IAC-22-A6.4.1

Evaluation of the Space capacity share used by a mission

Camilla Colombo[a]*, Mirko Trisolini[a], Andrea Muciaccia[a], Lorenzo Giudici[a], Juan Luis Gonzalo[a], Stefan Frey[b], Borja Del Campo[c], Francesca Letizia[d], Stijn Lemmens[d]

[a] *Department of Aerospace Science and Technology, Politecnico di Milano, Italy*. camilla.colombo@polimi.it, andrea.muciaccia@polimi.it, lorenzo1.giudici@polimi.it, juanluis.gonzalo@polimi.it
[b] Vyoma, Germany, stefan.frey@vyoma.space
[c] *Deimos Space UK Ltd*, United Kingdom, borja.delcampo@elecnor.es
[d] *European Space Agency (ESA), Germany*, francesca.letizia@esa.int; stijn.lemmens@esa.int
* Corresponding Author

Abstract

In the context of space sustainability and space traffic coordination and management, it is important to define an internationally recognised and accepted approach to measure the Space capacity, defined as the quantity and type of missions/objects that the Space environment can sustain. In parallel to the study on how the capacity can be measured, it is important to define an acceptable threshold of the space capacity and to link such measure to the contribution that each new and already flying mission apport to it, in order to better drive the definition of mitigation guidelines.

The THEMIS tool is being developed along these lines: to Track the Health of the Environment and Missions in Space. The software, that will be opened to the whole Space community (i.e., satellite operators, regulators, space debris experts, and general public) through a Web user Interface, is being developed by Politecnico di Milano and Deimos UK within a project funded by the European Space Agency. The space debris mode of the THEMIS tool allows the computation of the space debris index given the profile of a mission, the spacecraft characteristics, orbit characterisation and operational aspects such as collision avoidance manoeuvre efficacy and post mission disposal capabilities and reliability. Then the space capacity mode of the THEMIS tool, currently under development, is described. As part of this task, we perform a literature review of proposed approaches to measure the carrying capacity of other ecosystems to inspire the discussion ongoing in the Space community.
Keywords: Space debris index, space capacity, carrying capacity, seating capacity, space debris environment, space sustainability

Acronyms/Abbreviations

CAM	Collision Avoidance Manoeuvre
ECOB	Environmental Consequences of Orbital Breakups
KPI	Key Performance Indicator
LEO	Low Earth Orbit
PMD	Post Mission Disposal
RAAN	Right Ascension of Ascending Node
THEMIS	Tracking the Health of the Environment and Missions in Space
WUI	Web User Interface

1. Introduction

Space, as any other ecosystem, has a finite capacity. The continuous growth of space activities, due to our increasing reliance on services from Space, the privatisation of the space market and the lower cost of deploying smaller and distributed missions in orbit is contributing to the improvement of the quality of life. However, it is also overloading this delicate ecosystem. As of today, the space debris problem is internationally recognised, and thus the environmental concern in Space activities is becoming a priority. To tackle this issue, a clear and actionable definition of space capacity is required. Indeed, in the context of space sustainability and space traffic coordination and management, it is important to define an internationally recognised and accepted approach to measure the Space capacity, defined as the quantity and type of missions/objects that the Space environment can sustain. In parallel to the study on how the capacity can be measured, it is important to define an acceptable threshold of the space capacity and to link such measure to the contribution that each new and already flying mission apport to it to better drive the definition of mitigation guidelines.

The THEMIS tool is being developed along these lines: to Track the Health of the Environment and Missions in Space [1][2]. The software, that will be opened to the whole Space community (i.e., satellite operators, regulators, space debris experts, and general public) through a Web User Interface (WUI), is being developed by Politecnico di Milano and Deimos UK within a project funded by the European Space Agency. The space debris mode of the THEMIS tool allows the computation of the space debris index given the profile of a mission, the spacecraft characteristics, orbit characterisation and operational aspects such as collision avoidance manoeuvre efficacy and post mission disposal capabilities and reliability. The space debris index of a single mission is based on the assessment of the risk of collisions and explosion during the mission profile and the evaluation of the effects of such an event on the whole active satellite population, in terms of cumulative probability of collision of the simulated resulting debris cloud on a set of representative targets [3].

Then the space capacity mode of the THEMIS tool, currently under development, is described. The space capacity mode allows the computation of the space capacity share used by orbiting spacecraft. This is obtained comparing the space debris index with long-term DELTA simulations to represent the evolution of the background population and by aggregating and comparing the space debris index of several missions [4]. As part of this task, we perform a literature review of proposed approaches to measure the carrying capacity of other ecosystems to inspire the discussion ongoing in the Space community [5]-[10].

The paper will present the development and consolidation of the different building blocks required for the definition of the space debris index and the environmental capacity, and the development the WUI to support the management of the capacity through its computation and allocation and interaction with the Space community.

The paper is organised as follows: Section 2 describes the important aspects in the definition of the space debris index that relies on a novel approach developed for the fragment cloud propagation and collision risk estimation summarised in Section 3. The procedure to compute the space debris index within THEMIS is drafted in Section 4. Then a literature review of space capacity, carrying capacity and seating capacity is given in Section 5, also embracing other environmental fields. This task is in preparation to the development of the space capacity model of THEMIS defined in Section 6. Section 7 introduces the WUI that will be made available to the Space community, while Section 8 discusses on the next steps.

2. Space debris index

As described in [1], the space debris index in THEMIS follows the formulation of the Environmental Consequences of Orbital Breakups (ECOB) index [3] and is defined as a risk indicator. The formulation is composed by a probability term (p), which quantifies the collision probability due to the space debris background population and the explosion probability of the analysed object, and a severity term (e) associated to the effects of the fragmentation of the analysed object on the on the sustainability of the space environment. The index evaluation at a single time epoch is computed as

$$I = p_c \cdot e_c + p_e \cdot e_e \tag{1}$$

where p_c and p_e represent the collision and explosion probabilities, and e_c and e_e represent the collision and explosion effects, respectively. A grid approach is used for the computation of the probability term and the explosion terms [11][12].

Following the approach in Letizia et al. [4], the space debris index at a single time epoch is computed using Eq. (1) and the evaluation is performed for each time epoch in each phase of the mission (i.e. launch, orbit injection, cruise, end-of-life disposal). In the case the spacecraft is active, the computation of Eq. (1) is performed twice, with and without Collision Avoidance Manoeuvre (CAM) capabilities, so that, at a generic time epoch of the mission the index is

$$I = \beta \cdot I_{CAM} + (1-\beta) \cdot I_{no-CAM} \tag{2}$$

where I_{cam} is the index at a single epoch when CAM capabilities are considered, I_{no-cam} is the index at a single epoch when No-CAM capabilities are considered, and β is the CAM efficacy that can be set between 0 and 1 or can be computed using the ESA ARES tool based on the fractional risk reduction, which measures the efficacy of the avoidance strategy [13] (Fig. 1).

