GUIDELINES FOR SPACE DEBRIS AND METEOROID IMPACT RISK ASSESSMENT WITH DRAMA/MIDAS

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ABSTRACT

The space debris mitigation guidelines require the assessment of the impact risk with space debris and meteoroid objects. In order to assess the collision probability and the impact consequences, statistical flux models as well as impact and damage analysis tools are employed. DRAMA/MIDAS (Debris Risk Assessment and Mitigation Analysis/MASTER-based Impact Flux and Damage Assessment) is a comprehensive tool that can be used during early mission phases. This paper proposes two methodologies to address the impact risk with space debris and meteoroid particles using the new release of DRAMA/MIDAS 3.1.0: a) Break-up risk assessment and b) Probability of damage or failure due to collision. In support of the international standards and ESA's space debris mitigation process, practical guidelines and instructive examples using the latest software release are presented.

Keywords: DRAMA; MIDAS; Space debris mitigation guidelines; Impact risk assessment.

1. INTRODUCTION

As the space debris population continues to grow rapidly, the likelihood of collisions is expected to increase likewise. In response to this challenge, the Inter-Agency Space Debris Coordination Committee (IADC) published its first edition of the Space Debris Mitigation Guidelines in 2002, aiming at limiting the debris released during operations, minimising the risk of explosive break-ups and collisions, and removing defunct objects from populated areas. Following the publication of the IADC guidelines, the International Organization for Standardization (ISO) took up the task of transforming the guidelines and practices from the IADC, also recognised on UN level, into a set of international space debris mitigation standards [1]. The first ISO standards were published in 2010, and since then ten more standards have been released, with the third edition of the latest ISO 24113 standards published in 2019 [3]. The space debris mitigation requirements of the latest ISO standards are adopted by the European Cooperation for Space Standardization (ECSS) [4].

One aspect of the space debris mitigation guidelines involves assessing the risk from a space debris or meteoroid impact during the design phase of a space mission. Risk assessment studies may additionally be performed during the operational phase of the mission, if required. Impact risk analyses can help identify the most vulnerable components in the design of a spacecraft, and take important decisions to minimise the risks of a collision with a space debris or meteoroid object. Such analyses are of particular importance when the non-trackable population is considered: trackable objects (larger than approximately 10 cm in LEO and 50-100 cm in GEO) are too large for shielding measures, and the main protective actions against them are collision avoidance manoeuvres, which are performed if the assessed collision risk is deemed too high [5]. For objects that cannot be tracked, or for spacecraft with no manoeuvre capabilities, statistical flux models, and impact and damage analysis tools can be used to assess the impact risk with space debris or meteoroids, and decide on design changes (e.g. shielding) to minimize the probabilities of a break-up or the damaging of the satellite such that successful post-mission disposal can no longer be achieved.

This paper provides practical guidelines on how the space debris mitigation requirements and standards can be met using the new release of DRAMA/MIDAS 3.1.0. Break-up risk analyses, as well as damage/failure analyses to assess the likelihood of a successful post-mission disposal are presented in detail.

2. THE DRAMA SOFTWARE SUITE

The DRAMA software suite consists of several independent tools designed to provide an assessment of the compliance of a user-defined mission with various aspects of the space debris mitigation guidelines [2]:

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- *The Assessment of Risk Event Statistics* (ARES) tool allows to assess the annual rates of close approaches between an operational spacecraft and tracked objects in Earth orbits along with statistics on the required number of collision avoidance manoeuvres, and associated Δv and propellant mass.
- The *MASTER-based Impact Flux and Damage Assessment Software* (MIDAS) facilitates the evaluation of debris and meteoroid impact rates during the lifetime of a satellite based on input coming from ESA's MASTER model and, by applying single and multiple wall equations, the probability of penetration for a given wall design.
- The *Orbital SpaceCraft Active Removal* (OSCAR) tool allows for the computation of the orbital lifetime and the evaluation of different disposal options after the End-of-Life (EOL).
- The *re-entry Survival And Risk Analysis* (SARA) tool accesses which and how many components of a spacecraft would survive re-entry and computes the combined on-ground casualty risk given a world population model and the impact footprint of all surviving fragments.
- The *Cross-section Of Complex Bodies* (CROC) tool computes the cross-section of a 3D-modelled satellite, either randomly tumbling or taking a fixed orientation and/or rotation axis.

DRAMA was first released in 2004 and was upgraded to DRAMA-2 in 2014. In 2019 another major upgrade was released with DRAMA-3 [2]. The latest DRAMA version 3.1.0 introduces among others, additional features in the MIDAS tool focused on this paper. The background population used by both ARES and MIDAS uses the input from ESA's MASTER-8 model. Both DRAMA and MASTER are available as a free download from ESA's Space Debris Portal `https://sdup.esoc.esa.int/drama/` [6].

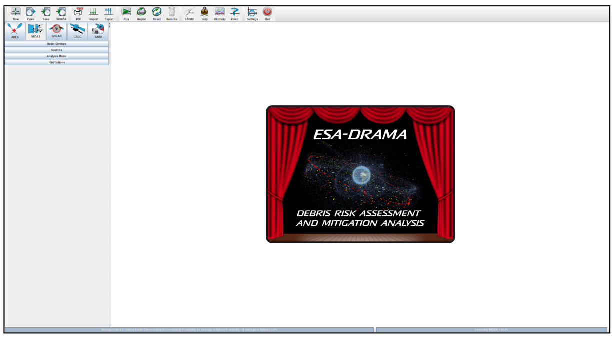

Figure 1. The DRAMA software suite

2.1. The MIDAS Tool

The MASTER-based Impact Flux and Damage Assessment Software (MIDAS) tool of the Debris Risk Assessment and Mitigation Analysis (DRAMA) software suite is an impact and damage analysis tool that can support risk and vulnerability assessments, in the frame of evaluating and reducing a space mission's risk from space debris or meteoroid impacts during early mission planning. The tool combines the orbital, mission and spacecraft parameters provided by the user and the debris and meteoroid flux from MASTER to result in an impact flux or a damage analysis. It accounts for:

- the mission duration,
- the orbital regimes crossed and resided in,
- the geometrical spacecraft parameters,
- debris and meteoroid sources and population clouds,
- the evolution of the space debris environment.

