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Assessing the impact of a space mission on the sustainability of the space environment

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Abstract

Space, like any other ecosystem, has a finite capacity. The continuous growth of space activities is contributing to overload this delicate ecosystem. In this paper, the THEMIS software tool will be presented, conceived to assess the impact of a space mission on the space environment and its contribution to the overall Space capacity. THEMIS is developed by Politecnico di Milano and Deimos Space within an ESA-funded study. A density-based approach is used for propagating the fragments originating from collisions and explosions in space. This is used in the definition of a debris index to assess the impact of a space object on the environment, based on mission information such as its orbit, mass, cross-section, and risk of fragmentation due to accidental collisions or break-up. The output of the environmental analysis is summarised into a single score, which is integrated in the ESA database DISCOS for reporting analyses and which is also suitable for integration into a life cycle assessment procedure.
Keywords: Space capacity, Space debris index, Space sustainability, Space missions, Space debris

Acronyms/Abbreviations

CAM	Collision Avoidance Manoeuvre
MOC	Method Of Characteristics
NASA SBM	NASA Standard Breakup model
GMM	Gaussian Mixture Model
CRS	Compressed Row Storage
EKMR	Extended Karnaugh Map Representation
WUI	Web User Interface

1. Introduction

Space, like any other ecosystem, has a finite capacity [1][11][15]. The continuous growth of space activities, due to the increasing reliance of our daily lives on services from Space, the privatisation of the space market, and the lower cost of deploying smaller and distributed missions in orbit, is improving human-life quality. However, it is also contributing to overload 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. Several formulations of debris indexes have been proposed to model distinct aspects of the space debris environment, mainly focussing on monitoring the possible increase in the number of objects in space, and on the risk they pose to current and future satellites.

In this paper, we will present the latest advances in the design of the THEMIS software tool to assess the impact of a space mission on the space environment and its contribution to the overall Space capacity, developed by Politecnico di Milano and Deimos Space within an ESA-funded study [2]. A density-based approach is used for propagating the fragments originating from collisions and explosions in space. This is used in the definition of a debris index to assess the impact of a space object on the environment, based on mission information such as its orbit, mass, cross-section, and risk of fragmentation due to accidental collisions or break-up. The output of the environmental analysis is summarised into a single score, which is integrated in the ESA database DISCOS for reporting analyses, and which is also suitable for integration into a life cycle assessment procedure. The paper will present the development and consolidation of the different building blocks required for the definition of the environmental capacity and the development of a database to support the management of the capacity, through its computation and allocation. An overview of the expected user interface functionalities will also be presented.

2. THEMIS software tool

The THEMIS software purpose is twofold. Firstly, to allow different users to assess the impact of a space mission on the space debris environment, and to determine the share of the capacity of space used by that mission under analysis. Secondly, to allow the computation of the overall space capacity used by orbiting spacecraft and to analyse possible definitions of the capacity threshold. Different types of users are foreseen for this software; having different goals for the use of this tool, a different level of knowledge of the problem, and available information for the required input. Therefore, associated to each user, a different level of access to the tool will be available; either through a Web User Interface (WUI) or to the backend software tool for the computation of the environmental index and the capacity consumption (Figure 1).

The frontend serves as the main interface for external users to access the information on the missions' characteristics and assess their impact on the space environment. It allows the user to also have an overview of the overall status of the space environment. In addition, it allows registered users to submit their mission for evaluation of its environmental impact both in terms of index and capacity consumption.

The backend contains all the building blocks necessary for the computation of the environmental index and capacity. These building blocks are the processing modules, which are required to compute the different ingredients of the environmental index: the collision and explosion probability, and the collision and explosion effects. These blocks are based on the modelling of break-ups and the evolution of a fragment cloud in time. Additionally, the backend takes care of performing long-term propagation using ESA DELTA to compute the available capacity of the space environment.

Alongside the processing modules, the backend interfaces with existing software suites. Specifically, DRAMA for the computation of the disposal strategy and of the collision avoidance manoeuvres, MASTER-8 for the prediction of the debris fluxes acting on a spacecraft, and DELTA for the long-term evolutionary predictions of the space environment. Finally, the interface with the DISCOS database provides the access to the underlying data required by the processing modules.

