13TH EASN CONFERENCE 2023

Estimating the scheduled maintenance implications for a hydrogen-powered aircraft

R. Meissner, P. Sieb, J. Kensbock, K. Wicke, G. Wende

DLR

Agenda

- Introduction (*Why you should bother)*
- Fundamentals on Aircraft Maintenance *(What the broader context is)*
- Our Approach *(What we have done specifically)*
- Results & Insights *(What we found out)*
- Way Forward *(What comes next)*

Introduction

Regulatory Initiatives

Governmental restrictions (e.g., European Green New Deal) aim at climate-neutral aviation by 2050.

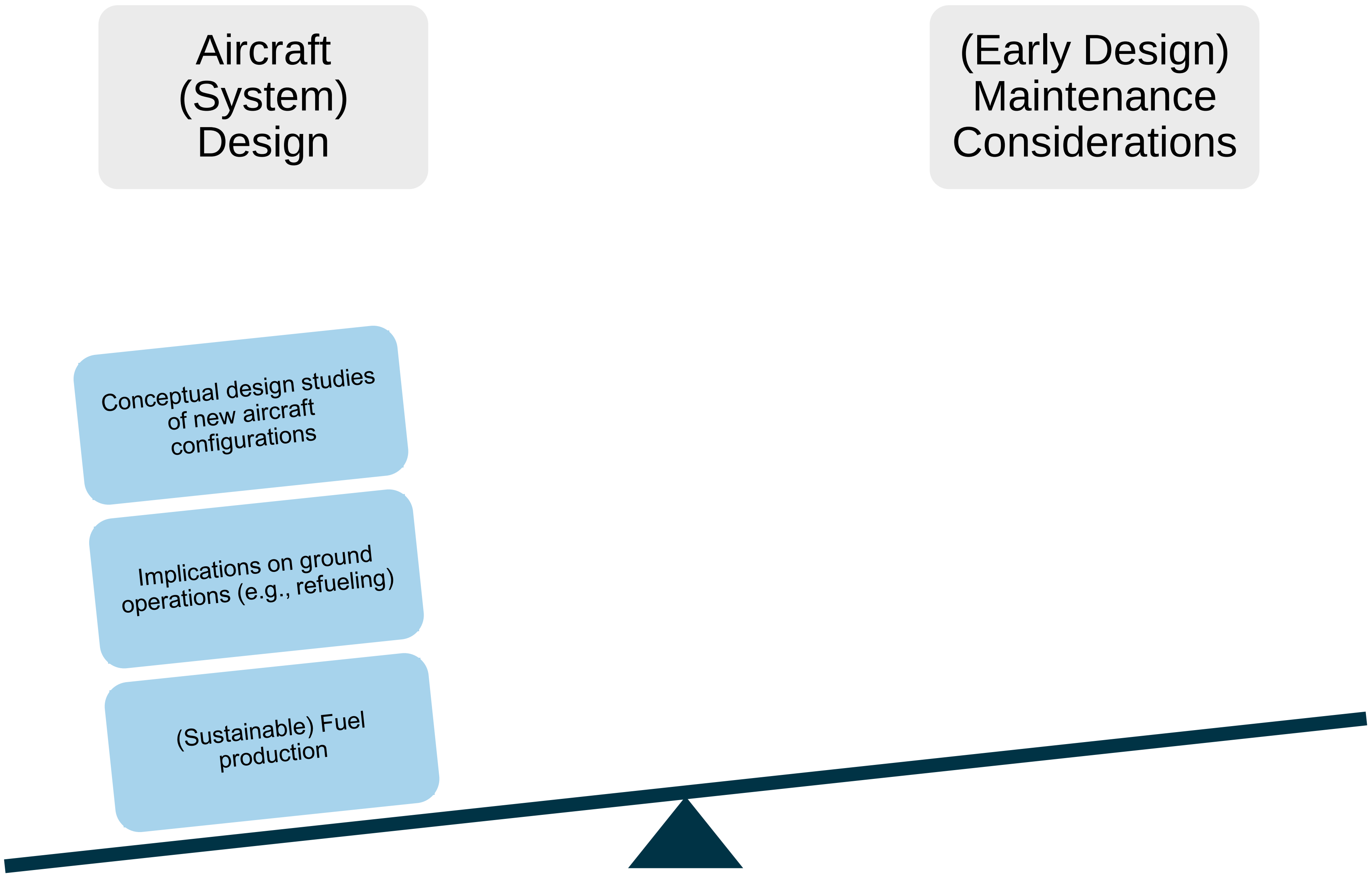
Technological Improvements

Incremental efficiency gains of conventional kerosene-based combustion systems outperformed by increased air traffic.

