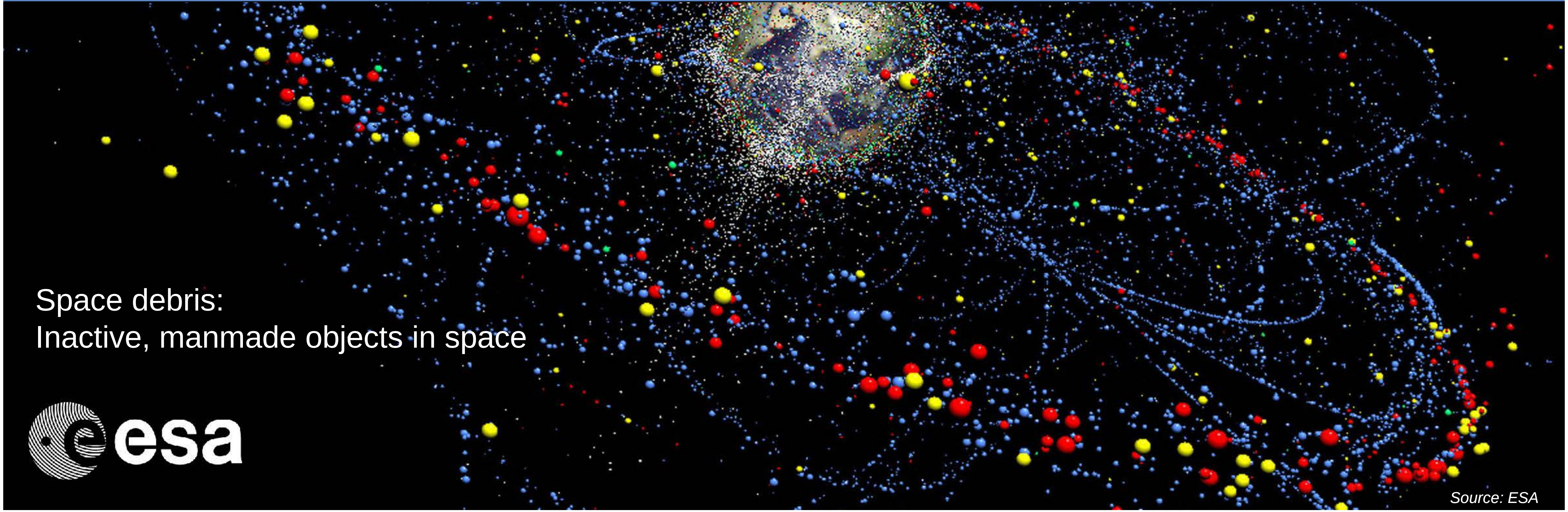
A first design for demise analysis for launch vehicles

Henrik Simon, Stijn Lemmens



Overview

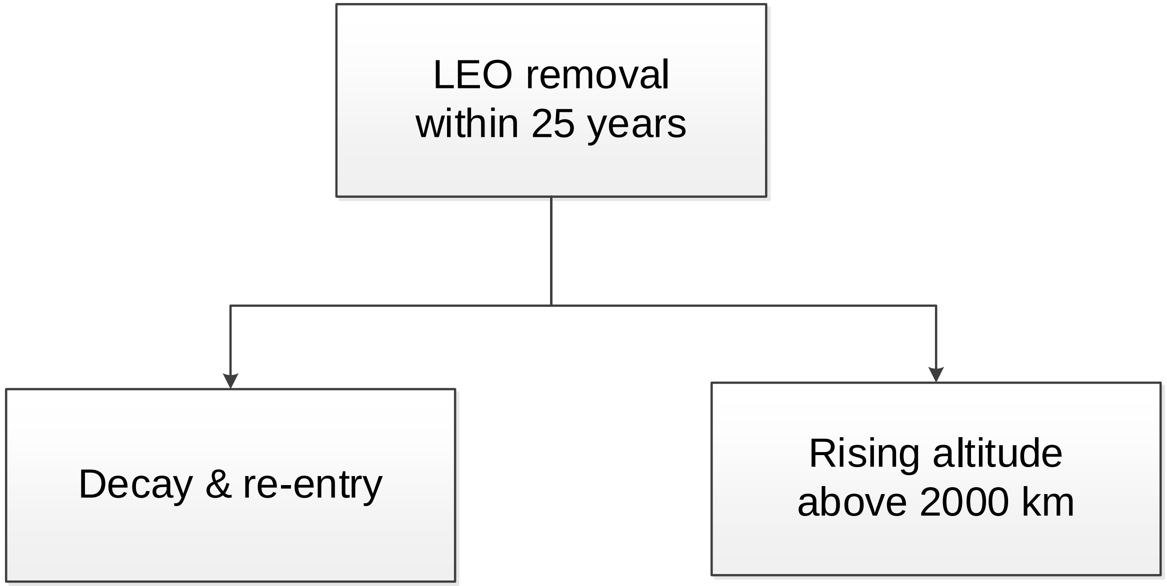
- Introduction
- Fundamentals
- Modelling approach
- Results and discussion
- Summary and outlook

What is the motivation and task?

INTRODUCTION

Motivation

- Mitigation: Prevention of creation and limitation of long-term presence
- Guidelines:
  - LEO removal within 25 years after mission end
  - Casualty risk limit for re-entry: 1 in 10,000

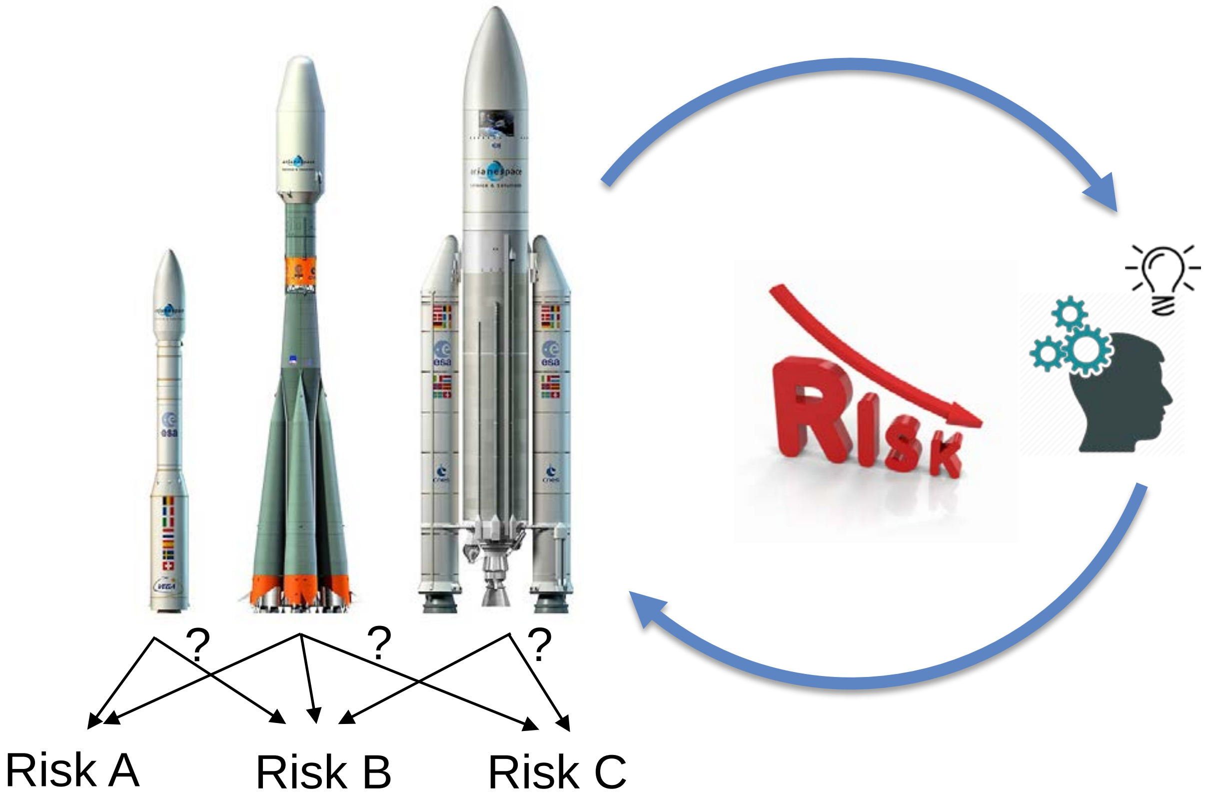


Solution: Design for demise

Scope of the thesis

- Typical design of upper stages
- General Risk assessment

- Design for demise solutions to reduce the risk



Source: CNES

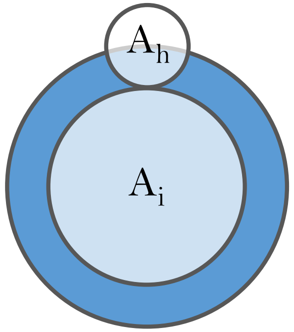
How do we assess the risk and simulate the re-entry?

FUNDAMENTALS

Fundamentals: Ground risk assessment

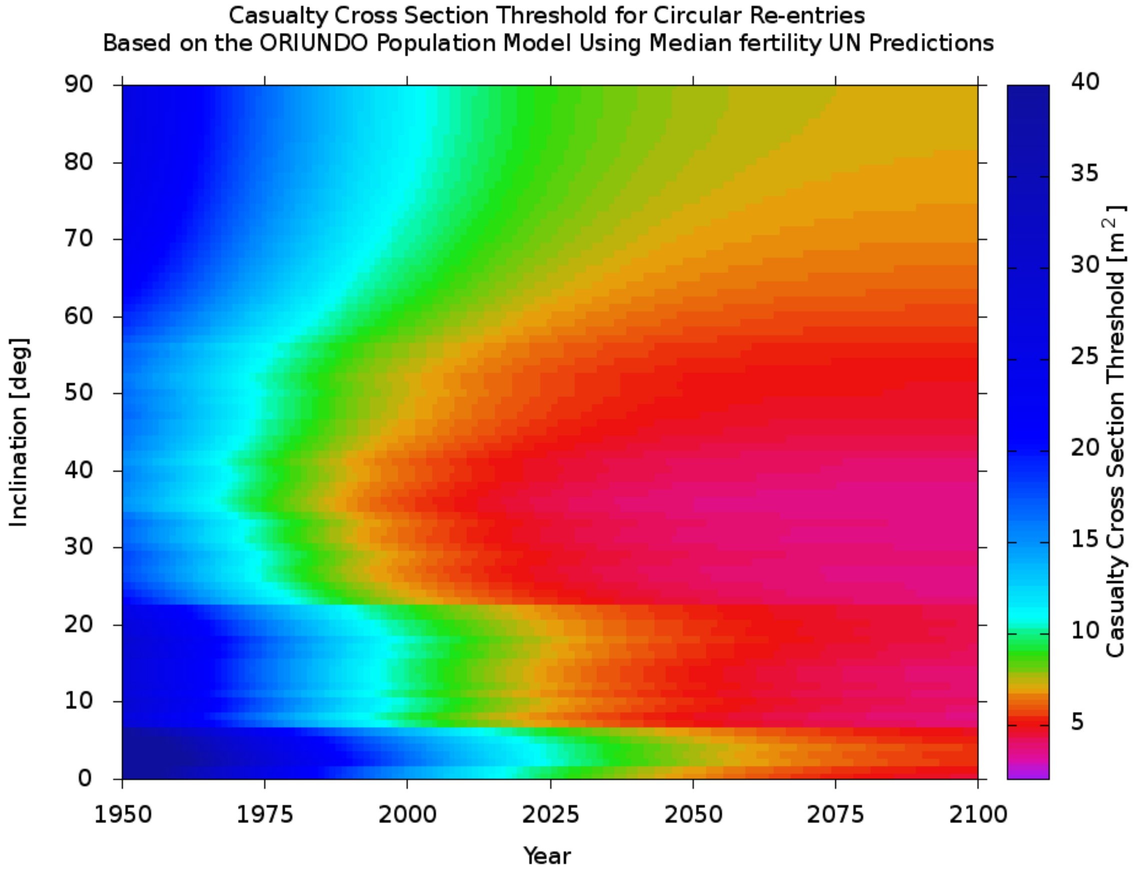
$$A_C = \sum_{i=1}^{N} \left(\sqrt{A_h} + \sqrt{A_i}\right)^2$$