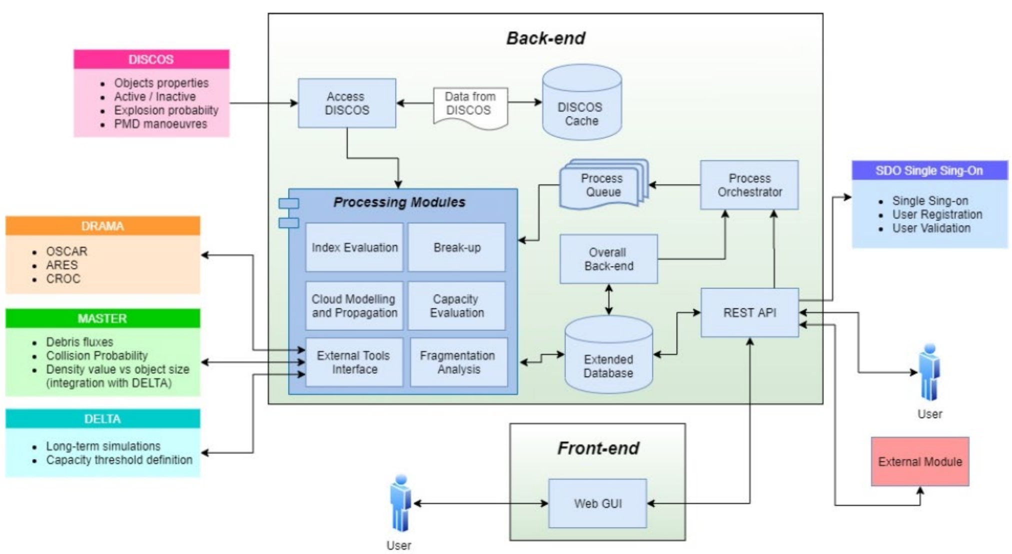

Figure 1. Overall architecture of the system.

3. Space debris index for assessing the impact of space missions

The THEMIS tool space debris mode has the aim of assessing the impact of a space mission on the space environment and to measure the share of the space capacity used by a single mission.

The space debris index implemented in this tool will follow the definition of the ECOB index in Letizia et al. [12], which is defined as a risk indicator composed by a probability term (p) and an effect term (e), which considers the contribution of fragmentations on the sustainability of the space environment. The expression of the index is as follows:

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

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. Each term can be evaluated based on the characteristics of the object (i.e., mass and cross-section), its orbit and the mission scenario. The probability of collision (p_c) is evaluated using a flux-based model of the space debris environment and exploiting the analogy with the kinetic gas theory as follows:

$$p_c = 1 - e^{\rho \cdot \Delta v \cdot A \cdot \Delta t} \quad (2)$$

where ρ is the debris density, Δv is the relative impact velocity, A is the cross-sectional area of the object and Δt is the time span considered. The value of the debris density and of the impact velocity are extracted from ESA MASTER, considering the debris population at a specified epoch. The cross-section of the object is obtained from a satellite database such as DISCOS.

When computing the collision probability, we only consider debris fluxes of particles whose diameter is large enough to generate a catastrophic collision. The criterion adopted is based on the energy of the collision, which should be greater than 40 J/g. In this way, we define a minimum required diameter that will generate a catastrophic collision. The relevant flux used in the computation of p_c is the cumulative flux associated to this diameter. However, the debris index calculation can also consider the possibility of performing Collision Avoidance Manoeuvres (CAM). With this respect, the general approach is to consider that objects larger than 10 cm can be tracked from Earth. Therefore, a satellite with collision avoidance manoeuvres capabilities will be able to avoid such debris. This is reflected in the collision term of the debris index by adding an upper limit on the particle diameter, which in turn result in a modified debris flux.

However, the traceability of debris particle also depends on the orbital altitude of the debris. In fact, the lower the altitude, the higher is the capability of telescopes of tracking smaller particles. The expression of the traceable diameter, d_t, as a function of the altitude is the following:

$$d_t = d_{ref} \cdot \left(\frac{h}{h_{ref}}\right)^2 \quad (3)$$

where h is the orbit altitude, $d_{ref} = 0.32$ m is a reference diameter, and $h_{ref} = 2000$ km a reference altitude. Using this expression in place of a constant diameter of 10 cm, the collision probability changes, particularly for lower altitudes. In [2] a comparison of collision probability maps was shown in altitude and inclination for the same satellite but with different upper limits for the collision avoidance diameter. A constant 10 cm threshold can be used of a variable one, based on Eq. (9). In the second case (reported in Figure 2), the lower altitude band, until about 900 km, shows a null collision probability. This is because at lower altitude smaller particle diameters can be tracked. This results in an upper diameter threshold that is smaller than the lower threshold needed to generate a catastrophic collision. Therefore, in this case, the satellite can avoid all the debris particles that can generate a catastrophic collision. This is of course valid assuming a 100% reliability of the CAM.