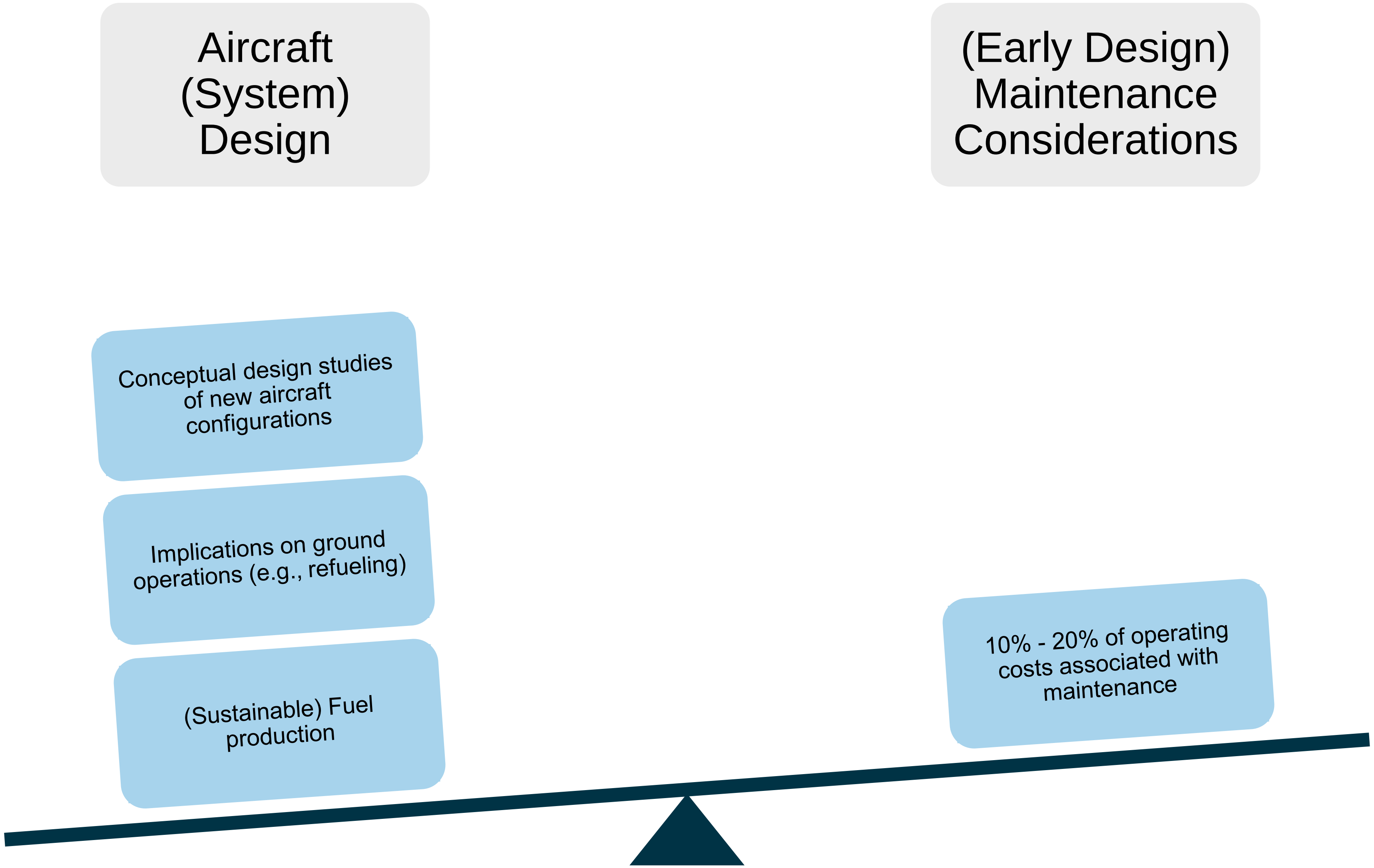
New Aircraft Concepts

Development of alternative energy carrier concepts with new system layouts and different, unknown maintenance needs.

