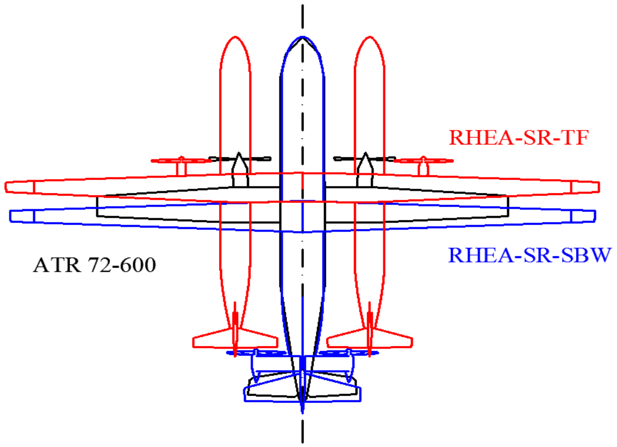


Long-range

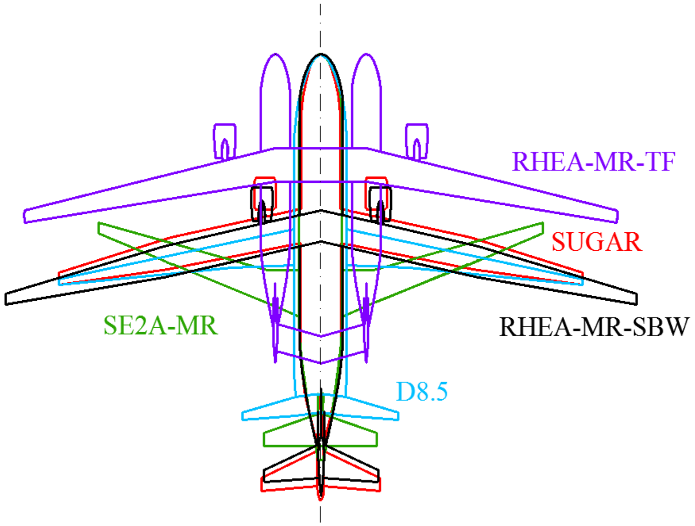
Aircraft conceptual design

Preliminary comparisons have been conducted for the different missions respectively, including geometric dimensions, fuel weight, max. takeoff weight, cargo capacity, etc.

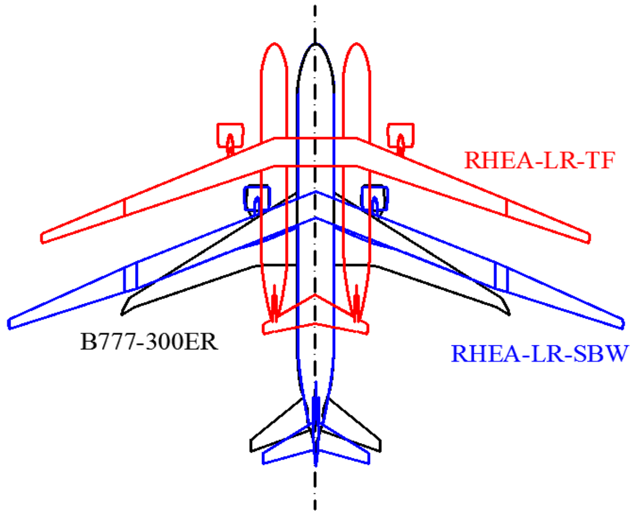
OpenVSP used for the visualization of the initially sized aircraft configurations.



