Spacecraft design indicator for space debris

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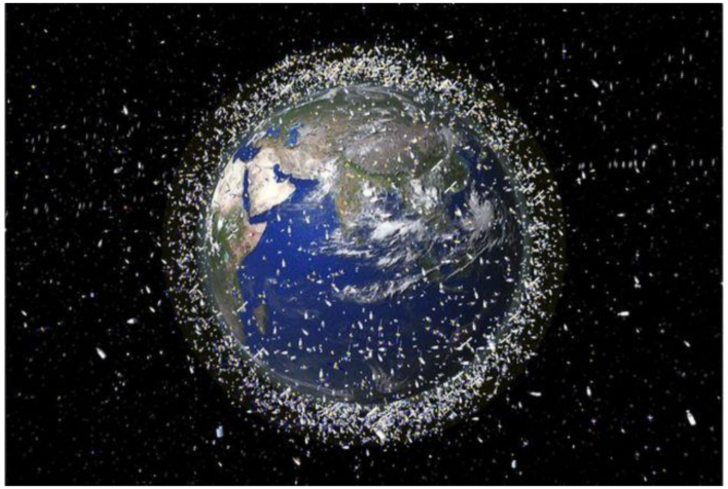


INTRODUCTION

Introduction
Objectives

ESA successfully applied **Life Cycle Assessment (LCA)** to evaluate the environmental impacts of space projects over their whole life cycle, from resource extraction through manufacture and use to end-of-life, covering spacecraft and launcher-related activities as well as ground segment activities

Objective of the design indicator for space debris

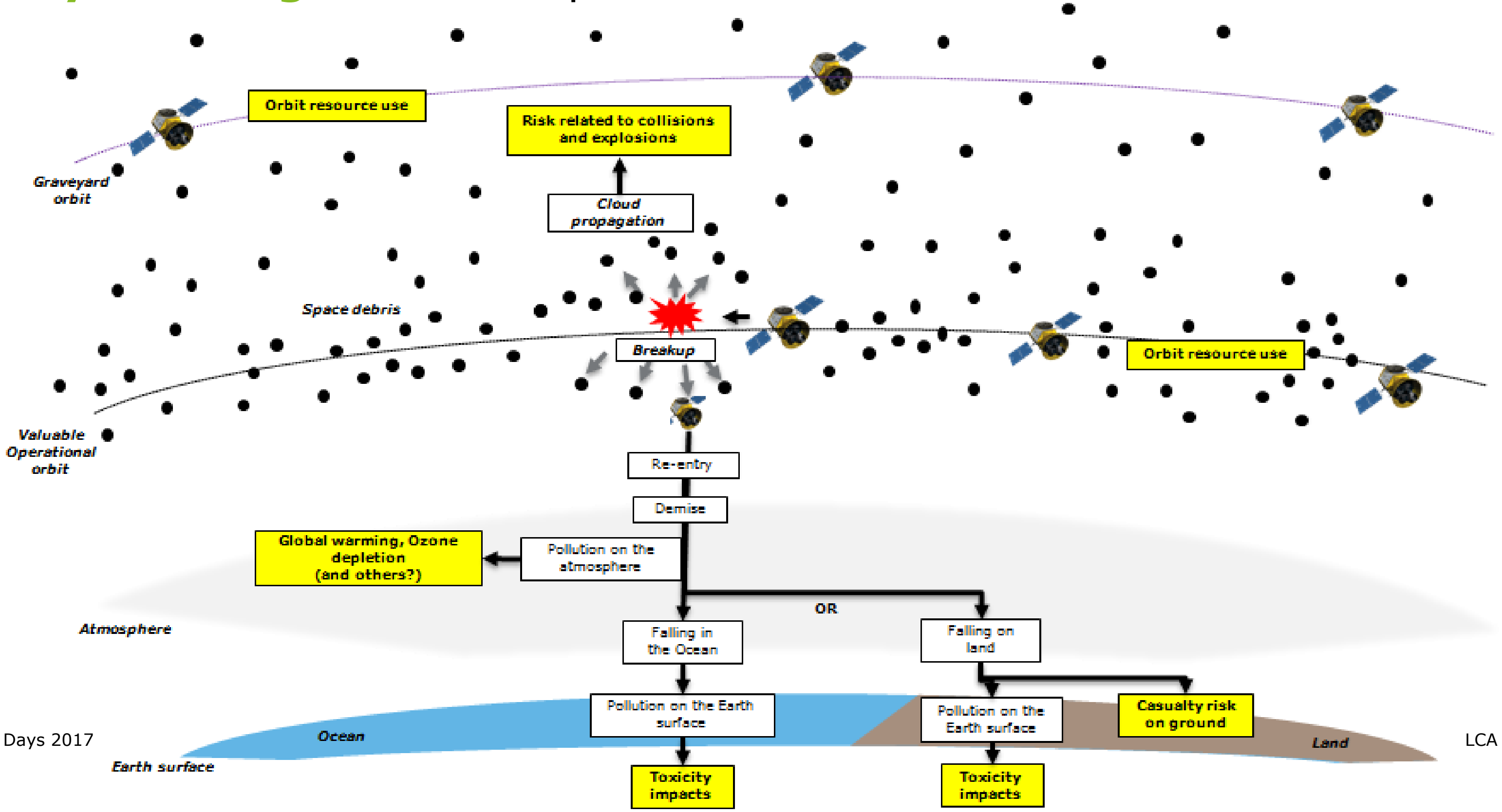
- Integrating a space **sustainability criterion** in the design phase of space missions
- **Comparing end-of-life or design options** of one single mission
- **Raising awareness** about the general approach, towards a target audience *to be defined*

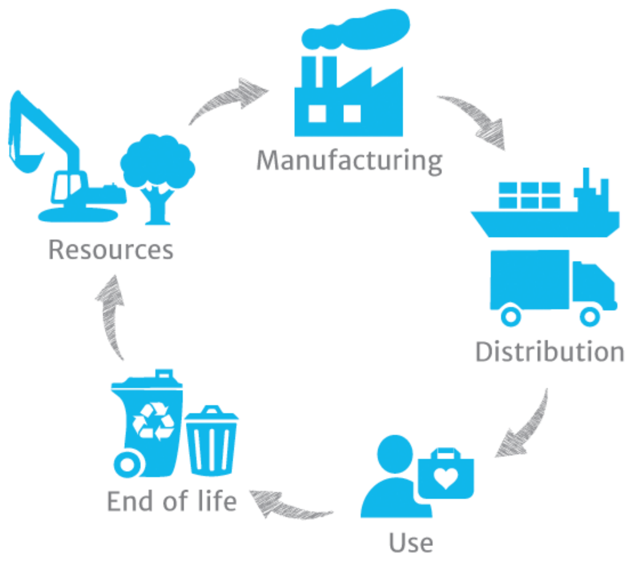
Introduction

Design indicator for space debris

The following issues related to space debris need to be addressed:

- **Potential for pollution** on the atmosphere and on Earth surface
- **Orbit resource use**: the operational S/C or the mission under study occupy a certain area of space, seen as a resource
- **Risk related to collisions and explosions**: probability of collisions and explosions and effect of such collisions and explosions on the space environment
- **Casualty risk on ground**: risk posed to humans and infrastructures on Earth