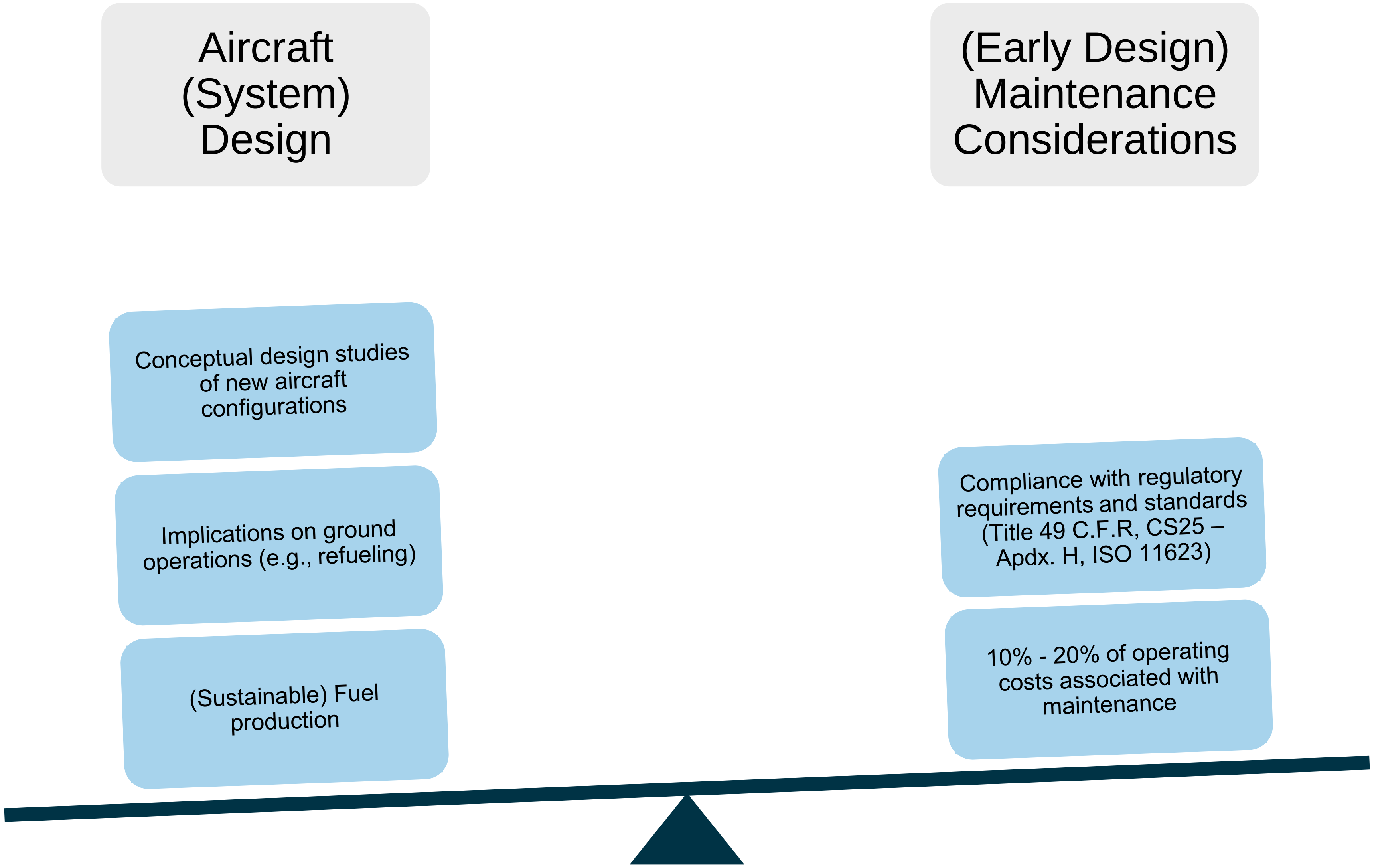
Introduction



Introduction



Introduction

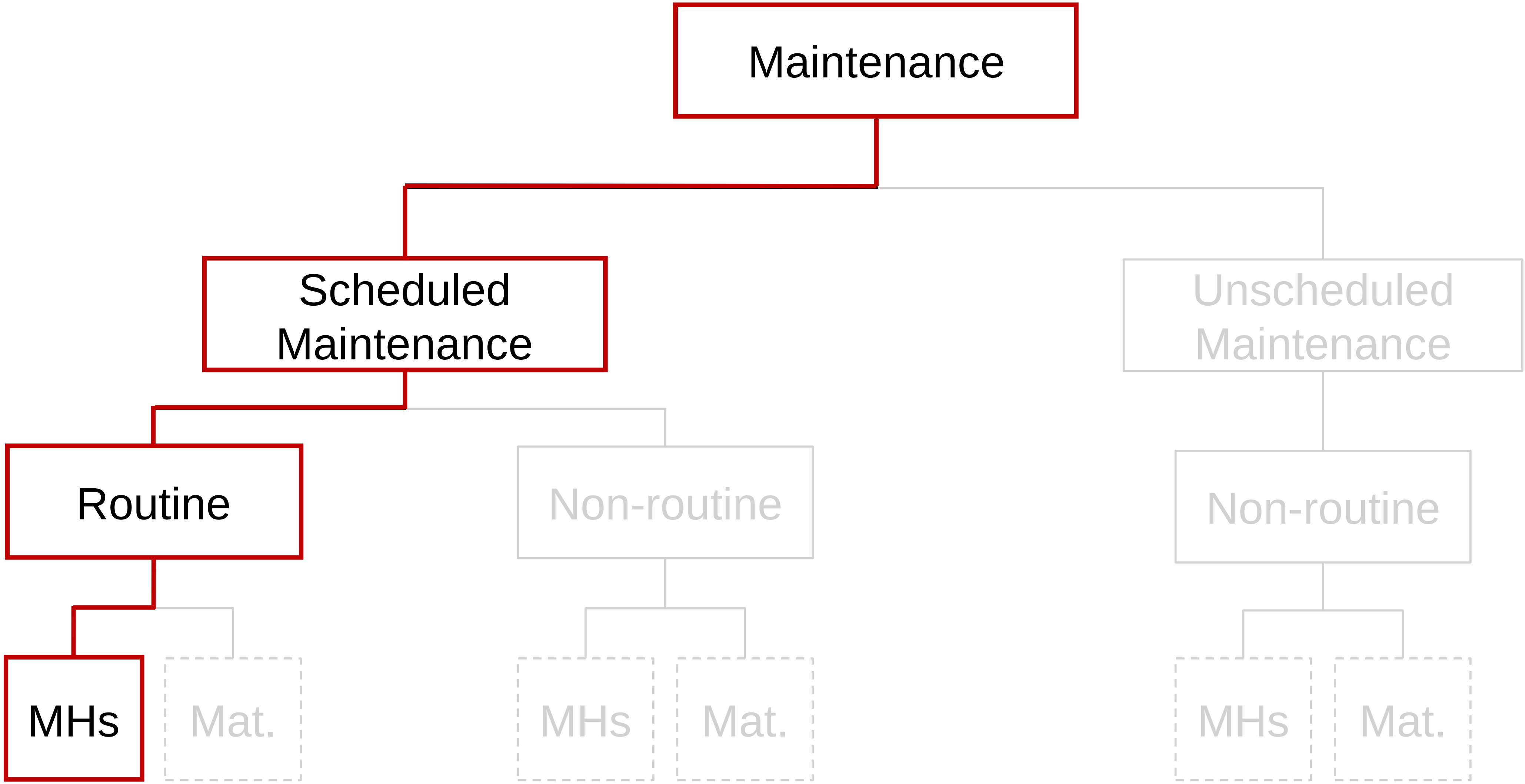


Introduction

How can the necessary maintenance effort be expected to change when substituting a kerosene-powered Auxiliary Power Unit (APU) by an hydrogen-powered equivalent?

Fundamentals – Aircraft Maintenance

Maintenance Classification



Our Approach