Short-range mission



Mid-range mission



Long-range mission

Aircraft geometric comparison

Aircraft conceptual design

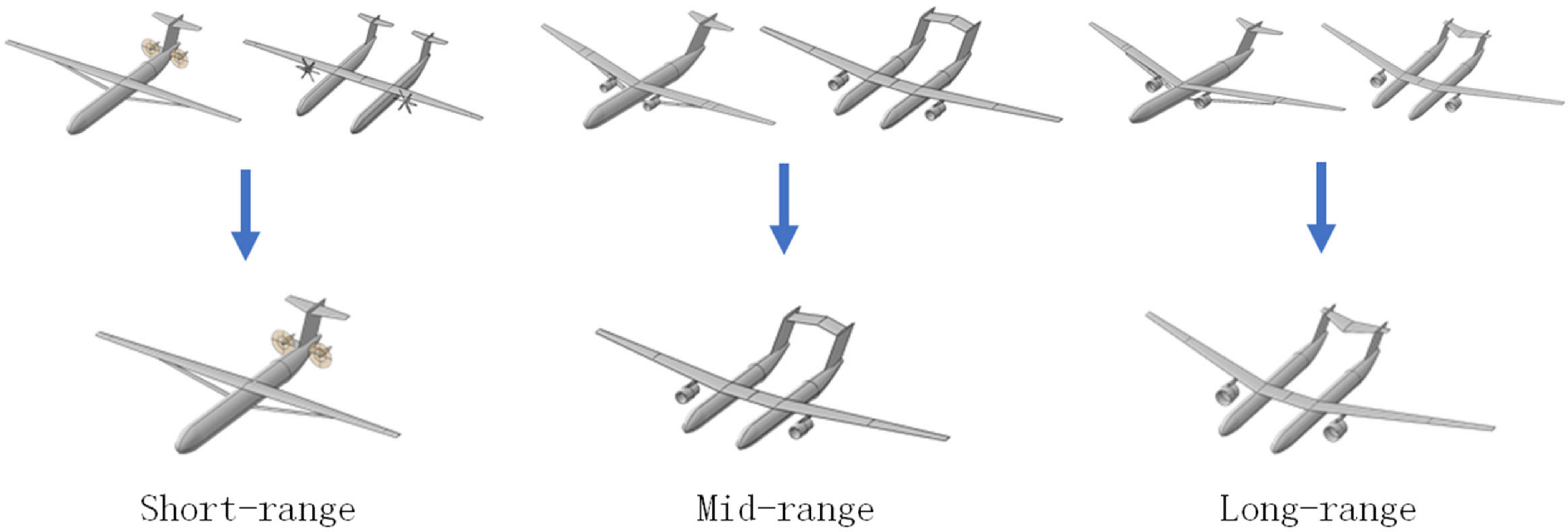
Preliminary comparisons have been conducted for the different missions respectively, including geometric dimensions, fuel weight, max. takeoff weight, cargo capacity, etc.

Weight breakdown comparison

Mission	Short-range			Mid-range			Long-range		
Group	SR-SBW	SR-TF	ATR 72-600	MR-SBW	MR-TF	A320neo	LR-SBW	LR-TF	B777-300ER
Max. takeoff weight, kg	**22229**	22945	22800	67929	**57777**	79000	262962	**210955**	351535
Fuel weight, kg	**1432**	1523	2000	16127	**13328**	20980	89716	**80037**	145538
Empty weight, kg	**12821**	13447	13500	37582	**30229**	44300	140066	**97737**	167829
Empty weight breakdown									
Wing, kg	2103	1482		9393	4631		47401	16630	
Fuselages, kg	2497	3052		7066	5241		25757	20596	
Propulsion, kg	1019	1047		4493	3710		18650	15038	
Nacelles, kg	269	275		527	490		2460	2270	
Landing gear, kg	643	661		2292	1976		7023	5735	
Horizontal tail, kg	201	214		414	772		1483	1478	
Vertical tail, kg	312	326		902	844		2923	2392	
Paint, kg	199	240		447	415		1237	1153	
Systems, kg	5579	6150		12049	12151		33133	32446	

Aircraft conceptual design

According to the comparison results, the “best-in-class” configuration has been initially determined for each mission.



Uncertainty/Sensitivity Analysis for Conceptual Design

- The previous unconventional configurations, SBW and TF, have been considered in addition to novel airframe technologies, such as
  - Hybrid Laminar Flow Control (HLFC),
  - advanced materials and structures,
  - active load alleviation,
  - folding wingtips,

  in order to improve the overall performance of the aircraft.
- Since the unconventional configurations and novel airframe technologies described above are for future sustainable aviation and their Technology Readiness Level (TRL) is not currently high enough, there are many **uncertainties** in applying these technologies to next-generation aircraft design.
- Aircraft conceptual design methodology and uncertainty analysis are combined at the conceptual design phase to study the effect of novel airframe technologies on six aircraft conceptual design outcomes.