DEBRIS INDICATOR

Debris indicator

General formula of the space debris indicator

Design indicator to be included in the LCA framework for the eco-design of space missions developed by ESA

$$I_{\substack{\text{space}\\\text{debris}}} = I_{\substack{\text{casualty}\\\text{risk}}} \cdot n_{\substack{\text{casualty}\\\text{risk}}} \cdot w_{\substack{\text{casualty}\\\text{risk}}} + I_{\substack{\text{orbit}\\\text{resource}}} \cdot n_{\substack{\text{orbit}\\\text{resource}}} \cdot w_{\substack{\text{orbit}\\\text{resource}}} + I_{\substack{\text{debris}\\\text{risk}}} \cdot n_{\substack{\text{debris}\\\text{risk}}} \cdot w_{\substack{\text{debris}\\\text{risk}}}$$

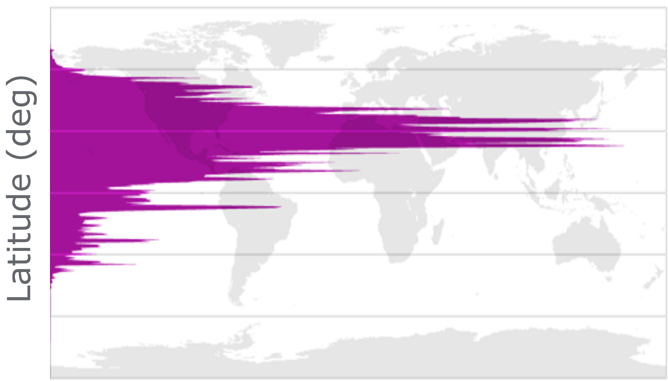
- I: calculation of each individual term of the formula, for each of the four environmental concerns identified
- n: normalisation values proper for each environmental issue
- w: weighting factors defined for each environmental issue

The term ”potential for pollution” is included directly into the LCA framework. Will not be presented here

Casualty risk on ground
Definition

Total casualty risk

Dependence on several parameters: orbit, re-entry condition, re-entry epoch, s/c configuration, population distribution.



(horizontal axis shows the sum of all population at each degree of latitude)

$$E_c = 1 - \prod_{j=1}^{J}\left(1 - E_{c,j}\right)$$

j = 1,..,J
surviving objects

$$E_{c,j} = \sum_{k=1}^{N}\left(P_i\right)_k \left(\bar{\rho}_p\right)_k \hat{A}_c$$

k= 1,..,N the number of bins in which the re-entry corridor is subdivided

uniform impact probability for a given orbit inclination

the population density averaged in longitude

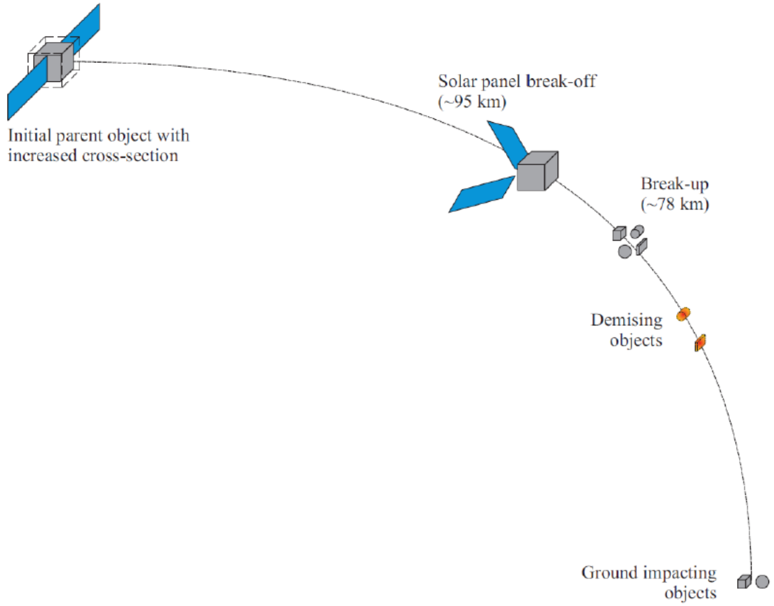
mean casualty area (weighted average over all possible along-track impact locations, with weights provided by the impact probability density function)

Casualty risk on ground

Index computation

Index computed using the ESA software suite **DRAMA**

- Standardised procedure for casualty risk calculation
- Assures reproducible results
- Takes care of computing the averaged casualty risk



Inputs

- Orbital parameters of the re-entry orbit
- Re-entry epoch
- Spacecraft configuration
  - Definition of **dimension, material, mass, shape, and quantity** of the satellite components

Outputs

Average Casualty Risk	Impact Mass
Used for the **casualty risk index** inside the debris indicator	Related to **ground and atmospheric pollution** • Impact mass pollutes the ground • Demised mass pollutes the atmosphere

Orbit resource use

Use of Space

Aim: to **measure of the use of Space** (use of given orbital region for a given class of missions)

Analogy: **LCA indicator for land use**

- Number of operational spacecraft per orbit bin
  - Currently **Union of Concerned Scientist Database used.** Could be substituted with DISCOS. Future use of space may be also be extrapolated for comparison
- Cross area/volume of the spacecraft is not considered here as during s/c operations this is not taken into account
- Mission phase:
  - Operational phase
  - EOL disposal orbit (e.g., for graveyard)

$$I_{orbit\ rescource} = fun\left(a, e, i, N_{s/c}, T\right)$$

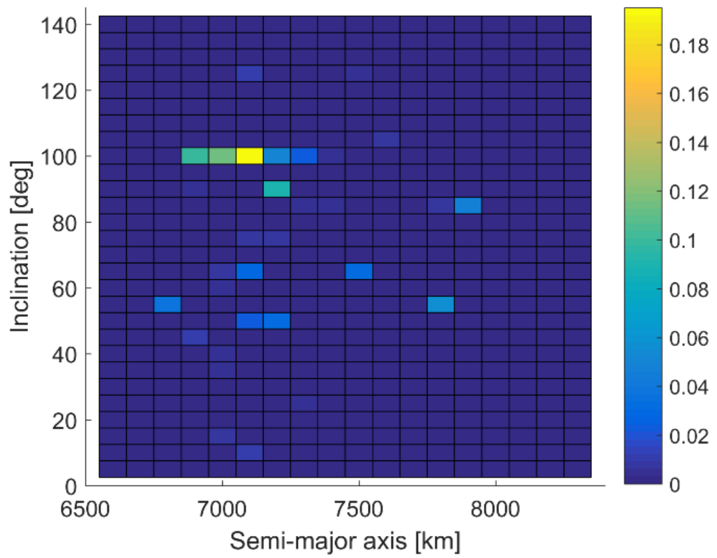
a, e, i	Spacecraft operational orbit
$N_{s/c}$	Number of operational spacecraft
T	Residence time

Orbit resource use

Index calculation

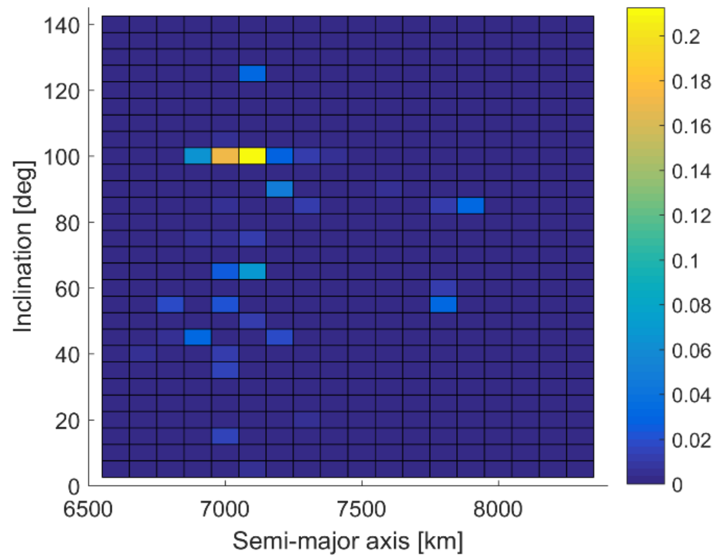
$$I_{bin} = \frac{\sum_{k=1}^{N_{s/c}} (k \in bin_{a,e,i})}{N_{s/c}}$$