# ACPL	Man. Rate	Risk Red.	Res. Risk	Rem. Risk	F.Risk.Red	F.Res.Risk	F.Rem.Risk	False Alarm R.
0.100000E-05	0.852097E+00	0.242689E-04	0.132525E-05	0.132525E-0	0.948221E+00	.517795E-01	0.517795E-01	0.999972E+00
0.100000E-04	0.169877E+00	0.221305E-04	0.346364E-05	0.346364E-0	0.864670E+00	.135330E+00	0.135330E+00	0.999870E+00
0.500000E-04	0.503085E-01	0.198149E-04	0.577925E-05	0.577925E-0	0.774196E+00	.225804E+00	0.225804E+00	0.999606E+00
0.800000E-04	0.373881E-01	0.190059E-04	0.658822E-05	0.658822E-0	0.742588E+00	.257412E+00	0.257412E+00	0.999492E+00
0.100000E-03	0.330757E-01	0.186206E-04	0.697357E-05	0.697357E-0	0.727532E+00	.272468E+00	0.272468E+00	0.999437E+00
0.400000E-03	0.104424E-01	0.139054E-04	0.116887E-04	0.116887E-0	0.543304E+00	.456696E+00	0.456696E+00	0.998668E+00
0.500000E-03	0.819204E-02	0.129046E-04	0.126895E-04	0.126895E-0	0.504201E+00	.495799E+00	0.495799E+00	0.998425E+00
0.100000E-02	0.382592E-02	0.984719E-05	0.157469E-04	0.157469E-0	0.384744E+00	.615256E+00	0.615256E+00	0.997426E+00
0.150000E-02	0.210410E-02	0.774594E-05	0.178482E-04	0.178482E-0	0.302645E+00	.697355E+00	0.697355E+00	0.996319E+00
0.100000E-01	0.108156E-03	0.181994E-05	0.237742E-04	0.237742E-0	0.711078E-01	.928892E+00	0.928892E+00	0.983173E+00

Fig. 1. ARES output for the evaluation of the CAM efficacy.

To assess the impact of the entire mission space environment, the value of the index is computed as:

$$I_t = \int_{t_0}^{t_{EOL}} I\,dt + \alpha \cdot \int_{t_{EOL}}^{t_{end}} I\,dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I\,dt \tag{3}$$

where t_0 is the starting epoch, t_{EOL} is the epoch at which the operational phase ends. The first term of Eq. (3) refers to the operational phase of the object. The second and the third term refer to the Post-Mission Disposal (PMD) phase where it is contemplated that the End-Of-Life (EOL) disposal may fail [4]. The reliability of the PMD is included through the parameter α to be set between 0 and 1, t_{end} is the epoch at which the disposal ends, and t_f is the epoch at which the object would naturally decay from its initial orbit. An upper limit for t_f can be used, for example 100 years [4].

3. Cloud propagation and collision risk estimation

The computation of the effects of an explosion or a collision in Eq. (11) requires the modelling of a fragmentation event, the propagation of the fragments' trajectories and the computation of the probability of collision of these fragments on other objects. To this aim a continuum approach was developed at Politecnico di Milano an implemented in the Starling V2.0 suite. These building blocks will be described in the following sections.

3.1 Breakup model

As commonly done in other probabilistic space debris models, the NASA Standard Breakup Model [14] (NASA SBM) is used for characterising the ejected fragments due to a fragmentation event, either collision or explosion. The NASA SBM was reformulated in a probabilistic manner in [15], where three probability density functions in characteristic length L, area-to-mass ratio A/M, and ejection velocity Δv were derived. In [11][12] it is demonstrated how the phase space domain in Keplerian elements and area-to-mass ratio occupied by the ejected fragments can be evaluated semi-analytically on the basis of the cumulative density functions in area-to-mass ratio and ejection velocity Δv. This allows to bound the region interested by the fragmentation event and, thus, to estimate the density distribution at a reduced computational cost. The distribution is approximated through a binning approach [12], which means that the density varies discretely over the phase space.

3.2 Density propagation

The density distribution estimated in Section 3.1 is propagated applying the method of characteristics [16] to the continuity equation; this allows converting it from a partial differential equation into a system of ordinary differential equations, as follows.

$$\begin{cases} \dfrac{\mathrm{d}\mathbf{y}}{\mathrm{dt}} = \mathbf{F} \\ \dfrac{\mathrm{dn}_{\mathbf{x}}}{\mathrm{dt}} = -\mathrm{n}_{\mathbf{x}}\, \nabla_{\mathbf{y}} \cdot \mathbf{F} \end{cases} \tag{4}$$

where $\mathbf{F}$ is the force field, $\mathbf{y}$ the phase space variables, and $\mathrm{n}_{\mathbf{x}}$ the phase space density. The PlanODyn propagator [17] is adopted for the semi-analytical integration of Eq. (4) under atmospheric drag, J_2 perturbation, solar radiation pressure and third-body perturbation. The propagator adopts either single or double averaged dynamics [18] to reduce the computational cost. The propagated characteristics are eventually interpolated through the binning approach for sparse distributions proposed in [2].

3.3 Collision risk

The impact rate $\dot{\eta}$ between a debris' cloud and a given target can be obtained evaluating the flux of fragments against the target cross section A_c, directly from the density in Keplerian elements $n_{\boldsymbol{\alpha},\boldsymbol{\beta}}$, according to the following expression [15]:

$$\dot{\eta} = \mathrm{A_c} \iiint_{\mathbb{R}^3} \sum_{k=1}^{4} \frac{n_{\boldsymbol{\alpha},\boldsymbol{\beta}}\left(\boldsymbol{\alpha}, \boldsymbol{\beta}^{(k)}\right)}{\left|\det \mathrm{J}_{\mathbf{r}\rightarrow\boldsymbol{\beta}}^{(\mathrm{k})}\right|} \cdots \left\| \mathbf{v}_{\mathrm{T}} - \mathbf{v}\left(\boldsymbol{\alpha}, \boldsymbol{\beta}^{(\mathrm{k})}\right) \right\| \mathrm{d}\boldsymbol{\alpha} \tag{5}$$

where $\boldsymbol{\alpha}$ stands for the subset of orbital elements (a, e, i), $\boldsymbol{\beta}$ for (Ω, ω, f), $\mathbf{v}_{\mathrm{T}}$ is the target velocity, $\mathbf{v}$ is the fragments' velocity, and $\mathrm{J}_{\mathbf{r}\rightarrow\boldsymbol{\beta}}$ is the Jacobian of the transformation from position vector $\mathbf{r}$ to $\boldsymbol{\beta}$. The apex k indicates the four possible intersections with the target position $\mathbf{r}_{\mathrm{T}}$, given $\boldsymbol{\alpha}$.

The probability of collision P_c is modelled according to a Poisson distribution through an analogy with the gas kinetic theory [19], as follows.

$$\mathrm{P_c} = 1 - \exp\left(-\mathrm{N(t)}\right) \tag{6}$$

where the number of impacts at time t, $\mathrm{N(t)}$, is obtained integrating the impact rate of Eq. (5) over time.