$$R_C = A_C \cdot P_D$$



$A_C \approx 3.5\ \mathrm{m}^2$

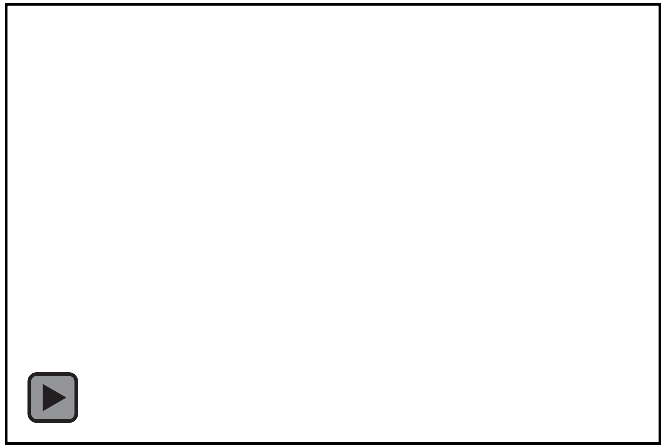
$A_C \approx 5.0\ \mathrm{m}^2$

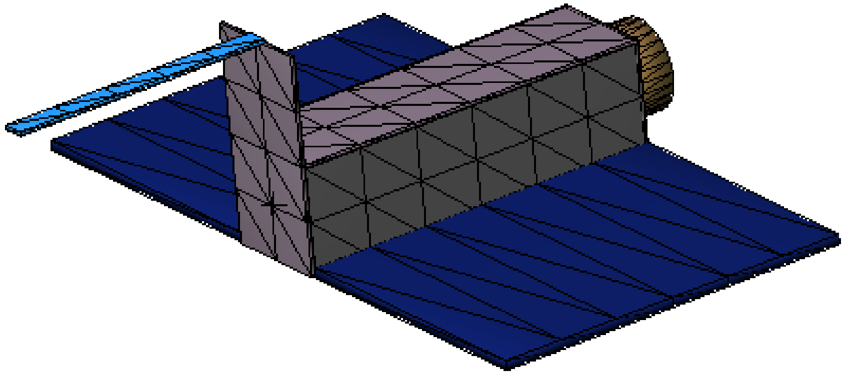


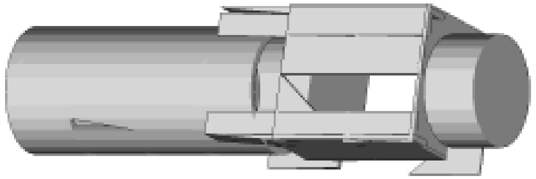
Fundamentals: Re-entry simulation tools

SCARAB: Spacecraft-oriented approach

- CAD-like modelling
- 6 DoF flight dynamics
- Break-up / fragmentation computed







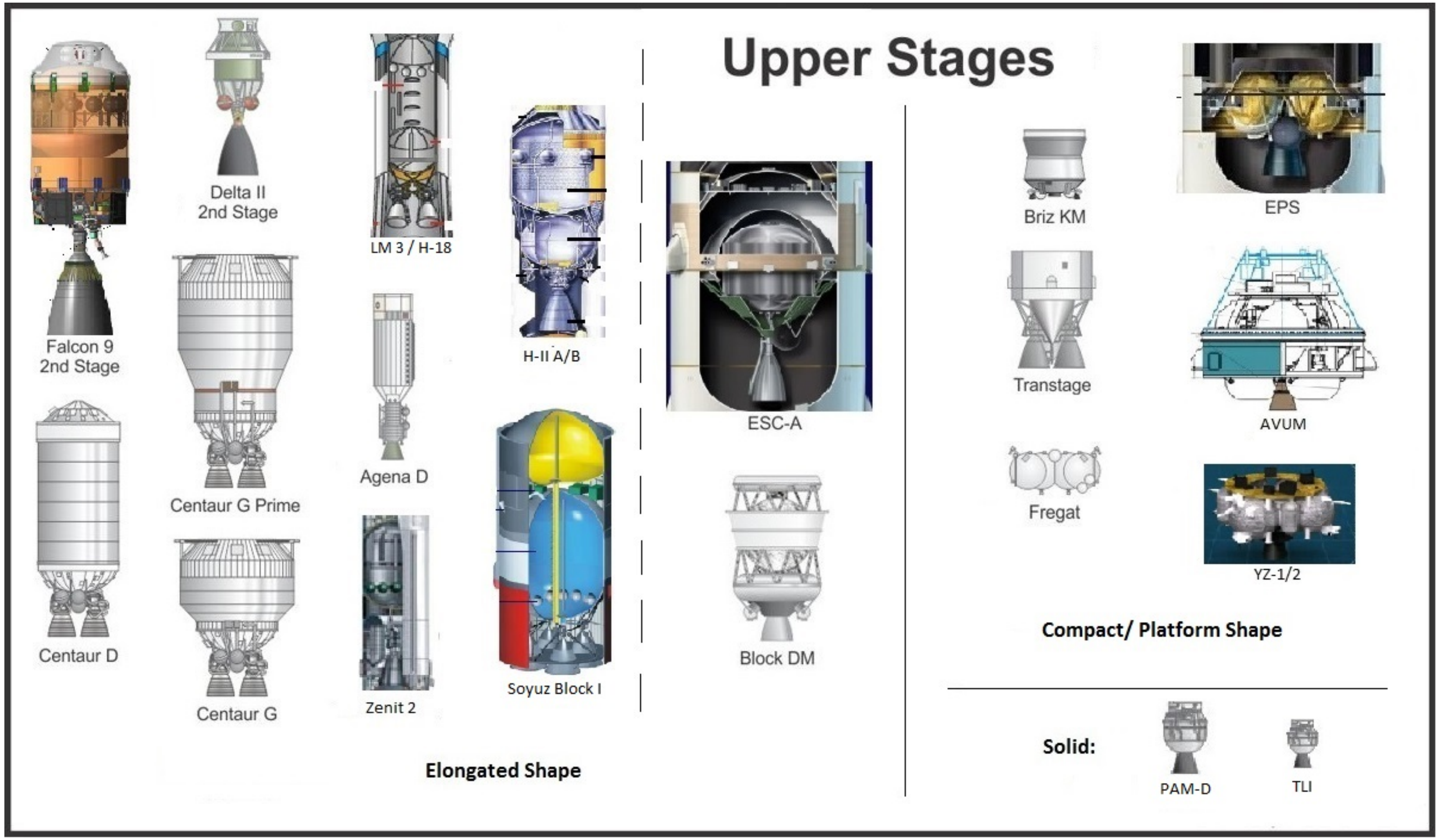
How does a rocket upper stage look like?

MODELLING

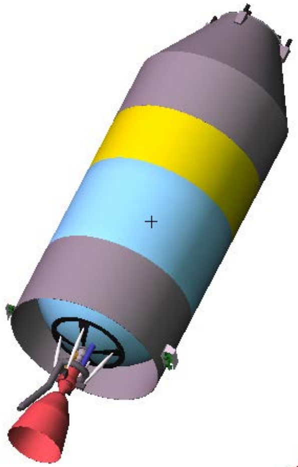
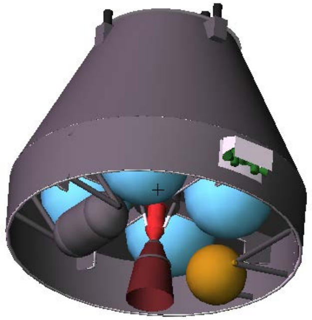
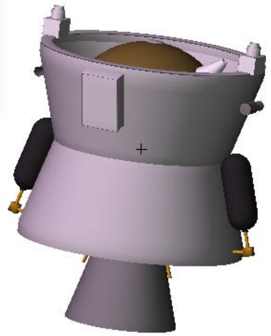
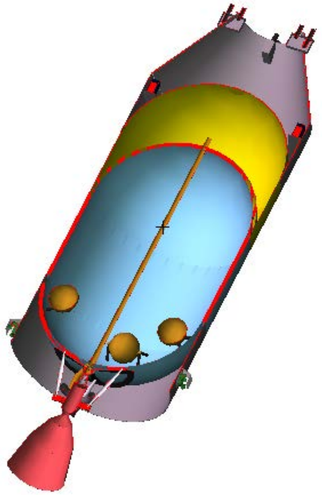
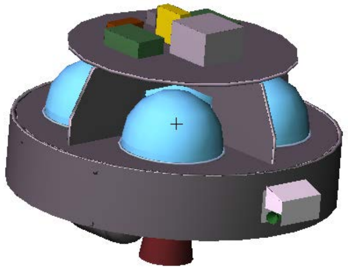
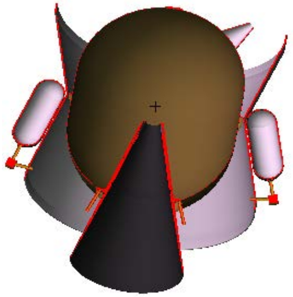
Modelling approach

- Research on typical design:
  - Elongated
  - Platform
  - Solid Rocket Motor

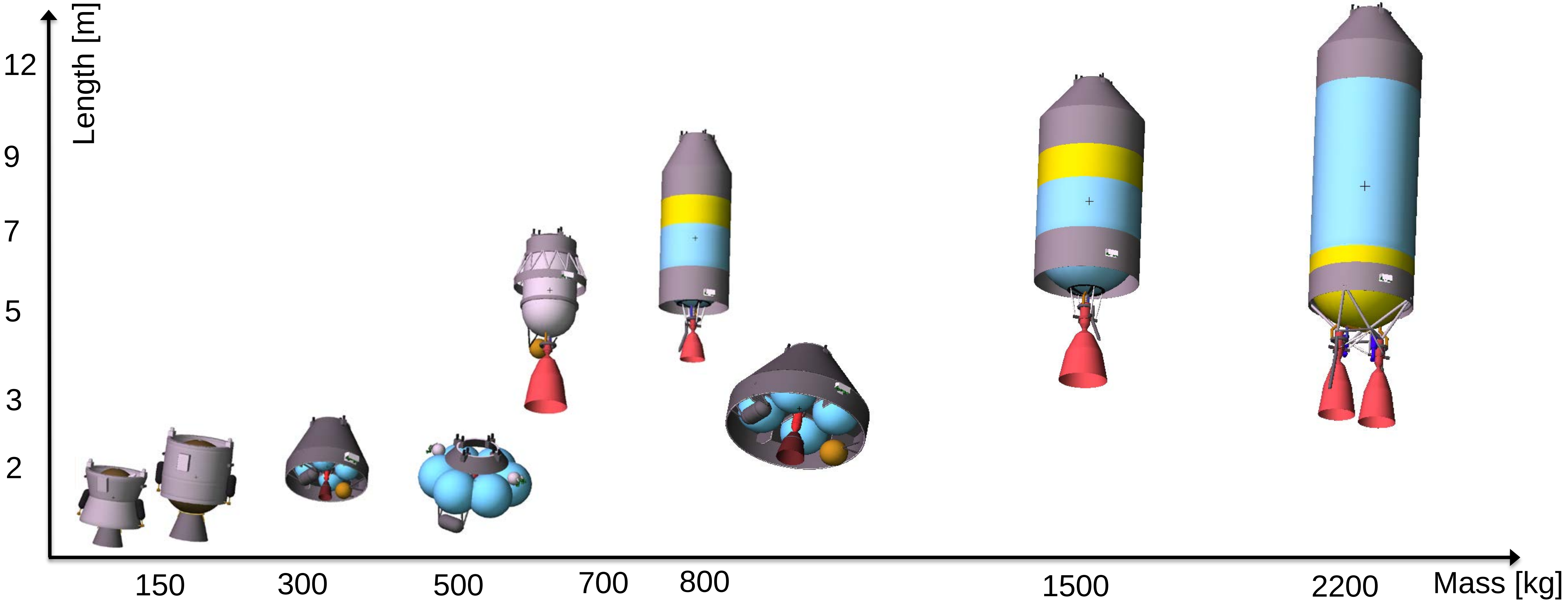
- Lack of information:
  - Create common intersection
  - Deliberately stay top-level and only compare effects



Modelling approach

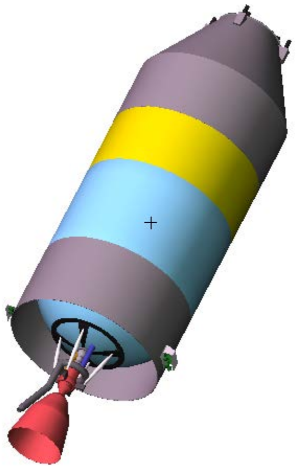
Modelling approach



How much is the risk and how can we reduce it?