Number of operational spacecraft in orbit bin normalised by total number



$$I_{bin,\,revenue} = \frac{\sum_{k=1}^{N_{s/c}} (k \in bin_{a,e,i}) \cdot Q_{bin}}{Tot\ revenue}$$

Number of operational spacecraft in orbit bin multiplied by bin revenue normalised by total revenue



Index is calculated over mission profile:

$$I_{\substack{\text{orbit}\\\text{resource}}} = \int_{t_{\text{mission start}}}^{t_{\text{mission end}}} I_{bin}(t)\,dt$$

$$I_{\substack{\text{orbit}\\\text{resource}}} = \frac{1}{\text{mission rev}} \int_{t_{\text{mission start}}}^{t_{\text{mission end}}} I_{\text{bin, revenue}}(t)\,dt$$

Could consider also mission revenue (discarded option as difficult to assess)

Collision and explosion on-orbit risk

Proposed formulation

The interaction of a space mission or an EOL scenario with the space debris environment:

- **Probability**: probability of fragmentation caused by the space debris environment on the analysed mission (Probability of collision) and from stored energy on-board (Probability of explosion)
- **Severity**: consequent effect caused on operational spacecraft by the analysed mission scenario

The two terms can be multiplied to give the total **Risk** of an object to/in the space environment

With respect to other proposed indexes, this formulation

- Considers both **causes** and **effects**
- Considers both **explosion** and **collisions**
- Allows the analysis of **EOL strategies**

- Does not include **feedback effect**

Collision and explosion on-orbit risk

Proposed formulation

$$I_{\substack{\text{debris}\\\text{risk}}} = p_c \cdot e_c + p_e \cdot e_e$$

Collision probability

Effects of the collision on operational satellites

Explosion probability

Effects of the explosion on operational satellites

In case active spacecraft performs collision avoidance manoeuvers:
collision probability is computed considering only objects smaller than 10 cm (and bigger than the threshold defined by the condition for catastrophic collisions).

Results generated by extension of the **Environmental Consequences of Orbital Breakups index**

- *Letizia F., Colombo C., Lewis H. G., and Krag H. (2017), Extending the ECOB Space Debris Index with Fragmentation Risk Estimation. In Proceedings of the 7th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany. 18 - 21 April 2017.*
- *Letizia F., Colombo C., Lewis H. G., and Krag H. (2016). Assessment of breakup severity on operational satellites, Advances in Space Research, Vol. 58, No. 7, pp. 1255–1274.*

Collision and explosion on-orbit risk

Collisions

Probability of collision: kinetic gas theory

$$p_c = 1 - \exp\left(\rho\left(a, \mathrm{i}, \mathrm{e}\right)\Delta v\left(a, i, e = 0\right)A\Delta t\right)$$

debris density at the spacecraft orbit

collision velocity (most likely impact velocity from MASTER simulations)

collision area

fixed time interval (e.g. 1 year)

Effects of the collision on operational satellites

Set of targets (operational satellite selected) selected over a grid of *a* and *i* and cumulative cross sectional area

Fragmentation triggered in each *a* and *i* position

Resulting cloud propagated through density based approach

Weighted collision probability on all representative target computed

$$e_c = \sum_{j}^{N_{tar}} w_j p_{c,j}$$

- *Letizia F., Colombo C., Lewis H. G., and Krag H. (2017), Extending the ECOB Space Debris Index with Fragmentation Risk Estimation. In Proceedings of the 7th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany. 18 - 21 April 2017.*

Collision and explosion on-orbit risk

Explosions

Probability of explosion: analysing statistical data from DISCOS

- Time elapsed between the launch of the object and its fragmentation
- Two different curves are derived for payloads and rocket bodies

Effects of the explosion on operational satellites

Same approach as collisions

$$I_{\substack{\text{debris}\\\text{risk}}} = p_c \cdot e_c + p_e \cdot e_e$$

Scaled wrt fragmenting mass

Spacecraft trajectory is integrated and for each time step (1 year) and the value of the index over the mission profile can be extracted

➢ *Letizia F., Colombo C., Lewis H. G., and Krag H. (2017), Extending the ECOB Space Debris Index with Fragmentation Risk Estimation. In Proceedings of the 7th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany. 18 - 21 April 2017.*

NORMALISATION

Normalisation

An ideal reference spacecraft has been used for normalisation with the following characterisitcs:

- Mass: 1 tonne
- Effective cross section area: 9 m^2
- Orbit: 800 km SSO, 7 year lifetime with 25 year re-entry uncontrolled
- Casualty risk: 10^{-4}

Casualty risk normalisation

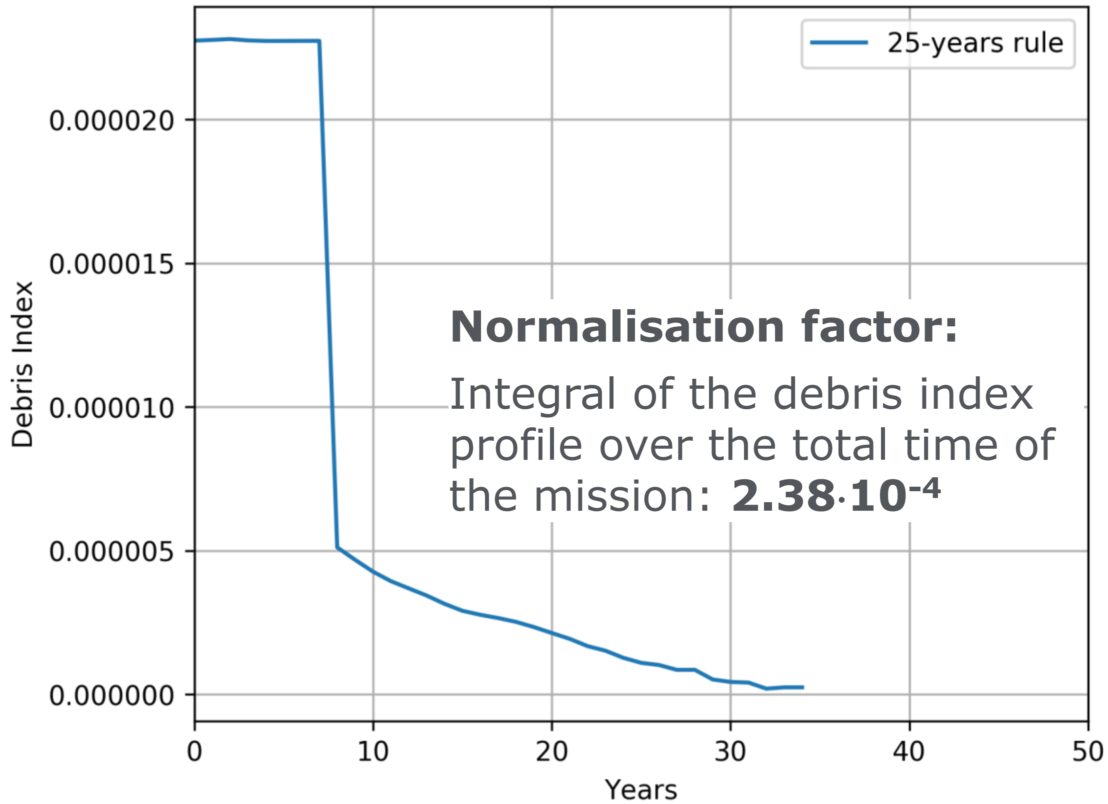
The standard threshold value of **10^{-4}** has been used for the casualty risk normalisation.