MIDAS may additionally be used for top-level impact risk assessments during later stages of design, but it is not always the most suitable solution. For a less conservative assessment, and/or further analyses using cloud modelling, and/or component shielding aspects, higher fidelity tools can be employed [7].

MIDAS supports two types of analysis modes [8]:

1. the *Impact Flux Analysis*,
2. the *Damage Analysis*.

The *Impact Flux Analysis* mode of the MIDAS tool can be used to assess the flux of the impacting particles on the surface of a spacecraft or launch vehicle. For a selected time frame and particle size range, the probability of collision with respect to time, as well as the probability of collision with respect to the mass and size of the impactor are computed. In the frame of this paper, the analysis can be used to assess the break-up risk of a spacecraft or launch vehicle.

The *Damage Analysis* mode of the MIDAS tool can be used to assess the damage caused by the impacting particles on the surface of the spacecraft or launch vehicle. In the frame of this paper, the analysis can be utilized to compute the probability of damage or failure due to collision. The user has the option to study surfaces of the spacecraft individually, as defined in an Earth-fixed, Sun-fixed or inertially fixed frame [5]. The *Damage Analysis* of MIDAS includes pre-defined ballistic limit equations (BLEs) which can be used to compute the critical particle diameter necessary to produce a component failure via perforation. In the new version of MIDAS the original and the recalibrated (Rudolph) Schäfer-Ryan-Lambert (SRL) BLEs, as well as the carbon fibre reinforced polymer (CFRP) BLEs are introduced. The user may also define additional ballistic limit equations.

3. GUIDELINES FOR IMPACT RISK ASSESSMENT

Among others, the space debris mitigation guidelines require an early assessment of the break-up (i.e. complete or partial destruction of an object that generates space debris [3]) risk of a spacecraft or launch vehicle orbital stage, as well as an early assessment of the risk that a space debris or meteoroid impact will prevent the successful mission disposal [3]). In the frame of this paper, two methodologies for assessing the on-orbit break-up risk and the risk of an unsuccessful disposal are described.

3.1. Break-up Risk Assessment

The process for assessing and reducing a spacecraft or launch vehicle orbital stage risk from a space debris or meteoroid impact is addressed and extensively discussed in [7], [9] and [10]. Based on the developed strategies, guidelines for assessing the risk of the destructive structural break-up due to a space debris or meteoroid impact (catastrophic collision) with DRAMA/MIDAS are proposed. The assessment of the partial break-up of a spacecraft requires more complex considerations and is not part of this analysis. The proposed analysis steps are presented below.

Definition of input parameters

1. Definition of the life cycle phase(s) of the spacecraft or launch vehicle stage [3]. All phases before the spacecraft/launch vehicle's end-of-life (EOL) shall be considered, unless indicated differently by the selected break-up requirements.
2. Definition of the phase(s) duration over the orbit.
3. Definition of the orbit state vector and its evolution according to the phase(s) under analysis.
4. Definition of the design parameters of the spacecraft or launch vehicle stage.

Thresholds and requirements

5. Definition of a threshold above which a space debris or meteoroid particle would cause the break-up of the spacecraft or launch vehicle stage.
6. Expression of the break-up requirement in terms of a maximum allowed probability value P_{max} (e.g. 10^{-3} or 10^{-4} for LEO orbits).

MIDAS simulations and analysis

7. Determination of the number of catastrophic impacts over the life cycle phase(s) duration.
8. Determination of the catastrophic impact probability P_{cat} over the life cycle phase(s) duration.
9. Comparison of P_{cat} against the requirement probability P_{max}. For $P_{cat} < P_{max}$ the requirement is met and the analysis is considered complete. For $P_{cat} > P_{max}$ the requirement is not met and iteration of the analysis is required. Revision of the analysis assumptions and improvement of the spacecraft modelling is advised to be performed in order to minimize the probability of a catastrophic collision.

3.1.1. Break-up threshold

A commonly used threshold for the assessment of a catastrophic collision with an impactor is the energy-to-mass ratio (EMR). The EMR is defined as [10, 11]:

$$EMR = \frac{1}{2} \cdot \frac{M_c \cdot V_{imp}^2}{M_t} \tag{1}$$

where

M_c	the mass of the projectile (impacting space debris or meteoroid object) in kg,
M_t	the mass of the target (spacecraft or launch vehicle) in kg,
V_{imp}	the impact velocity (relative velocity between projectile and target) in m/s.

A typically accepted value for the EMR threshold for catastrophic collisions is 40 J/g [11]:

$$EMR \geq EMR_{cc} = 40\ J/g \tag{2}$$

The new version of DRAMA/MIDAS 3.1.0 supports the computation of the number of catastrophic impacts based on the EMR criterion, using the impact velocity and projectile mass computed by MASTER. In the frame of this assessment, a catastrophic impact corresponds to the complete break-up of the studied object (e.g. spacecraft or launch vehicle stage).