4. Space debris index computation with THEMIS

The space debris mode of the THEMIS tool assesses the impact of a space mission on the space debris environment based on mission information such as orbit, mass, cross-section, and risk of fragmentation due to accidental collisions or break-up. The space debris index formulation is the one described in Section 2, however all the terms were built from scratch following a grid-like approach and implementing the novel cloud propagation and collision risk estimation method described in Section 3. The physical characteristics of the object such the cross area, the mass, and the mission profile in terms of phases and orbits, are retrieved from the THEMIS database which stores the information inputted by the user of the tool. The operational orbit data are considered as constant or variable through CCSDS (Consultative Committee for Space Data Systems) Orbit Ephemeris Message (OEM) format. The orbit evolution for the definition of the mission analysis is also provided as OEM file or evaluated using the ESA OSCAR tool [20]. In this way different disposal options are available (i.e., direct disposal, targeted deorbit, re-orbit or natural decay) and considering a ranges of possible propulsion technologies (i.e., chemical, electric, drag augmentation devices) with the corresponding design parameters (i.e., specific impulse, maximum thrust and thrusting time, augmented cross-section, drag and reflectivity coefficient).

The THEMIS backend defines the orbital region and the orbital element domain for the computation of the explosion and collision effect maps:

- Low Earth Orbit (LEO)
- Medium Earth Orbit (MEO)
- Geosynchronous Orbit (GO): 37948 km < *a* < 46380 km, *e* < 0.25. This region includes:

   - Geostationary Orbit (GEO)
   - Inclined Geosynchronous Orbit (IGO)
   - Extended Geostationary Orbit (EGO)
- GEO Transfer Orbit (GTO)
- Highly eccentric and crossing orbits (HECO): $h_a >$ 2000 km
   - LEO-MEO Crossing Orbits
   - MEO-GEO Crossing Orbits
   - GEO-superGEO Crossing Orbits (GHO)
   - High Altitude Earth Orbits (HAO)
   - Highly Eccentric Earth Orbit (HEO)

For each of these regions, a set of orbital parameters was defined as the minimum one to obtain accurate estimation of the probability and severity terms in Eq. (1). For example, for the LEO region, a grid in semi-major axis and inclination [3] is adopted. The grid is defined for a range of altitudes from 400 km to 2000 km and a range of inclinations from 0 to 180 degrees. The selection of the bin size is not fixed but can be chosen arbitrarily, considering a default cell size of 10 km in semi-major axis and 10 degrees in inclination [11][12]. Even if the extension to other orbital regions is still under development, a preliminary selection of the orbital parameters to be used for the other orbital region is [18]:

- MEO: semi-major axis, inclination, and Right Ascension of Ascending Node
- GEO: longitude
- GTO: semi-major axis, inclination, right ascension of ascending node and argument of perigee
- HECO: semi-major axis, eccentricity, inclination, RAAN and argument of perigee

The cumulative probability of explosion as function of time from launch $\mathrm{p_e}(\mathrm{t})$ is derived from historical data from the ESA DISCOS database [21] for payloads and rocket bodies considered as two separated classes.

$$\mathrm{p_e}(\mathrm{t}) = 1 - \hat{\mathrm{S}}(\mathrm{t}) \tag{7}$$

Two estimators for evaluating the explosion probability are considered. The first estimator is the Kaplan-Meyer estimator [6], which estimates the survival rate $\hat{\mathrm{S}}(\mathrm{t})$ from a statistic on the number of explosion and the number of survived objects up to a time t for a given class (i.e., rocket bodies or payload). The second estimator is Nelson-Aalen estimator [22], can directly evaluate the cumulative hazard rate function $\tilde{\mathrm{H}}(\mathrm{t})$.

The collision probability p_c in Eq. (1) is evaluated flying the spacecraft under analysis though the debris environment and adopting the kinetic gas theory [23][24]

$$\mathrm{p_c}(\mathrm{t}) = 1 - \exp(-\Phi(\mathrm{t}) \cdot A_c \cdot \Delta t) \tag{8}$$

where $\Phi(\mathrm{t})$ is the average flux of space debris in 1/m^2/year, A_c the cross-sectional area of the object in m^2, and Δt the time span considered in year. The value of the average debris flux is computed from ESA MASTER 8 [25] software tool. Alongside the debris flux, ESA MASTER 8 is used to compute the average impact speed of the space debris on a spacecraft. This computation is performed on the same grid used for the debris flux. The resulting average speed is evaluated by weighting each impact speed by its associated flux.

Fig. 2 shows the probability of collision of an object (mass equal to 1000 kg and cross-section equal to 10 m^2) in LEO with the space debris background population, considering a time interval of 1 year and varying the semi-major axis and the inclination of the orbit. The left plot shows the collision probability considering catastrophic collisions and no CAM capabilities. The centre plot considers that the spacecraft can avoid space debris larger than a fixed upper diameter of 10 cm. The right most plot, instead, considers a variable traceability threshold

$$r_{d_{up}} = r_{d_{ref}} \cdot \left(\frac{a_{sc} - R_E}{h_{ref}}\right)^{exp} \tag{9}$$

being $r_{d_{ref}}$ the minimum detectable radius at the reference altitude, a_{sc} the semi-major axis of the spacecraft orbit, R_E the radius of the Earth (6378.1 km), h_{ref} the reference altitude. The two defined thresholds are used to filter the flux of debris to be used in the collision probability. This can have a significant effect on the results, by shifting the most critical regions to higher orbits. It is clear the difference in both magnitude and distribution of the collision probability when we consider the contribution of collision avoidance manoeuvres.

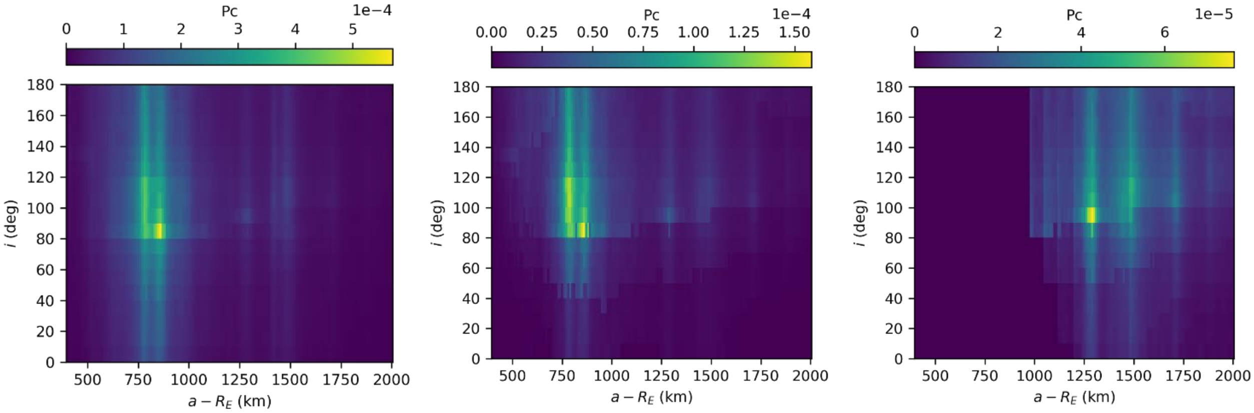

Fig. 2. Collision probability of an object in LEO considering no-CAM capability (left), CAM capability and a threshold of 10 cm for the trackable debris (centre), CAM capability and a variable diameter threshold for the trackable debris.