Debris Index and Space as Resource normalisation

<u>Mission profile normalisation</u>

The value of the index over the **mission profile** is normalised with the value for the **reference element** over a **reference profile**

Debris index profile for the reference spacecraft



Normalisation factor:

Integral of the debris index profile over the total time of the mission: **$2.38 \cdot 10^{-4}$**

TEST CASES FOR THE DEBRIS INDICATOR

Test case selection

Design indicator to be used to evaluate at **design phase** a **single phase mission**:

- Influenced by
  - ✓ Type of object (launcher, space mission, product)
  - ✓ Initial orbit
  - ✓ Mass
  - ✓ Cross area
  - ✓ Mission lifetime
- Comparison of different technological options (design for demise option)
- Comparison of different end-of-life scenarios for one space mission

Test cases

1. Envisat:	Casualty area 44 ± 5 m^2	CAMs 1 (for 10 years)
2. Sentinel 1A	Casualty area 15 m^2	CAMs 1 (for 10 years)
3. MetOpA	Casualty area 33 ± 5 m^2	CAMs 1 (for 10 years)
4. Mega constellation	Casualty area 3 m^2 Orbit altitude 1100 km, Inclination - 85 degrees, Mass = 200 kg, Effective cross section area = 1 m^2, Lifetime 6 year, deorbit = 1 year	CAMs 1 (for 6 years)
5. Vega AVUM - SSO orbit 800 km		CAMs 0
6. Vega AVUM - SSO orbit 800 km – @ Sentinel orbit		CAMs 0
7. Ariane 5 ECA - GTO orbit		CAMs 0

Test cases

MetOpA

Artist's view of the MetOp-A spacecraft in orbit (image credit: ESA, EUMETSAT)

Reason for choice

- Sensitivity on area, mass with respect to case 1 and 3 (on similar orbit)
- Performing a re-entry is currently under study

Characteristics and orbit

h = 827 km, inc =92.72 deg, m= 4085 kg, A = 37.5 m^2

Configuration

- Spacecraft bus similar to MetOp-A, Envisat | ERS 1,2 | Spot 1,2,3,4
- Demise: casualty area provided by ESA of 33 m^2

End-of-life options

- EOL1: No disposal
- EOL2: Disposal 25 yr (h_p = 530.0955 km)
- EOL3: Direct re-entry
- EOL4: Disposal 50 yr (h_p = 574 km)

Test cases
MetOpA

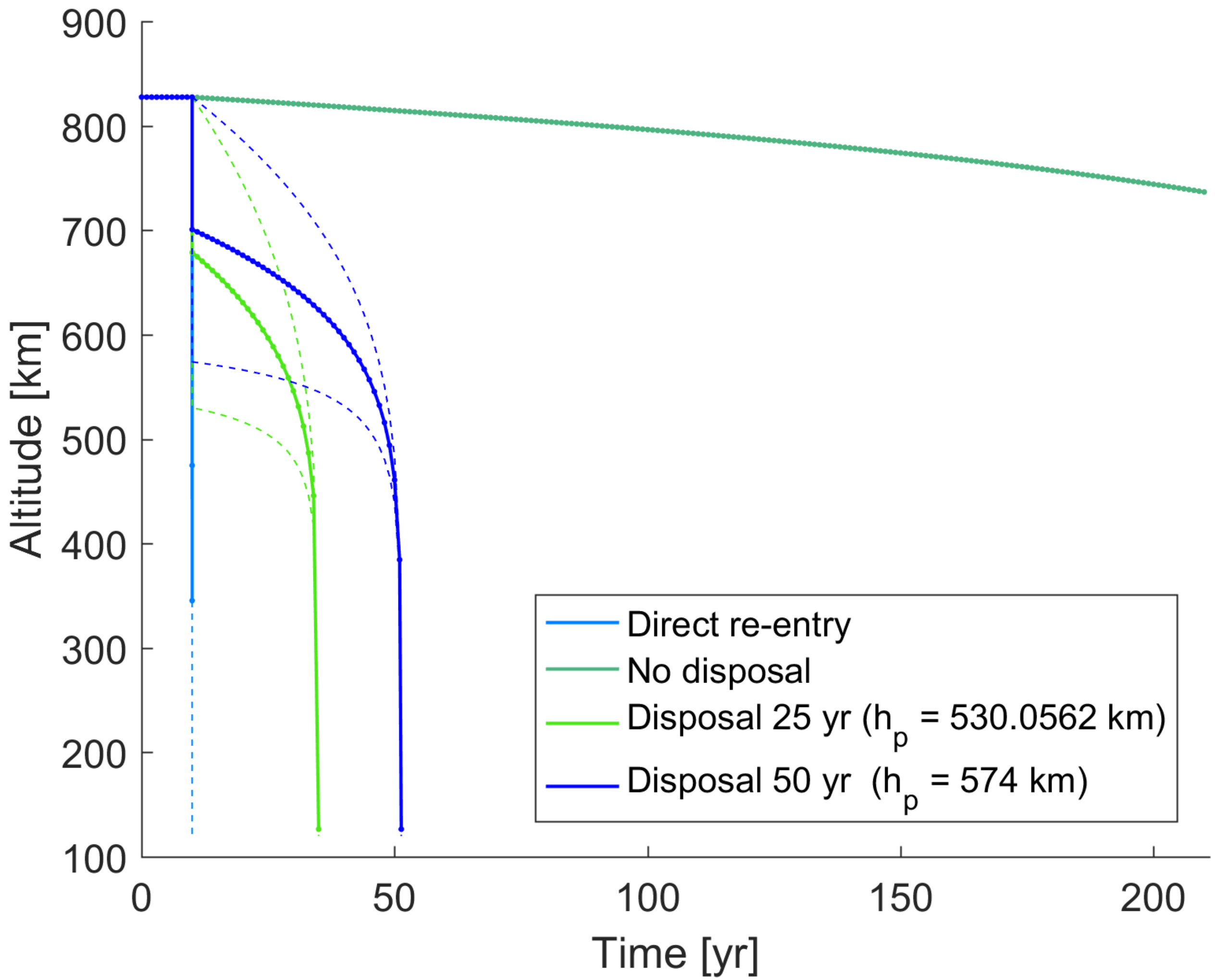
Disposal options:

EOL1: No disposal

EOL2: Disposal 25 yr (h_p = 530.0955 km)

