THE USE OF STRESS TESTS TO EVALUATE SPACE DEBRIS MITIGATION MEASURES

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ABSTRACT

Computational models of the space debris population are used to identify and evaluate mitigation guidelines aiming to prevent the generation of new space debris. Conventionally, these models evaluate different scenarios featuring variations of proposed interventions with respect to a reference scenario in which the intervention is not implemented. However, this approach can lead to mitigation solutions that appear to be optimal but, nonetheless, have unintended and potentially harmful consequences. In this paper, we propose the application of hypothetical stress tests to evaluate potential mitigation guidelines and to find unintended consequences. As an example, we simulate the collisional breakup of objects from the top 50 statistically most concerning objects (recently identified in McKnight et al., 2020) using the DAMAGE model in scenarios featuring variations of post-mission disposal. Results demonstrate the robustness of post-mission disposal to the stress test but highlight some known and new issues at low altitudes.

1 INTRODUCTION

Since space debris was first identified as a hazard, computational models of the space debris population have been used to identify and evaluate interventions aiming to prevent the generation of new space debris. Conventionally, computational models are used to evaluate different scenarios featuring variations of a proposed mitigation solution; scenarios that are ultimately compared to a reference scenario in which the intervention is not implemented. In general, if an intervention induces a large deviation from the reference scenario, in terms of the predicted number of objects in the orbital population or the number of collisions over a representative timeframe, it is deemed to be successful.

A particularly notable outcome of this use of computational models was the guideline for post-mission disposal (PMD) of objects passing through the low Earth orbit (LEO) region, developed by the Inter-Agency Space Debris Coordination Committee (IADC) [1]. This so-called '25-year rule' states that, "*Spacecraft or orbital stages that are terminating their operational phase in orbits that pass through the LEO region… should be de-orbited (direct entry is preferred) or where appropriate manoeuvred into an orbit with an expected residual orbital lifetime of 25 years or shorter.*" Awareness of this debris mitigation guideline is widespread, and it has been adopted by many standards and regulatory bodies.

To arrive at this outcome, members of the IADC Working Group 2 used computational models to study the effects of different post-mission orbital lifetimes, including immediate de-orbit, on the evolution of the LEO space debris population (see Fig. 1). While the results suggested it was "*desirable to shorten post-mission lifetime as far as possible in order to reduce population levels and collision risks in the long-term,*" the IADC recognised [2] that "*shorter post-mission lifetimes are costlier for space systems to achieve using on-board propulsion systems*."

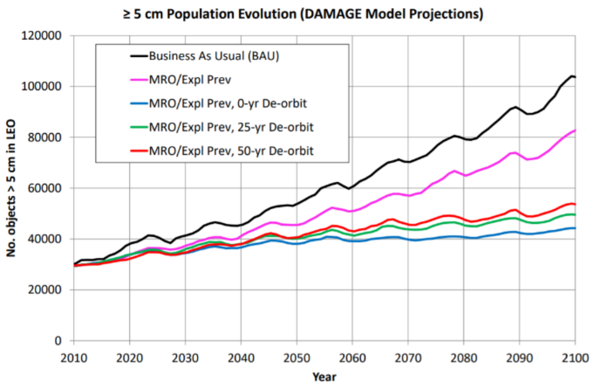

Figure 1. Predictions of the population of objects ≥ 5 cm for different post-mission lifetimes as cited in [2].

However, the assessment and subsequent selection of debris mitigation guidelines based solely on their consequences for the population as a whole might lead to mitigation solutions that appear to be optimal over the long-term but, nonetheless, have unintended and potentially harmful consequences, such as elevated collision risks associated with particular orbital regimes, particular populations or space systems.

Indeed, the impact of post-mission disposal manoeuvres on collision activity below 700 km was realised in [3], which said, "*The act of reducing perigee of all intacts at end-of-life increases the time spent at the lower altitudes and also increases the likelihood of collision at those low altitudes.*" This study by Krisko et al. found that orbits of spacecraft and upper stages originally deployed to higher

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altitudes will traverse the region below 700 km altitude following manoeuvres to comply with the ‘25-year rule’. Given the target of a 90% post-mission disposal success rate [1], it is evident that most spacecraft and orbital stages launched to higher altitudes in LEO would subsequently spend 25 years crossing altitudes below 700 km. In a 1000-year study by Lewis [4], two-thirds (66.24%) of all catastrophic collisions involving an intact primary and an intact secondary also comprised at least one spacecraft or upper stage that had manoeuvred to be fully compliant with the ‘25-year rule’ (see Fig. 2).