Uncertainty/Sensitivity Analysis for Conceptual Design

Uncertainties

Six main uncertainties, four technologies related and two mission-related ones, have been identified:

- the achievable area of laminar flow over the wing,
- the achievable level of load reduction,
- the amount of structural weight reduction by using new materials and structures,
- the weight penalties on the wing due to folding mechanisms
- the aircraft cruise Mach number
- cruise altitude.

Uncertainty inputs parameters

- Cruise altitude, H_c
- Cruise Mach, M_c
- Vehicle range, R
- Maximum positive load factor, $n_{+,max}$
- Laminar transition (main wing), T_{Lw}
- Weight reduction factor (main wing), W_{Rw}
- Weight reduction factor (stabilizer), W_{Rs}
- Weight reduction factor (fuselage), W_{Rf}
- Wing weight penalty (due to the folding mechanisms), W_{lw}

Uncertainty/Sensitivity Analysis for Conceptual Design

W_f bounds from optimisation

To estimate the variability of W_f due to the uncertainties, two optimisation processes have been performed for each tested configuration:

$$\min_{\boldsymbol{U}} W_f \text{ (best case scenario) } \quad \text{and} \quad \max_{\boldsymbol{U}} W_f \text{ (worst case scenario)}$$

where $\boldsymbol{U}=\{ H_c, M_c, R, n_{+,max}, T_{Lw}, W_{Rw}, W_{Rs}, W_{Rf}, W_{lw}\}$

Sensitivity analysis

A-cut-HDMR approach decomposes the general function response, *f(**U**)*, in a sum of the contributions given by each uncertainty variable and each one of their interactions through the model, considered as increments with the respect to the response in the anchor point (not necessarily the nominal response), f_c:

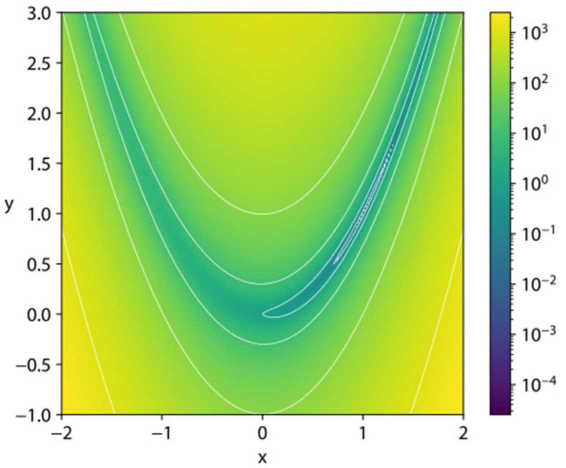
$$f(\boldsymbol{U}) = f_c + \sum_{i=1}^{n_u} F_i(U_i) + \sum_{i \le i < j \le n_u} F_{i,j}(U_i, U_j) + \ldots + F_{1,2,\ldots,n_u}(U_1, U_2, \ldots, U_{n_u})$$

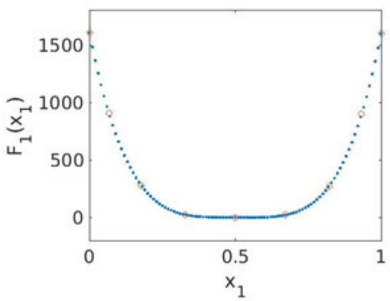
A surrogate model representation can be independently generated for each incremental contribution and only for the non-zero elements. The contribution of each term of the sum to the global response can be quantified independently so that higher-order interactions with low or zero contribution can be neglected already by analysing the lower-order terms. The A-cut-HDMR is adaptive in terms of sampling and truncation of terms.