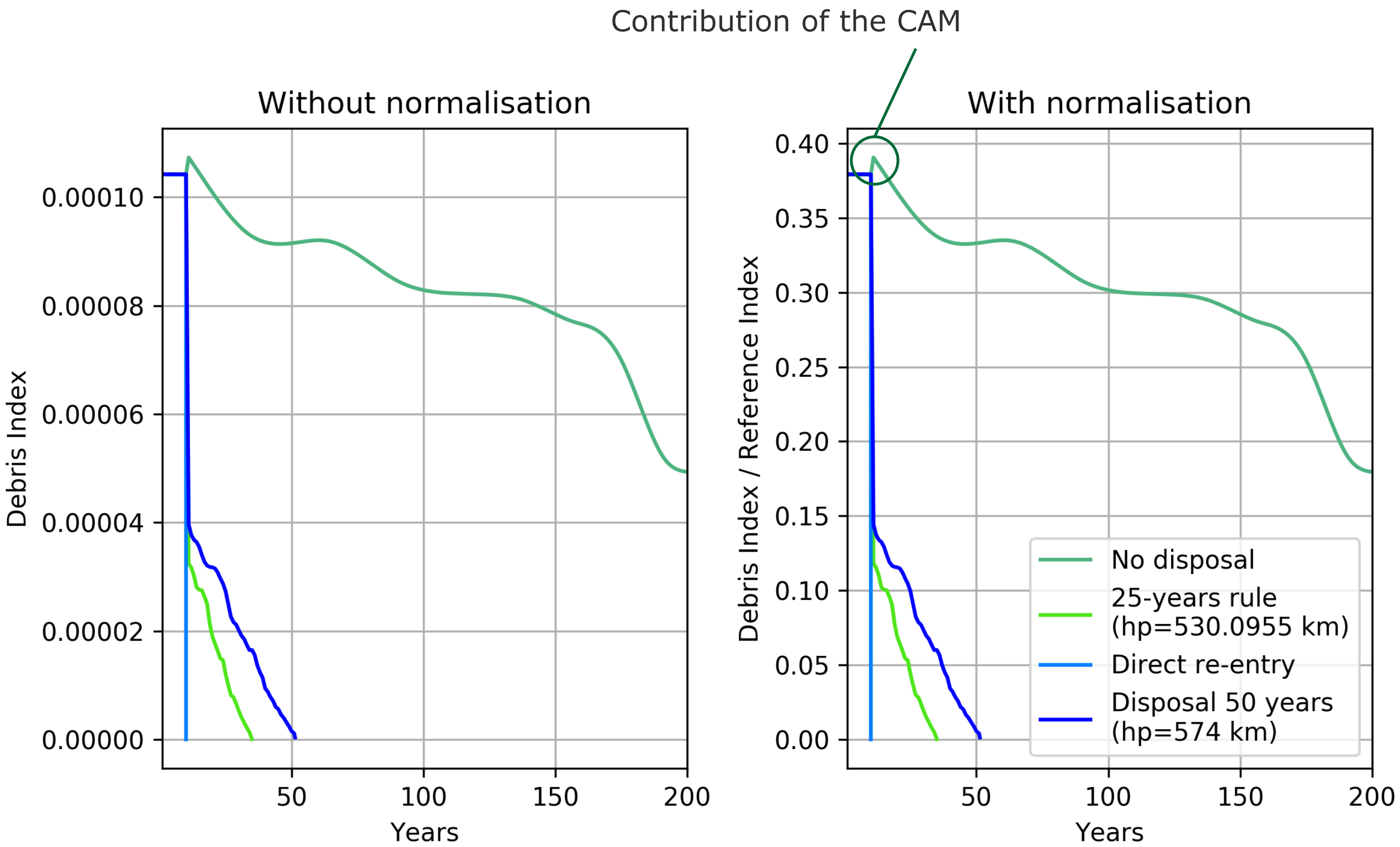
EOL3: Direct re-entry

EOL4: Disposal 50 yr (h_p = 574 km) from [ref]