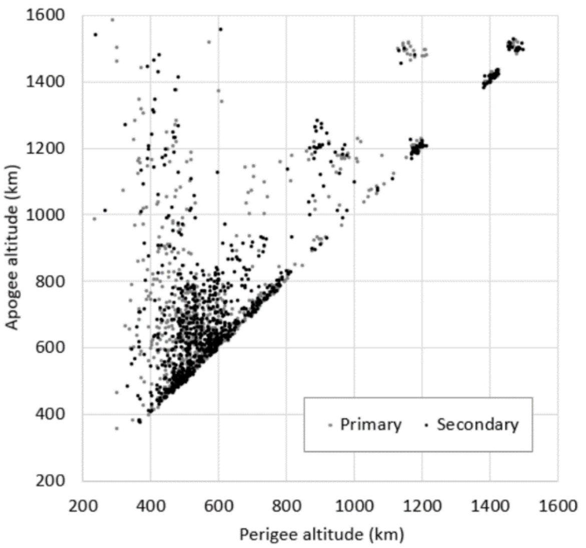

Figure 2. The orbits of intact primary and secondary objects experiencing catastrophic collisions in a 1000-year study [4]. The cluster of points between 400 km and 700 km, and above the diagonal are not seen in the launch traffic or the initial population and represent objects that have manoeuvred to eccentric disposal orbits, with apogee altitudes higher than the perigee altitudes.

The IADC guideline for post-mission disposal (PMD) of objects passing through the low Earth orbit (LEO) region [1] also recognises that for some space systems or specific operations, “*a shorter residual lifetime and/or a higher probability of success may be necessary*.” In its Statement on Large Constellations of Satellites, the IADC further acknowledges there is, “*a question regarding the robustness of the existing debris mitigation guidelines to effectively manage the new constellations and their impact on the orbital environment in a sustainable manner*,” specifically indicating that the 25-year lifetime may need to be reduced. In a 200-year study focused on the environmental impacts of a large (1080-satellite) constellation at 1100 km altitude, Lewis et al. found that whilst high PMD success rates resulted in a five-fold decrease in the number of constellation-versus-background catastrophic collisions, shorter post-mission lifetimes were also required to limit the impact of the constellation on the background population at altitudes below 600 km (see Fig. 3) [6].

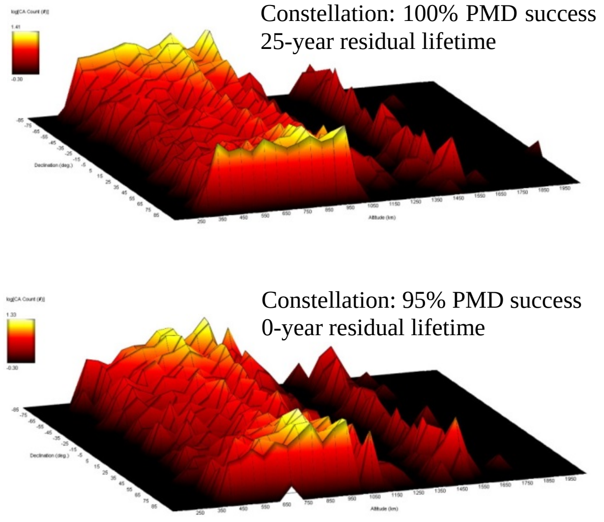

Figure 3. Comparison of the spatial distribution of collisions for different post-mission disposal options. The number of collisions decreases at altitudes below 600 km for 0-year post-mission lifetimes. Note the change in scale of the z (depth) axis between the plots [6].

1.1 Stress testing

Since the 2008 financial crisis, regulators have required financial institutions to carry out stress tests to ensure their capital holdings and other assets are adequate [7]. Stress tests are a computer-simulated technique to analyse how these institutions perform in severe (but generally plausible) economic scenarios and to detect hidden vulnerabilities. Kenton and Scott [7] identify three distinct types of scenario: historical, hypothetical, and stylized. In a historical scenario, the business is subject to a simulation based on a previous crisis, such as the stock market crash of October 1987. A hypothetical scenario might focus on a specific crisis, such as the aftermath of a natural hazard. Finally, a stylized scenario aims to modify one (or a few) parameters only, such as a stock market losing 10% of its value. In each case, a Monte Carlo simulation approach offers the ability to model the probabilities of various outcomes given specific variables.