3.1.2. Break-up probability threshold

A globally supported value to limit the break-up probability caused by space debris or meteoroids as part of the mission design has not yet been defined. However, international standards such as [3] do limit the break-up probability caused by internal sources of energy during normal operations to 10^{-3}, based on the argument that targeting this probability of occurrence would lead to an order of magnitude reduction in on-orbit rates observed. These break-ups currently drive the generation of the space debris environment. Therefore, it is sensible to not accept a break-up probability caused by the environment higher than the probability of break-up due to internal causes.

In addition, it can be shown that an annual and per object catastrophic collision probability, in LEO, above 10^{-4} correlates with a long-term growth of the space debris population [12]. As such, one can argue that such risk should be mitigated, at least during normal operations and possibly extended to the end of the orbital lifetime for a critical orbital region such as LEO.

3.1.3. Catastrophic impact probability

From the number of catastrophic impacts, the probability of a catastrophic impact P_{cat} may additionally be computed by expressing the probability of the number of catastrophic impacts as the complement of the probability of no impact using Poisson statistics:

$$P_{cat} = 1 - e^{-N} \quad (3)$$

where N is the total number of catastrophic impacts.

3.2. Probability of Damage or Failure due to Collision

The probability analysis for assessing the vulnerability of the spacecraft or launch vehicle stage to an impact with space debris or meteoroids is addressed and discussed in [7], [9] and [10]. Vulnerability assessment methodologies using higher fidelity analysis tools have also been developed (e.g. [13, 14, 15]). The assessment of the probability of damage or failure due to collision using DRAMA/MIDAS includes the following steps:

Definition of input parameters

1. Definition of the life cycle phase(s) of the spacecraft or launch vehicle stage [3]. All phases before the spacecraft/launch vehicle's end-of-life (EOL) shall be considered, unless indicated differently by the selected survivability requirements.

2. Definition of the phase(s) duration over the orbit.

3. Definition of the orbit state vector and its evolution according to the phase(s) under analysis.

4. Definition of the architectural design of the spacecraft or launch vehicle stage.

5. Identification of the critical components i.e. the components which, when damaged by an impact, would prevent a critical function e.g. disposal. For each component, the most critical surface and the at-risk area of the surface is additionally identified. For the computation of the at-risk area, the protection/shielding by other spacecraft components, the exposure to space and the directionality of the flux with respect to the component under analysis are taken into account. Example guidelines for computing the at-risk area are provided in [10].

Thresholds and requirements

6. Identification of the ballistic limit i.e. the impact-induced threshold of failure for each critical surface via the application of a dedicated ballistic limit equation.

7. Expression of the survivability requirement in terms of a minimum allowed value of impact-induced Probability of No Failure PNF_{min} of the spacecraft. For DRAMA/MIDAS, the Probability of No Failure (PNF) corresponds to the Probability of No Penetration (PNP). It is suggested to derive the value for PNF_{min} as part of the overall system requirement for successful disposal (e.g. 0.90 in [3]).

MIDAS simulations and analysis

8. Determination of the expected number of impacts likely to cause damage or failure, which can optionally be used as an additional metric for the vulnerability assessment of the spacecraft.

9. Determination of the Probability of No Failure (PNF) for each critical component.

10. Combination of the PNF of all critical components and determination of the $\text{PNF}_{S/C}$ (of the spacecraft).

11. Comparison of the computed $\text{PNF}_{S/C}$ with the required PNF_{min}. For $\text{PNF}_{S/C} > \text{PNF}_{min}$ the analysis is considered complete. For $\text{PNF}_{S/C} < \text{PNF}_{min}$ the requirement is not met and an iteration is required. Revision of the analysis assumptions and improvement of the spacecraft modelling is advised to be performed first. Other options include usage of a higher fidelity tool, changes of the spacecraft design, (e.g. wall thickness, materials, shield structure or location of the critical components), reorientation of the spacecraft or its components to minimize the impacts from space debris or meteoroids or orbit design change if the mission allows. Additional testing to calibrate new BLEs can also be performed [7, 9].

4. END-TO-END EXAMPLES WITH MIDAS

After launching DRAMA, the user can create a workspace folder for his/her project. In this example, two projects are created:

1. Break-up risk assessment,

2. Probability of damage or failure due to collision.

4.1. General Guidelines

Once the project folder have been created, the user can select the MIDAS tool from the toolbox bar.

In the *Basic Settings* tab, the start and the end date of the mission to be analysed need to be defined. The respective orbital elements or orbital states can then be added. The user is required to define the spacecraft parameters and specify a size interval for the impactors to be considered by MASTER.

In the *Sources* tab, the debris and/or meteoroid sources to be considered in the analysis can be selected. The user may either select the condensed population of MASTER, which considers the contribution from all available space debris sources, or study separately the contribution of the different sources. Population clouds of individual fragmentation events can also be independently analysed. The meteoroid sources are not part of the condensed population or the population clouds, and their contribution can be considered by selecting a suitable meteoroid model.

In the *Analysis Mode* tab the user can select between the two modes of analyses: a) *Impact Flux Analysis* and b) *Damage Analysis*. The *Impact Flux Analysis* can be used to compute the number of expected impacts during the life cycle phase duration as well as the probability of collision. The new version of DRAMA/MIDAS 3.1.0 also outputs the number of catastrophic impacts with respect to the impactors mass and diameter. For this analysis mode the surface of the spacecraft or launch vehicle stage can either be defined as a sphere or a as randomly tumbling plate. When the user selects to perform a *Damage Analysis* then, in addition to the flux estimates the *Impact Flux Analysis* offers, the damage caused by the impacting particles on a specified surface can be assessed. In this analysis mode up to 10 surfaces can be individually analysed. For each selected surface, the orientation, the area, a ballistic limit equation and the wall specifications need to be defined.