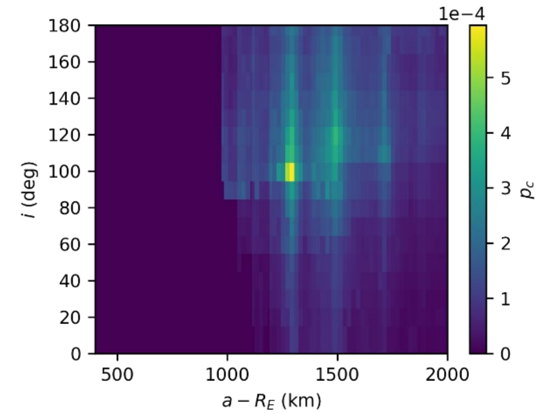

Figure 2. Collision probability map for a 1000 kg spacecraft with a 10 m^2 cross-section with a variable threshold.

The probability of explosion (p_e), instead, is derived from historical data gathered form the ESA DISCOS database in terms of epoch, altitude, event type, Id and class of the objects involved [12]. Given the difference between the number of fragmentations occurred in payloads and rocket bodies, these two classes are considered separately in the modelling of p_e. In addition, fragmentation events due to collisions, deliberate destructions, atmospheric forces, and attitude are excluded [2].

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 resulting increase in the collision probability for operational satellites is used for the assessment of the consequences. The fragmentation is modelled following the NASA SBM [15], which provides the distribution of the generated fragments as a function of the object orbit and mass for both collisions and explosions. However, in this work the implementation proposed by Frey et al. is used that directly describes the distribution of the fragments in orbital elements exploiting the formulation in Gauss's planetary equations written for finite differences [16]. As proposed in the ECOB formulation [12] to assess the effects on the population of operational satellites, a set of representative targets is defined by considering the distribution of the cross-sectional area of the operational satellites on grids, whose definition depends on the orbital region considered. The MASTER ESA tool [17] is used to derive grid for the representative targets and effect maps. Different orbital regions are defined to this aim 10[8]:

- Low Earth Orbit (LEO): hp < 2000 km, ha < 2000 km

- Medium Earth Orbit (MEO): 2000 km < hp < 31570 km, 2000 km < ha < 31570 km

  - Navigation Satellites Orbit (NSO): 50° < i < 70°, 18100 km < hp < 24300 km, 18100 km < ha < 24300 km)

- Geosynchronous Orbit (GO): 37948 km < a < 46380 km, e < 0.25
  - Geostationary Orbit (GEO): i < 25°, 35586 km < hp < 35986 km, 35586 km < ha < 35986 km
  - Inclined Geosynchronous Orbit (IGO): 37948 km < a < 46380 km, e < 0.25, 25° < i < 180°.
  - Extended Geostationary Orbit (EGO): 37948 km < a < 46380 km, e < 0.25, i < 25°

- GEO Transfer Orbit (GTO): i < 90°, hp < 2000 km, 31570 km < ha < 40002 km

- Highly Eccentric and Crossing Orbits (HECO): ha > 2000 km
  - LEO-MEO Crossing Orbits (LMO): hp < 2000 km, 2000 km < ha < 31570 km
  - MEO-GEO Crossing Orbits (MGO): 2000 km < hp < 31570 km, 31570 km < ha < 40002 km
  - GEO-superGEO Crossing Orbits (GHO): 31570 km < hp < 40002 km, ha > 40002 km
  - High Altitude Earth Orbits (HAO): hp > 40002 km, ha > 40002 km
  - Highly Eccentric Earth Orbit (HEO): hp < 31570 km, ha > 40002 km

Then, the parameters needed to define the girds for the representative targets are selected according to the orbital region considered:

- LEO: semi-major axis and inclination;

- MEO: semi-major axis, inclination, and right ascension of ascending node;

- GEO: longitude (λ) and inclination;

- GTO or HECO: semi-major axis, eccentricity, inclination, right ascension of ascending node, and argument of perigee.

Figure 3 shows the representative targets in the LEO region in a semi-major axis and inclination grid, considering a step of 10 km in semi-major axis and 10 deg in inclination. Figure 4 contains the GEO region representative targets in longitude and inclination (18 deg step and 10 deg step respectively), while Figure 5 and Figure 6 displays the representative targets in the MEO region considering two possible pairs of orbital parameters for the grid definition: the first with right ascension of ascending node (step of 18 deg) and inclination (step of 10 deg), while the second with the semi-major axis (step of 100 km) and inclination (step of 10 deg).