The effect terms of both collisions (e_c) and explosions (e_e) depend on the characteristics of the fragmentation, and on the evolution of the cloud of debris and its interaction with the objects' population. Specifically, the effects are defined following [3] as the resulting increase in the collision probability for operational satellites. This is used as a measure of the consequences of a fragmentation in orbit. To this aim, given an orbital region of the one listed above a set of *representative targets*, representative of the entire population of active objects, need to be defined. The operational satellites and their operational status and orbit are extracted from ESA DISCOS [21]. In the current implementation the targets to be considered are chosen based on the cross-sectional area of operational satellites on the orbital elements grid defined above. A cumulative cross-section $\sum A_c$ for each domain grid is computed. The representative target map is updated every year or more often, whenever the picture of the Space environment in terms of active satellites has a considerable change, for example when a large constellation is deployed [26]. The effects map is generated evaluating the probability of collision with the representative targets. For each bin belonging to the grid, a fragmentation (collision, payload explosion or rocket body explosion) is triggered and propagated for a pre-defined time t_e (e.g., $t_e = 15$ years). Over this time span, the cumulative probability of collision with the population of representative targets is estimated, and the effects e are computed as:

$$e = \frac{1}{A_{TOT}} \sum_{i=1}^{N_t} p_c(t_e)\, A_i \qquad (10)$$

where A_{TOT} is the cumulated spacecraft's cross-section over the 90% of the representative targets, A_i is the cumulative cross-section of the objects belonging to the i^{th} bin, and p_c is the collision probability. As highlighted in [26], since the effect map is rescaled with the cumulated spacecraft's cross-section over the 90% of the representative targets, the effect does not increase if the effect map is computed at a later year where the A_{TOT} has increased.

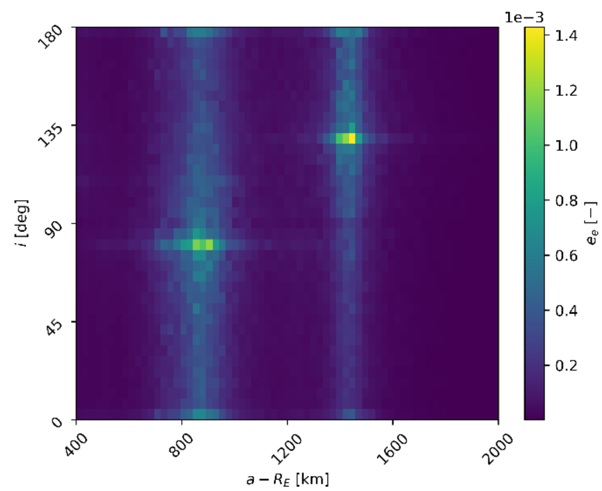

Fig. 3. Effects map for payload explosions in LEO, computed by the THEMIS software.

When comparing the effect maps obtained with the THEMIS software (Fig. 4) with the ones generated by the software CiELO and presented in [3], we can observe a relevant difference. In these latest maps, the previously symmetry of the effect peaks in inclination (i.e., fragmentation at $i_1 = i$ and $i_2 = \pi - i$) is now lost. This is due to an error in the computation of the mean relative velocity used for the computation of the collision probability in the effect evaluation in [3].

Now that all the input of the space debris index are defined, the index can be computed with the stored maps and can be used for many mission assessments. Once a mission is defined in terms of spacecraft characteristics and mission phases, the index is evaluated following the procedure outlined in Section 2. As an example, Fig. 5 shows the index profile for the Sentinel 6 mission comparing different PMDs while in Fig. 6 the total index value per mission phase is shown. The total index for each test case is reported in Table 1.

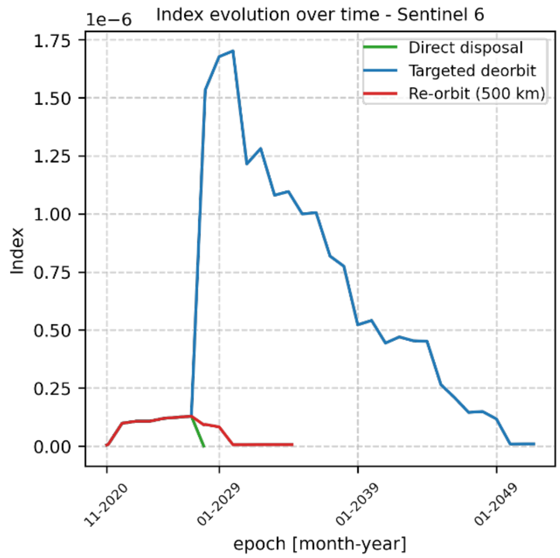

Fig. 5. Index profile for the Sentinel 6 mission comparing different PMDs.

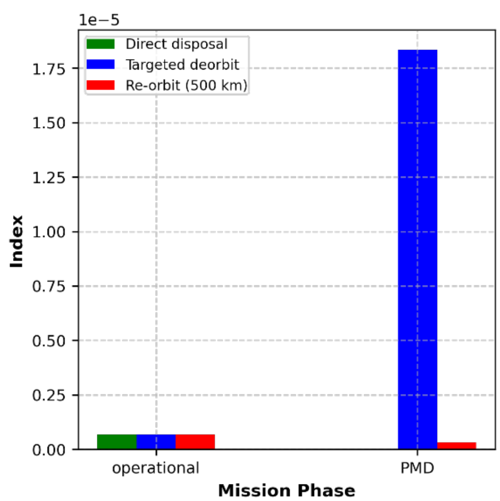

Fig. 6. Index evolution per phase - Sentinel 6 mission comparing different PMDs.

Table 1. Sentinel 6 total index for diffrent PMDs.

PMD strategy	Index
Direct disposal	$3.22 \cdot 10^{-6}$
Targeted deorbit	$1.98 \cdot 10^{-5}$
Re-orbit (500 km)	$3.52 \cdot 10^{-6}$

5. Space capacity, carrying capacity and seating capacity

In this paragraph the concept of space capacity will be introduced and then, following the review in [7], the concept of carrying capacity and seating capacity will be reviewed from other environmental fields.

5.1 Space capacity

Space can be seen as a common good or a resource, as the orbit occupied by a certain mission for its lifetime cannot be used by other missions [27][28][29][30]. In addition, Space is filling up with space debris; therefore, an unregulated access to space and use of space in terms of operating procedures may lead to a future scenario where space is difficult to access. To this extent, recent studies have introduced the concept of a space environment capacity [5][6][7][9][10] that is to define a measure of the number and type of missions the space environment can allocate, in time, to avoid its overcrowding, and to keep a limited number of space debris or a limited risk for other missions. Space capacity is strongly connected to the concept of debris index; indeed, a debris index can be used to measure the impact of a mission on the space debris environment and, when combined with long-term simulations can also link with the evolution of the debris environment in time. This combination can facilitate the definition of an available environmental capacity as this can become measurable and most of all, the contribution of each mission to it can be identified. However, consensus on the index to be used and its way of aggregation is a priority, as recent works [9][8] have shown that applying different index definitions and different evolutionary models can lead to widely varying results in terms of absolute values of capacity and assigned capacity allocation. This highlights the importance of a concerted framework for the definition, computation, monitoring, and allocation of the space environment capacity.

5.2 Carrying capacity

The concept of carrying capacity, often linked to the study of the evolution of population size, was found to be of interest in the context of space capacity [7][9]. The carrying capacity of an environment is the maximum population size of a biological species that can be sustained in that specific environment, given the resources available [31].