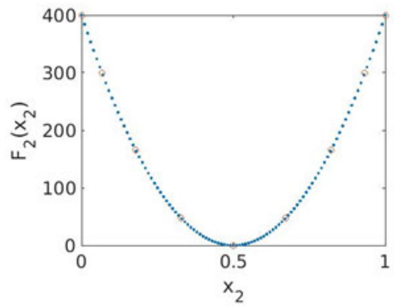
Uncertainty/Sensitivity Analysis for Conceptual Design

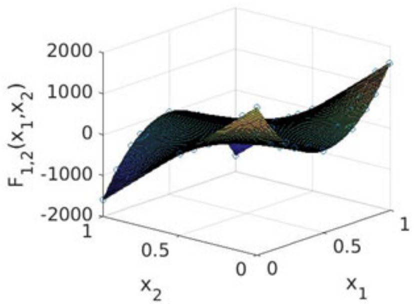
A-cut-HDMR example

2D Rosenbrock function $f = 100.0 * (x_2 - x_1^2)^2 + (1.0 - x_1)^2$









$$f_c = 1$$

$$F_1(x_1) = f(x_1) - f_c$$

$$F_2(x_2) = f(x_2) - f_c$$

$$F_{1,2}(x_1, x_2) = f(x_1, x_2) - f_c - F_1(x_1) - F_2(x_2)$$

$$\boldsymbol{f(x_1, x_2) = f_c + F_1(x_1) + F_2(x_2) + F_{1,2}(x_1, x_2)}$$

Uncertainty/Sensitivity Analysis for Conceptual Design

MR – W_f bounds from optimisation

ID	Uncertain parameters	Lb	Ub	Min W_f SBW	Max W_f SBW	Min W_f TF	Max W_f TF
1	H_c [km]	8.53	13.716	13.04	8.53	13.37	8.53
2	M_c	0.71	0.78	0.735	0.78	0.740	0.78
3	R [nm]	3300	3500	3300	3500	3300	3500
4	n_{+max} [g]	1.5	2.5	1.5	2.5	1.5	2.5
5	T_{Lw}	0.5	0.75	0.75	0.5	0.75	0.5
6	W_{Rw}	0.1	0.25	0.25	0.1	0.25	0.1
7	W_{Rs}	0.1	0.25	0.25	0.1	0.25	0.1
8	W_{Rf}	0.1	0.25	0.25	0.1	0.25	0.1
9	W_{Iw}	0.05	0.1	0.05	0.1	0.05	0.1

SBW best-case scenario (minimisation process) $W_f = 10603\ kg$.
SBW worst-case scenario (maximisation process) $W_f = 17943\ kg$.

TF best-case scenario (minimisation process) $W_f = 9870\ kg$.
TF worst-case scenario (maximisation process) $W_f = 15310\ kg$.

Uncertainty/Sensitivity Analysis for Conceptual Design

MR SBW – W_f sensitivity

Fc = 12,878 kg

Increment function	Min ΔFuel Burn	Max ΔFuel Burn	Range(Fuel Burn)	Range(ΣFuel Burn)
5 (Laminar transition)	-11.45%	11.43%	22.88%	22.88%
1 (Cruise altitude)	-3.49%	8.58%	12.07%	12.07%
4 (Max load factor)	-3.07%	5.45%	8.53%	8.53%
2 (Cruise Mach)	-1.53%	2.21%	3.74%	3.74%
6 (Weight reduction wing)	-0.75%	0.78%	1.53%	1.53%
8 (Weight reduction fuselage)	-0.72%	0.72%	1.44%	1.44%
9 (Weight penalty folding)	-0.19%	0.20%	0.39%	0.39%
7 (Weight reduction stabiliser)	-0.13%	0.13%	0.27%	0.27%
2 (Cruise Mach) 4 (Max load factor)	-0.03%	0.06%	0.10%	12.35%
All surrogates	-21.35%	29.50%	50.85%	50.85%