Scheduled Maintenance Task Definition

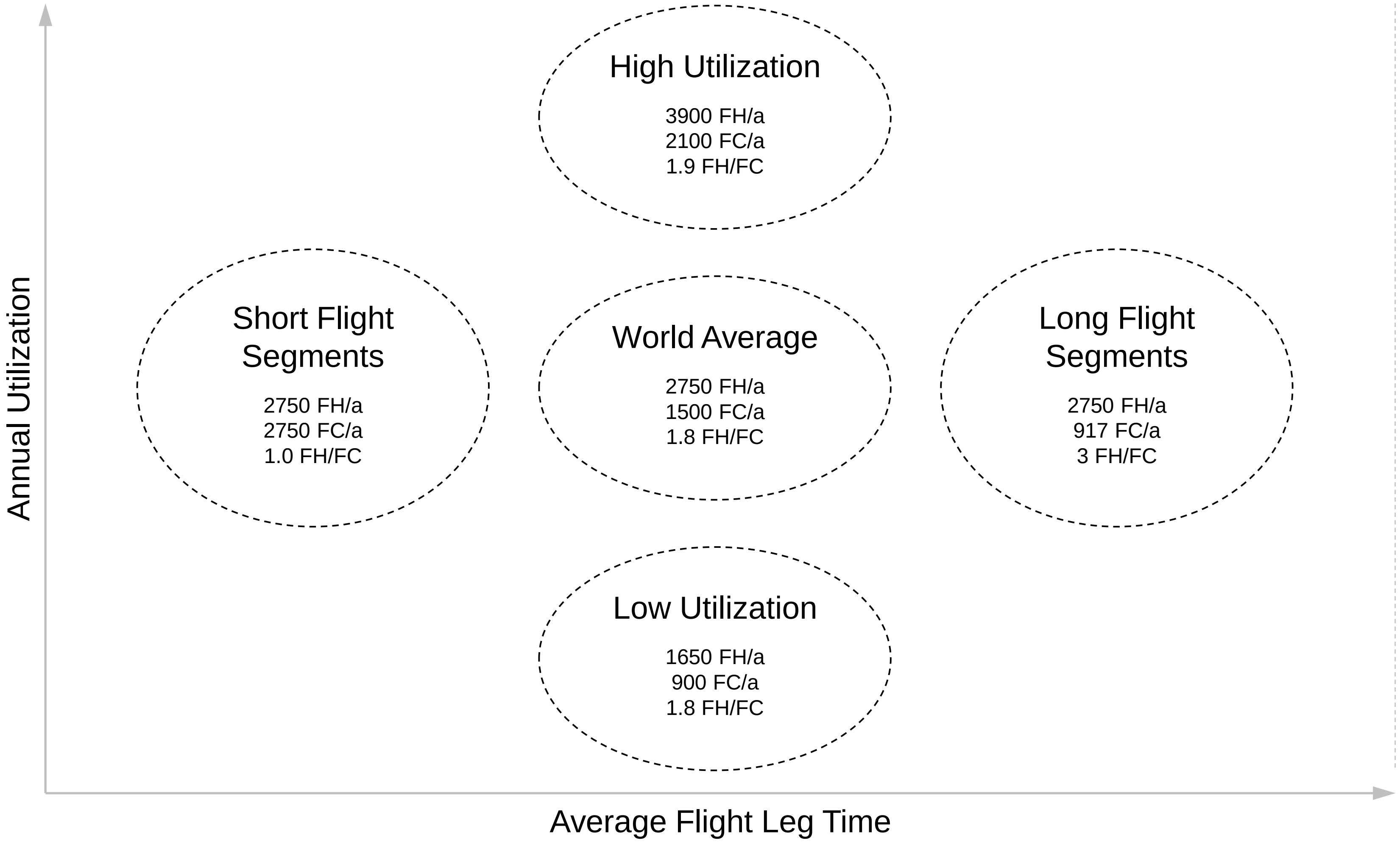
	Steps	Resources
	System Design Definition	ISO Norms, Expert Knowledge[1]
MSG-3	Functional Failure Analysis	Engineering Judgement
MSG-3	Maintenance Task Identification	Engineering Judgement
	Maintenance Interval Estimation	ISO Norms and National Standards, Industry Practices
	Task Effort Estimation	Legacy Maintenance Planning Document