In the *Plot Options* tab the data lines which will be displayed in the plots can optionally be customized. By default, four data lines will be displayed. The first three lines represent the total of all debris sources, the total of all meteoroid sources and the total of all clouds respectively, while the fourth line represents the overall total results.

4.2. Break-up Risk Assessment

For the first example, a fictitious satellite in the Low Earth Orbit (LEO) is considered. Following the methodology for performing a break-up risk assessment with DRAMA/MIDAS described in section 3.1, the life cycle phase of the satellite is defined first. For the selected example, all life cycle phases until the satellite's EOL are considered. It is assumed that the mission phase began on August 1st, 2020, while the disposal phase will end after a 5-year period, on August 1st, 2025.

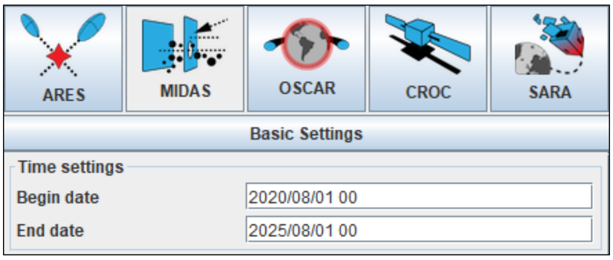

Figure 2. Basic parameters settings

Following the definition of the phases' duration, the orbit of the satellite needs to be defined. The orbit parameters are added as single averaged elements in the corresponding MIDAS tab. We consider a sun-synchronous, near-circular orbit, with an orbital height of 700 km. Due to the stochastic nature of the space debris environment, the right ascension of the ascending node does not play a role for LEO orbits in the frequency of close encounters and is set to 0 deg. The argument of perigee, which is only relevant in case of eccentric orbits, is also set to 0 deg [16].

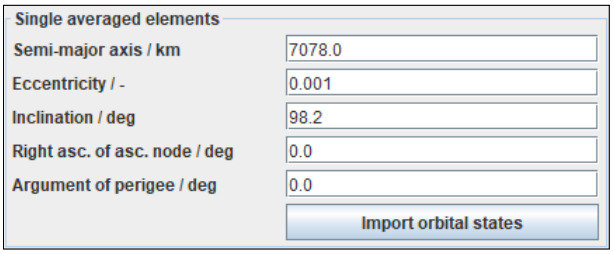

Figure 3. Orbital parameters settings

The design parameters of the satellite can be defined in the *Spacecraft parameters* fields. A satellite with a cross-sectional area of 5 m^2 (main satellite body) and a mass of 2100 kg is considered. For the drag and reflectivity coefficients, the default values are used.

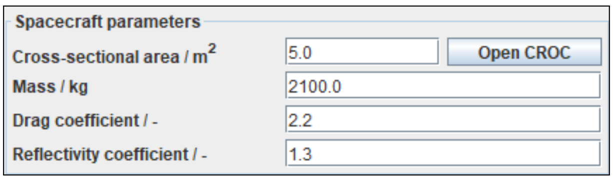

Figure 4. Spacecraft parameters settings

The fifth step of the break-up risk assessment requires the definition of a threshold above which a space debris or meteoroid particle would cause the break-up of the satellite. For this example, the complete break-up of the satellite is assessed (catastrophic collision). MIDAS computes the number of catastrophic impacts using the 40 J/g EMR criterion. MASTER is used as a background model in order to compute the flux as a function of size, impact direction and impact velocity. Using the MASTER size and impact velocity output, MIDAS computes the number of impacts that exceed the EMR threshold and are therefore accounted as catastrophic impacts.

The sixth step of the assessment requires the expression of the break-up requirement in terms of a maximum allowed probability value P_{max}. Based on section 3.1.1 the value 10^{-4} is chosen. The size interval taken into account for the example considers all space debris and meteoroid object objects within the range 10 μm – 100 m. It is assumed that particles with size less than 10 μm will only cause degradation of the spacecraft's surface and are therefore not included in the simulation.

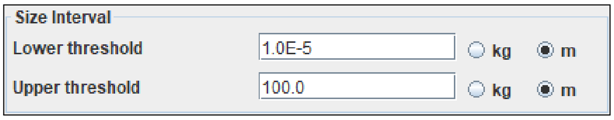

Figure 5. Impactor size interval definition

Following the definition of the impactors' size interval, the sources to be included in the analysis are selected. By selecting the *Condensed Debris Sources*, all debris sources, as included in the condensed population files of MASTER, are considered. The meteoroid fluxes are modelled using the Grün model with a Taylor velocity distribution.

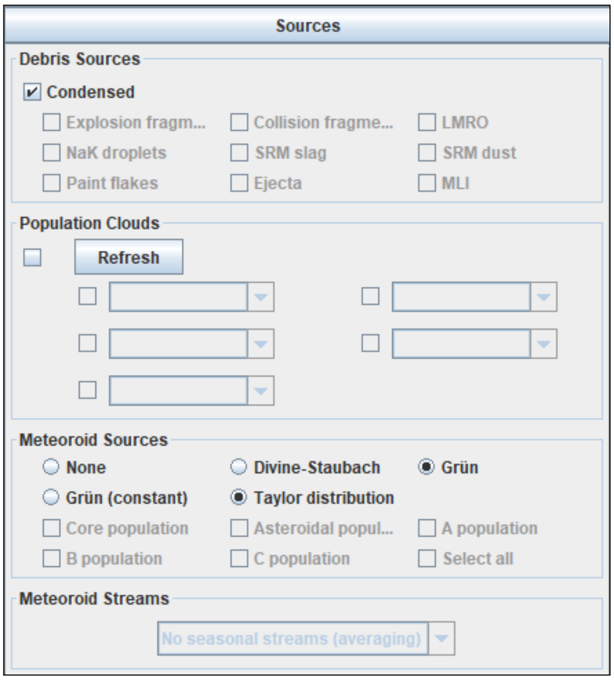

Figure 6. Space debris and meteoroid sources

For the break-up risk assessment, the *Impact Flux Analysis* of MIDAS is selected. The satellite surface is defined as a sphere.