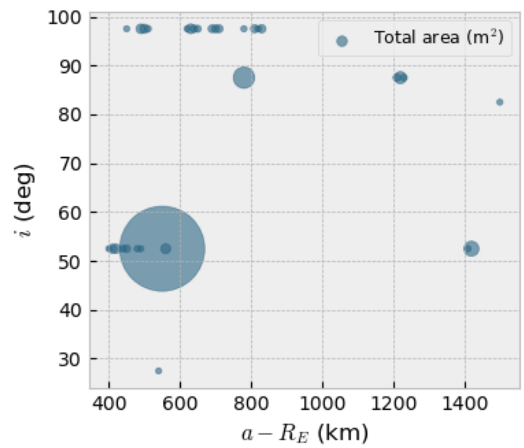

Figure 3. LEO region representative objects in a semi-major axis and inclination grid.

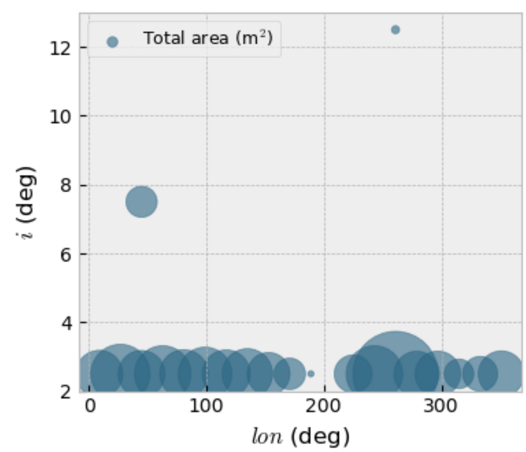

Figure 4. GEO region representative objects in longitude and inclination.

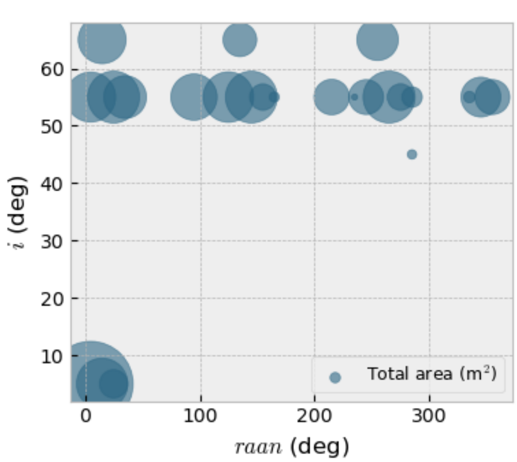

Figure 5. MEO region representative objects in right ascension of ascending node and inclination.

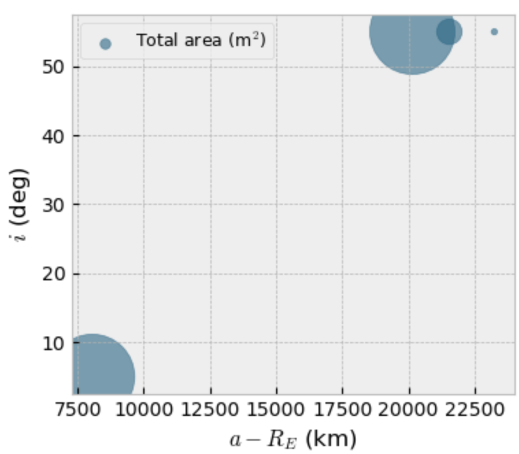

Figure 6. MEO region representative objects in semi-major axis and inclination.

The effect of fragmentations is evaluated by simulating a catastrophic collision or explosion for each grid cell and evaluating the increased collision probability for the target objects. The numerical and methodological approached developed to this aim will be presented in Section 5.

The effect e_c and e_e terms are then obtained with a weighted sum of the cumulative collision probability on each target, with the weights depending on the share of cross-sectional area represented by the representative object map cell.

The index in Eq. (7) is then assessed over time to get its cumulative value for the mission lifetime. As proposed in [13] the formulation include the reliability of post-mission disposal manoeuvres with a coefficient α.

$$I_t = \int_{t_0}^{t_{EOL}} I\,dt + \alpha \cdot \int_{t_{EOL}}^{t_e} I\,dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I\,dt \tag{4}$$

where t_{EOL} is the epoch at which the operational phase ends, t_e 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.

4. Fragments cloud propagation through binning

When a fragmentation is simulated to compute the effect terms, it is necessary to propagate the resulting cloud and to compute the collision risk of that cloud with the chosen representative targets.