1 The work here has been part of the “Hydrogen Aviation Lab” project.

Our Approach

Operating Scenarios

Aircraft



Auxiliary Power Unit

Operating Time per Flight

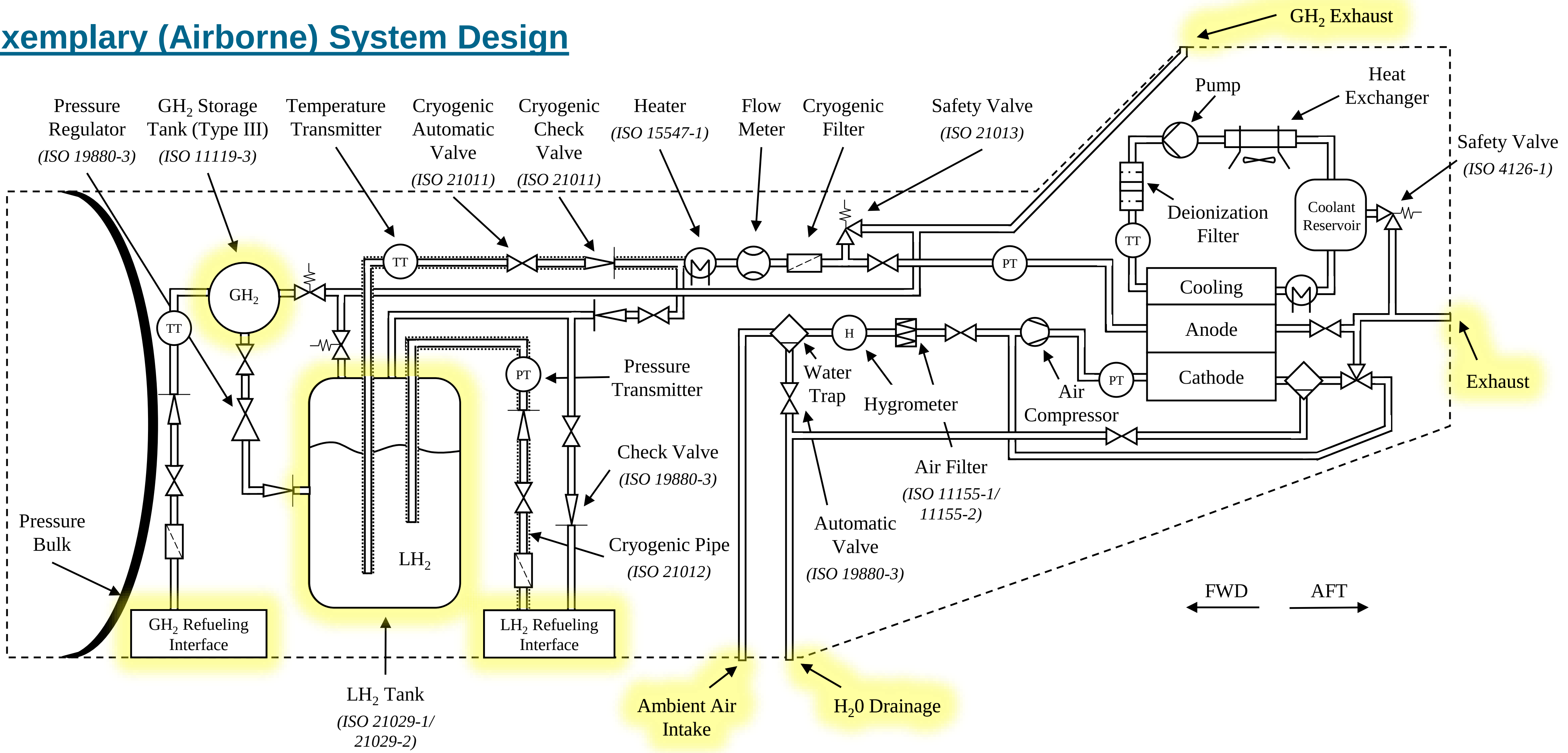
45 min.

Operating Cycles per Flight

1 APUC

Results & Insights

Exemplary (Airborne) System Design



Substituting an APU by a Fuel Cell may also result in additional design changes, e.g., for bleed air generation.

Results & Insights

Gained Insights

ATA	Type	Maintenance Man Hours (MMH) / 1,000 FHs				
		AVG	LUR	HUR	SFS	LFS
28 - Fuel	conventional	8.3	13.3	6.0	8.3	8.3
	hydrogen-based	10.4	16.2	7.9	10.9	10.2
	change	+ 26%	+ 22%	+ 30%	+ 32%	+ 23%
49 - APU	conventional	0.9	1.1	0.8	0.9	1.0
	hydrogen-based	1.7	2.1	1.5	2.7	1.3
	change	+ 96%	+ 92%	+ 98%	+ 213%	+ 30%
Total	conventional	9.2	14.4	6.8	9.2	9.3
	hydrogen-powered	12.1	18.3	9.4	13.6	11.5
	change	+ 32%	+ 27%	+ 38%	+ 48%	+ 24%

AVG ... Average annual utilization, LUR ... Low utilization rate,
HUR ... High utilization rate, SFS ... Short flight segments, LFS ... Long flight segments

Operating an aircraft with kerosene (propulsion) and hydrogen (APU) simultaneously, will increase the maintenance effort by $^1/_5$ to $^1/_3$.