In population ecology, carrying capacity is defined as the environment's maximal load, which is different from the concept of population equilibrium, which may be far below an environment's carrying capacity [31]. The carrying capacity is "the limit of growth or development of each and all hierarchical levels of biological integration, beginning with the population, and shaped by processes and interdependent relationships between finite resources and the consumers of those resources" [32]. The effect of carrying capacity on population dynamics may be modelled with a logistic function which is a common *S*-shaped curve [32]. It is a modified Malthusian growth model (based on the hypothesis of an exponential increase of the human population) where the concept of *saturation level* was included. This quantity, referred as "carrying capacity", is the maximum population level that a given environment can support given finite resources.

The 'ecological' form of the logistic equation of population growth is a simple model of population self-regulation [32] that is:

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) \quad (11)$$

where P is the number of individuals, K is the carrying capacity and r is the growth rate with an initial population of P_0.

The generality of this definition of carrying capacity makes it interesting also for a possible translation of the concept in the field of spatial environment capacity. Previously, the orbital space has been treated as a resource that can be used by missions, thus comparing it to food, water, etc. Unlike in the natural systems, the population of satellites is not self-regulating. The space system is not naturally predisposed to a decrease in population due to lack of resources, such as the orbital space, as is the case with living species because 'births' (launches) are not strictly related to population size nor to 'deaths' (re-entries into the atmosphere). Due to the lack of this automatic adjustment of the number of objects, the uncontrolled increase of objects in space, known as Kessler syndrome, is possible [33].

The logistic equation in a slightly different form is also used in other contexts, even very different ones [7]. In fact, it is applied in the modelling of the carbon dioxide (CO_2) emissions from fossil fuel combustion. Since the industrial times, the concentration of carbon dioxide in the atmosphere has increased about 25% because of human activities. Except for a few countries, the main figures of CO_2 emission from fossil fuel combustion are S-shaped curves [34], represented by the equation:

$$P(t) = \frac{K}{1 + e^{\alpha(t - t_{half})}} \quad (12)$$

where α is the time decay constant and t_{half} is the symmetric inflection point.

Parametric estimation methods of the logistic equation have been studied and further adopted to model the CO_2 emission curve from fossil fuel combustion; in this way, the parameters representing the equation and the carrying capacity are obtained from the fitting of real data describing the particles emission. When enough data from actual observations are not available, the carrying capacity can be calculated from thresholds for correlated quantities [35].

The approach of defining a threshold for some representative quantities of the problem could be useful also in the case of the definition of the space environment capacity. As already mentioned, a maximum acceptable collision probability could be imposed as a general boundary, also considering the repercussions on the number of collision avoidance manoeuvres.

5.3 Seating capacity

Another interesting example from a totally different field is the seating capacity [7]. In fact, the capacity of a building, place, or vehicle, also known as seating capacity, is the number of people or things it can contain, and it is of importance for an optimal and safe success of operations and events.

Simple steps to determine event capacity estimates, such as how many square feet per person would be needed for a meeting, or how many people can be hosted within a venue, can be identified. In the last years, the pandemic has given many examples of the importance of this concept and how safety parameters can change and completely disrupt table arrangements and personal spaces dedicated to the individual.

It is interesting how the definition of seating capacity is based on the idea of assigning each person a slot of the total available space. An application of this underlying idea can already be found in the space field, specifically for the allocation of satellites and their communication frequencies in the Geostationary Earth Orbit (GEO) protected region, to regulate the population in highly competitive areas [36]. Also, the works on constellation slot occupancy [37] can be related to the concept of seating capacity as each satellite in the constellation can occupy only an assigned slot.

The good results obtained with this approach in the GEO region led to think that just as every operator in space must acquire a license for radio-frequency slot even in the Low Earth orbit (LEO) region, regardless of orbit, it may be necessary to expand the licensing regime to the orbits themselves. Licensing for orbits, along with the disposal requirements, would allow for an enterprise-level assessment of the impact of future launch activity, both on the debris environment as a whole and on the operations of satellites already in orbit.

6. Space capacity estimation with THEMIS

The space capacity mode of the THEMIS tool allows:

- The computation of the share of the Space capacity used up by a mission under analysis
- The computation of the overall Space capacity
- The analysis of possible definitions and proxy of the capacity threshold.

The space capacity mode is still under development; however, the following section describes the procedures that will be followed for the computation of the overall space capacity and the share of the capacity by a single mission. As proposed in Letizia et al. [4], the first approach implemented will be to cumulate the space debris index as computed in Eq. (3) on the index across the whole population of intact objects as:

$$I_{global} = \sum_{i=1}^{N_{intact}} I_t \tag{13}$$

Eq. (13) can be computed on different class of objects (i.e., rocket bodies, non-manoeuvrable payloads, or manoeuvrable payloads). As proposed in [4][10], long term simulations with DELTA will be run to compute I_{global} on all the objects generated in simulation with yearly snapshots. The allocation of space resources in a sustainable way requires the knowledge of the overall space capacity consumed by the current assets in orbit and the maximum capacity that can be allocated. The first approach that will be implemented for evaluating the overall consumed space capacity is through the aggregated space debris index of all objects in orbit as in Letizia et al. [4][10].

However, the assessment of the available space capacity depends on the evolution of the space environment. It is thus necessary to propagate the current situation of the space environment into a distant future (200 years) through ESA's DELTA software and aggregate the space debris index of the resulting objects. Subtracting the consumed capacity to this figure will provide us with the available capacity for an operationally sustainable space environment. The propagation of the current situation into the future requires to assume a series of premises related to some key parameters (launch rate, explosion rate, PMD rate) which will lead to different scenarios depending on the selected values. The launch rate is obtained extrapolating from the launch pattern in the last four years. The explosion rate is set leveraging statistical explosion historical data from DISCOS, splitting objects into different classes with similar explosion patterns. The PMD rate is defined by the disposal success probability, taking into account the data gathered in the ESA Space Debris Mitigation Guidelines and the ESA Space Environment Annual reports.

The DELTA simulations are used to derive MASTER like maps of the debris flux under different hypothesis to reflect possible evolutions of the space debris environment, for example with different launch rates, deployment of large constellations, adherence to PMD requirements, etc. For this reason in the DELTA simulations it is necessary to define:

- Year of initial population
- Simulation timespan (e.g., 100, 200 years)
- Launch traffic
- Explosion rate
- Constellations configuration since as shown in [26] they affect the map computation substantially.

In this way the evolution of the cumulative global index I_{global} can be studied as a possible proxy of the space capacity. Alongside the evaluation of the debris index on intact objects, the ESA DELTA software is used to evaluate the objects' density at yearly snapshots, which is in turn used to compute the collision probability term in Eq. (1), in substitution of ESA MASTER 8. However, DELTA only returns information on objects with size equal or larger than 10 cm. Therefore, for a proper evaluation of the collision probability it is necessary to extrapolate the density information also to smaller diameters. This is achieved using the same functional dependency of the density value as a function of the particle size as extracted from ESA MASTER [4]. In addition, to compute the collision probability, it is necessary to have information on the debris flux. This information is not directly available from DELTA, as only the density can be extracted. Therefore, to obtain the flux, we require the knowledge of the impact speed. This can also be extracted from ESA MASTER for different orbital regions. Otherwise, a fixed value can also be used [4]. The driver to choose those values consists of avoiding future scenarios which present exponential growth behaviour in usual Key Performance Indicators (KPIs), like the cumulated number of objects in orbit or the cumulated number of catastrophic collisions, which would lead to Kessler syndrome scenarios.