This section is devoted to explaining the model adopted for the estimation of the initial distribution of fragments, after a fragmentation event, and its propagation under orbital perturbations. The traditional piece-by-piece approach, which propagates the orbit of each fragment separately, is not feasible from a computational point of view, unless the analysis is limited to relatively big debris. However, even the impact of a satellite with a fragment of dimension smaller than 1 cm could cause the failure of the mission. This problem is here addressed in a probabilistic fashion: the dispersion of fragments is translated into a density distribution, which is propagated applying the Method Of Characteristics (MOC) to the continuity equation here recalled:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{F}) = 0 \tag{5}$$

where t is time, n the phase space density, $\boldsymbol{x}$ the phase space variables and $\boldsymbol{F} = \frac{dx}{dt}$ the dynamics.

The reformulated NASA Standard Breakup Model (NASA SBM), proposed in [17], is adopted for the sampling procedure: it maps a 4D distribution in velocity and area-to-mass into a 7D distribution in Keplerian elements and area-to-mass, in the domain probabilistically reachable by the ejected fragments. It is worth noticing that the sampled characteristics form a scattered point cloud in the phase space of Keplerian elements, which means that an interpolation technique is mandatory. In [3][4], the Gaussian Mixture Model (GMM) was applied to retrieve the density distribution, both from the sampled and propagated characteristics. Currently, this method cannot account for forces that lead to resonances on a small subset of the phase space, as it could be the case of third-body perturbation or solar radiation pressure [5]. Therefore, a binning approach for the interpolation of the density is here preferred, with the aim of defining a method that is independent from the dynamical regime under analysis [6]. This alternative method introduces an innovative approach in the sampling procedure: the domain for the fragmentation under study is defined a priori, based on the likelihood for a fragment to reach a certain region (i.e., bin) of the phase space of Keplerian elements and area-to-mass ratio. The density gradient is used as index for the definition of the step-size adopted for the division of the domain into bins; indeed, it shows of how slow/fast the density decreases when the 'distance' in Keplerian elements increases from the fragmentation point. Currently, the domain is partitioned in equally sized bins, which means that the averaged density gradient is used for the definition of the step-size. With the domain and the step-size defined, the grid in Keplerian elements can be computed. An average value of the density is estimated, through the sampling of the reformulated NASA SBM, in each bin belonging to the reachable domain. The number of samples from which the mean value is computed is defined based on the estimated density gradient in that bin; indeed, it is reasonable to average a higher number of samples in the region of the phase space where gradient of the density is higher.

It is worth mentioning that, even though the final density distribution is defined in the full set of Keplerian elements and area-to-mass, the sampling procedure is performed in a 4D domain in semi-major axis, eccentricity, inclination and area-to-mass, which is then extended to the 7D distribution. Indeed, just after the fragmentation, the debris are considered in the same position as the fragmenting object but distributed in velocity and area-to-mass. This means that all the orbits of the generated fragments must intersect the orbit of the parent object in the fragmentation point; as a result, only a subset of Keplerian elements (three of them) are free to vary, while the others come as a consequence of the intersection constraint. In other words, the Cartesian-to-Keplerian mapping procedure preserves the dimensionality of the distribution, that is then extended to the target 7D distribution through the intersection condition.

Once that the density distribution is estimated through the averaging procedure in each bin, some representative samples are extracted and propagated. The idea is to have the minimum set of characteristics able to cover the whole domain, well-represent the density distribution and dense enough to describe the evolution of the cloud under the dynamical model adopted. If the fragments occupy a huge region of the phase space (i.e., the gradient of the density is low), it might happen that the constraint on the dynamics imposes to take more than one representative sample for the same bin; indeed, even though they are assumed to share the same density value at fragmentation epoch, they will evolve differently under the orbital perturbations, and will occupy separate regions of the phase space in a future time.

The propagated characteristics are finally interpolated through the binning in semi-major axis, eccentricity, inclination, right ascension, argument of periapsis and area-to-mass, adopting a step-size coherent with dynamical constraint imposed. This binning procedure in a six-dimensional space is a tremendous challenge from a memory usage standpoint. However, in most of the cases, the debris generated by a fragmentation event remain bounded in certain regions of the phase space. Hence, a Compressed-Row-Storage (CRS) [7] technique is applied to the highly-sparse bins matrices to conveniently store the density distribution. The Extended Karnaugh Map Representation (EKMR) [9] is used to transform the six-dimensional array of density values into a series of two-dimensional matrices, as depicted in Figure 7. The CRS technique is then applied to the set of two-dimensional arrays.