Although a fuel cell system will require substantially more maintenance than a kerosene-powered APU, the overall maintenance effort is still significantly less than for the storage and distribution system.

To minimize the addition of maintenance effort, a hydrogen-powered auxiliary power generation is ideally operated on longer flights with high FH-to-FC ratios.

Results & Insights

The Bigger Picture

Scheduled maintenance expenditures for the fuel system and APU can be expected to rise between roughly 25% up to almost 50%.

However, scheduled maintenance for these systems only contributes between 4% to 6% to the total scheduled maintenance expenditures.

This translates to ...

ATA		Maintenance Man Hours (MMH) / 1,000 FHs				
No.	Description	AVG	LUR	HUR	SFS	LFS
53	Fuselage	33.5 (18.0%)	46.8 (18.2%)	27.5 (17.6%)	44.9 (19.8%)	30.7 (17.1%)
57	Wings	26.6 (14.3%)	30.8 (12.0%)	24.6 (15.7%)	43.9 (19.3%)	24.9 (13.9%)
20	Standard Practices - Airframe Systems	20.4 (10.9%)	33.9 (13.2%)	14.4 (9.2%)	20.4 (9.0%)	20.4 (11.4%)
32	Landing Gear	20.2 (10.8%)	28.9 (11.2%)	17.4 (11.1%)	26.8 (11.8%)	19.0 (10.6%)
25	Equipment / Furnishings	14.6 (7.8%)	22.2 (8.6%)	11.3 (7.2%)	14.9 (6.6%)	14.5 (8.1%)
27	Flight Controls	9.0 (4.8%)	13.5 (5.3%)	7.1 (4.6%)	9.1 (4.0%)	9.0 (5.0%)
28	Fuel	8.3 (4.4%)	13.3 (5.2%)	6.0 (3.9%)	8.3 (3.6%)	8.3 (4.6%)
⋮	⋮	⋮	⋮	⋮	⋮	⋮
49	Auxiliary Power Unit	0.9 (0.5%)	1.1 (0.4%)	0.8 (0.5%)	0.9 (0.4%)	1.0 (0.6%)
⋮	⋮	⋮	⋮	⋮	⋮	⋮
Total Maintenance Effort		186.6	257.2	156.4	226.9	179.4

AVG ... Average annual utilization, LUR ... Low utilization rate,
HUR ... High utilization rate, SFS ... Short flight segments, LFS ... Long flight segments

Results & Insights

The Bigger Picture

Description	Type	Maintenance Man Hours (MMH) / 1,000 FHs				
		AVG	LUR	HUR	SFS	LFS
Total Maintenance Effort	conventional	186.6	257.2	156.4	226.9	179.4
	hydrogen-powered	189.5	261.1	159.0	231.4	181.6
	change	+ 2%	+ 2%	+ 2%	+ 2%	+ 1%