SIMULATIONS

Example of SCARAB re-entry simulation



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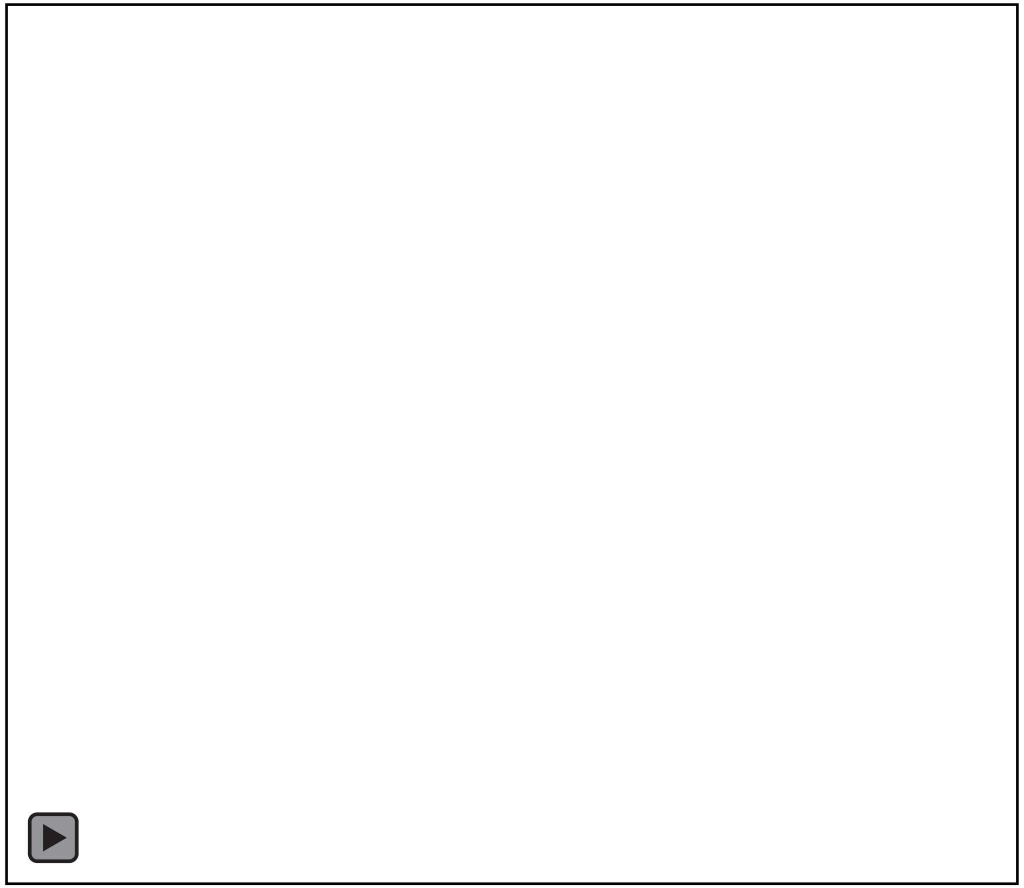
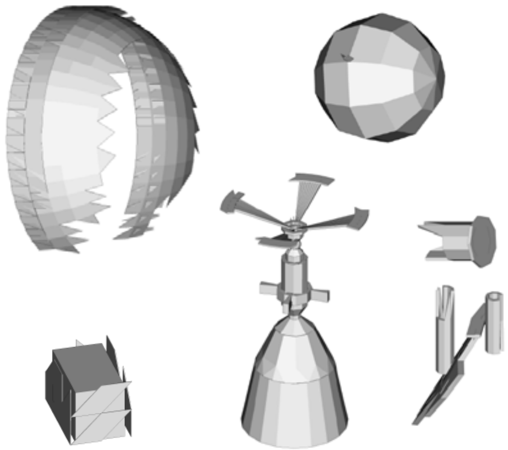
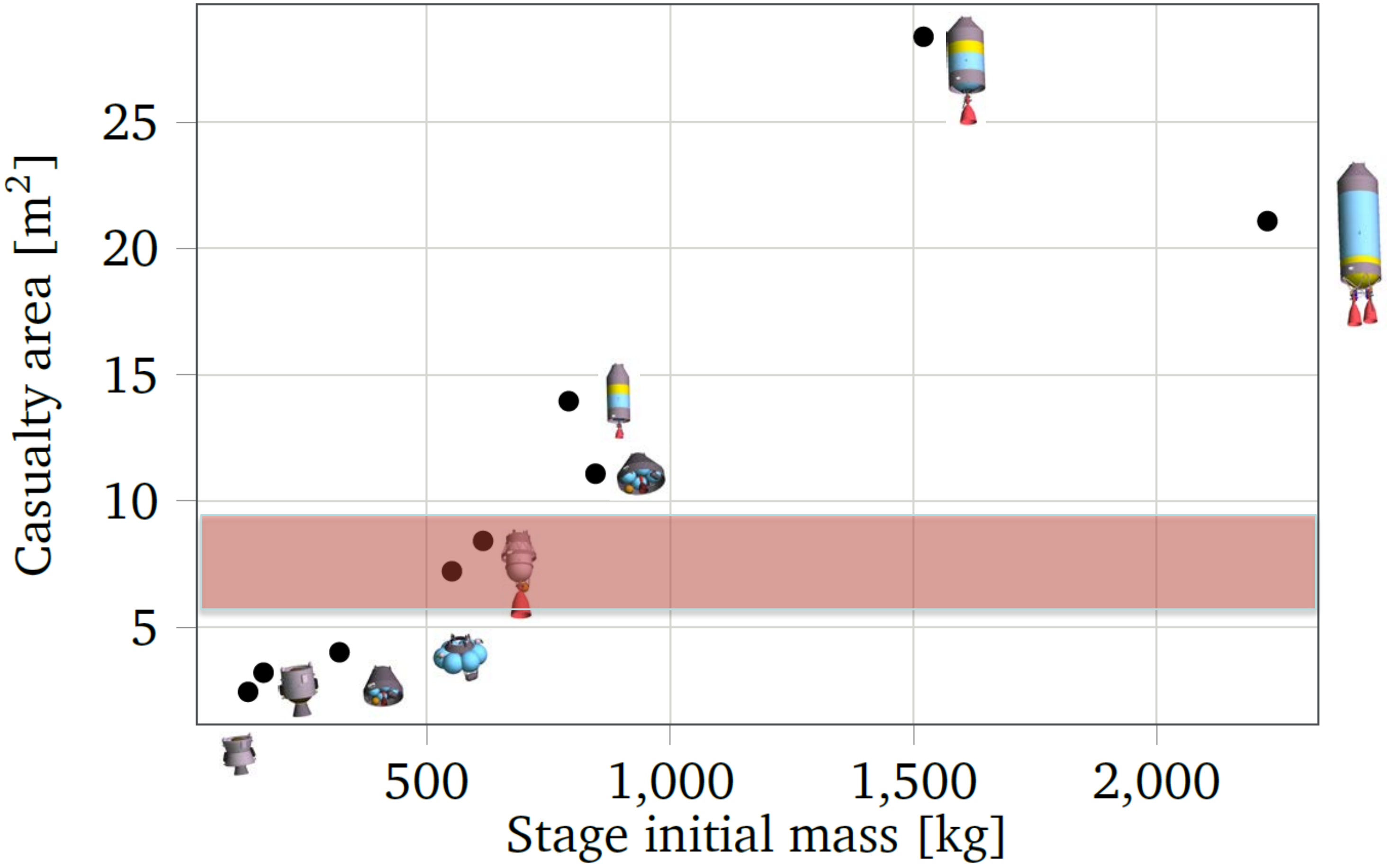
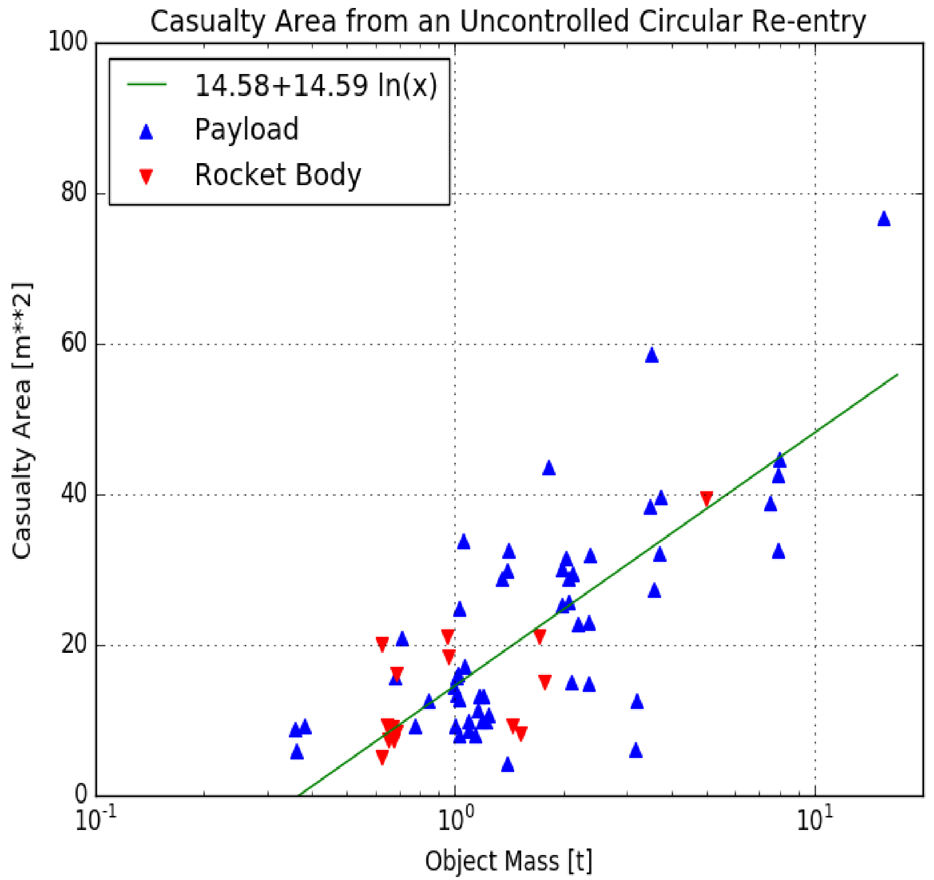