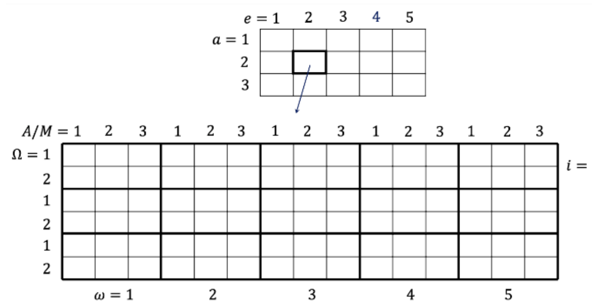

Figure 7. EKMR scheme.

The density distribution in Keplerian elements can be transformed into a distribution in Cartesian coordinates (i.e., position and velocity). Assuming the fragments to be randomised in mean anomaly, this transformation can be done sampling a sufficient number of characteristics from the distribution in Keplerian elements, converting them into Cartesian coordinates and binning the transformed samples in the new phase space. This allows to estimate the impact rate $\dot{\eta}$ of the fragments with a chosen target, as follows [10]:

$$\dot{\eta}(\boldsymbol{r}^*, \boldsymbol{v}^*) = \int_{\mathbb{R}^3} A_c\left(\frac{\boldsymbol{v} - \boldsymbol{v}^*}{\|\boldsymbol{v} - \boldsymbol{v}^*\|}\right) n_{r,v}(\boldsymbol{r}^*, \boldsymbol{v}) \|\boldsymbol{v} - \boldsymbol{v}^*\|^3 \mathrm{d}^3\boldsymbol{v} \tag{6}$$

where $\boldsymbol{r}^*, \boldsymbol{v}^*$ are the position and velocity vectors of the target, A_c is the cross-sectional area exposed to the incoming flux and $n_{r,v}(\boldsymbol{r}^*, \boldsymbol{v})$ is the fragments' density at the target position. The number of impacts, η, can be computed by integrating Eq. (6) over time t:

$$\eta(t) = \int_{t_0}^{t} \dot{\eta}(\boldsymbol{r}^*(t), \boldsymbol{v}^*(t))\mathrm{d}t \tag{7}$$

In the following, the presented model is adopted for the propagation of the fragments' cloud density associated to the explosion of the satellite Fengyun-1C. The Keplerian elements at fragmentation are reported in Table 1.

Table 1: Fragmentation Keplerian elements of Fengyun-1C.

Element	Value
a [km]	7231
e [−]	0.00135
i [deg]	98.65
Ω [deg]	106.11
ω [deg]	262.01
f [deg]	133.46

In Figure 8 is represented the initial density distribution in semi-major axis, eccentricity and inclination. As it can be observed, in the semi-major axis – eccentricity domain the fragments are distributed in a V-shape known as gabbard diagram. This is a peculiar shape associated to fragments' clouds generated by the fragmentation of an object in a quasi-circular orbit. The regions below the V are forbidden by the intersection constraint previously mentioned.

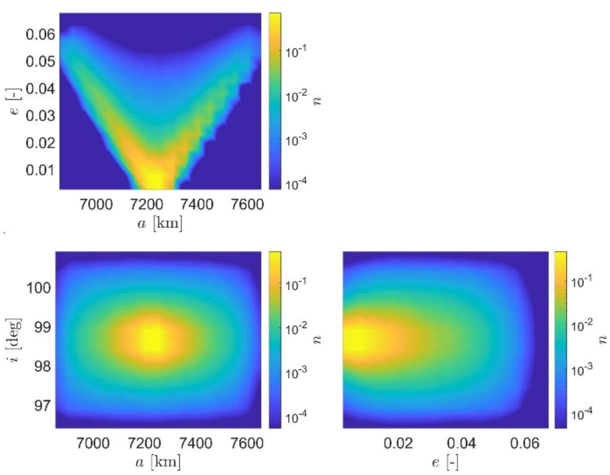

Figure 8. Initial density distribution - Fengyun-1C.

In Figure 9 is depicted the density distribution ten years after the fragmentation event. As it can be noticed, the left leg of the V-shape in the semi-major axis – eccentricity domain has disappeared, as the drag effect has caused the fragments with the lowest perigee altitudes to re-enter in the atmosphere. Furthermore, the density peak has decreased of two orders of magnitude for the same reason. The same behaviour can be assessed by looking at the cumulative distributions shown in Figure 10, where it can be further observed the decrease of the number of fragments over time. Note that, the re-entry rate progressively slows down as the fragments at low altitude burn in the atmosphere and the drag effect reduces its action on the fragments' cloud.