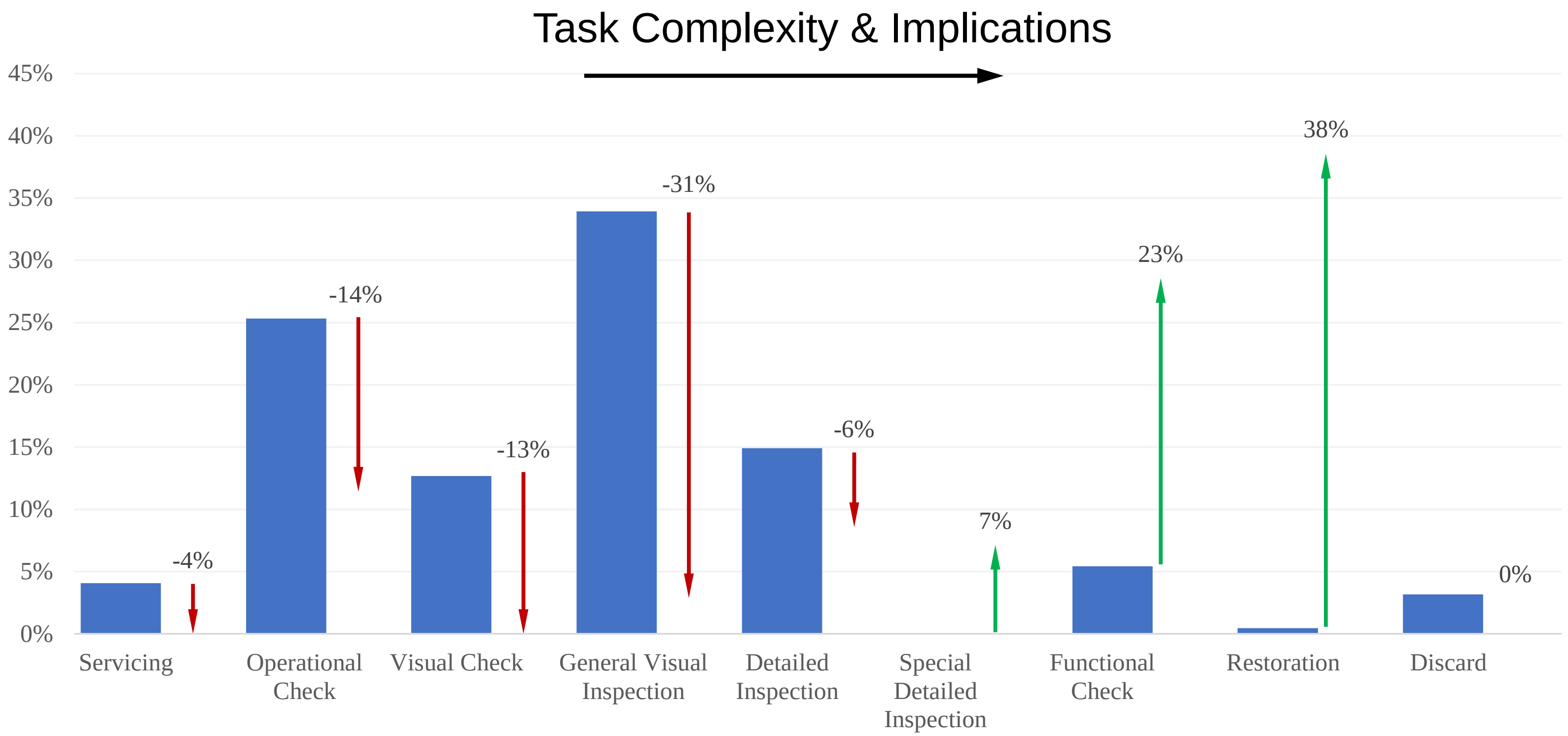
AVG ... Average annual utilization, LUR ... Low utilization rate,
HUR ... High utilization rate, SFS ... Short flight segments, LFS ... Long flight segments

... an increase of the total maintenance effort by 1% to 2%.

So, all good?

Results & Insights

Broadening the Scope



System Philosophy	Tank System	Auxiliary Power Unit (APU) / Fuel Cell (FC)			
		APS 3200	131-9(A)	GTCP 36-300	Avg. APU
conventional	0%	22%	13%	0%	9%
hydrogen-powered	48%	58%	58%	58%	58%
difference	+ 48%	+ 36%	+ 45%	+ 58%	+ 49%

Not quite ...

... scheduled maintenance tasks will become more complex ...

... and will require more frequent off-aircraft maintenance with the subsequent logistics implications.

Way Forward

Estimation of Non-Routine Task Intervals

Identification of Possible Off-Wing Maintenance Workscopes

Sustainability Assessment

Comparative Analysis with All-Electric System Concept

THANK YOU FOR YOUR ATTENTION

KEY
TAKEAWAYS

01 Maintenance aspects have to be considered in early stage design phases already to ensure regulatory compliance!

02 Due to the technical complexity of an airborne liquid hydrogen system, maintenance will demand more skilled labor and will require a more sophisticated maintenance network for off-aircraft maintenance!

03 Although just slightly, scheduled maintenance effort can be expected to increase if hydrogen-powered systems will remain add-ons to kerosene-powered systems!

Additional Information – Scheduled Maintenance Program

LH_2 Tank System

Task no.	Task description	Task code	Interval	No. of units installed	MMH (each unit)	MMH (total)	Interval References
01	Borescope inspection of inner hydrogen tank	SDI	120 MO or 10,000 FC	1	1.0	1.0	ISO 21029-1 [81, p. 32] ISO 21029-2 [82, p. 18]
02	General visual inspection of hydrogen tank's structural integrity	GVI	10,000 FC	1	0.58	0.58	ISO 21029-1 [81, p. 32]
03	Detailed inspection of refuel/defuel connectors	DET	72 MO or 5,000 FC	3	0.1	0.3	Legacy MPD [75]
04	Special detailed inspection of the tank fixtures	SDI	10,000 FC or 20,000 FH	4	0.4	1.6	Legacy MPD [75]
05	Detailed inspection of cryogenic piping system	DET	5,500 FC	1	1.0	1.0	SAE [63]
06	Detailed inspection of GH_2 piping system	DET	5,500 FC	1	1.0	1.0	SAE [63]
07	Operational check of cryogenic check valve	OPC	60 MO	2	0.2	0.4	ISO 21029-2 [82, p. 18] Lu et al. [137]
08	Removal of cryogenic check valve for in-shop restoration	RST	15,000 FC	2	1.49	2.98	ISO 13985 [113]
09	Operational check of cryogenic automatic valves	OPC	60 MO	2	0.2	0.4	ISO 21029-2 [82, p. 18] Lu et al. [137]
10	Removal of cryogenic automatic valve for in-shop restoration	RST	15,000 FC	2	1.49	2.98	ISO 13985 [113]
11	Functional check of the safety valve unit (Cat. B)	FNC	27 MO	2	0.83	1.66	Own calculation acc. Eq. 2
12	Removal of safety valve unit for in-shop restoration (Cat. B)	RST	60 MO	2	0.65	1.3	ISO 21029-2 [82, p. 18] Miller [123] Keogh et al. [124]
13	Functional check of the safety valve unit (Cat. A)	FNC	60 MO	3	0.83	2.49	ISO 21029-2 [82, p. 17]
14	Removal of safety valve unit for in-shop restoration (Cat. A)	RST	120 MO	3	0.65	1.95	ISO 21029-2 [82, p. 18]
15	Removal of pressure regulator for in-shop restoration	RST	180 MO or 8,000 FH	1	2.0	2.0	Legacy MPD [75]
16	Operational check of GH_2 automatic valve	OPC	72 MO	2	0.2	0.4	Legacy MPD [75]