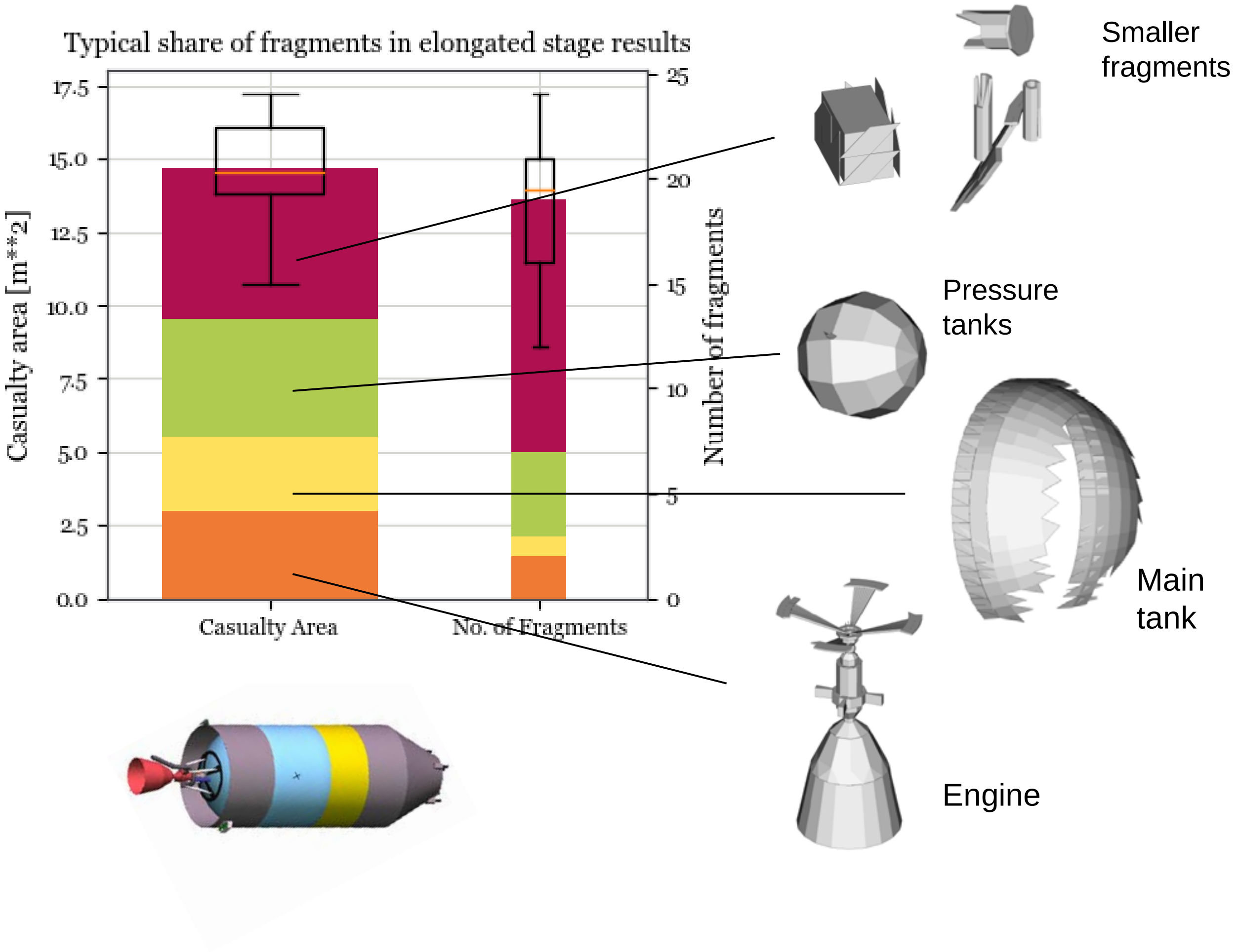


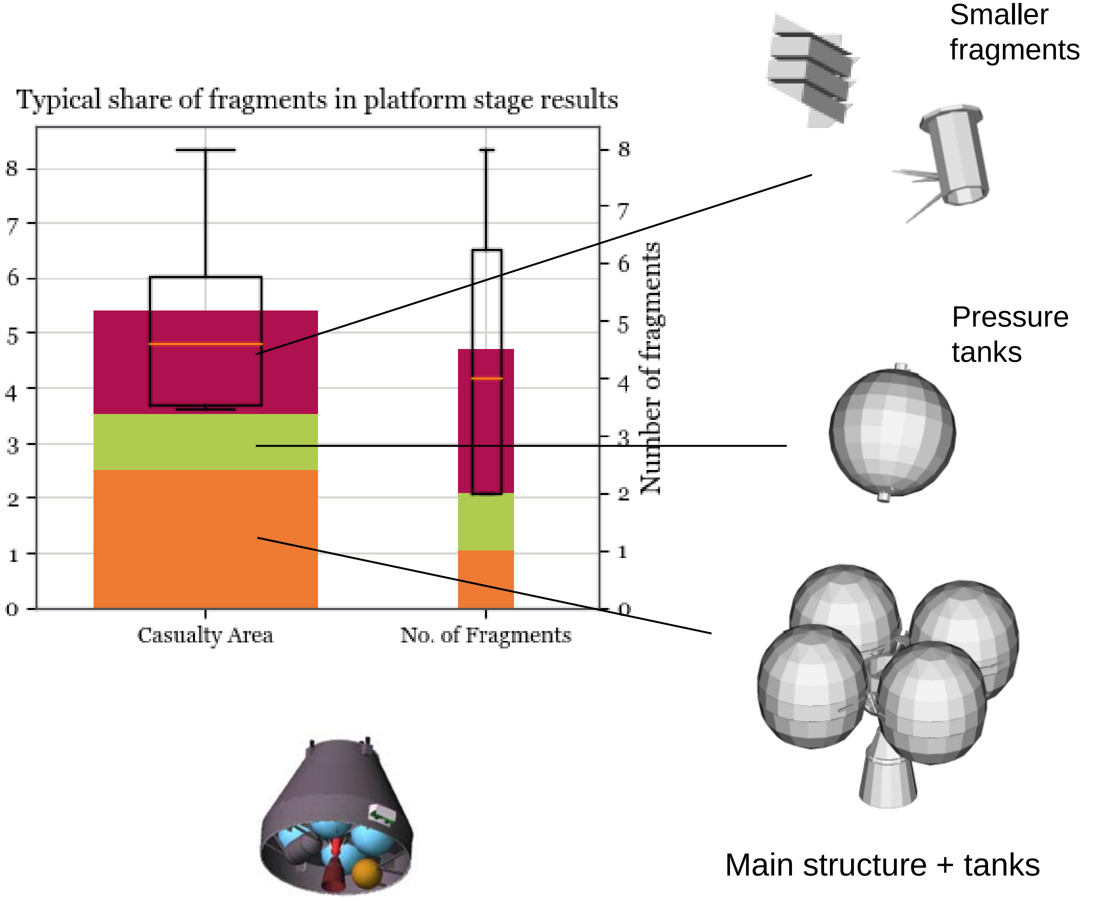
Casualty risk of all reference cases





Typical survivors

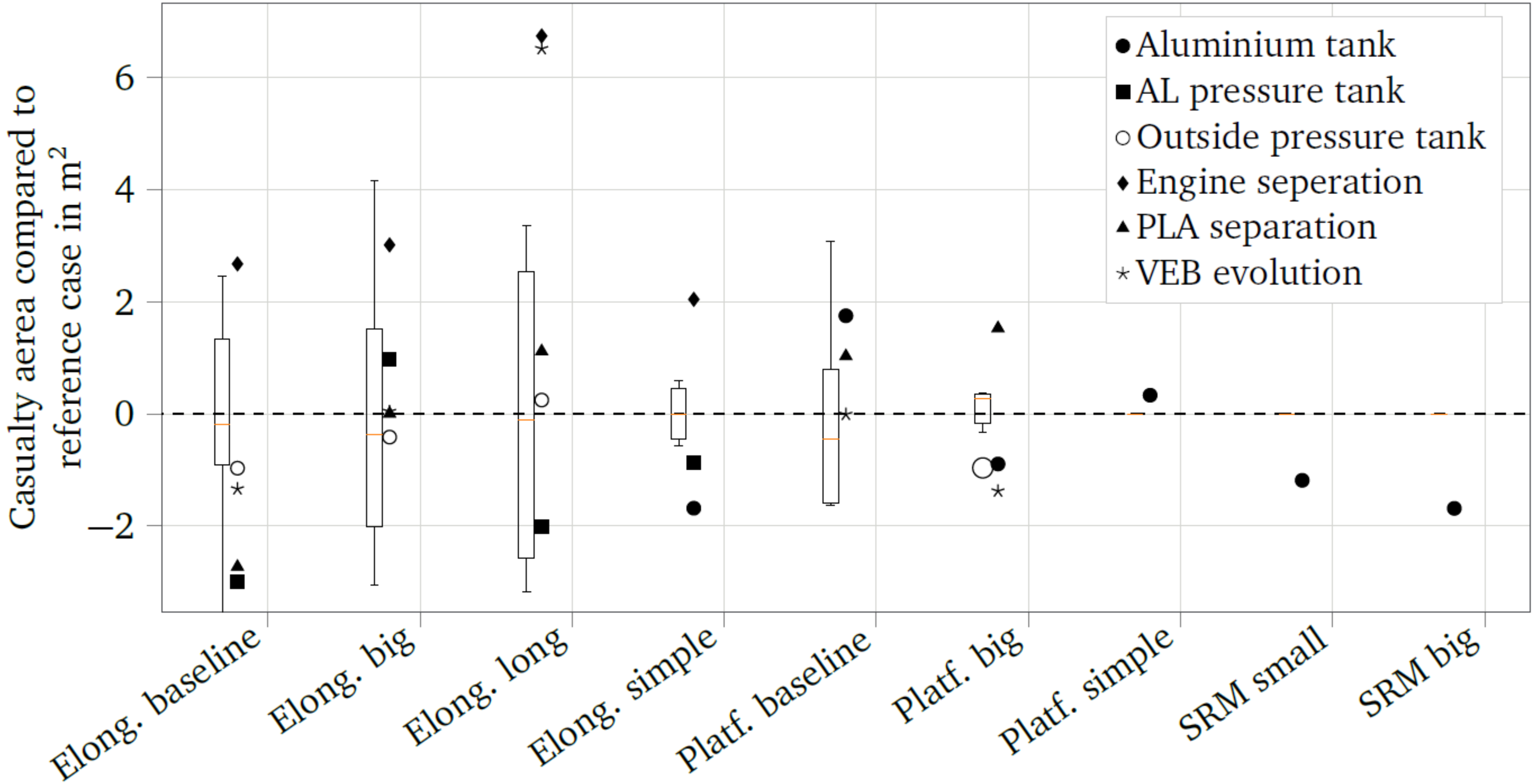




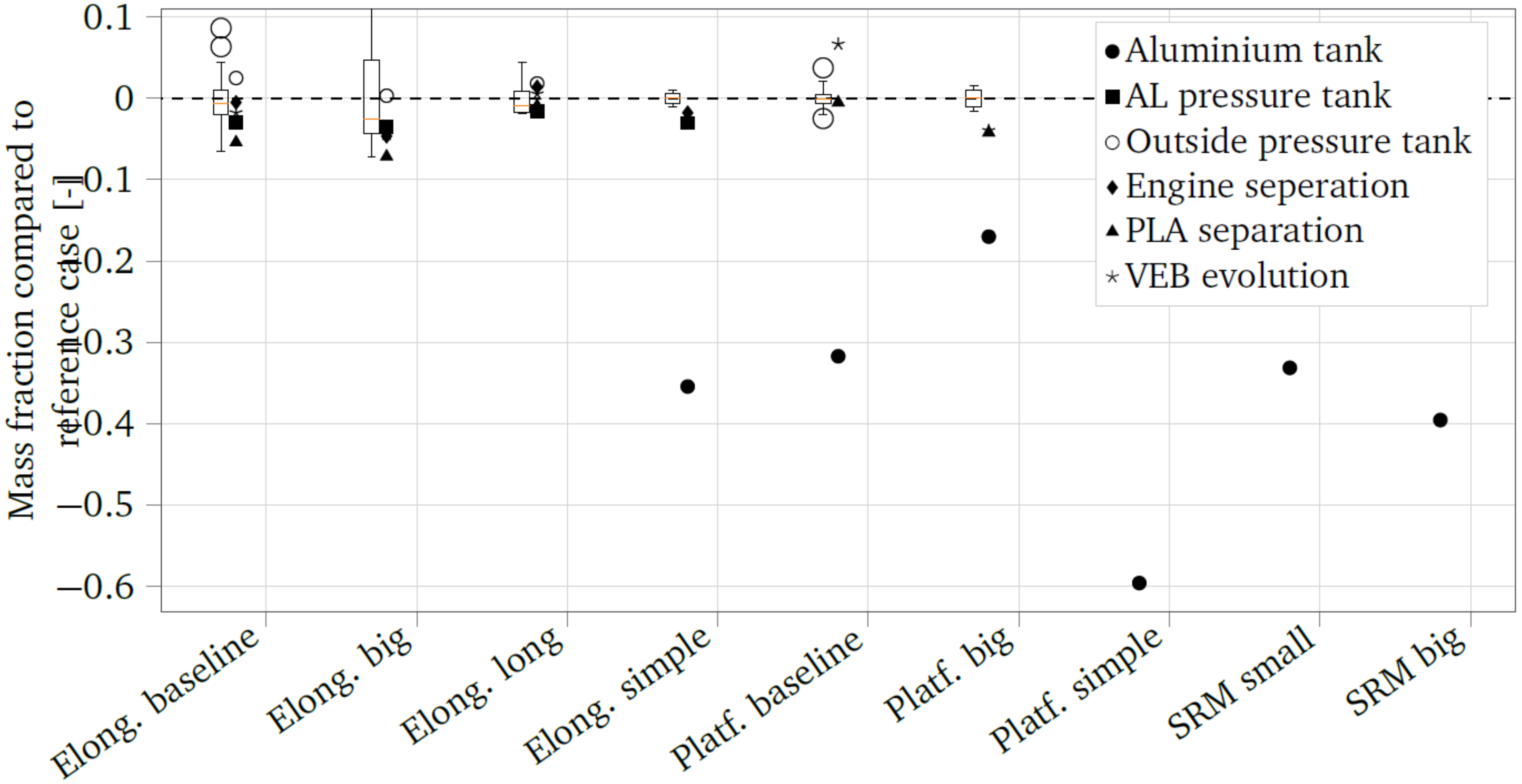
Design for Demise

- Early exposure to the environment
  - Engine separation
  - Payload adapter separation
  - Pressure tank outside
- Material substitution for critical materials
  - Aluminium tank
  - Aluminium pressure tank
  - Electronic components evolution

D4D techniques influence: Casualty area



D4D techniques influence: Mass fraction

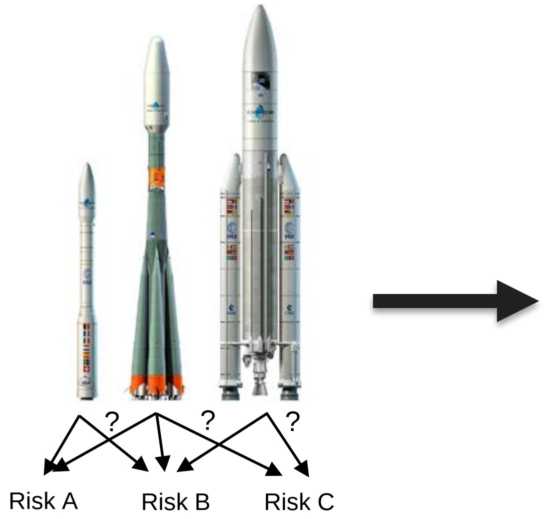


CONCLUSIONS

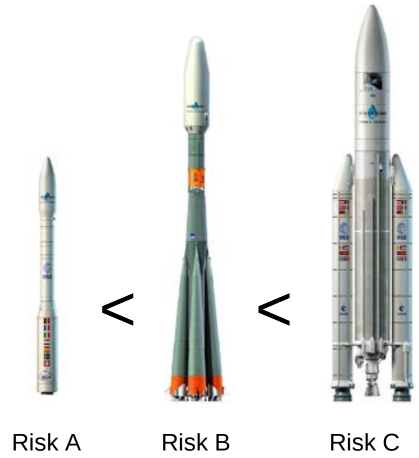
Conclusions: Risk assessment

- Most critical components:
  - Engine
  - Pressure tanks (titanium)
  - Larger tank fragments
- Number of fragments is the key driver

- Detailed risk model could not be derived
- General assessment possible



Source: CNES



Source: CNES

Conclusions: Design for demise

- All techniques reduced surviving mass fraction
- Large spread in results: Clear statement difficult

- Success of a technique dependent on:
  - Architecture
  - Reference case demise advance

- Avoid increase of number of fragments

Outlook

- This was not a risk assessment, reliable design information would be needed

- Orbital parameter sensitivity study, e.g. for initial break-up altitude

- Top-level assessment of the thermal versus phenomenological break-up concept

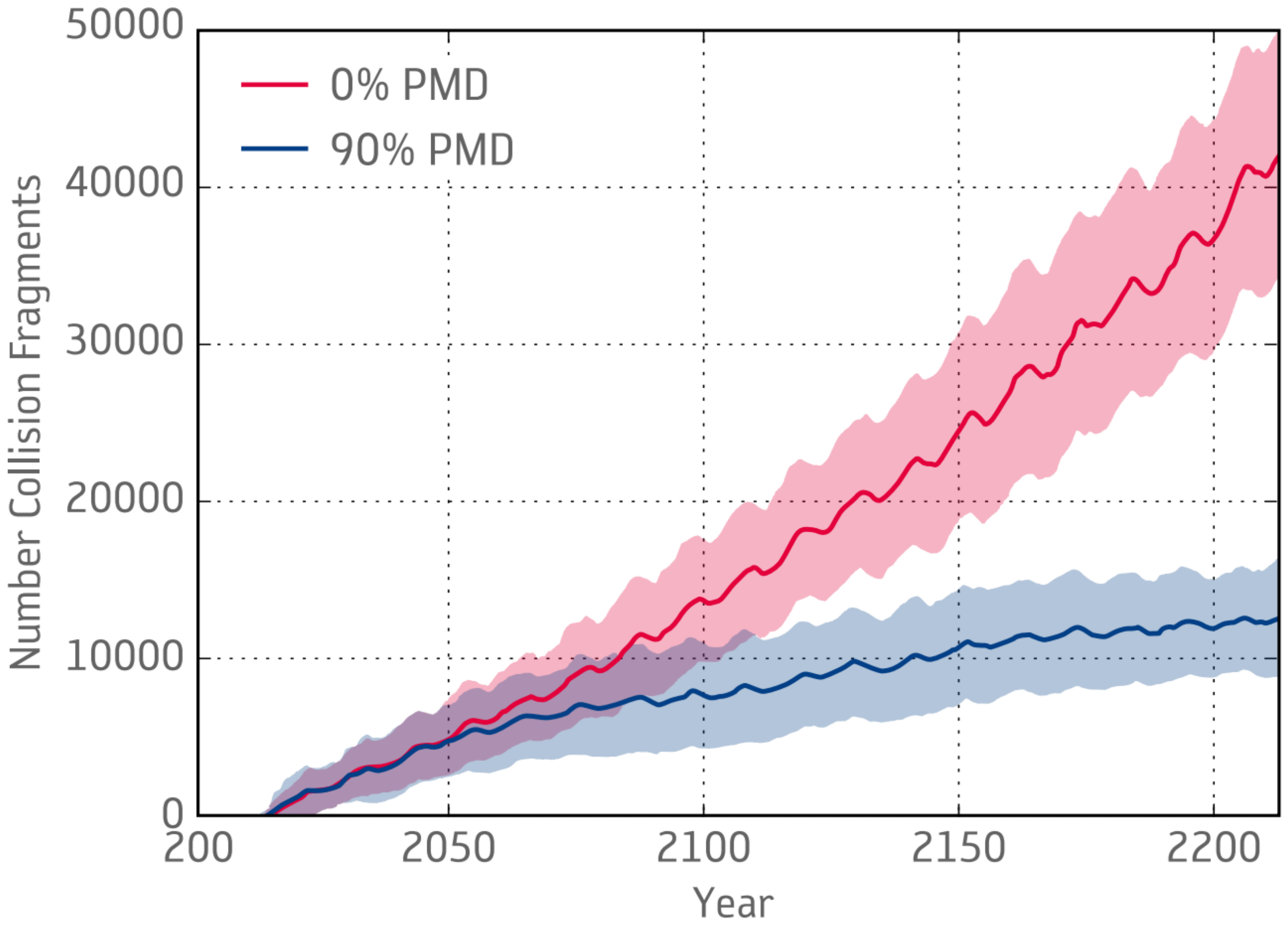
Questions?

THANK YOU FOR YOUR ATTENTION

BACKUP

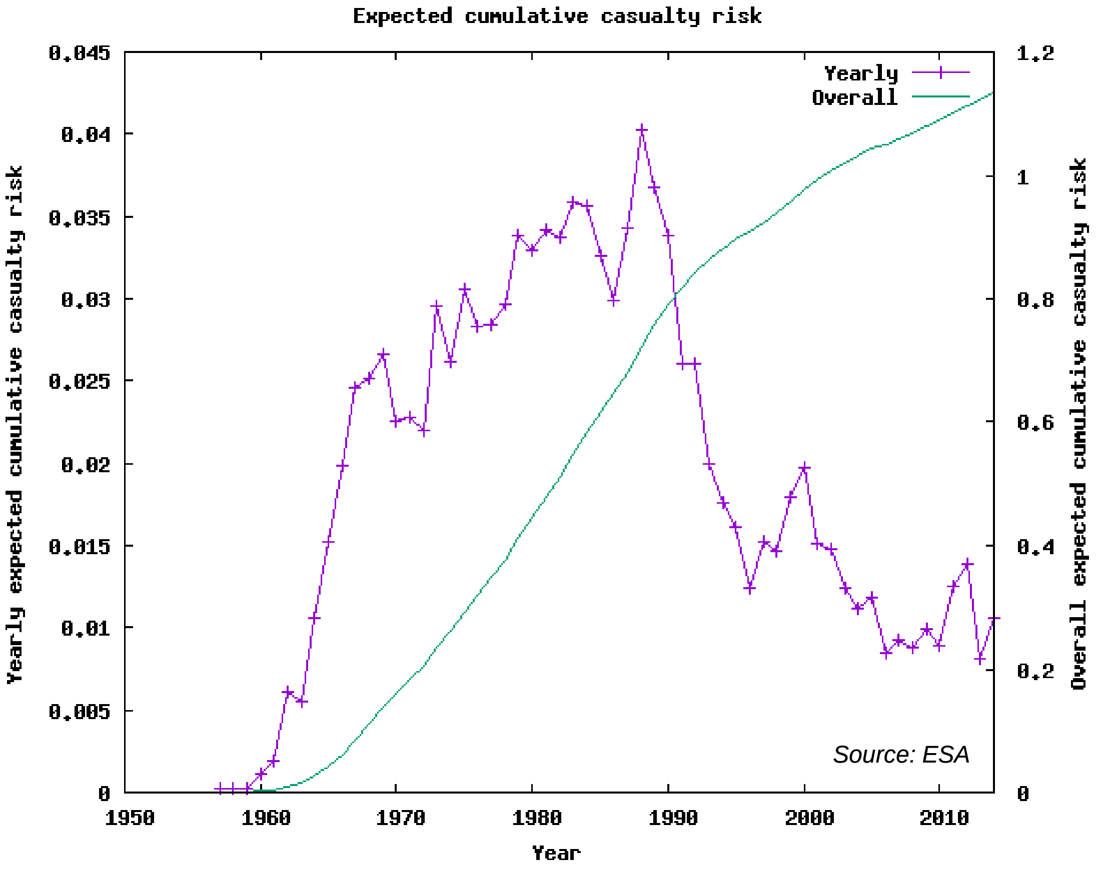
Introduction

- Mitigation:
  - Prevention of creation and limitation of long-term presence



Backup: Motivation

- Space debris
- Mitigation
- Risk guidelines
  - Casualty risk limit for re-entry: 1 in 10,000