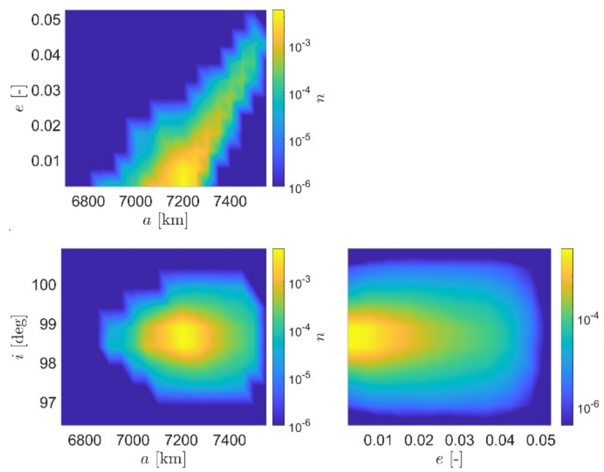

Figure 9. Density distribution 10 years after the fragmentation event - Fengyun-1C.

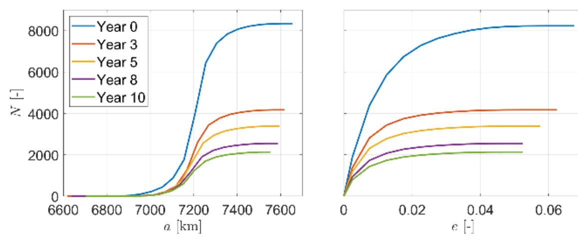

Figure 10. Cumulative distribution as function of time - Fengyun-1C.

5. DISCOS and MASTER database interface

6. Preliminary software design

Figure 11 shows a basic functional analysis of the system subdivided by sections in terms of first-level functional classification focusing on accounts management, environmental analysis, mission analysis, and configuration. As described in Section 2 two main modes are defined:

1. *Space-debris mode*: To compute the space debris index for a given mission and to assess the space capacity share used by this mission.
2. *Space-capacity mode*: To assess the overall capacity of space and a placeholder for the future inclusion of the capability to generate the environment report.

For the *space-debris mode* a mission can be constructed through a guided setup process using different categories available within the *mission analysis* section. These categories, allow the definition of a desired mission in a flexible way: single and multi-satellite mission architectures can be considered, and the contribution of the launcher can also be included. The options selected in the mission analysis section are saved in DISCOS tables to be provided as output to the simulation for result reproducibility. This capability would also allow satellite operators to release new mission profiles and make them available to the other users of the WUI, or simply to have them associated to their own account. Different levels of sharing the data associated to a mission are available: none, save in the o/o account, release to policy agent, and release to public.

When using the *space-debris mode*, the approving agent is also able to design and submit via the mission analysis section more than one mission with similar characteristics to allow comparisons. For these missions the *mission analysis* options can differ, for example, in the post mission disposal strategy or reliability, in the operational capabilities, in the mission architecture, etc. Some possible comparisons will be defined. Once a mission profile and architecture are defined, the main computational engine of the THEMIS software is used to compute the space debris index associated to the inputted mission following the technical procedure described in Section 3. The outputs of the space debris mode are described further in Section 6.3.

For the *space-capacity mode* the results of long-term space debris simulation through DELTA are used, together with a defined initial population and PMD rules for the considered space debris object, to study the evolution of the space capacity and to define the feasible threshold for the overall capacity. The goal of the *space-capacity mode* is to analyse different space debris evolution scenarios, and in a future extension of this project to produce the space environment report and to guide the definition of guidelines by approving agents.

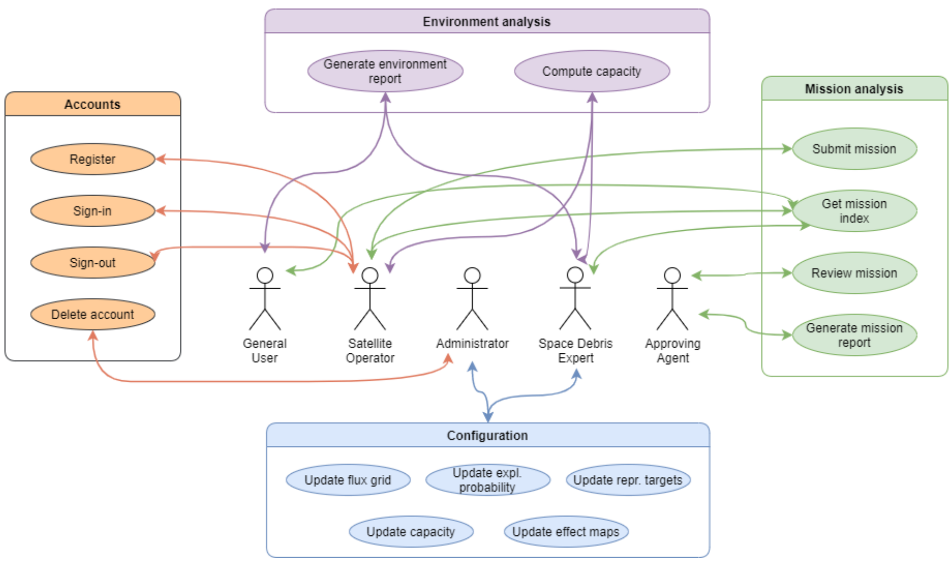

Figure 11. Basic functional analysis of the system subdivided by sections.