Additional Information – Scheduled Maintenance Program

LH$_2$ Tank System

Task no.	Task description	Task code	Interval	No. of units installed	MMH (each unit)	MMH (total)	Interval References
17	Removal of GH_2 automatic valve for in-shop restoration	RST	180 MO or 40,000 FH	2	1.49	2.98	Legacy MPD [75] ISO 19880-3 [133]
18	Operational check of GH_2 check valve	OPC	72 MO	2	0.2	0.4	Legacy MPD [75]
19	Removal of GH_2 check valve for in-shop restoration	RST	180 MO or 40,000 FH	2	1.49	2.98	Legacy MPD [75] ISO 19880-3 [133]
20	Removal of vaporizer for in-shop inspection	FNC	108 MO or 12,000 FH	1	1.3	1.3	Legacy MPD [75]
21	Inspection and cleaning of cryogenic filter	RST	72 MO or 8,500 FH	1	0.15	0.15	Legacy MPD [75]
22	Inspection and cleaning of GH_2 filter	RST	72 MO or 8,500 FH	2	0.15	0.3	Legacy MPD [75]
23	Removal of mass flow meter unit for in-shop functional check	FNC	180 MO	1	0.92	0.92	Liao et al. [132]
24	Removal of pressure transducer unit for in-shop functional check	FNC	72 MO	1	0.92	0.92	Legacy MPD [75]
25	Removal of temperature transducer unit for in-shop functional check	FNC	72 MO	2	0.92	1.84	Legacy MPD [75]
26	Removal of GH_2 tank for in-shop inspection	FNC	60 MO or 12,000 FC	1	0.2	0.2	ISO 11119-3 [101] DIN EN 12245 [128] Title 49 CFR §180.207
27	Removal of GH_2 tank for in-shop restoration	RST	180 MO	1	0.2	0.2	United Nations [129] Title 49 CFR §178.71(l)(1)

Additional Information – Scheduled Maintenance Program

Fuel Cell

Task no.	Task description	Task code	Interval	No. of units installed	MMH (each unit)	MMH (total)	Interval References
01	Leak-down test	FNC	1,200 APUH	1	0.7	0.7	Legacy MPD [1]
02	Transfer-leak test	FNC	3,000 APUH	1	0.7	0.7	Legacy MPD [1]
03	External-leak test	FNC	3,000 APUH	1	0.7	0.7	Legacy MPD [1]
04	Removal of shut-off solenoid vales for in-shop restoration	RST	16,000 APUC	2	0.65	1.3	ISO 19880 [2]
05	Removal of purging solenoid vales for in-shop restoration	RST	1,300 APUH	2	0.65	1.3	ISO 19880 [2]
06	Removal of mixing valve for in-shop restoration	RST	1,300 APUH	1	0.65	0.65	Legacy MPD [1]
07	Functional check of safety valve	FNC	60 MO	1	0.83	0.83	ISO 21029-2 [3]
08	Removal of safety valve for in-shop restoration	RST	120 MO	1	0.65	0.65	ISO 21029-2 [3]
09	Discard of air filter	DIS	72 MO or 8,500 APUH	1	0.15	0.15	Legacy MPD [1]
10	Cleaning of hydrogen filer	RST	72 MO or 8,500 APUH	1	0.15	0.15	Legacy MPD [1]
11	Discard of de-ionizing coolant filter	DIS	72 MO	1	0.92	0.92	Legacy MPD [1]
12	Removal of temperature transducer unit for in-shop functional check	FNC	72 MO	1	0.92	0.92	Legacy MPD [1]
13	Removal of temperature transducer unit for in-shop functional check	FNC	72 MO	2	0.92	1.84	Legacy MPD [1]
14	Removal of moisture sensing unit for in-shop functional check	FNC	72 MO	1	0.92	0.92	Legacy MPD [1]
15	Removal of air compressor for in-shop restoration	RST	30 MO or 18,000 APUH	1	0.42	0.42	Gardner Denver Deutschland GmbH [4]
16	Removal of coolant pump for in-shop restoration	RST	36 MO	1	0.42	0.42	Sumitomo Precision Products Co. Ltd. [5]
17	Detailed inspection of heat exchanger	DET	36 MO or 3,000 APUH	1	0.3	0.3	Legacy MPD [1]
18	Removal of heat exchanger for in-shop restoration	RST	108 MO or 12,000 APUH	1	0.42	0.42	Legacy MPD [1]
19	General visual inspection of fuel cell bearings	GVI	36 MO	2	0.55	1.1	Legacy MPD [1]