Since no clouds are taken into account for this MIDAS run, the respective line is removed from the *Plot Options*.

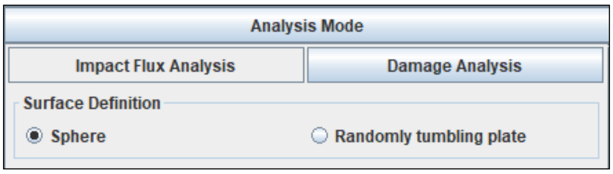

Figure 7. Impact Flux Analysis mode

Figure 8. Plot options

The *Impact Flux Analysis* mode outputs a total of nine plots. The first three plots depict the overall number of impacts with respect to time, the impactor diameter and impactor mass respectively.

In this particular example, a total number of 58.518 objects in the size range 10 μm – 100 m is estimated to impact the satellite during the studied life cycle phases (Fig. 9). Out of this total number of impacts, 77% is expected to be space debris impacts, while 23% meteoroid impacts.

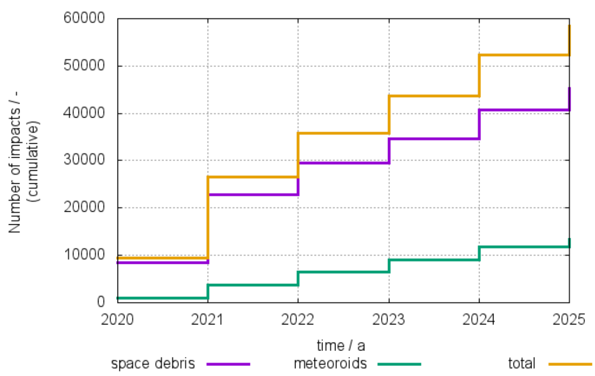

Figure 9. Number of total impacts vs time

The next three output plots show the probability of collision with respect to time, impactor diameter and impactor mass. For this example, the probability of collision is already at 100% in 2020. The cumulative *Probability of Collision* graphs vs mass and diameter (i.e. Fig. 10) depict the increase of the impact probability with decreasing mass/size of the impactor.

The last three plots of the *Impact Flux Analysis* results, first introduced in DRAMA/MIDAS 3.1.0, are the *Number of Catastrophic Impacts vs time* (Fig. 11), *mass* and *diameter* (Fig. 12). Objects that exceed the size of 8 cm

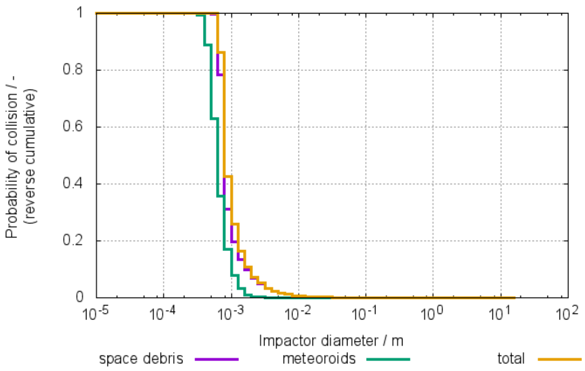

Figure 10. Probability of collision vs diameter

in diameter are most likely to result in the break-up of the satellite, however, during the operational phase of the spacecraft, a catastrophic collision with a tracked object can be mitigated with collision avoidance. Due to the higher flux of smaller objects, the number of catastrophic impacts seems to be increasing with decreasing object size.

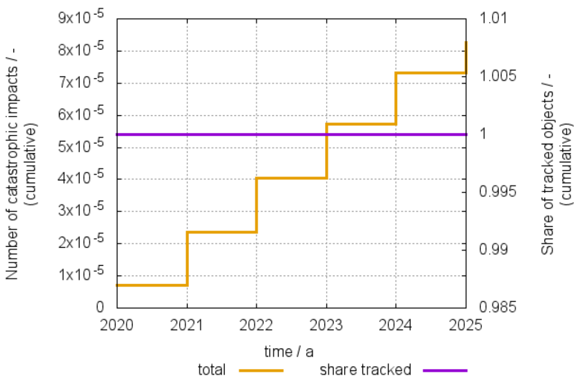

Figure 11. Number of catastrophic impacts vs time

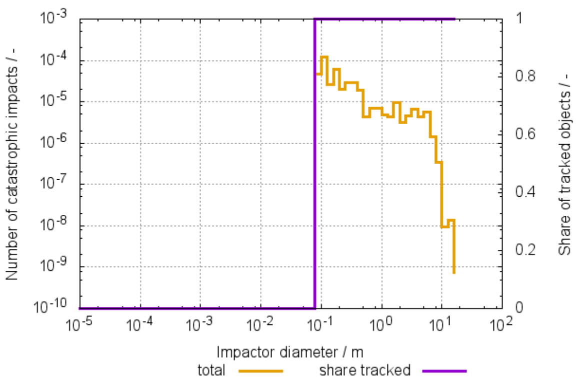

Figure 12. Number of catastrophic impacts vs diameter

The number of catastrophic impacts at the end of the 5-year period is computed to be 0.82729E-04. The probability of catastrophic impact can be derived using Eq. 1: $P_{cat} = 1 - e^{-N} = 0.00008$. For this example, $P_{cat} < P_{max}$ holds and the requirement is met.