Moreover, in order to study the sensitivity to different capacity proxies as highlighted in [9] other possible indicators will be considered, such as the number of objects larger than 10 cm, the cumulative number of catastrophic collisions, the number of close approaches of active s/c with debris larger than 1 m, the number of close approaches between inactive objects, the number of collision avoidance manoeuvres below a certain probability threshold. The possibility to consider all these alternatives proxies depends on the possibility to extract them from the current evolutionary model used, the ESA DELTA tool.

7. Web User Interface

The THEMIS software will allow the interaction with the user through a secure Web User Interface. The user introduces the credentials and accesses the application with the corresponding permissions after the authentication by the ESA Single Sign-On system. The WUI has a sidebar allowing the user to select the main functionalities of the software:

- Environment Impact Evaluation
- Environment Capacity Evaluation
- Mission Definition and Review

The *Environment Impact Evaluation* view lets the user computing the space debris index of a mission using only high-level information like physical properties, concept of operations, orbital data, disposal options, etc. The *Environment Capacity Evaluation* view allows the user to compute the overall capacity of the space environment and the allocation of such capacity to the different missions according to the space debris index of the mission. The *Mission Definition and Review* view shows an overview of the registered existing and planned missions, allowing the user to access the detailed data of those missions. Fig. 7 to Fig. 10 shows some snapshots of the THEMIS WUI that will be deployed on the ESA Website.

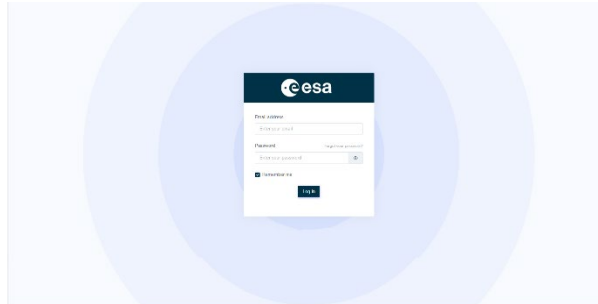

Fig. 7. THEMIS Single Sign-On.

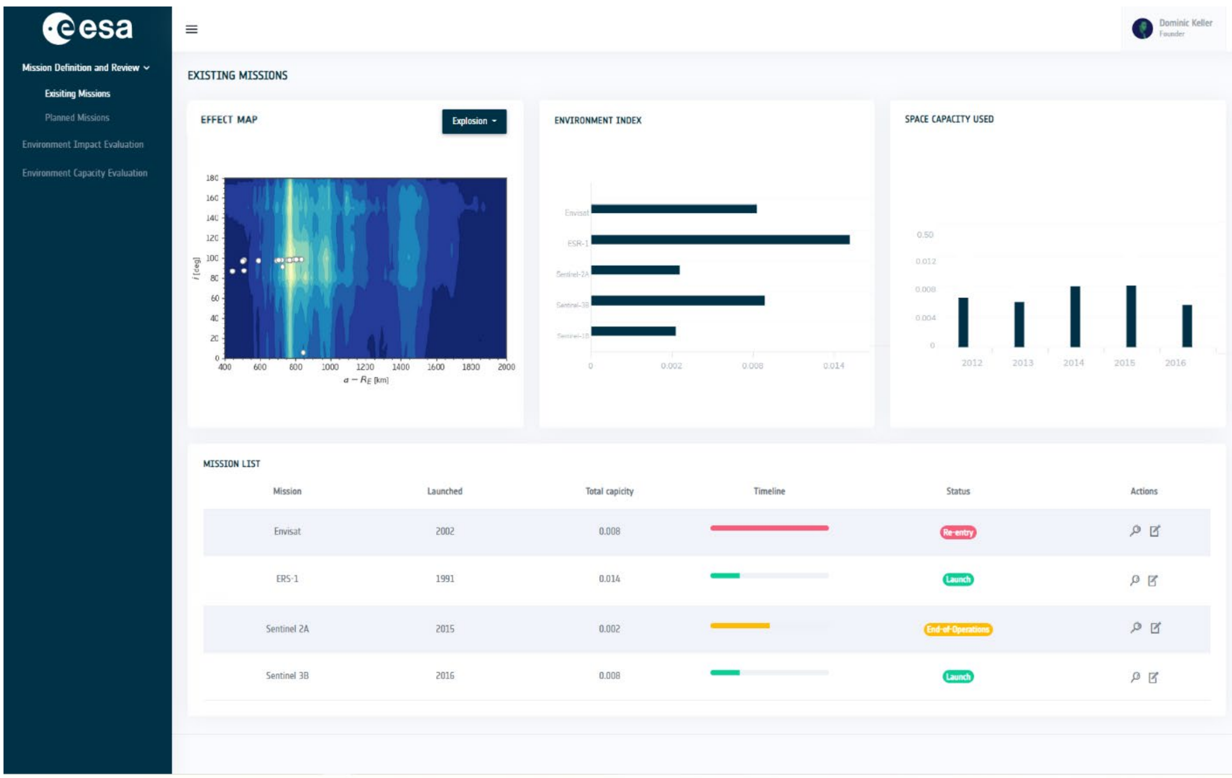

Fig. 8. THEMIS Existing mission evaluation.