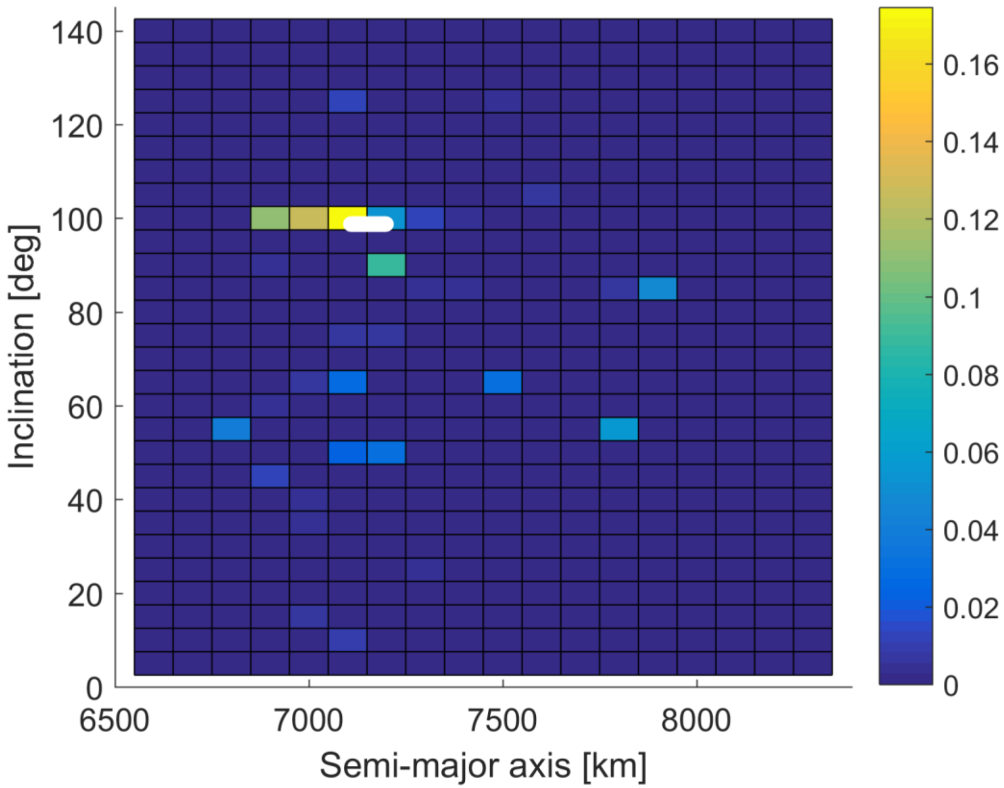
Test cases

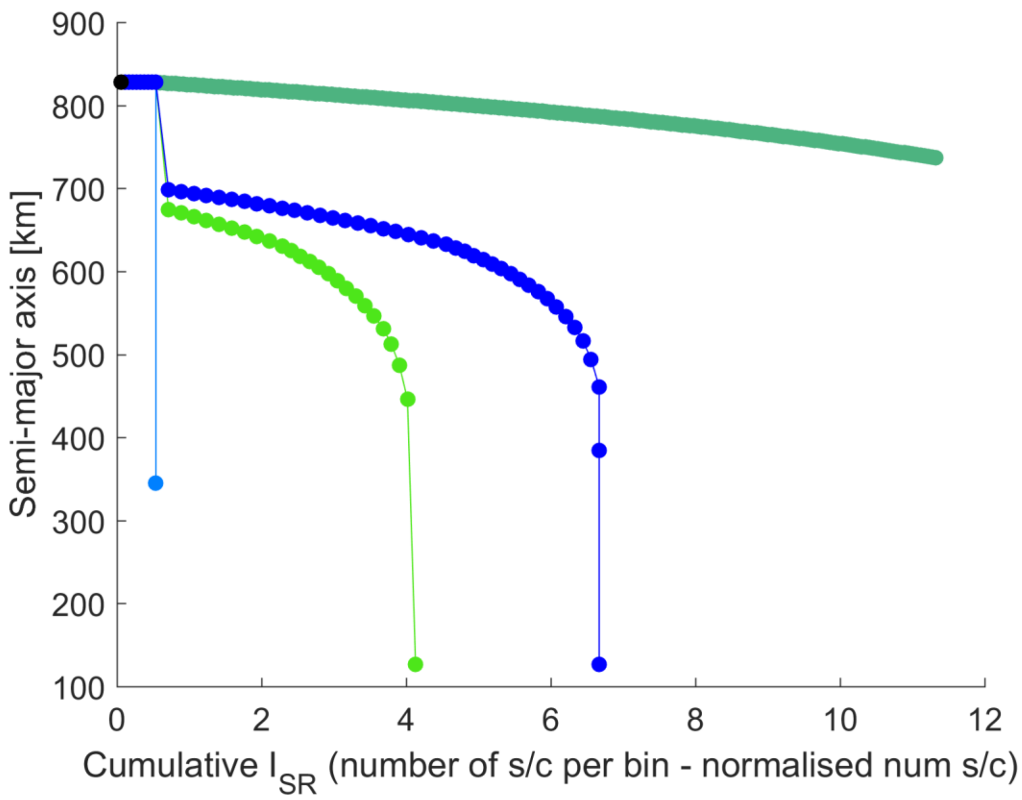
MetOpA



Test cases

MetOpA





Test cases
Envisat

Reason for choice

- Sensitivity on area, mass with respect to case 2 and 3 (on similar orbit)
- ESA inoperative satellite, high debris region, not controlled

Characteristics and Orbit

h = 773 km, inc =98.270 deg, m= 8100 kg, A = 74.3903 m^2

Configuration

- Spacecraft bus similar to MetOp-A, Envisat | ERS 1,2 | Spot 1,2,3,4
- Demise: Casualty risk Envisat given Casualty area by ESA

End-of-life options

- EOL1: No disposal i.e. remain in orbit due to failure
- EOL2: Disposal 25 yr (h_p = 553.4384 km)
- EOL3: Direct re-entry

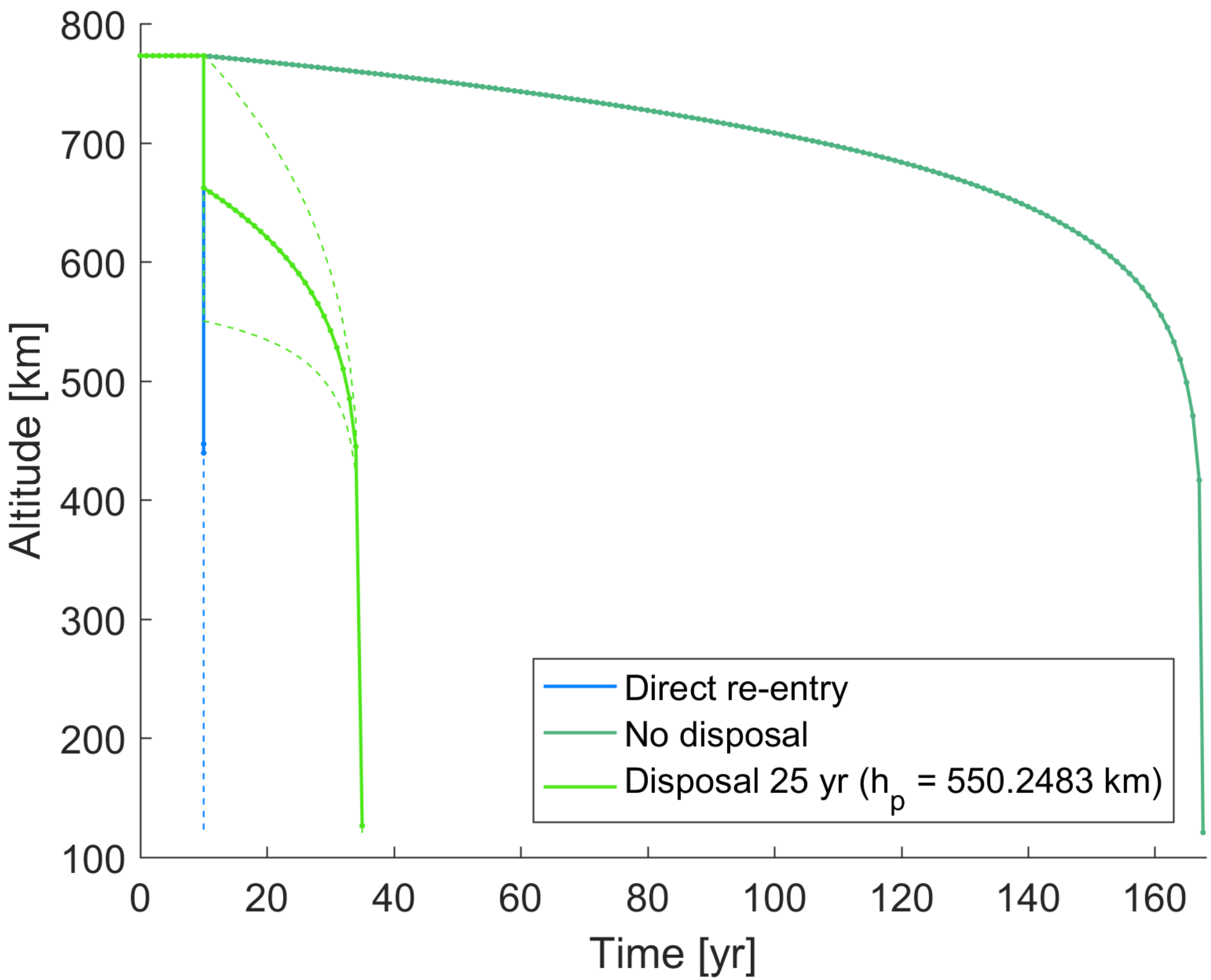
Test cases
Envisat

Disposal options:

EOL1: No disposal

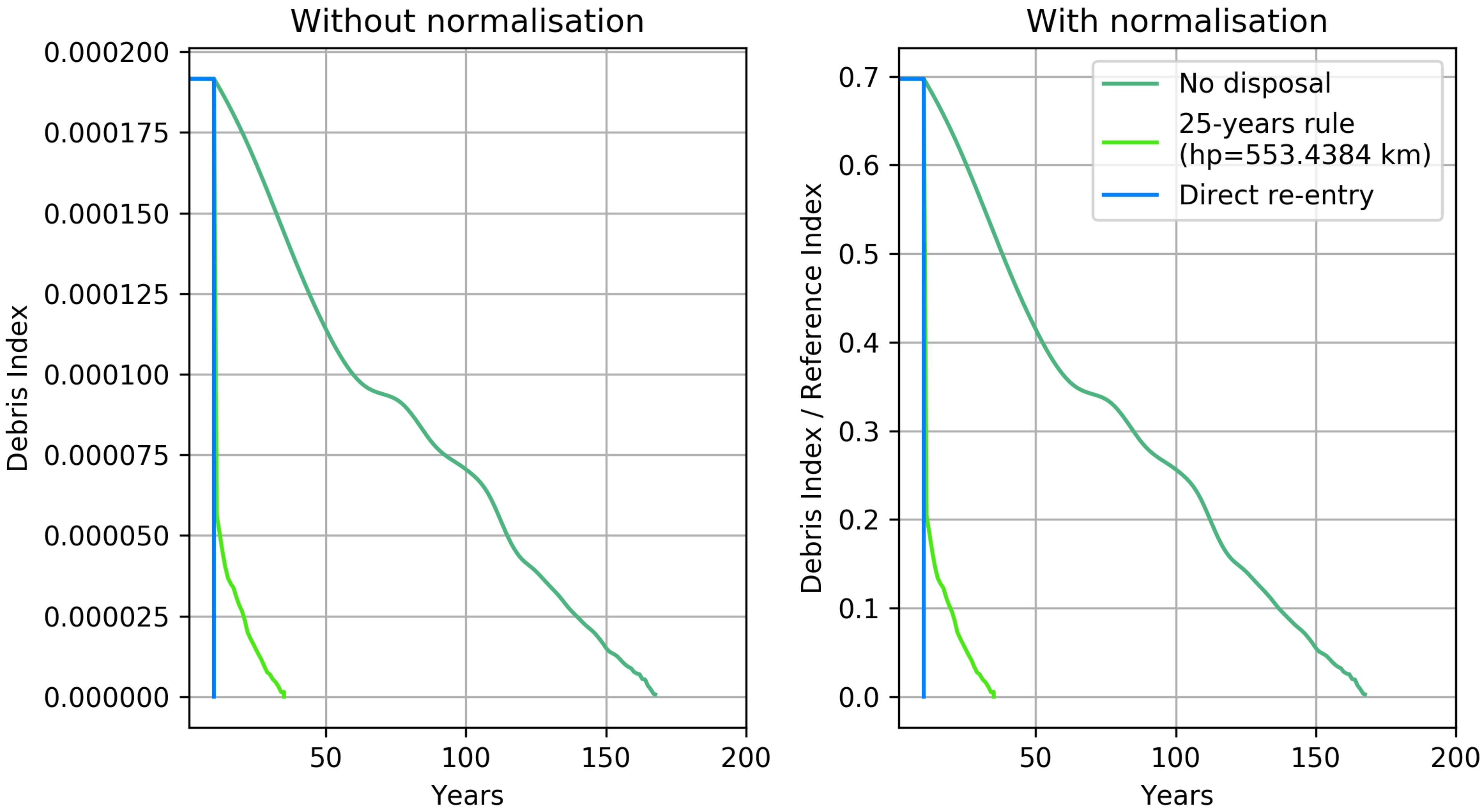
EOL2: Disposal 25 yr (h_p = 553.4384 km)