4.3. Probability of Damage or Failure due to Collision

In this example, the critical components of the previously described LEO satellite are studied in the frame of assessing the probability of the successful disposal of the satellite. The definition of the phases and their duration, as well as the orbital and main spacecraft parameters remain the same with steps 1-4 of the break-up risk assessment. However, knowledge of the geometrical characteristics of the satellite and the location and configuration of the critical components is additionally required.

A simple 3D model of the satellite can be constructed using DRAMA/CROC. For the particular example three critical components are considered: the propellant tank, positioned internally at the bottom of the satellite structure (Fig. 13, green line-filled area), and two identical batteries positioned internally at the upper part of the structure (Fig. 13, purple line-filled area). It is presumed that components such as the electronics box or the AOCS system are located in the centre of the satellite, with sufficient separation and protection from impacts.

Following the identification of the critical components, their critical surface needs to be defined and their area at-risk needs to be computed. The critical surface of the propellant tank is considered to be the surface facing the flight direction, since it is expected to be subject to higher space debris and meteoroid flux, and therefore more likely to suffer an impact that could result in damage or failure. Since the critical surface of the tank is equally protected by the satellite walls, the at-risk area of the critical surface of the tank is the total area facing the flight direction. Considering a spherical tank with a diameter of 0.5 m^2, the at-risk area of the tank is approximately 0.196 m^2 (surface area of a circle).

Similarly, the at-risk area of the batteries is computed. We assume cuboid Li-ion batteries, placed close to the satellite wall, with one of their surfaces facing the flight direction. We consider their critical surface as the surface facing the flight direction, with their at-risk being the area of the critical surface. The critical area for a battery with dimensions 130 x 60 x 270 mm (width x depth x height) positioned vertically next to the wall would be a 0.035 m^2 (width x height).

Step six of the assessment requires the identification of the ballistic limit to be used for each critical surface. In all cases, the criterion for damage or failure is penetration/perforation. It is assumed that the tank and the batteries are positioned behind the structure walls of the satellite, with different spacing between the bumpers and the component's front wall or cover plate. A suitable equation to study components behind structure walls is the SRL (Schäfer-Ryan-Lambert) equation, named after its developers. The SRL equation is an extension of the ESA triple-wall equation, and can be used to study internal spacecraft equipment. The first and the second plates (outer and inner bumper) represent the structure wall of the spacecraft while the third plate represents the front

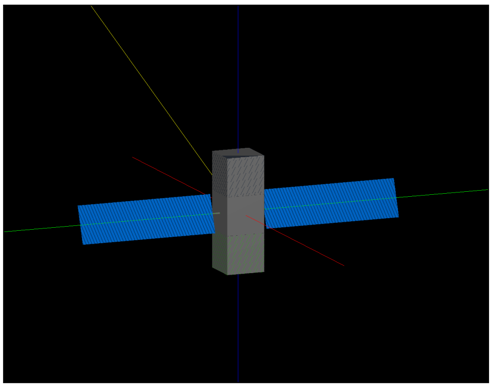

Figure 13. CROC satellite model

wall or cover plate of the equipment under analysis [17].

Step seven of the assessment requires the expression of the survivability requirement in terms of a minimum allowed PNF$_{min}$ for the spacecraft. The selection of an optimal value should originate from the project needs and the objective of the vulnerability assessment. [3] requires to guarantee the post-mission disposal with at least 0.90 reliability, and for the particular example PNF$_{min}$ = 0.90.

In order to determine the expected number of impacts likely to cause damage or failure, as well as the PNF for the three critical components, the *Damage Analysis* mode of MIDAS needs to be selected. We define three surfaces to be analysed, by switching on three respective surface tabs and providing the component-specific parameters in the dedicated fields. For all surfaces, an Earth-oriented reference frame is considered and the at-risk area of the critical surface of the components is added in the *Surface area* field.

For the propellant tank, the thickness of both outer and inner bumpers is assumed to be 0.5 cm, with a density of 2.7 g/cm^3 (aluminium). The thickness of the front wall of the propellant tank is assumed to be 0.4 cm. We consider a spacing of 10 cm between the inner bumper and the wall of the cover plate, and a spacing of 2 cm between the inner and outer bumper. The yield stress of the tank's cover plate is 73 ksi (aluminium alloy 7075-T651).

Table 1. Critical component specification

Critical component	Critical surface	At-risk area (m^2)	BLE
Propellant tank	Surface facing the flight direction	0.196	SRL
Li-ion Battery 1	Surface facing the flight direction	0.035	SRL
Li-ion Battery 2	Surface facing the flight direction	0.035	SRL

For the two Li-ion batteries, the thickness of the outer bumper is assumed to be 0.5 cm while the thickness of