Uncertainty/Sensitivity Analysis for Conceptual Design

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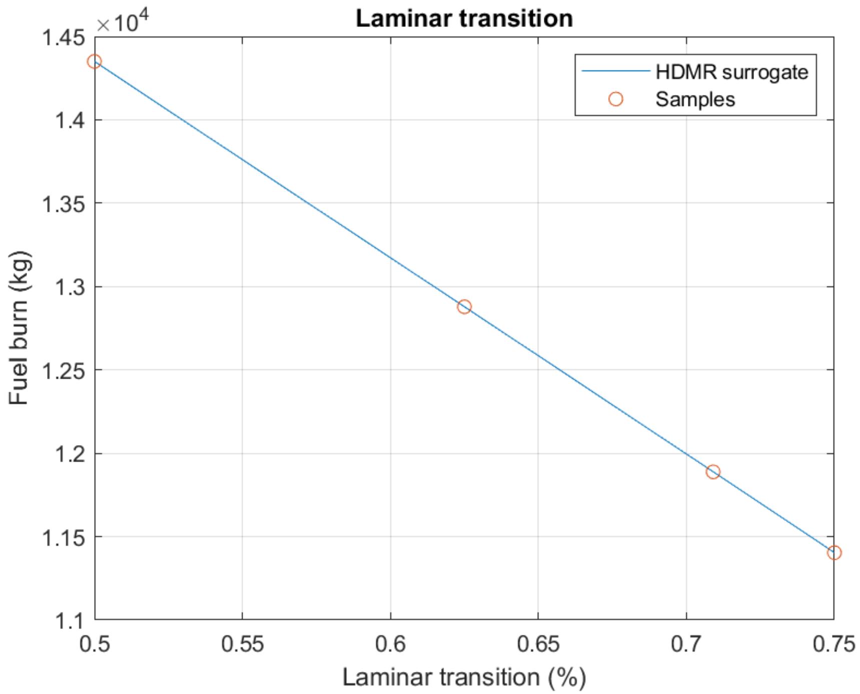