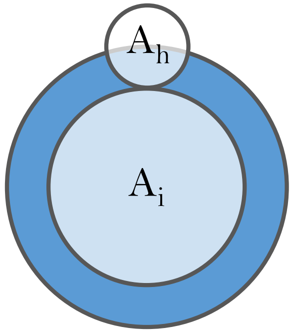


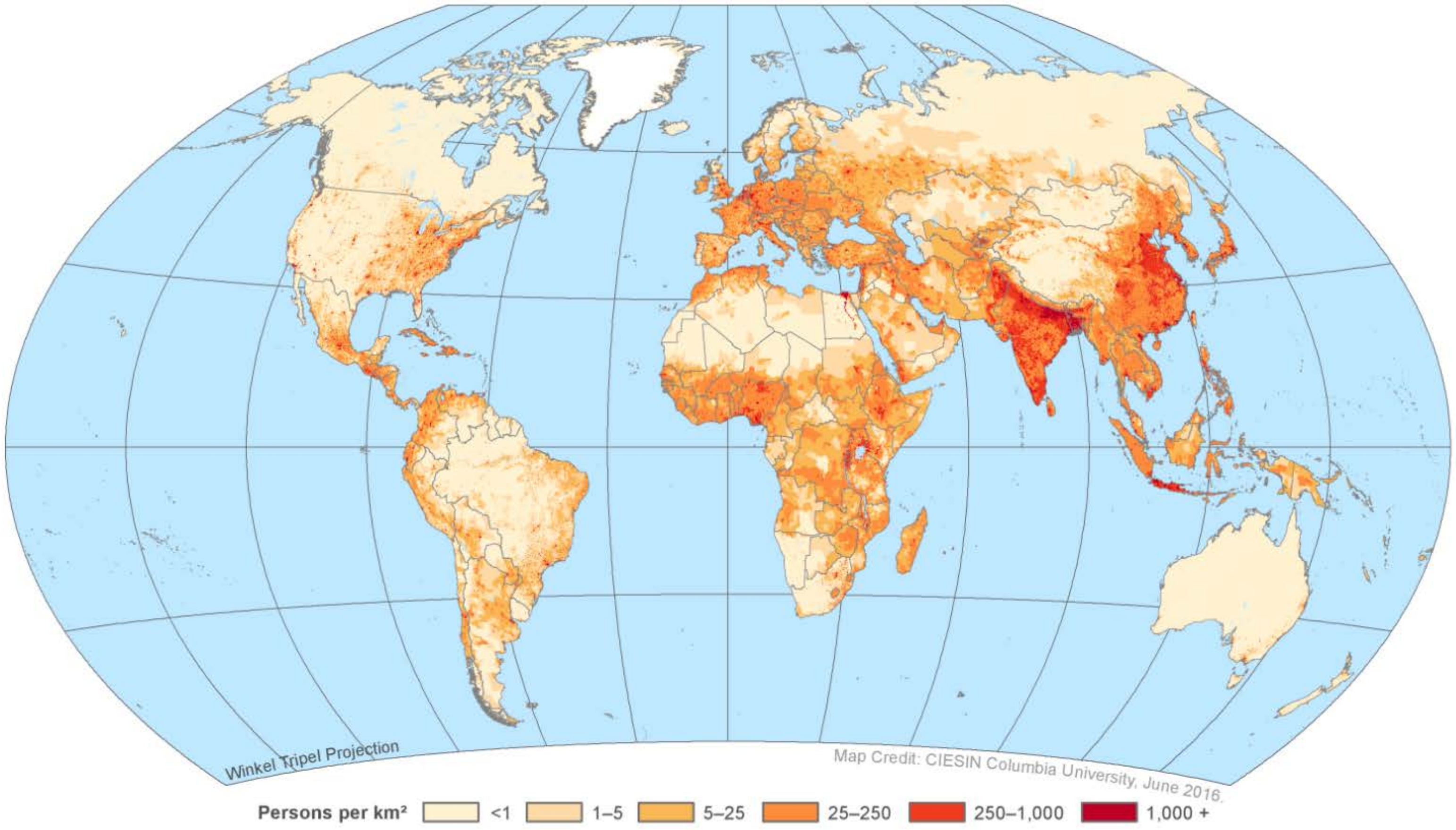
- Solution: Design for demise

Backup: Ground risk assessment

$$R_C = A_C \cdot P_D$$

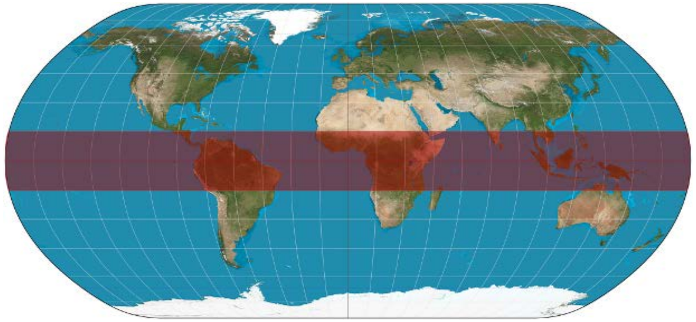
$$A_C = \sum_{i=1}^{N} \left(\sqrt{A_h} + \sqrt{A_i}\right)^2$$



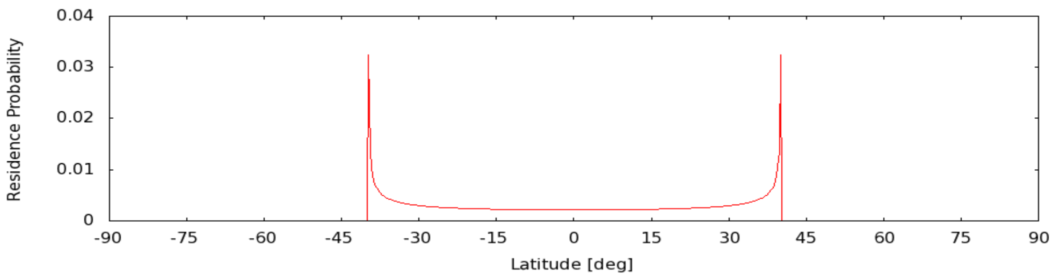


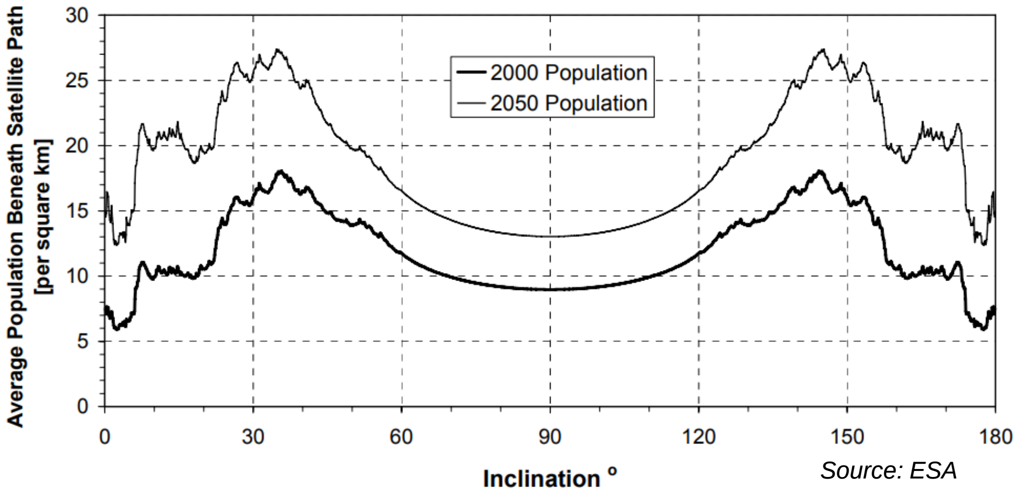
Source: Columbia University

Backup: Ground risk assessment



Source: ESA





Source: ESA

Backup: Ground risk assessment

Activity	Personal risk of fatality	
Coal mining	9.3×10^{-3}	1/107
Cancer	1.8×10^{-3}	1/545
Fire fighting	8.0×10^{-4}	1/1250
Motor vehicle operation	2.2×10^{-4}	1/4500
Home accidents	1.2×10^{-5}	1/83000
Air travel	2.0×10^{-6}	1/500000
Lightning	5.0×10^{-7}	1/2000000
Space object re-entry	8.0×10^{-12}	1/1200000000000

Backup: Re-entry equations

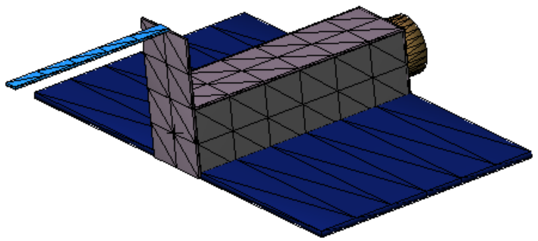
$$\dot{Q}_{tot} = \dot{Q}_{conv} + \dot{Q}_{rad} = mc_p \frac{dT}{dt}, \text{ if } T < T_m$$

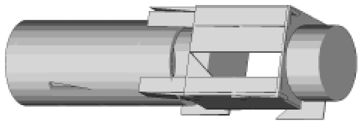
$$\dot{Q}_{tot} = -q_m \frac{dm}{dt}, \text{ if } T = T_m$$

Backup: Re-entry simulation tools

SCARAB: Spacecraft-oriented approach

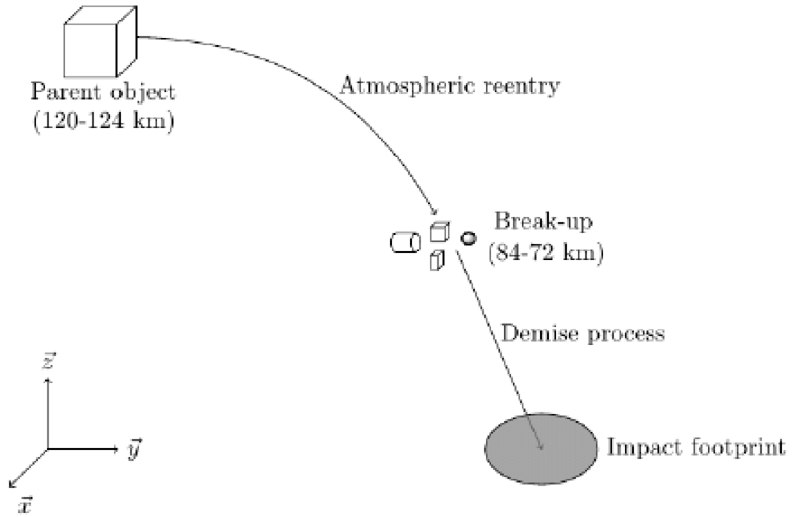
- CAD-like modelling
- 6 DoF flight dynamics
- Break-up / fragmentation computed