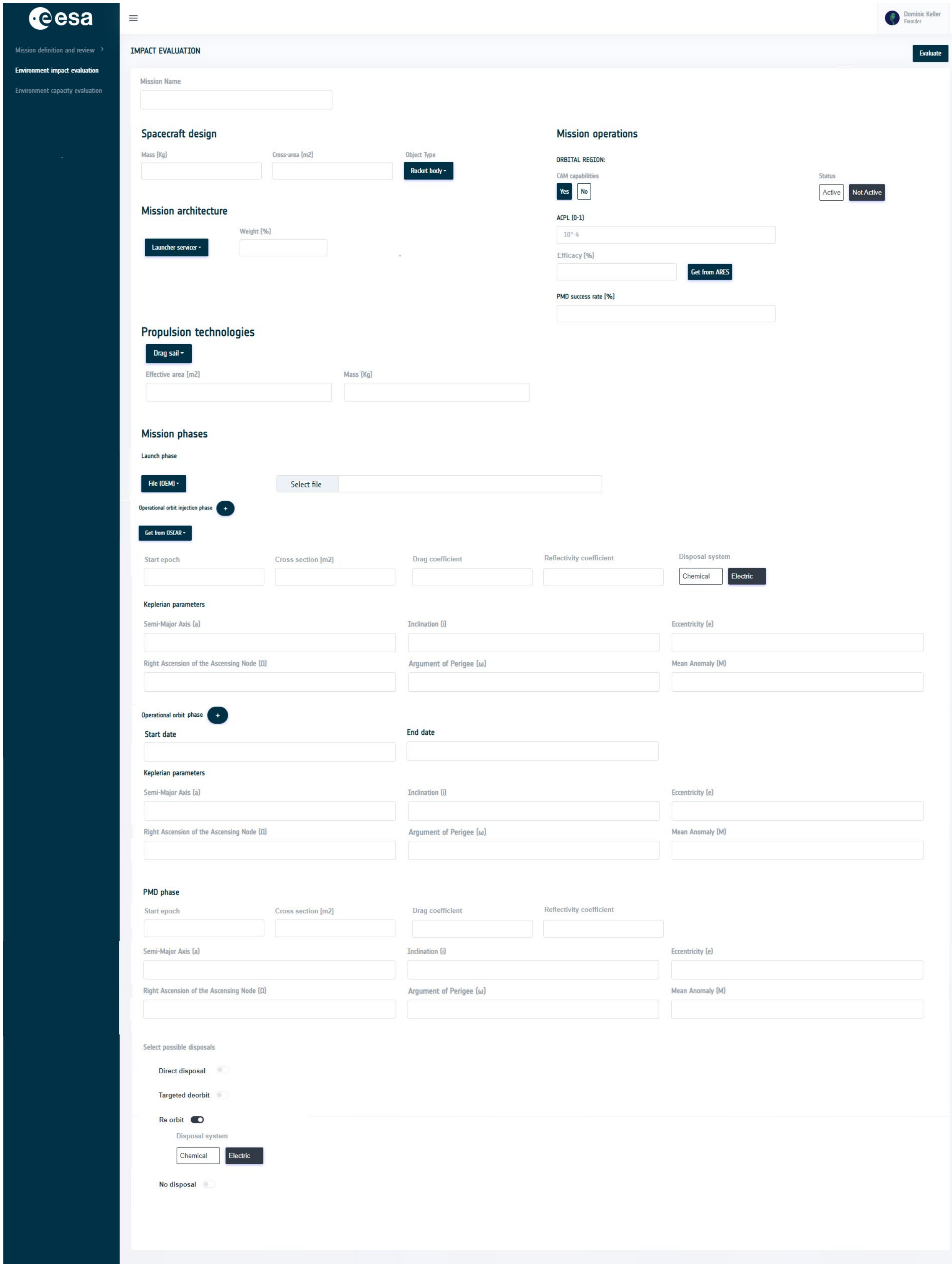

Fig. 9. THEMIS Mission design tool.

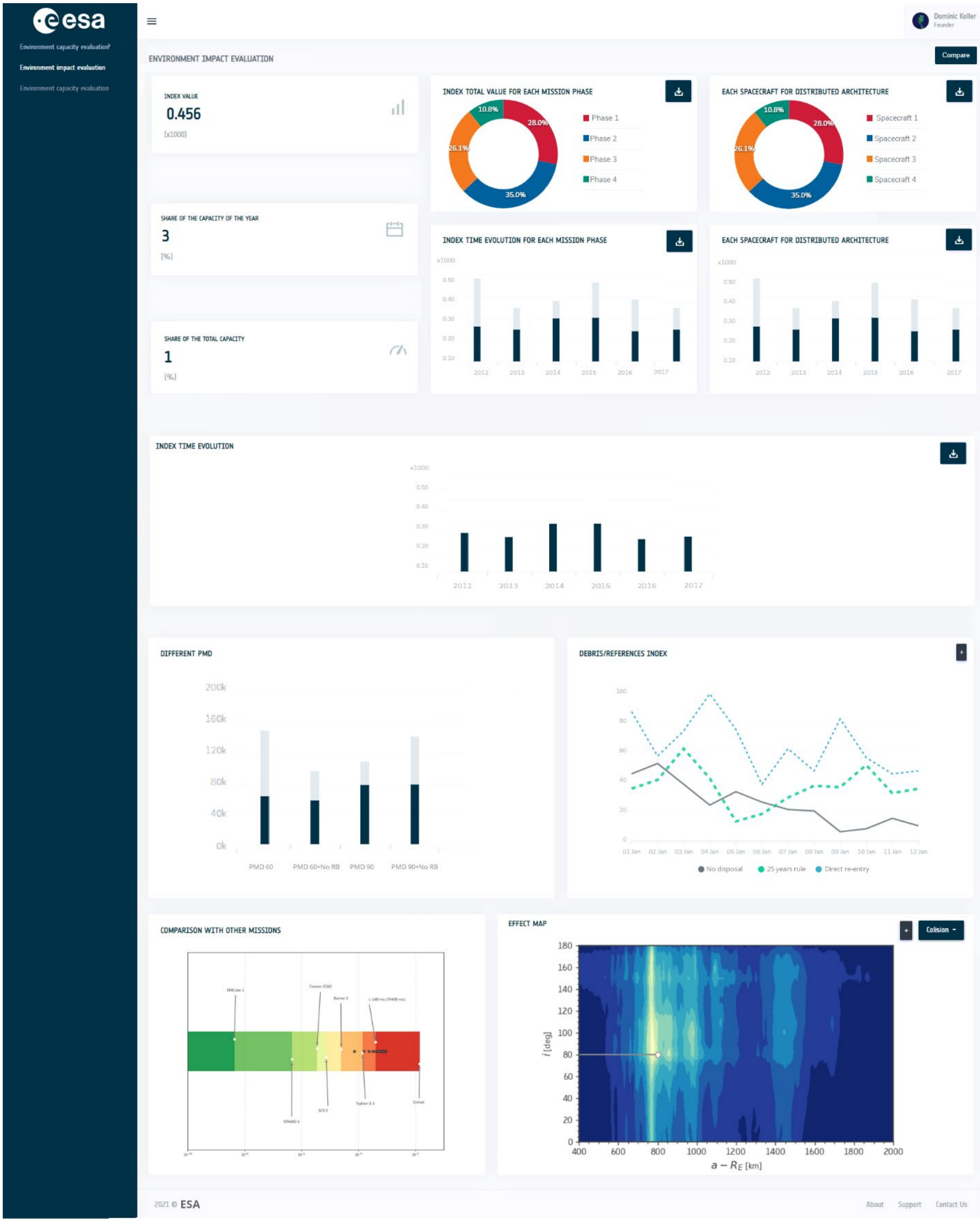

Fig. 10. THEMIS Space environnement impact evaluation.

8. Discussion and conclusions

The THEMIS tool has been presented in its space debris index and space capacity models. Many steps need to be yet taken to have a reliable assessment of the space carrying capacity and this tool represents one of the first steps towards this challenging objective. This tool, and in general the approaches to evaluate the space capacity, can be effective in managing the space as a resource and also in driving the direction for the definition of mitigation rules. Nonetheless, they require a comprehensive and international effort as the definition of capacity and its allocation policies must come from consensus. This is the challenge and responsibility to which as space debris community we are called in the next few years.

Acknowledgements

This research has received funding from the European Space Agency contract 4000133981/21/D/KS.

References

[1] Colombo C., Trisolini M., Gonzalo J.L., Giudici L., Frey S., Kerr E., Sánchez-Ortiz N., Del Campo B., Letizia F., Lemmens S., "Assessing the impact of a space mission on the sustainability of the space environment," *72nd International Astronautical Congress*, 25-29 October 2021, Dubai.

[2] Colombo C., Trisolini M., Gòmez J. L. et al., Design of a software to assess the impact of a space mission on the space environment, 8th European Conference on Space Debris, Virtual conference, 2021, April 20-23.

[3] Letizia, F., Colombo, C., Lewis, H.G., Krag, H., "Extending the ECOB Space Debris Index with Fragmentation Risk Estimation," 7th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany, 18-21 Apr. 2017.