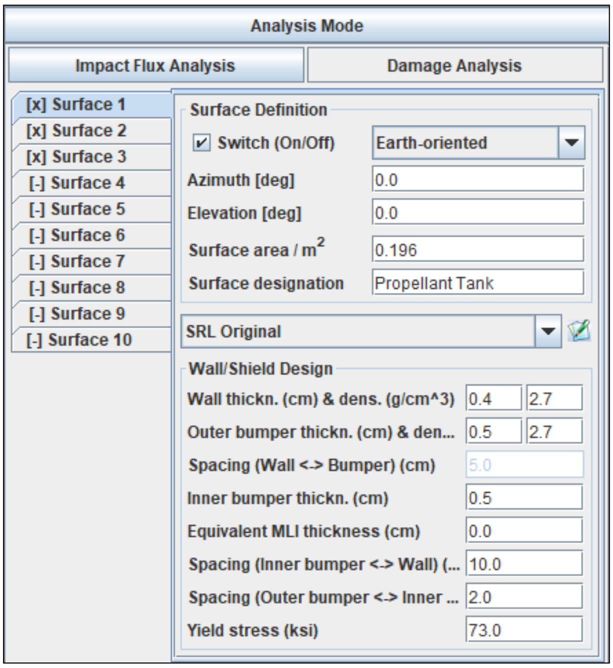

Figure 14. Propellant tank parameters

the inner bumper 0.05 cm (density of 2.7 g/cm^3). The spacing between the bumpers is 2 cm. Both batteries are considered to be placed right next to the inner bumper, with no spacing between their cover plate and the bumper. The thickness of the front wall of the battery is considered to be 0.1 cm, with a yield stress of 73 ksi.

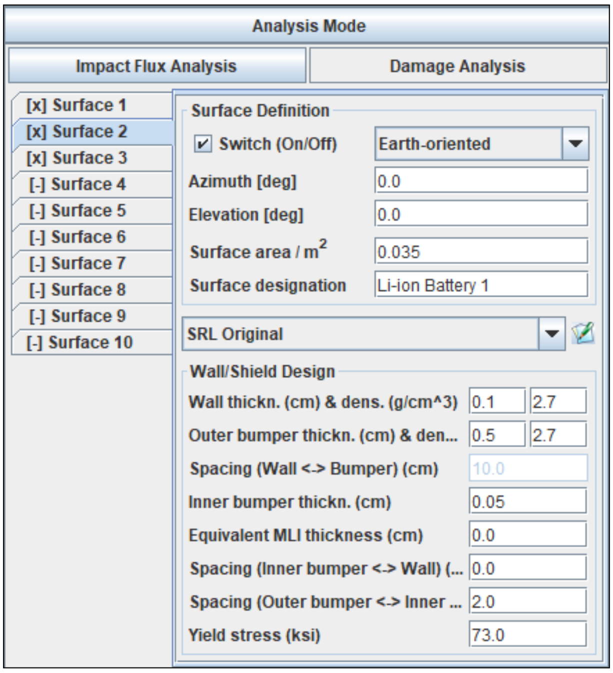

Figure 15. Li-ion batteries parameters

A *Damage Analysis* run typically requires more time than an *Impact Flux Analysis* run. For this example, the analy-

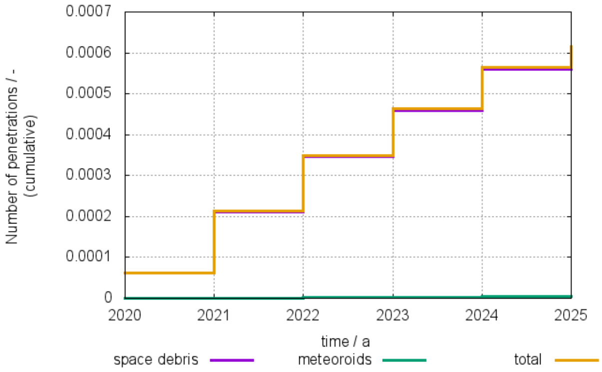

Figure 16. Number of Penetrations vs time for the propellant tank

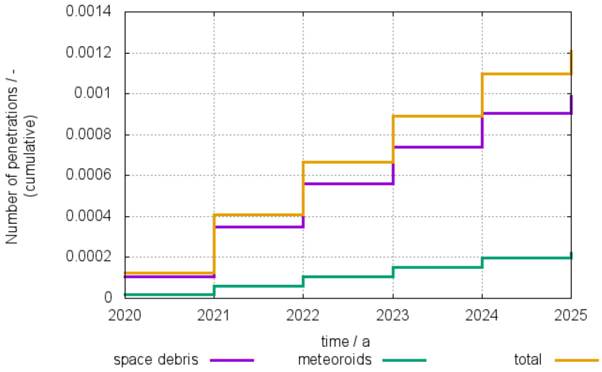

Figure 17. Number of Penetrations vs time for one of the two identical Li-ion batteries

sis produces four tabs: the first tab contains the plots and data files of the *Flux Analysis* for the spacecraft, while the other three tabs contain the damage plots and data files for each modelled component's surface. For every surface, a total of 21 plots are included. In addition to the *Number of Impacts*, the *Probability of Collision* and the *Number of Catastrophic Impacts* plots, the *Damage Analysis* produces *Failure Flux*, *Number of Penetrations*, *Probability of no Penetration* and *Probability of Penetration* plots. All graphs are provided as a function of time, mass and diameter, and are accompanied by their corresponding data file.

Step eight of the assessment requires the determination of the number of impacts likely to cause damage or failure. As the failure criterion has been defined to be penetration, representative output plots and data files are the *Number of Penetrations*, the *Number of No Penetrations* as well as the *Failure Flux* plots. The number of impacts that are expected to cause failure at the end of the studied period can be found in the data file of the *Number of Penetrations* (NoP) cumulative plots (Fig. 16, Fig. 17). For the studied surfaces, NoP_{tank} = 0.00062, while $\text{NoP}_{battery1}$ = $\text{NoP}_{battery2}$ = 0.00122.