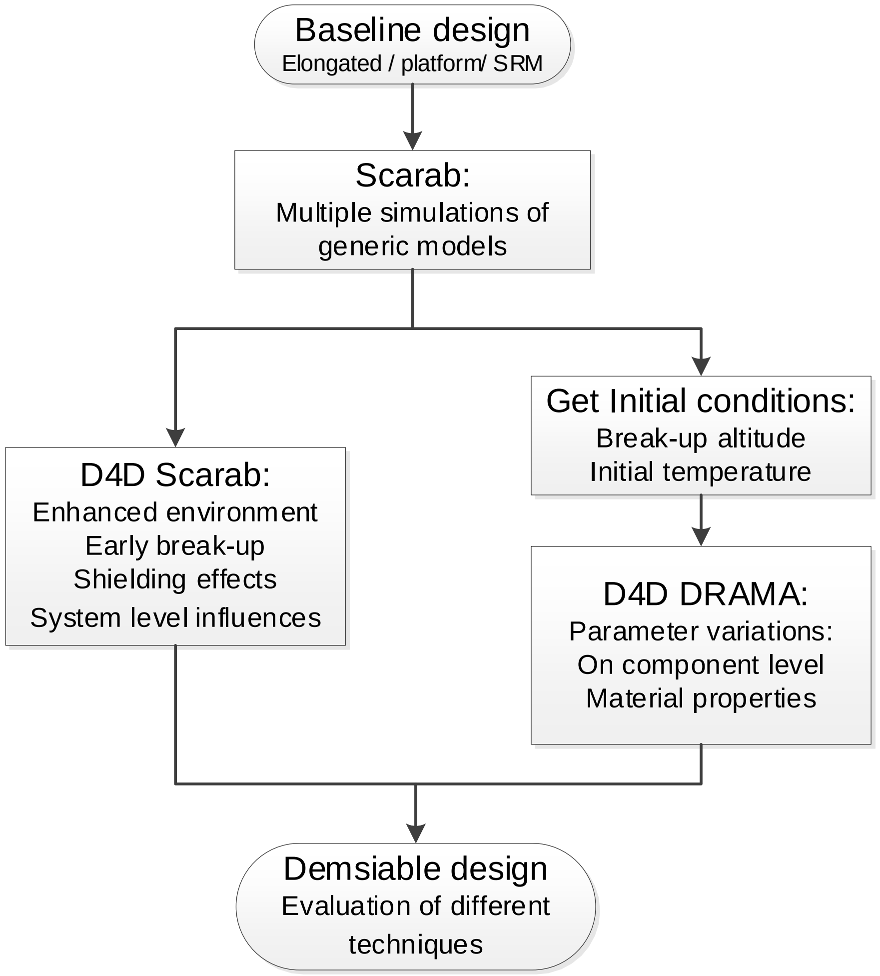


DRAMA: Object-oriented approach

- Simple shapes:
- Sphere, Cylinder, Box, Cone
- Relatively fast computation

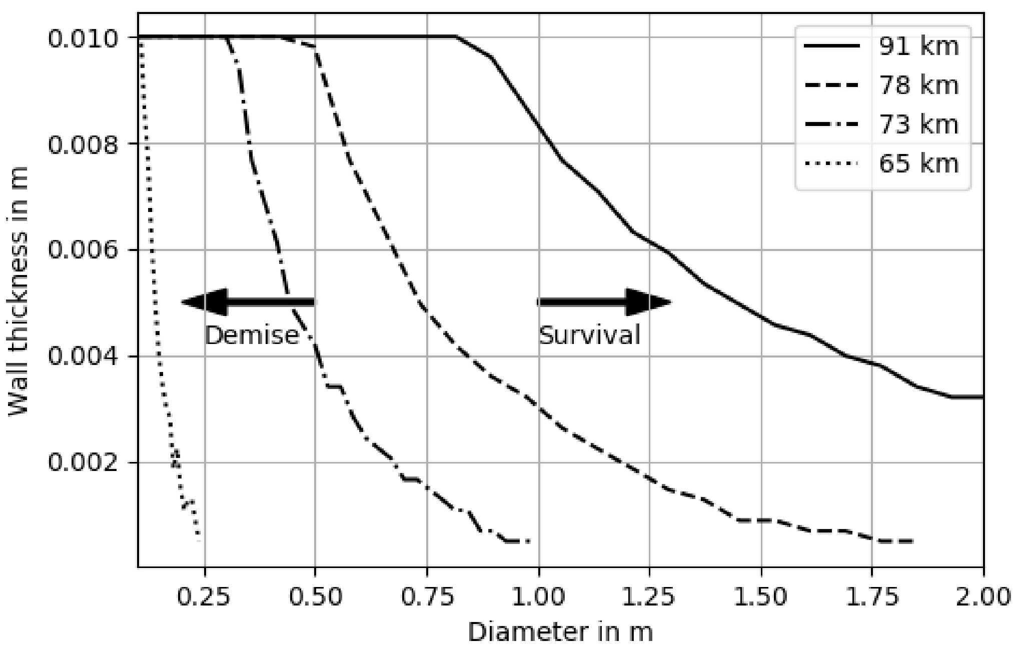


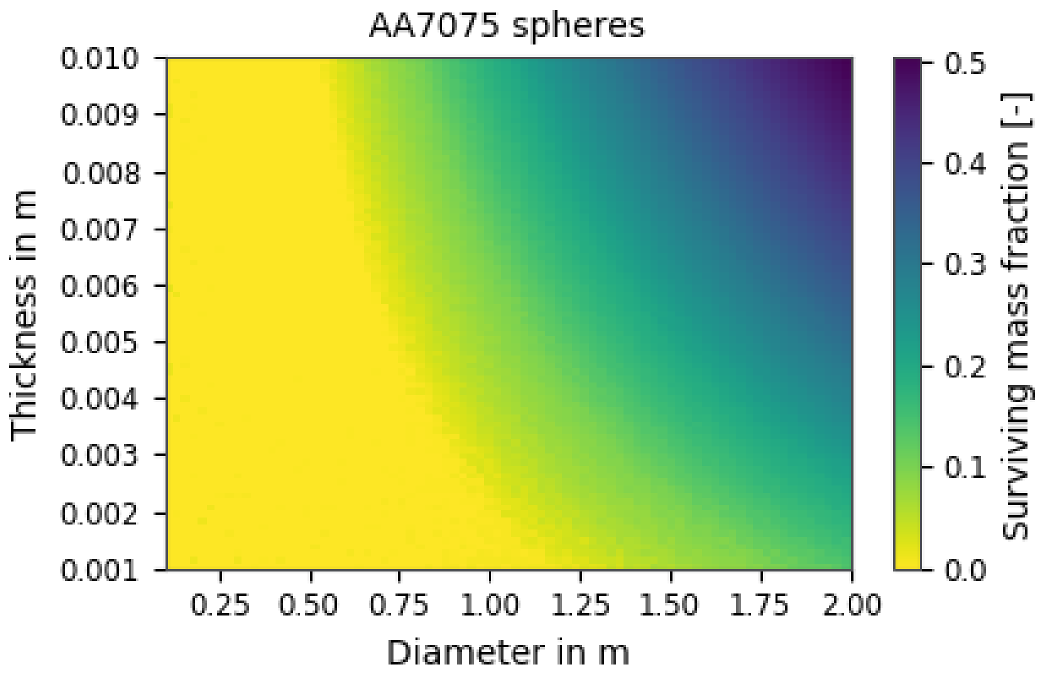
Backup: Simulations work logic



Backup: DRAMA analysis

- Analysis on component level:
  - Surviving of spherical aluminium tanks



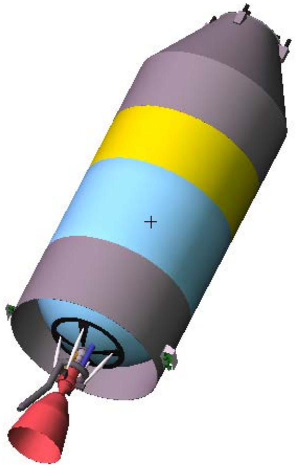


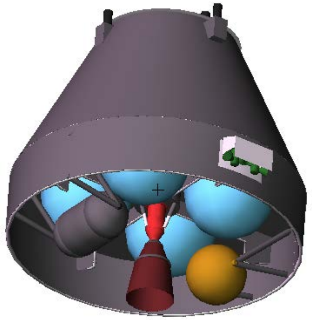
Backup: Lack of information on upper stages

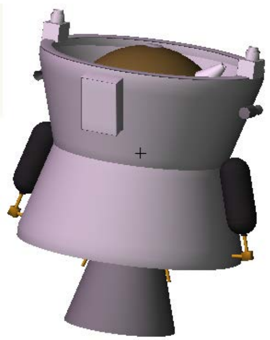
Platform stages:	stage			Engine							tank							pressurization						
Stage Name	diameter	length	dry mass	Re-igni	Name	Cycle	Diamet	length	mass	material	shape	diameter	length	mass	material	propellant	quant	pressurizati	shape	diameter	length	mass	material	quantit
EPS	3.96	3.35	1150	yes	Aestus	pressure fed	1.31	2.2	223		spherical	1.4	1.98	100	Al 2219	MMH/N2O	4	He tank	spherical	0.9	-	58	copv	2
AVUM	1.95	0.46-2.04 ?	418	yes	RD-843	pressure fed			16		cylindrical	0.61	0.7 ?	24.5	Al 2219	UDMH/N2	4	tank	cylindrical	0.34	0.68	23	COPV	1-2?
Fregat	3.35	1.5	950	yes	S 5.92	Gas generato	0.84	1.02	75		spherical	1.8 mm thick			AL AMG6	UDMH/N2	6	He tank	spherical	0.37	-			4
BRIZ-M	4.1	0.6 (2.65)	2380	yes	S 5.98M	staged comb	0.95	1.15	95		cylindrical/torus					UDMH/N2	2	tank	spherical		-		COPV	7-11 ?
Transtage	3.05	4.57	2090	yes	AJ10-138	pressure fed	0.84		95		cylindrical	1.2 / 1.5	4.1 / 3.2		Titanium?	A50/N2O4	2	He tank	spherical					2+
YZ-1/2 (LM-3)	2.8-3.8	2.2		yes	YF-50D						spherical					UDMH/N2	4							
Elongated stages:	stage			Engine							tank							pressurization						
Stage Name	diameter	length/hei	dry mass	Re-igni	Name	Enginge cycle	Diamet	length	mass	material	shape	diameter	length	mass	material	propellant	quant	pressurizati	shape	diameter	length	mass	material	quantit
ESC A	5.45	5.84	4400	no	HM7B	Gas generato	0.99	2.1	165	A316	spherical/cylin	5.45	3.74	2300	AL2219	LH2/LOX	1	tank	spherical	0.69 ?	-	50	Tial6v4	1
Block I	2.66	6.7	2355	no	RD 0110	Gas generato	1.57	2.24	408		cylindrical	2.66				LOX/Keros	2	GG/Oxygen	-	-	-	-	-	-
Block-D/DM	3.9	5.6	2200	yes	RD-58	staged comb	1.17	2.27	300		cylindrical/torus					RP-1/LOX	2		spherical					
Zenith II 2nd	3.9	10.41	8000-9000	no	RD 120	staged comb	1.95	3.87	1125		cylindrical/toru	3.9				RP-1/LOX	2	He tank	spherical					
Centaur G	4.3	6.0-9.0	2086	yes	RL10	Expander cyc	1.17	2.29	168		cylindrical	0.76 mm thick			stainless steel	LH2/LOX	2		spherical/cyl	0.66	0.9		COPV	4?
Centaur D/3/5	3.05	9.1-12.68	2086	yes	RL10	Expander cyc	1.52	2.32	168		cylindrical	0.76 mm thick			stainless steel	LH2/LOX	2		spherical/cyl	0.66	0.9		COPV	4?
Delta II 2nd	2.44	5.18	950	yes	AJ10-118K	pressure fed	0.84	2.5	95		cylindrical	1.5	2.7	250	Stainless Steel	A50/N2O4	2	He tank	spherical	0.6			Titanium	1
2nd stage	3.66	15	3200	yes	Merlin 1D	gas generato	2. ?		470		cylindrical				AlLi	RP-1/LOX	2	He tank	cylindrical	0.56	1.46	30	COPV	2?
Agena D	1.52	6.48	1590	yes	Bell 8096	gas generato	0.9	2.11	134		cylindrical/ bul	1.5	2.8 (for both)			UDMH/RFN	2						Titanium	3
L-17 (H-II)	4.07	10.0-11.0	3050	yes	LE-5B	expander bleed		2.79	285		cylindrical	4	5			LH2/LOX	2	He tank	spherical					
H 18 (LM-3)	3	12.375	2740	yes	YF-75	gas Generato	1.5	2.8	550		cylindrical	2.9	8			LH2/LOX	2	He tank	spherical					
LM 14.5 (LM-4)	2.90-3.35	4.8	900		YF 40	Gas generato	0.63	1.2	83		cylindrical		3.5			LH2/LOX	2	He tank	spherical					
	stage			Engine --> see tank							tank													
Stage Name	diameter	length/hei	dry mass	Re-igni	Name	Enginge cycle	Diamet	length	mass	material	shape	diameter	length	mass	material	propellant	quantity							
PAM-D	1.45	1.83-2.03	200	no	Star 48B						cylindrical	1.24	1.6	120	Titanium		1							
TLI	1.29	1.69	160	no	Star 37FM						cylindrical	0.93	1.1	86	Titanium		1							

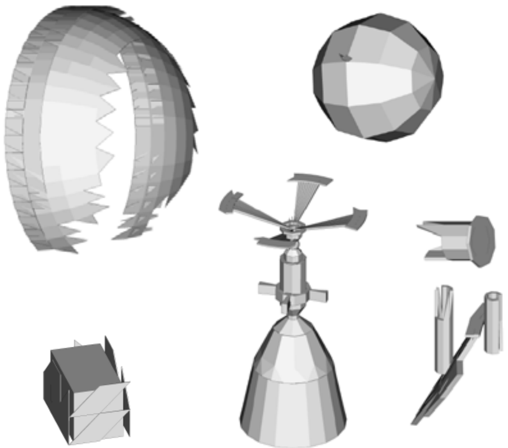
Backup: Modelling approach

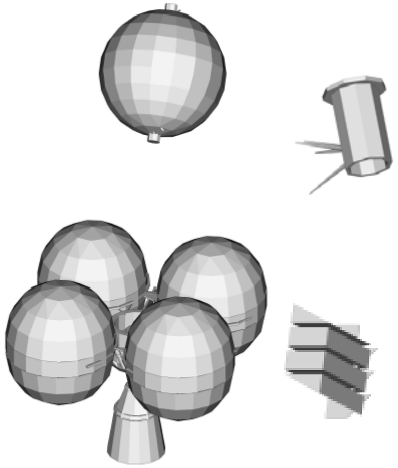
Backup: Reference cases

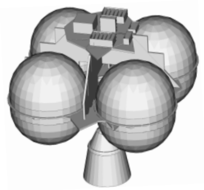


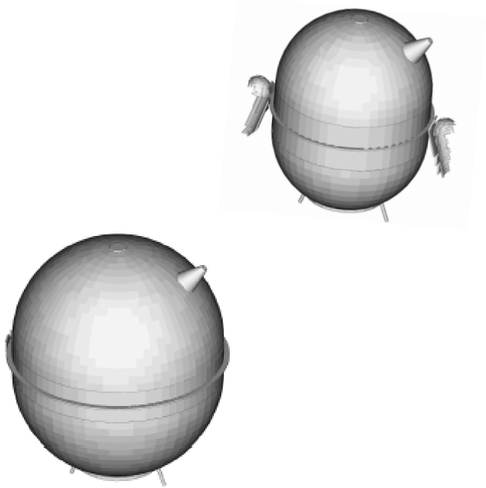










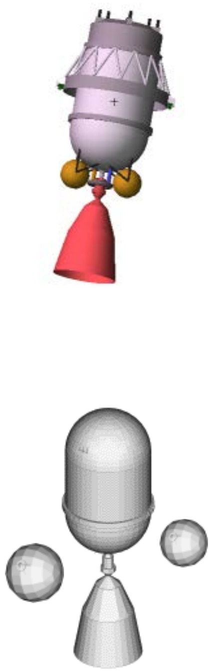


Backup: Reference cases

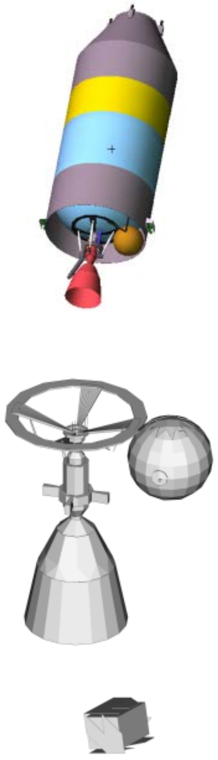
Subsystem	Platform [kg]	Elongated [kg]
RACS	9	9
Structure	42	131
Tanks	182	335+354
VEB	52	81
Engine	28	163
PLA	45	83
Total	358	1156