EOL3: Direct re-entry



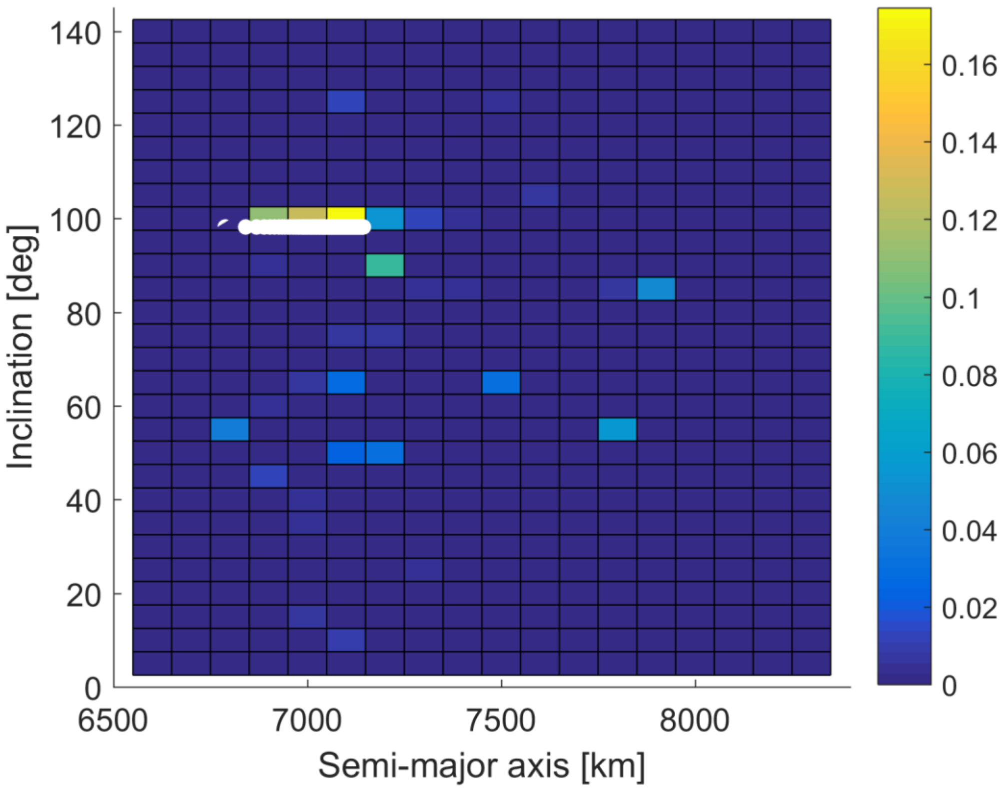
Test cases

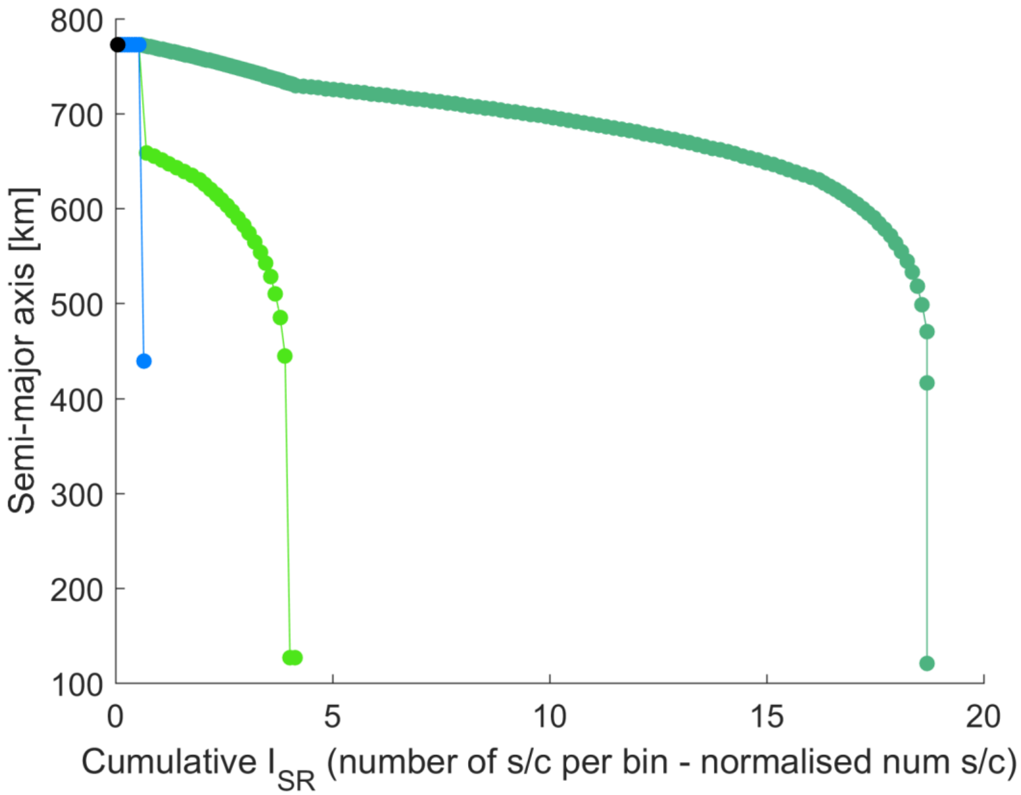
Envisat



Test cases

Envisat





Test cases

Design indicator - normalised

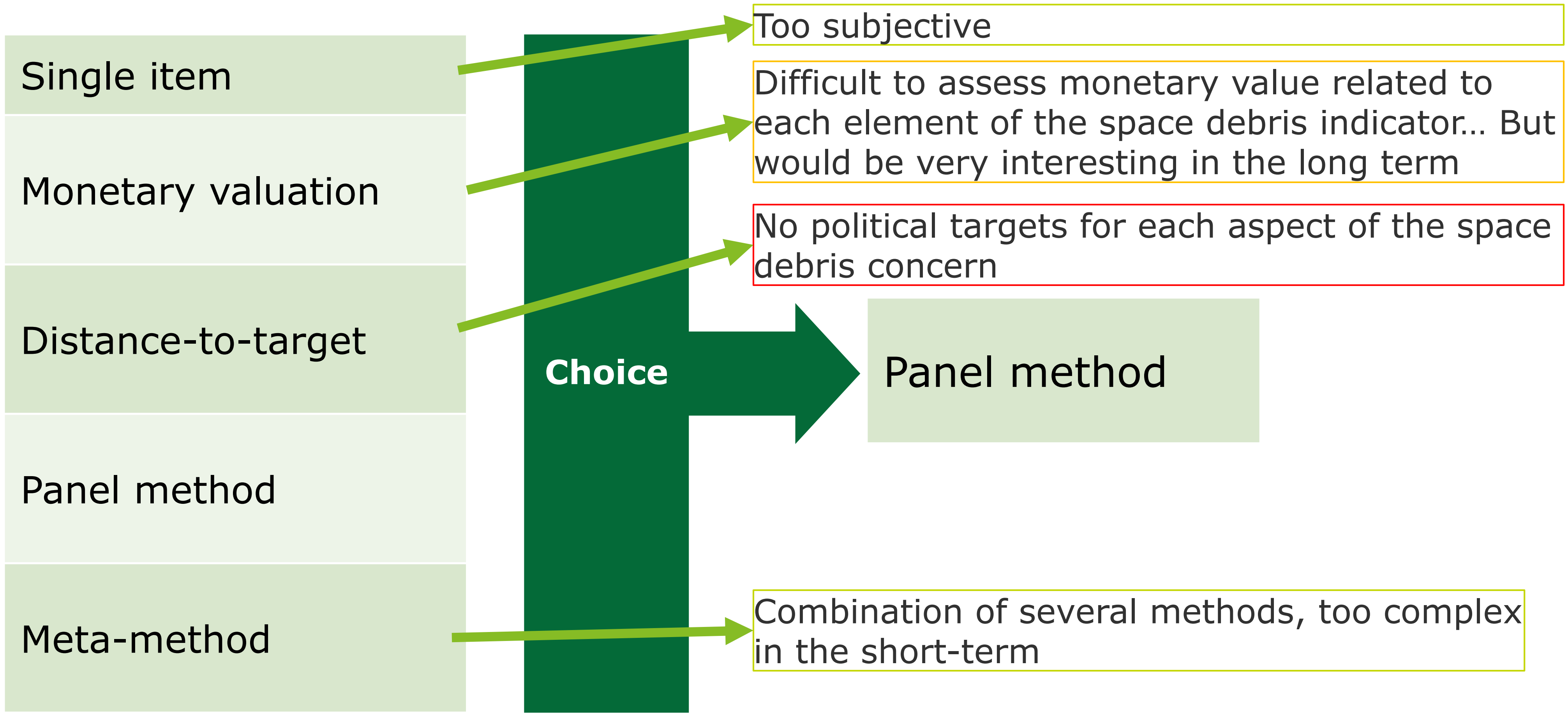
	Debris index norm. 2				Casualty risk norm.				Space as resource norm.			
Mission	**No disposal**	**25-yr**	**Direct re-entry**	**eol 4**	**No disposal**	**25-yr**	**Direct re-entry**	**eol 4**	**No disposal**	**25-yr**	**Direct re-entry**	**eol 4**
Reference	12.4090	1.0000	0.5786		n/a	1.0000	n/a		5.9200	1.0000	0.1303	
Envisat	53.4934	9.4614	6.9869		80.3400	8.6360	n/a		5.7502	1.0813	0.1800	
MetopA	62.5910	5.6405	3.7846	7.3872	n/a	7.0980	n/a	10.8000	3.4828	1.0211	0.1816	1.6735
Sentinel1A	4.6943	2.1943	1.3828		6.5530	4.1700	n/a		3.1061	1.5618	0.5588	
VEGA AVUM Sentinel	5.6405	0.3504	0.0004		18.2300	2.3170	n/a		4.5567	0.9368	0.0142	

WEIGHTING

Weighting

Our choice of weighting methodology

- Assigning distinct quantitative weights to different impact or damage categories, thereby expressing their relative importance
- Makes it possible to derive a single score to ease decision-making.



Panel method requires a preliminary normalisation step

Weighting
Test phase

YOU are the Space Debris weighting task force!

Let's put in application the methodology proposed

You have 100 points to distribute among three issues related to Space Debris. The more points you give to one issue, the more important it is to you.

All combinations are possible

Risk related to collisions and explosions:		points
Orbit resource use:		points
Casualty risk on ground:		points

You are: (a) public authority, (b) academics, (c) industry, (d) consultancy, (e) NGO.

Send your answers to achanoine@deloitte.fr

Weighting

Choice of weighting methodology

Debris index and casualty risk are requirements at ESA ➡ Equal weighting for these terms.

Remaining open question: weighting for the orbit resource use?

The three terms must be mathematically independent ➡ Is it the case for debris index & orbit resource use?

Both assess distinct aspects of the space debris issue, that can be understood if we think in terms of monetary value and what we finally want to protect:

- **Debris index**:

  Costs related to potential break-up, including: (**Direct**) cost for the analysed mission (**Indirect**) cost for other operational S/C and future missions

- **Orbit Resource use**:
  - Cost of "occupying" a slot in a finite space, that will not be available for other missions
  - Similar logic as LCIA indicators of "land occupation".
  - Currently, the orbit resource use does not consider the economic value of the orbits (this is an area for improvement). In the future, the two terms should be able to reflect situations of low-populated but highly valuable orbits.

CONCLUSION

Conclusions and way forward

- Design indicator to measure the management of end-of-life options and to compare different design options of a space mission from the perspective of the impacts of space debris.
- Could be used in preliminary mission design to optimise the eco-design of the spacecraft considering
  - Demise at the end-of-life and the casualty risk on ground
  - Interaction with respect to the space debris environment in term of the risk generated via a the collision with other spacecraft or explosion due to non-passivation of the spacecraft
  - Use of orbital space as resource.
- The pollution of the atmosphere, and the Earth’s surface considered directly in the Life Cycle Assessment framework.
- First attempt to define a normalisation and weighting that allows reaching a single-score indicator:
  - Application of the approach to more test cases
  - Weighting process such that a single score indicator is obtained and to the communication of the devised indicator in an easy, accessible and clear way.
  - Care is needed for external communication, work still needed

Spacecraft design indicator for space debris

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