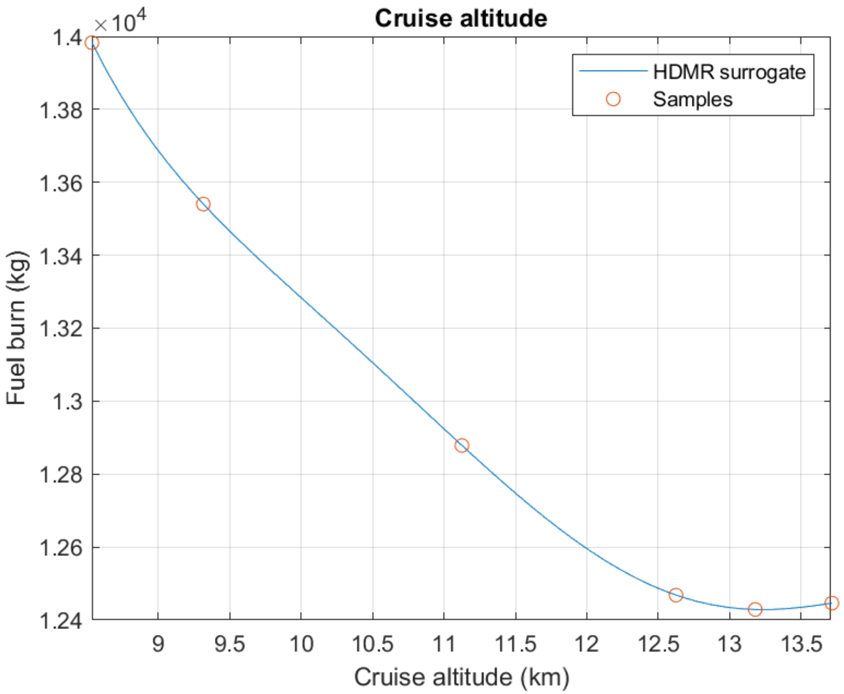

Uncertainty/Sensitivity Analysis for Conceptual Design

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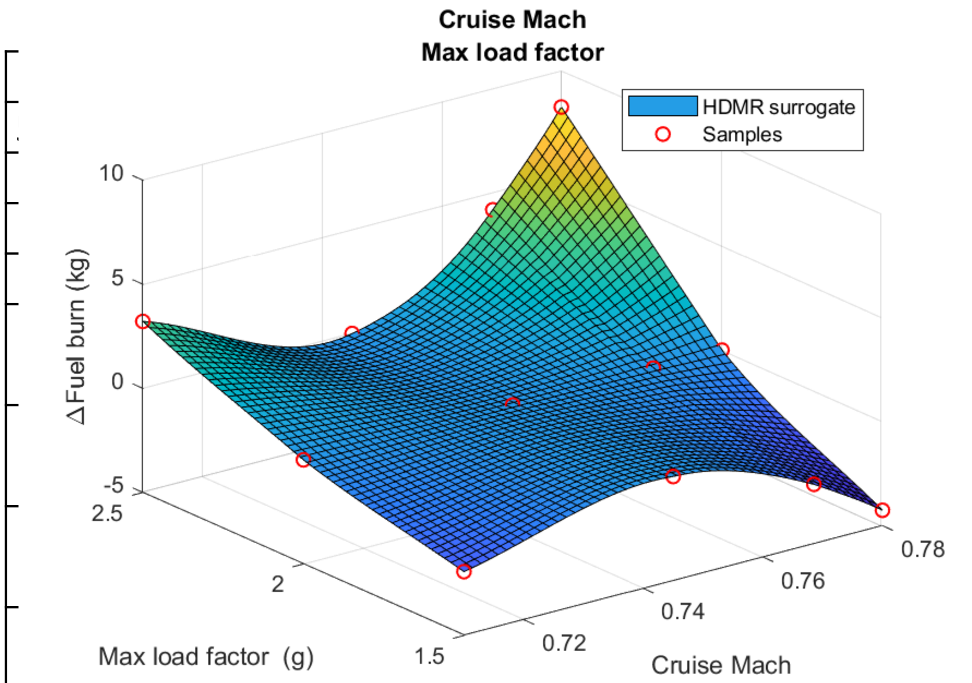

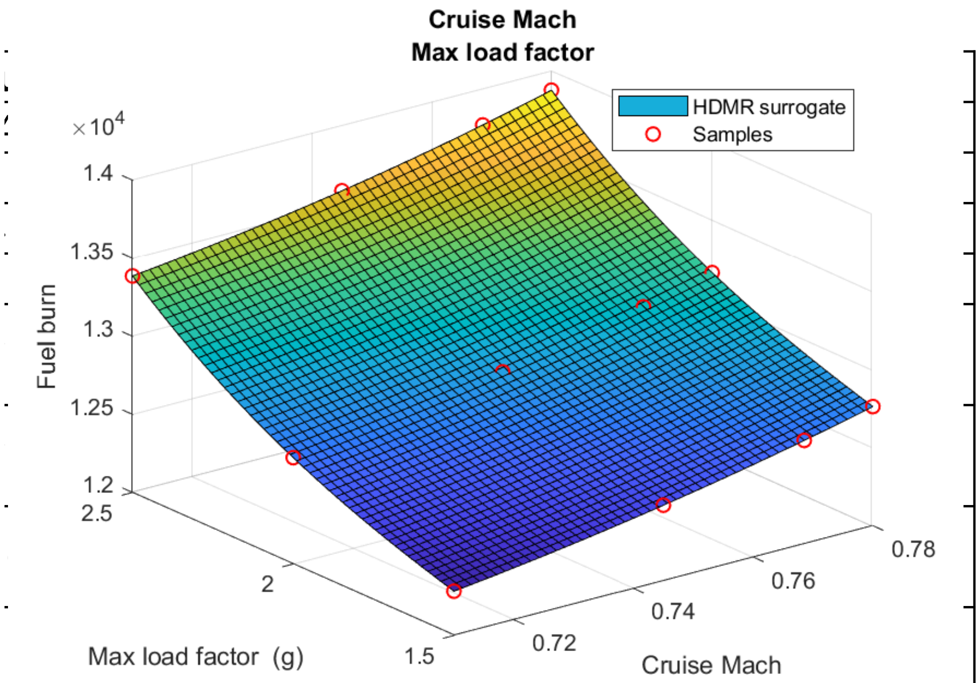

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All surrogates	-21.35%	29.50%	50.85%	50.85%

Uncertainty/Sensitivity Analysis for Conceptual Design

MR TF – W_f sensitivity Fc = 11,591 kg

Increment function	Min ΔFuel Burn	Max ΔFuel Burn	Range(Fuel Burn)	Range(ΣFuel Burn)
5 (Laminar transition)	-9.32%	9.34%	18.66%	18.66%
1 (Cruise altitude)	-4.46%	9.53%	13.99%	13.99%
2 (Cruise Mach)	-1.72%	2.33%	4.05%	4.05%
4 (Max load factor)	-1.42%	2.11%	3.53%	3.53%
8 (Weight reduction fuselage)	-0.60%	0.60%	1.19%	1.19%
6 (Weight reduction wing)	-0.54%	0.56%	1.09%	1.09%
7 (Weight reduction stabiliser)	-0.18%	0.18%	0.37%	0.37%
9 (Weight penalty folding)	-0.14%	0.14%	0.28%	0.28%
2 (Cruise Mach) 5 (Laminar transition)	-0.52%	0.55%	1.07%	22.82%
4 (Max load factor) 5 (Laminar transition)	-0.51%	0.56%	1.06%	22.41%
All surrogates	-18.64%	24.59%	43.23%	43.23%