[4] Letizia F., Lemmens S., Bastida Virgili B., Krag H., "Application of a debris index for global evaluation of mitigation strategies", Acta Astronautica, Vol. 161, 2019, pp. 348-362.

[5] Krag H., Lemmens S., Letizia F., "Space traffic management through the control of the space environment's capacity", *Proceedings of the 1st IAA Conference on Space Situational Awareness (ICSSA)*, 2017.

[6] Letizia F., Lemmens S., Krag H., "Environment capacity as an early mission design driver," *Acta Astronautica*, 2020, doi: 10.1016/j.actaastro.2020.04.041.

[7] Trozzi V., "Investigation of potential definitions of the space environment capacity to pursue sustainability of outer space activities over the long term", Meng Thesis, Politecnico di Milano, Apr. 2021. Supervisors: Colombo C., Trisolini M.

[8] Lewis H. G., Marsh N., "Deep time analysis of space debris and space sustainability", *8th European Conference on Space Debris,* 2021, 20–23 April, Darmstadt, Germany.

[9] Trozzi V., Trisolini M., Colombo C., "Analysis of possible definitions of the space environment capacity to pursue long-term sustainability of space activities," *72nd International Astronautical Congress*, 25-29 October 2021, Dubai.

[10] Letizia F., Bastida Virgili B., Lemmens S., "Assessment of orbital capacity thresholds through long-term simulations of the debris environment", Advances in Space Research, 2022, doi: 10.1016/j.asr.2022.06.010.

[11] Giudici L., Colombo C., Trisolini M., Gonzalo J. L., Letizia F., Frey S., Space debris cloud propagation through phase space domain binning, Aerospace Europe Conference, Warsaw, Poland, 2021, November 23-26.

[12] Giudici L., Trisolini M., Colombo C., Probabilistic multi-dimensional debris cloud propagation subject to non-linear dynamics, Advances in Space Research, (2022) - submitted.

[13] Sánchez-Ortiz, N., Domínguez-González, R., Krag, H., Flohrer, T., "Impact on mission design due to collision avoidance operations based on TLE or CSM information", Acta Astronautica 116 (2015) 368–381, doi: 10.1016/j.actaastro.2015.04.017.

[14] Johnson N. L., Krisko P., Liou J. C., NASA's new breakup model of evolve 4.0, Advances in Space Research, 28 (2001) 1377-1384.

[15] Frey S., Colombo C., Transformation of satellite breakup distribution for probabilistic orbital collision hazard analysis, Journal of Guidance, Control, and Dynamics, 44 (2021) 88-105.

[16] Frey S., "Evolution and hazard analysis of orbital fragmentation continua", PhD Thesis, Jul. 2020, Politecnico di Milano, Supervisors: C. Colombo, S. Lemmens, H. Krag, Link: https://www.politesi.polimi.it/handle/10589/165144

[17] Colombo C., Planetary orbital dynamics (PlanODyn) suite for long-term propagation in perturbed environment, 6th International Conference of Astrodynamics Tools and Techniques, 2016.

[18] Giudici L., Trisolini M., Colombo C., Phase space description of the debris' cloud dynamics through continuum approach, *73rd International Astronautical Congress*, Paris, France, 2022, September 18-22.

[19] McKnight D. S., A Phased Approach to Collision Hazard Analysis, Advances in Space Research, 10 (1990) 385-388.

[20] Braun V., Sánchez-Ortiz N., Gelhaus J., Kebschull C., Flegel S., Moeckel M., Wiedemann C., Krag H., Vörsmann P., "Upgrade of the ESA DRAMA OSCAR tool: Analysis of disposal strategies considering current standards for future solar and geomagnetic activity", 2013.

[21] Del Campo López B., Sanchez Saez N., "Design, development, and deployment of software infrastructure to assess the impact of a space

mission on the space environment", Technical Note 2, European Space Agency, Contract No.: 4000133981/21/D/KS, March 2022.

[22] Wayne Nelson (1969) Hazard Plotting for Incomplete Failure Data, Journal of Quality Technology, 1:1, 27-52, DOI: 10.1080/00224065.1969.11980344

[23] Su, S.-Y., and Kessler, D., "Contribution of explosion and future collision fragments to the orbital debris environment", Advances in Space Research, Vol. 5, pp. 25-34.

[24] Kessler, D., "Derivation of the collision probability between orbiting objects: the lifetimes of Jupiter's outer moons", Icarus, Vol. 48, pp. 39-48.

[25] Flegel, S., Gelhaus, J., Möckel, M., Wiedemann, C., and Kempf, D., "Maintenance of the ESA MASTER Model", Final Report, 2011.

[26] Muciaccia A., Trisolini M., Giudici L., Colombo C., Del Campo B., Letizia F., "Environmental impact of large constellations through a debris index analysis", 73rd International Astronautical Congress, Paris, France, 2022, September 18-22, IAC-22. B6.5.3.

[27] Martinez P., "The UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities", *Journal of Space Safety Engineering*, Vol. 8, 2021, pp. 98–107.

[28] Hardin G., "The Tragedy of the Commons", *Science,* Vol. 162, 1968, pp. 1243–1248.

[29] Colombo C., Letizia F., Trisolini M., Lewis H., Chanoine A., Duvernois P. A., Austin J., Lemmens S., "Life Cycle Assessment Indicator for Space Debris", *7th European Conference on Space Debris*, ESA/ESOC, 18-21 Apr. 2017, Darmstadt, Germany.

[30] Maury T., P. Loubet, M. Trisolini, A. Gallice, G. Sonnemann, C. Colombo, Assessing the impact of space debris on orbital resource in life cycle assessment: A proposed method and case study, Science of the Total Environment, 667 (2019), pp. 780-791.

[31] Hui C., "Carrying capacity, population equilibrium, and environment's maximal load," Ecological Modelling, 2006, Vol. 192, pp. 317-320.

[32] Monte-Luna, P., Brook, B., Zetina-Rejón, M., Cruz-Escalona, V., "The carrying capacity of ecosystems. Global Ecology and Biogeography," 2004, Vol. 13, pp. 485-495.

[33] Kessler D. J., Cour-Palais B. G., "Collision frequency of artificial satellites: The creation of a debris belt", *Journal of Geophysical Research*, Vol. 83 (A6): 2637–2646, 1978, doi: 10.1029/JA083iA06p02637.

[34] Meng, M., & Niu, D., "Modeling CO2 emissions from fossil fuel combustion using the logistic equation," Energy, 2011, Vol. 36, pp. 3355–3359

[35] Bjørn, M., A. and. Zwicky Hauschild, "Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level," The International Journal of Life Cycle Assessment, 2015, Vol. 20, pp. 1005-1018. doi:10.1007/s11367-015-0899-2.

[36] ITU, Current Practice and Procedures for Notifying Space Networks Currently Applicable to Nanosatellites and Picosatellites. Technical Report, ITU, 2015 ITU-R SA.2348-0.

[37] Arnas, D., Lifson, M., Linares, R., Avendano, M., "Definition of Low Earth Orbit Slotting Architectures Using 2D Lattice Flower Constellation," Advances in Space Research, 2020, doi: 10.1016/j.asr.2020.04.021.