6.1 Mission analysis categories

The mission analysis section defines the possible options for the THEMIS software space-debris mode. The user stories should cover scenarios of mission across different design and operational phases alongside large constellation scenarios. To define the mission in a general and complete way, a set of options are defined, organised in a series of categories.

These categories will cover:

- Mission architecture
- Spacecraft design
- Mission operational phases
- Mission operations

Each category contains a series of option that the user can select. Different *mission architectures* can be analysed by the software, namely:

- Single spacecraft.
- Satellite constellation (i.e., group of artificial satellites working together as a system). Satellite constellation includes also different satellites belonging to a distributed mission or formation flying missions.
- Launcher servicer that can offer a service as dedicated launch, shared launch, or piggyback launch. The launcher can be also re-usable. The option of mission architecture launcher is considered if the aim is to characterise the contribution of the launcher service on the space debris and space capacity. In general, the launcher contribution is considered as a share of the overall mission contribution. The breakdown associated to each contribution

(launcher, payload) is computed separately and can always be retrieved.

- Carrier spacecraft whose role is to deliver another spacecraft in the final operational orbit.

The *spacecraft design* category contains the characteristics of the spacecraft that affects the space debris index computation:

- Spacecraft mass: defined as single value or in ranges.
- Spacecraft cross-area: defined as single value or in ranges.

Each mission can be designed by considering a series of *mission operational phases* including:

- Year of launch (or year of analysis)
- Launch phase
- Operational orbit injection phase
- Operational phase (this phase can be repeated)
- Orbit transfer to new operational orbit phase (this phase can be repeated)
- Post Mission Disposal (PMD) phase:
    - Direct fully controlled disposal;
    - Semi-controlled disposal;
    - User-defined disposal time (default value is 25 years);
    - Drag sail disposal;
    - Solar sail disposal;
    - No disposal (i.e., the spacecraft remains in orbit uncontrolled);
    - Disposal enhancing the effect of natural perturbations.

The mission profile can be designed through a guided setup process where the expert user selects the mission phases and the corresponding orbit characteristics (orbital elements), duration, and propulsion system for the manoeuvre of the different phases. Additionally, the expert user can upload a trajectory file (in OEM format) for the evaluation of the mission scenario.

The *mission operation* category contains characteristics of the mission operation that affects the computation of the space debris index, namely:

- CAM/no CAM capabilities: this capability can be associated to a particular spacecraft mass category. Spacecraft belonging to the same constellation are considered to be collaborative among themselves for avoiding inter-satellite collisions.
- Trackability.
- Post-mission disposal reliability.

As previously discussed, all the proposed categories can be selected by the expert user during the guided setup. For the general non-expert user some default options will be available, or some selection can be done in a more simplified widget menu.

6.2 Environment analysis categories

As shown in Figure 11 two categories are included in the environment analysis section associated to the space-capacity mode of the THEMIS system.

- *Computation of the space capacity*
- *Generation of the environment report*

6.3 Software output

The software outputs for the *space-debris mode* are:

- Space debris index time evolution for the overall mission.
- Space debris index time evolution for each mission phase / each spacecraft for distributed architecture (e.g., satellite constellation, spacecraft plus launcher, etc.). This will also contain the space debris index for the launch phase contribution.
- Space debris index total value for the overall mission.
- Space debris index total value for each mission phase / each spacecraft for distributed architecture (e.g., satellite constellation, spacecraft plus launcher, etc.). This will also contain the space debris index for the launch phase contribution.
- Share of the space capacity by a single mission.
- Representative plots.

The software outputs for the *space-capacity mode* are:

- Space capacity evolution in time.
- Space capacity share divided in class of mission.
- Total space capacity.
- Object distribution in orbital elements.
- Representative plots.

Conclusions

The THEMIS software tool will allow to compute the space debris index for a given mission and to assess the space capacity share used by this mission. Moreover, in its space-capacity mode can be used to assess the overall capacity of space and a placeholder for the future inclusion of the capability to generate the environment report. This paper presented the overall software structure and briefly introduces the theoretical development behind the THEMIS backend. Future papers will describe each building blocks and will show some application results.

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