The number of impacts that will cause damage or failure can additionally be assessed from the *Failure Flux* plots

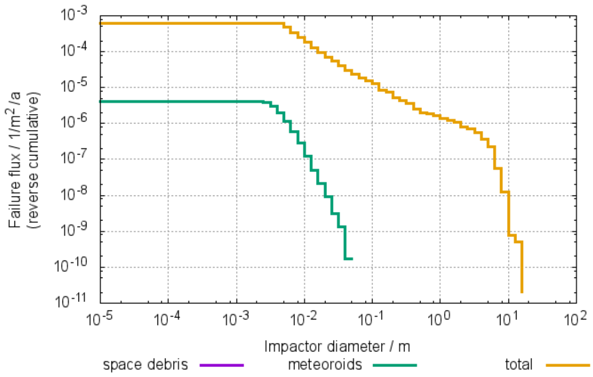

Figure 18. Failure flux vs diameter for the propellant tank

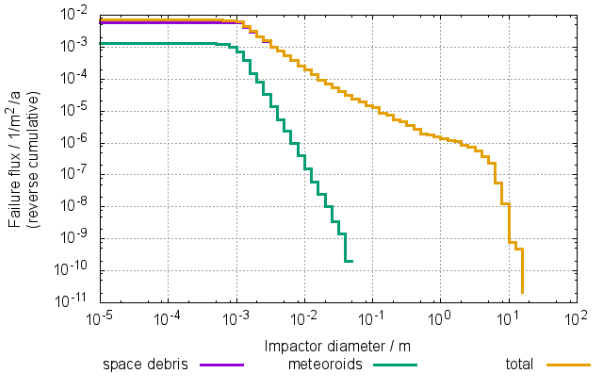

Figure 19. Failure flux vs diameter for one of the two identical batteries

(Fig. 18, Fig. 19) and the corresponding data files. The *Failure Flux* refers to a 1 m^2 surface and the period of a year and therefore needs to be scaled according to the surface area and the time period of interest [18].

$$NoP = Flux \times Area \times Time \qquad (4)$$

From the resulting NoPs we can infer that even though the number of penetrations is increasing the longer the mission is in orbit, no particle is expected to cause damage or failure throughout the mission and disposal phase of the spacecraft. It is worth mentioning that, in this example, space debris with diameter smaller than approximately 2 mm does not contribute to the *Failure Flux* of the propellant tank, while space debris smaller than 0.32 mm does not contribute to the *Failure Flux* of the two batteries.

The next step of the analysis requires the computation of the PNF of the individual critical components. The PNF of the components corresponds to the *Probability of No Penetration* (PNP) plots and data files. The probability values for the at-risk area of the critical surface of the three critical components can be extracted from the corresponding data files. At the end of the life cycle phases period, PNF_{tank} = 0.99938, while $\text{PNF}_{battery1}$ = $\text{PNF}_{battery1}$ = 0.99878.

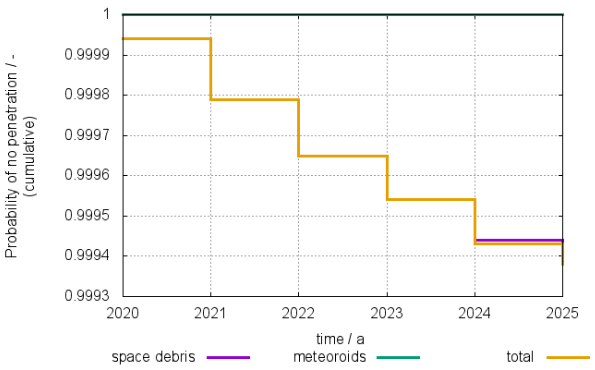

Figure 20. Probability of No Failure vs time for the propellant tank

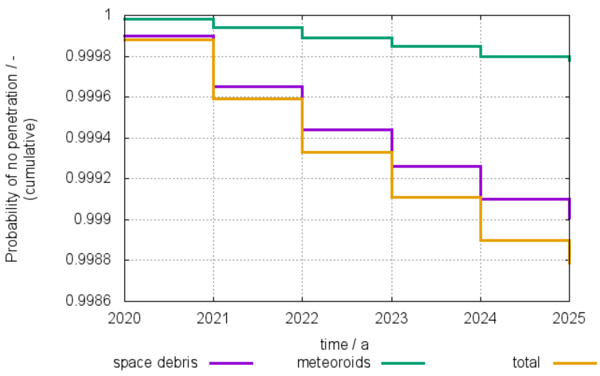

Figure 21. Probability of No Failure vs time for one of the two identical batteries

The Probability of No Failure of the spacecraft $\text{PNF}_{S/C}$ can now be computed by combining the of the three critical components: $\text{PNF}_{S/C}$ = $\text{PNF}_{tank} \cdot \text{PNF}_{battery1} \cdot \text{PNF}_{battery2}$ = 0.99694. $\text{PNF}_{S/C}$ can now be compared against the required PNF_{min}. For the particular example, $\text{PNF}_{S/C} > \text{PNF}_{min}$ holds and the analysis is considered complete.

5. CONCLUSION

DRAMA/MIDAS is an impact analysis tool that can support space debris and meteoroid impact risk assessment during the early planning of a space mission. The new DRAMA release 3.1.0 introduces updates on the MIDAS tool, reflecting the latest guidelines and standards for space debris mitigation. A methodology for assessing the risk of a destructive structural break-up of a spacecraft and a methodology for computing the probability of damage or failure of a critical component are proposed for the verification of the respective ISO requirements. Probability thresholds are defined, following the space debris mitigation requirements and standards.

This work contributes in the assessment of the ESA missions, in support of ESA's Space Debris Compliance Verification Guidelines [10] and its upcoming revision, and by reflecting the ISO 24113:2019 Space Debris Mitigation Requirements [3].

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