Typical survivors: Elongated shape

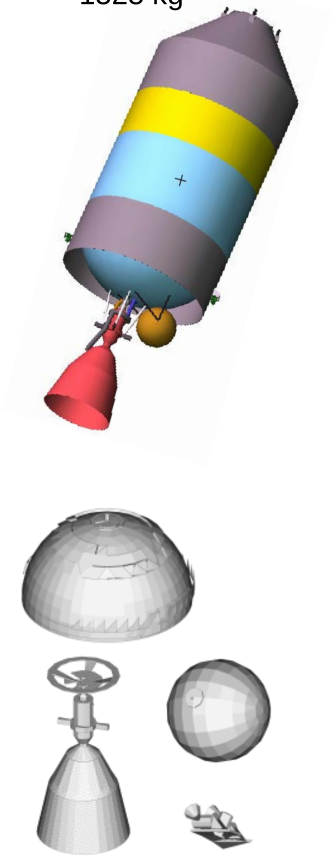
650 kg



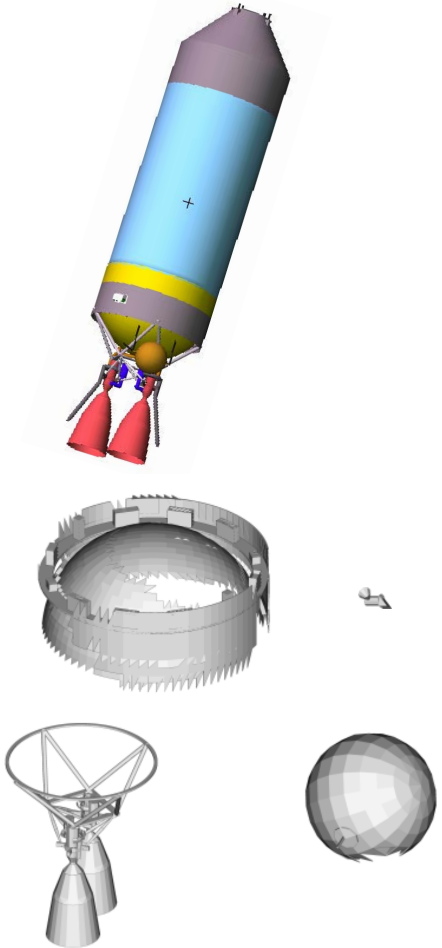
800 kg



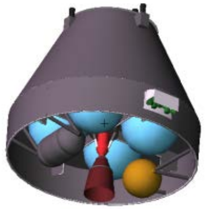
1525 kg



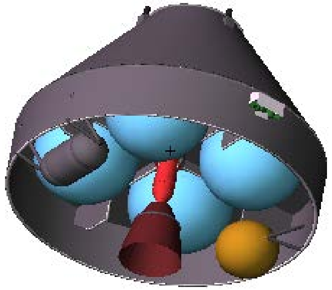
2270 kg



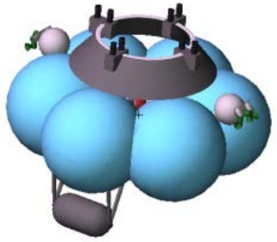
Typical survivors: Platform shape



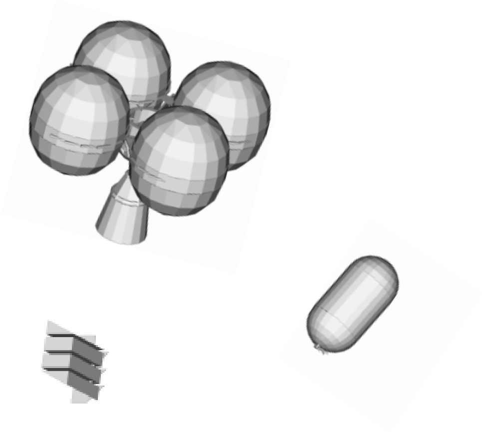
320 kg

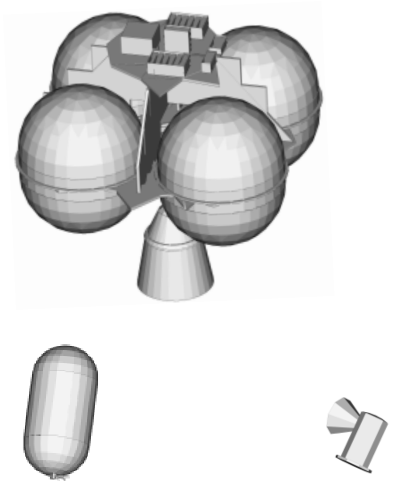


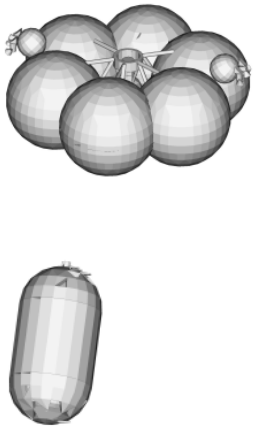
830 kg



550 kg



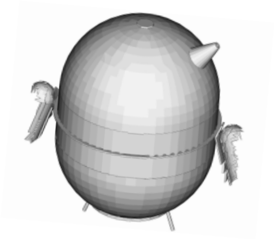


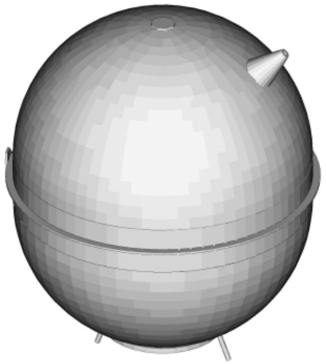


Typical survivors: SRM

133 kg

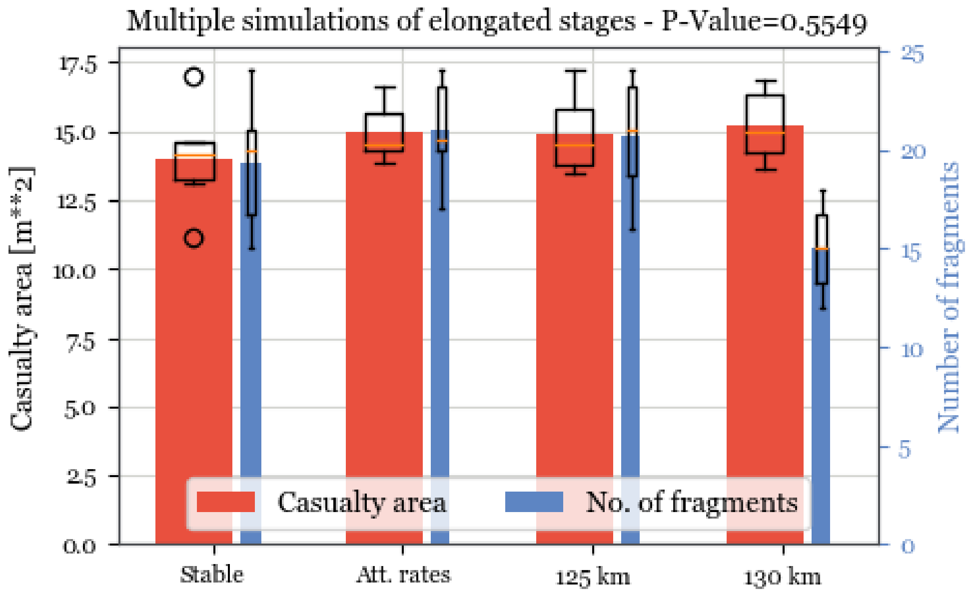
165 kg

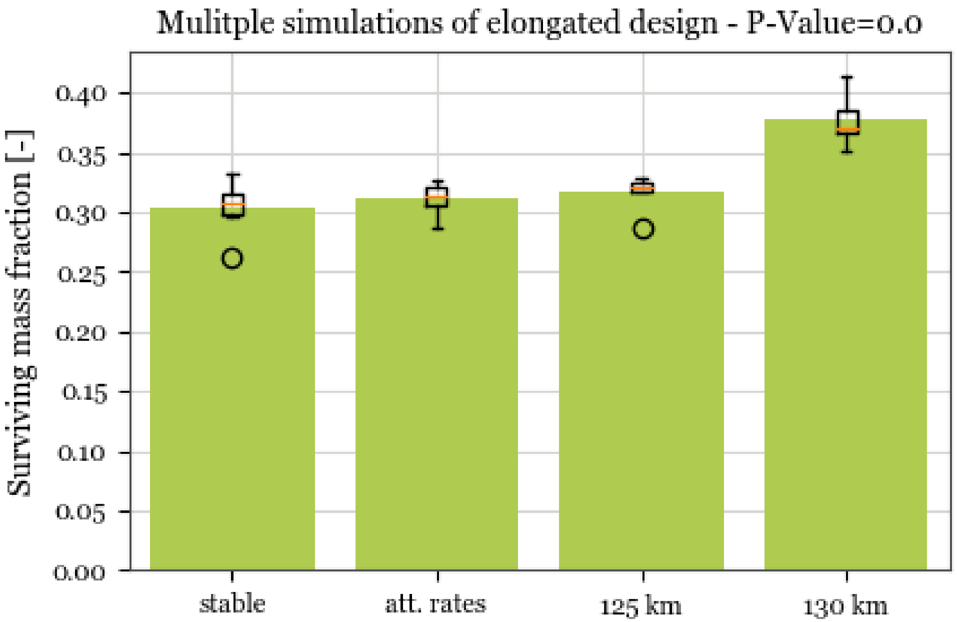




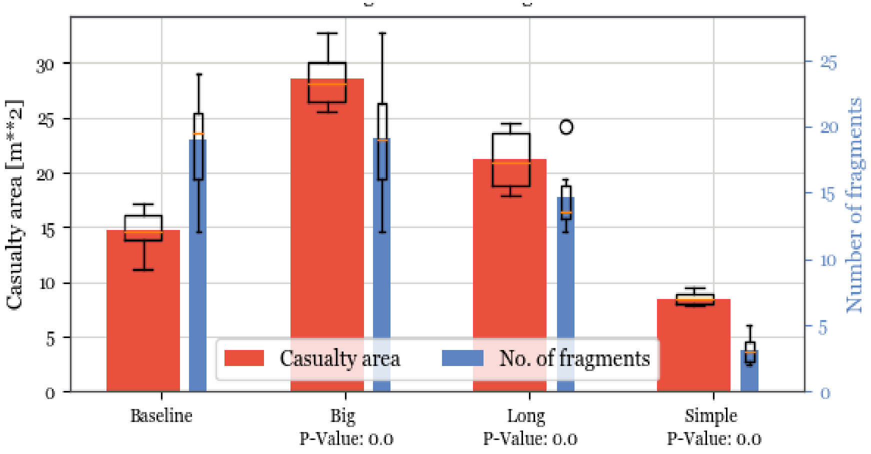
Backup: Initial parameters influence

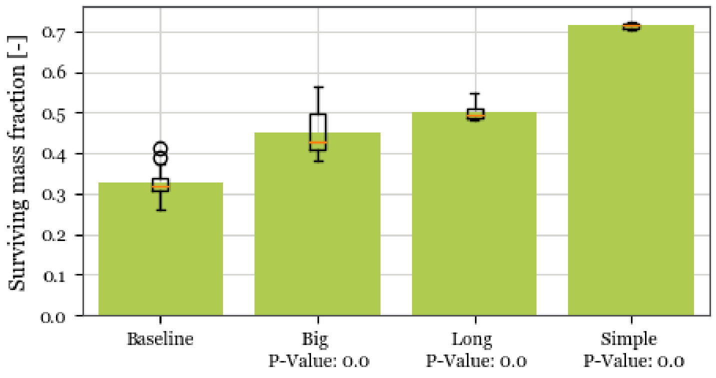
- 4x6 simulations of different initial states