Uncertainty/Sensitivity Analysis for Conceptual Design

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Fc = 11,591 kg

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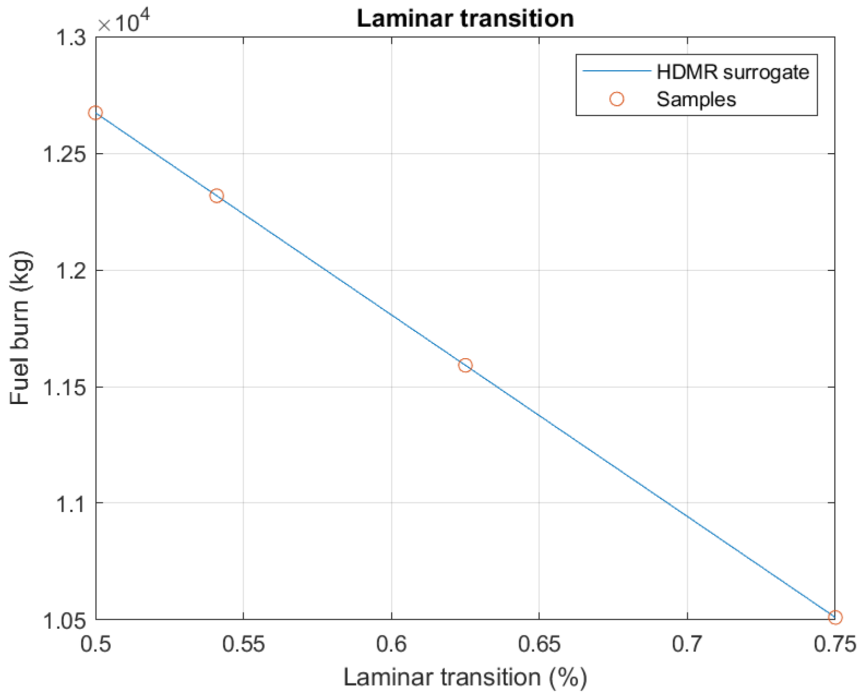
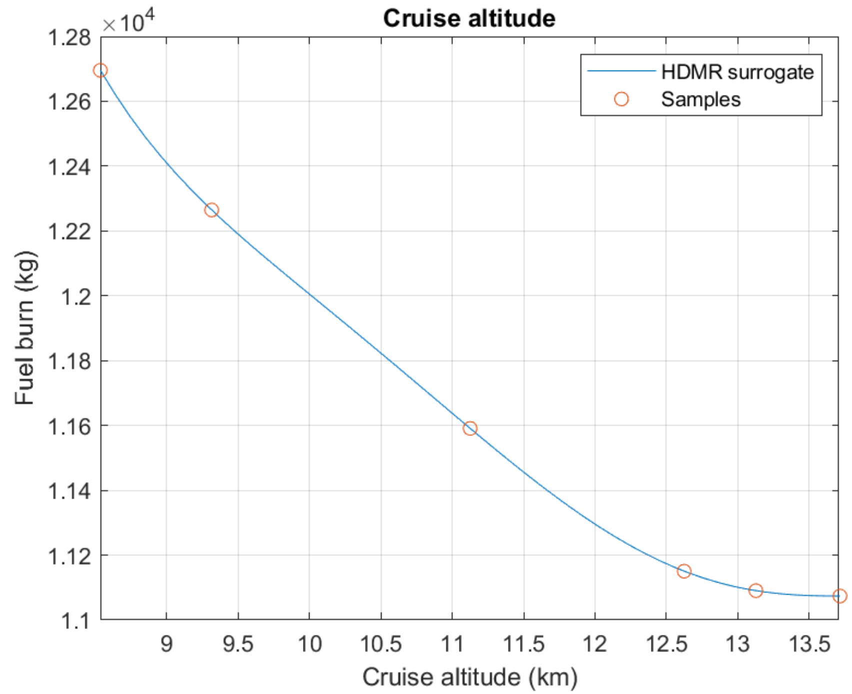
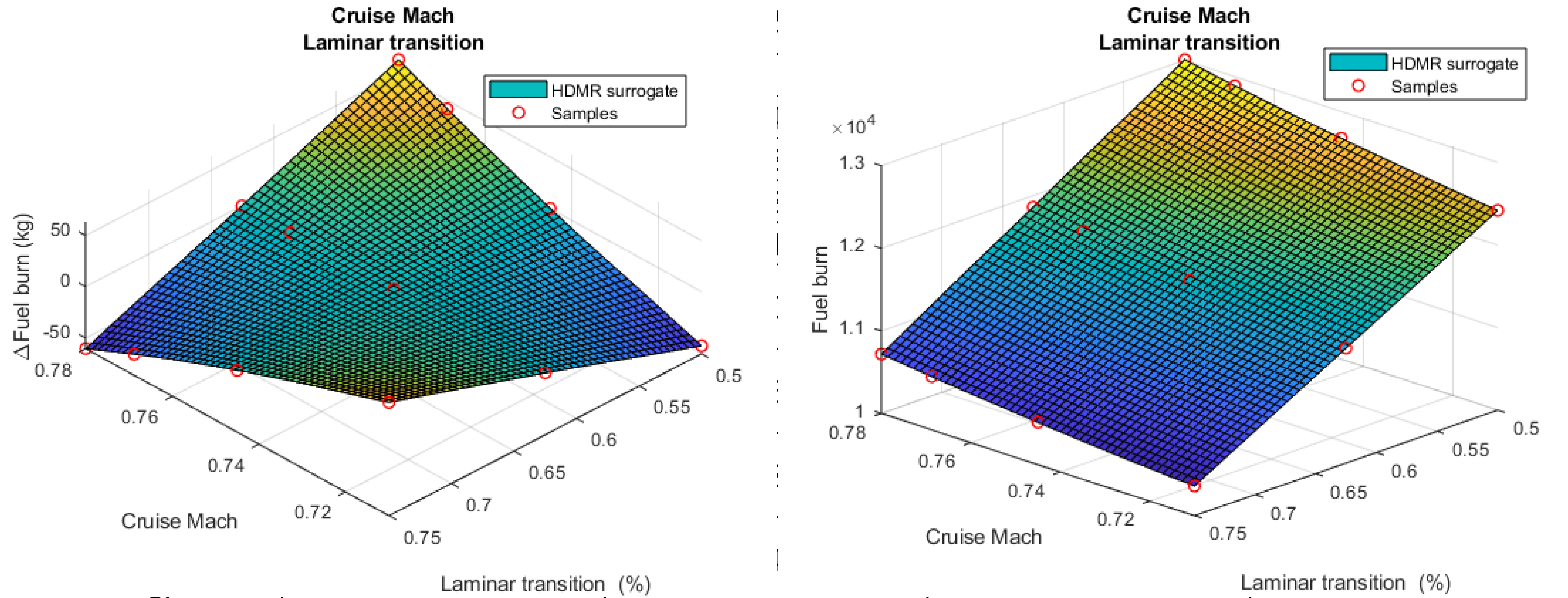




Uncertainty/Sensitivity Analysis for Conceptual Design



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4 (Max load factor) 5 (Laminar transition)	-0.51%	0.56%	1.06%	22.41%
All surrogates	-18.64%	24.59%	43.23%	43.23%

Uncertainty/Sensitivity Analysis for Conceptual Design

The **uncertainty/sensitivity analysis** showed that:

- the **TF configuration** is more robust for MR and LR missions, while there is no significant difference in the robustness of the SR configurations;
- the **technology uncertainty** is always a major player (e.g., laminar flow range);
- the operative conditions, i.e., cruise Mach and altitude, play a different role for each one of the configurations and missions
  - In particular, MR-SBW and MR-TF aircraft have the highest fuel efficiency at cruising Mach 0.73 to 0.74, and this lower Mach number also facilitates the achievement of natural laminar flow on the wings.

References

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RHEA

www.rhea-cleansky2.org

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