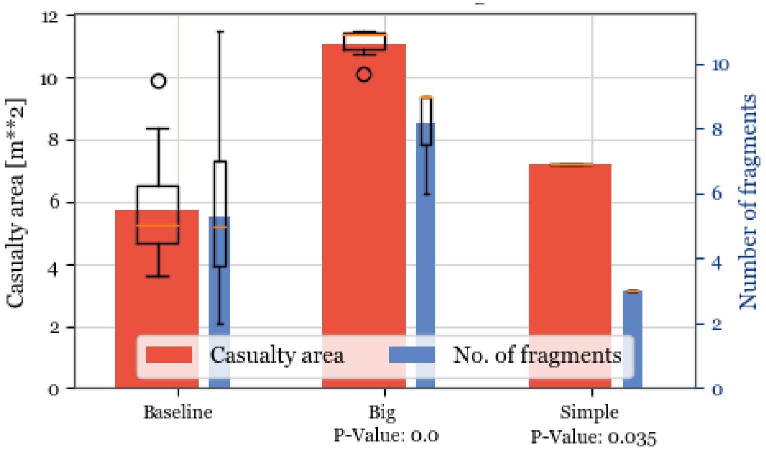


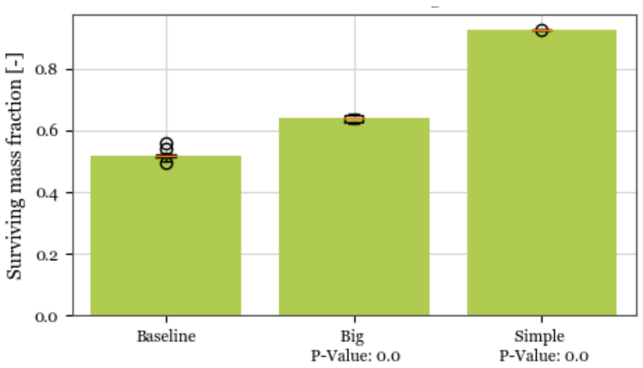
Backup: Reference case results



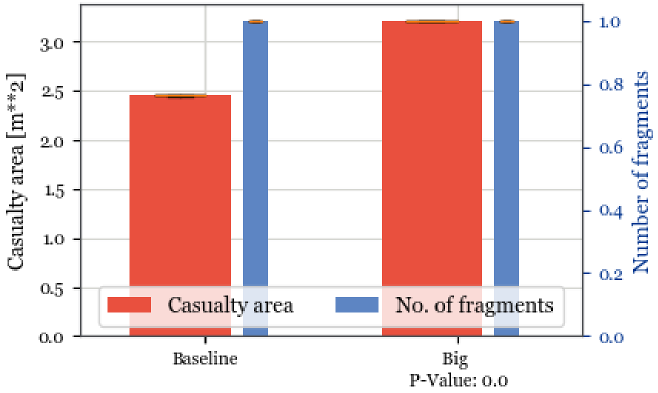


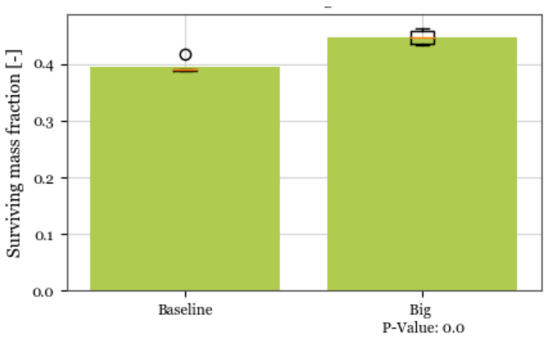
Elongated





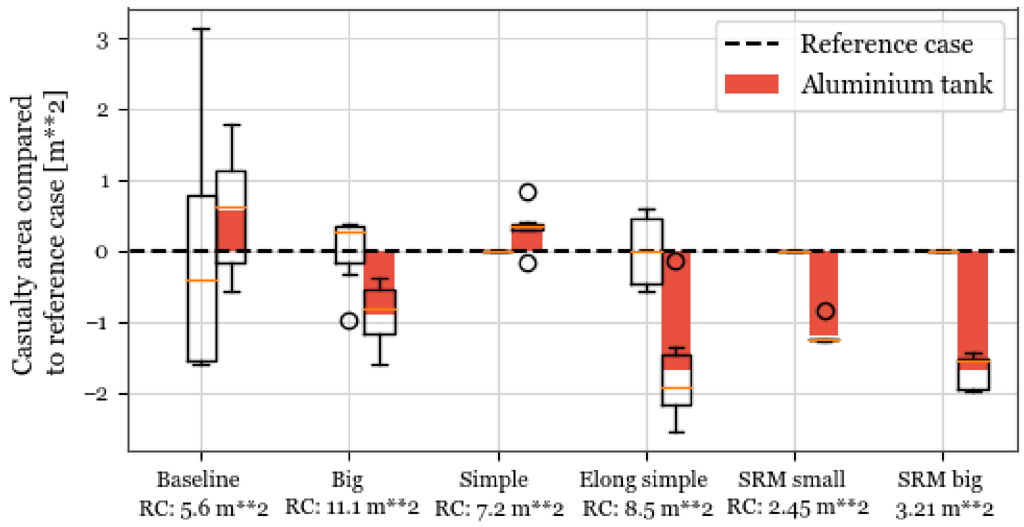
Platform

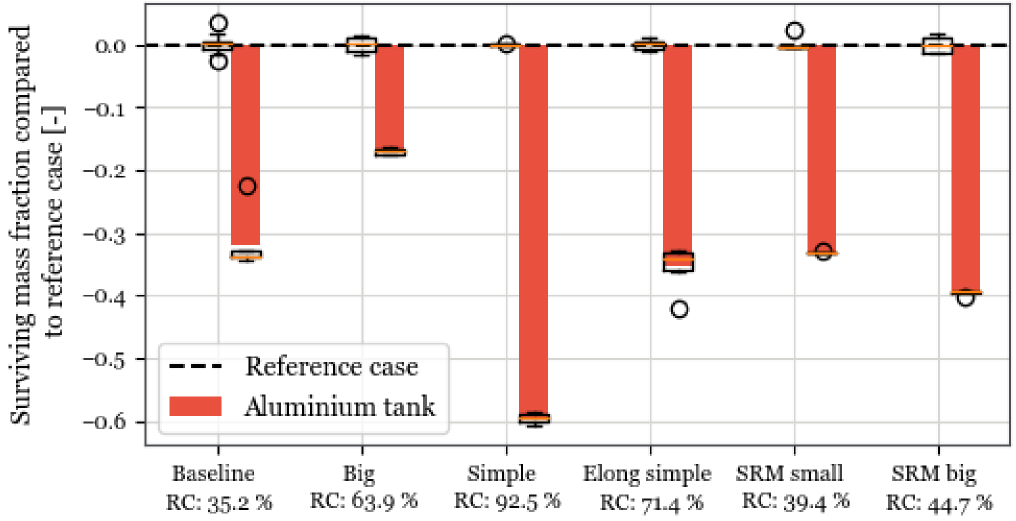




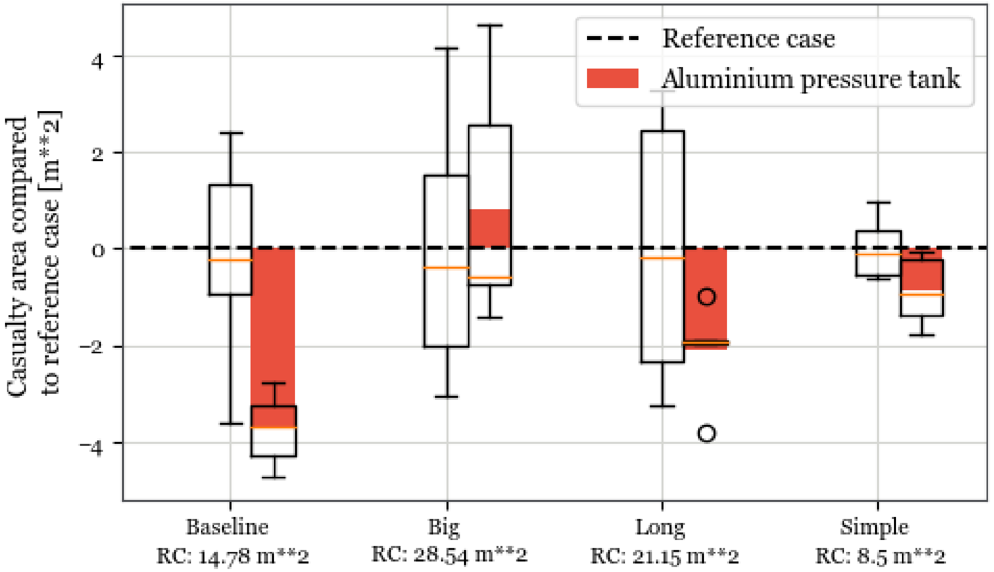
SRM

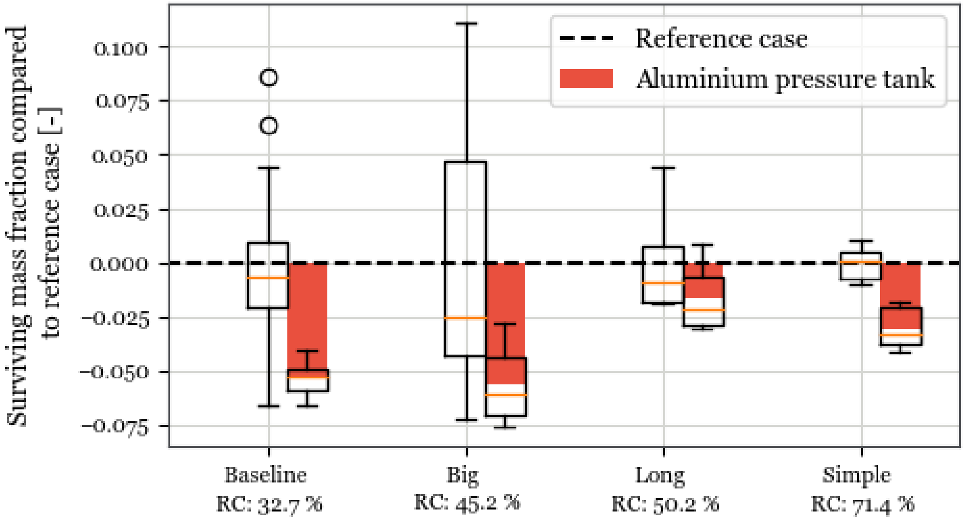
D4D – Aluminium tanks



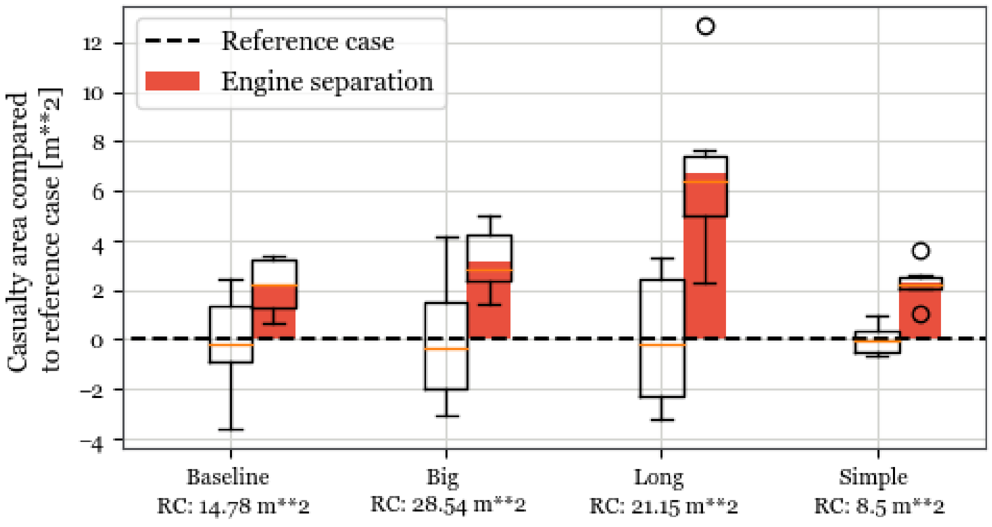


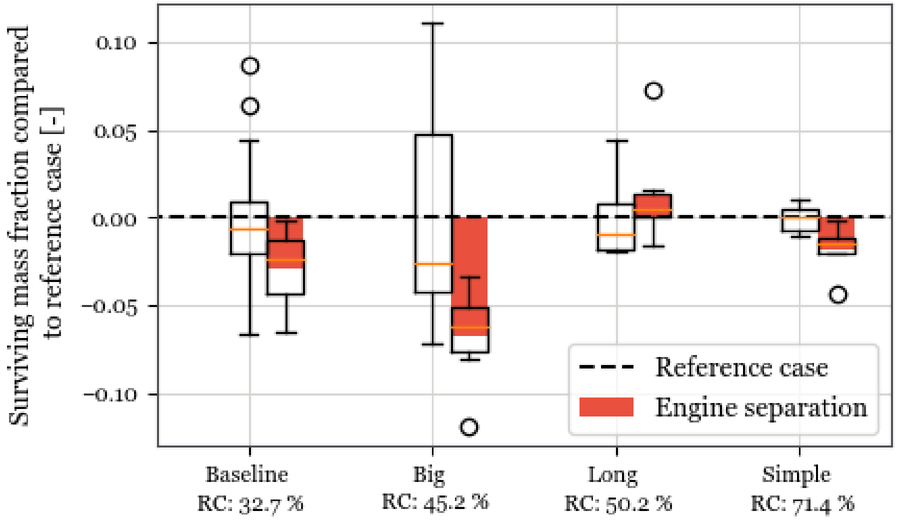
D4D – Aluminium pressure tanks



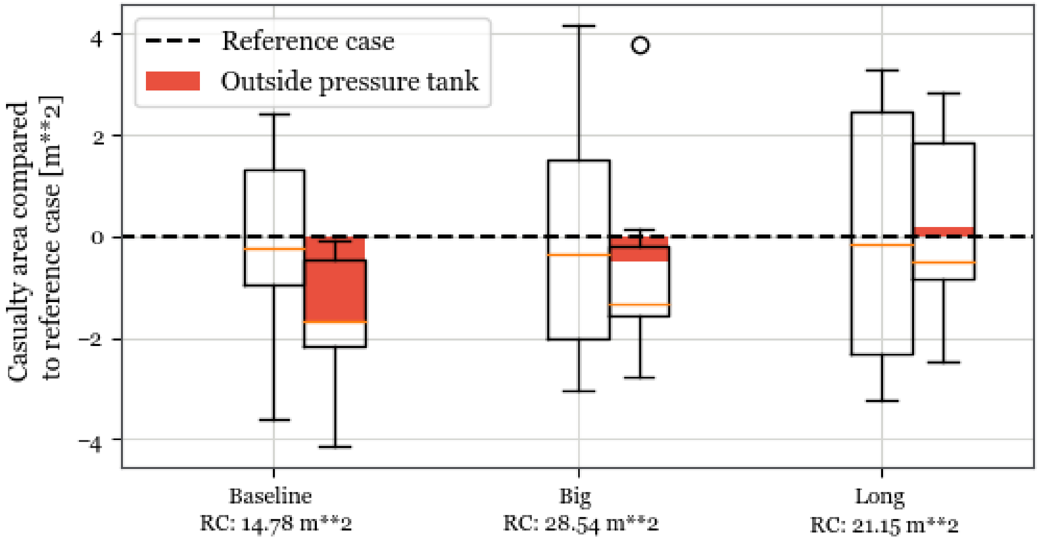


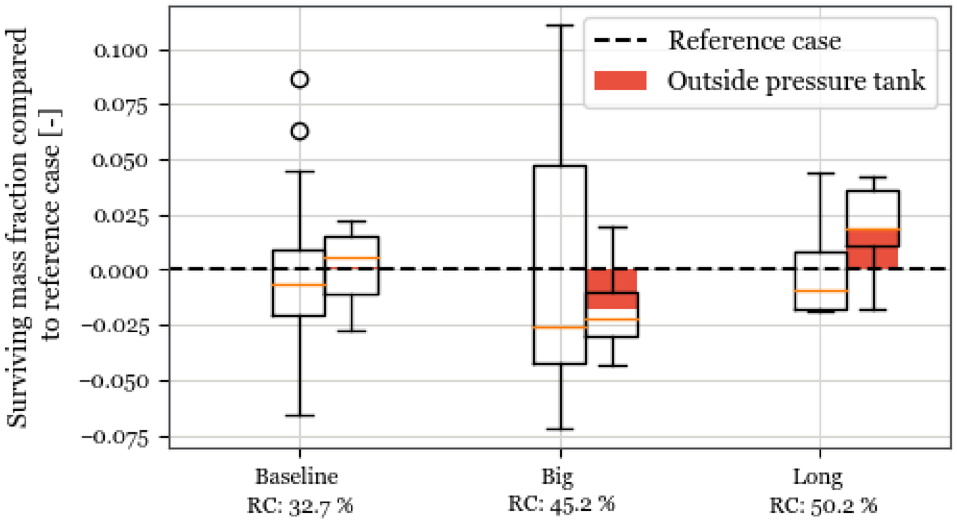
D4D – engine separation



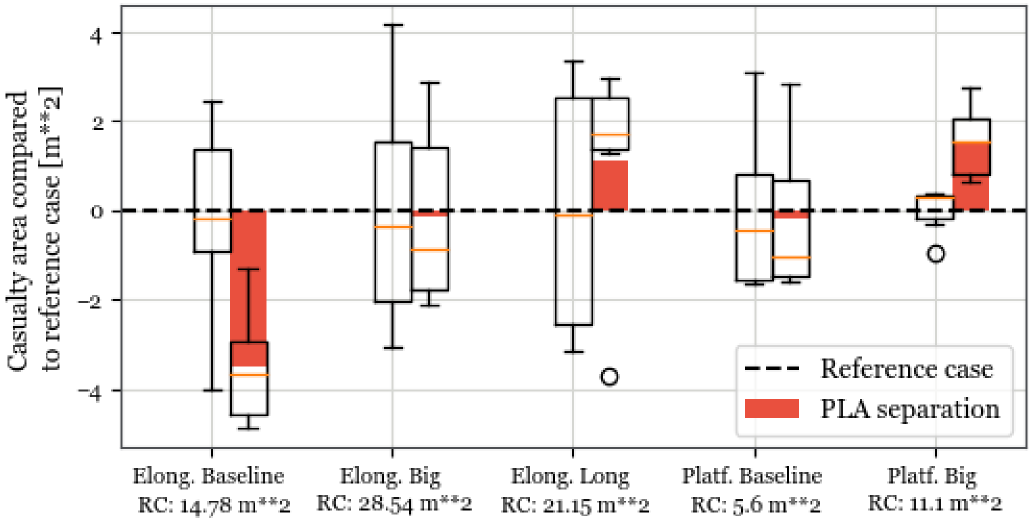


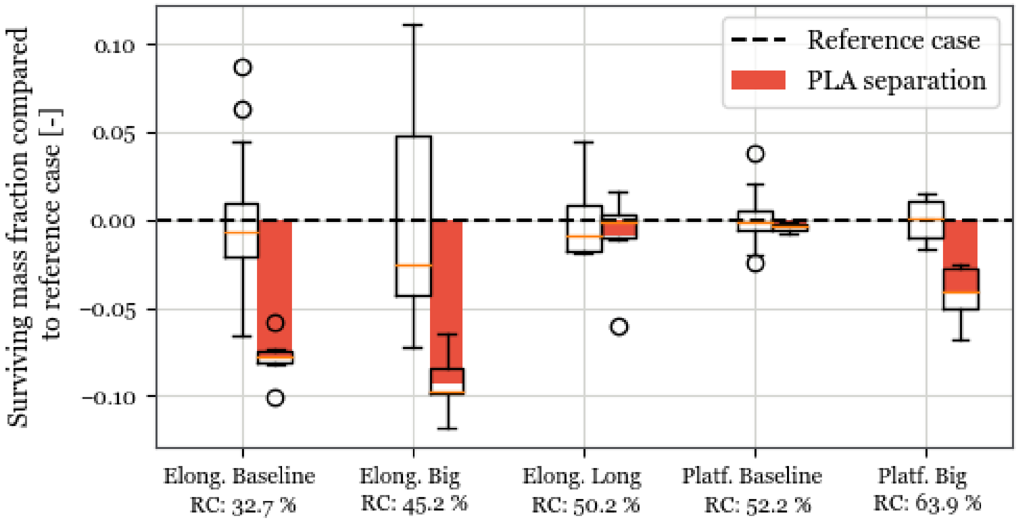
D4D – Pressure tank outside





D4D – PLA separation





D4D – VEB evolution