In addition, Sorge [8] identifies two main methodological approaches for macro stress-testing: a ‘piecewise’ approach that evaluates the vulnerability of the financial sector to single risk factors under various macroeconomic stress scenarios, and an ‘integrated’ approach that combines the analysis of financial system sensitivity to multiple risk factors into a single loss estimate for any given stress scenario. In all these cases, a key requirement is to quantify the direct impact of the simulated scenario on the financial institution or sector, e.g. through forecasts of financial soundness indicators of estimates of aggregate losses.

Instead of performing environmental projections on a ‘best estimate’ basis, such as those used to produce Fig. 1, we propose the use of stress tests to ensure that space debris mitigation is resilient to potential environmental crises and to find (and quantify) hidden consequences. The Monte Carlo simulation approach used by computational models of the space debris environment lends itself to such testing, as does the ability of such models to evaluate a wide range of indicators. For such an activity, we suggest the adoption of a hypothetical stress scenario and the evaluation of its impact in an ‘integrated’ manner, by combining the effects on the environment into a single loss estimate. This approach formalises the broadly similar process that is generally used by space debris models.

Many possible hypothetical stress scenarios exist, including some that have already been introduced in [4] and [6], and discussed above. For illustrative purposes, we simulated a hypothetical scenario comprising the near-simultaneous collisional breakup of objects from the top 50 statistically most concerning derelicts in LEO, recently identified by McKnight et al. [9] (see Fig. 4). In this scenario, fragments from the breakup of these derelict objects were added to the environment and the resilience of the 25-year post-mission disposal ‘rule’ was evaluated.

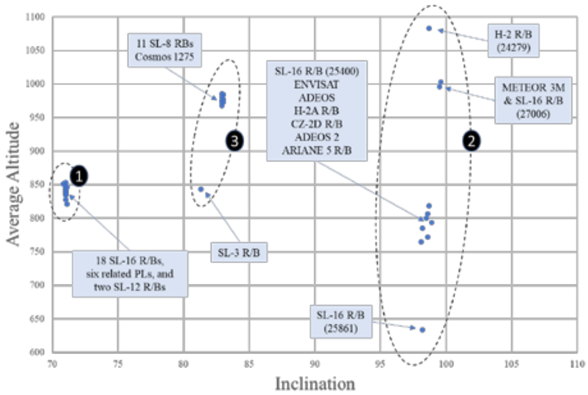

Figure 4. Top 50 statistically most-concerning derelicts in LEO from McKnight et al. [9].

2 METHOD

2.1 DAMAGE

The Debris Analysis and Monitoring Architecture to the Geosynchronous Environment (DAMAGE) model is a high-fidelity three-dimensional computational model capable of simulating the evolution of future debris populations. DAMAGE projections make use of a Monte Carlo approach to simulate future collisions. Within a given projection time step (here, 5 days), a random number is drawn and compared with the probability estimated for each pair of target and projectile objects found in close proximity (here, for a maximum miss distance of 10 km). The Monte Carlo process requires multiple projection runs to be performed and analysed before reliable and meaningful conclusions can be drawn from the outcome.

2.2 Stress test scenario and simulation parameters

The basic scenario used for this study corresponds to the one currently used by the IADC:

- A 1 February 2018 epoch with an initial population corresponding to all objects ≥ 10 cm residing within or crossing the LEO protected region
- Launch traffic was assumed to be represented by the repetition of recent launches (taken from 1 January 2010 to 31 December 2017) with small random adjustments made to the exact launch date and orbital parameters to avoid artificially enhancing the likelihood of collisions on launch
- New spacecraft and rocket upper stages were assumed to achieve a 90% success rate with respect to post-mission disposal, targeting an uncontrolled re-entry within 25 years by reducing the perigee altitude, as described in [2]. A graveyard option above the LEO Protected Region was not permitted.
- No collision avoidance manoeuvres were implemented. Further, vehicle passivation was assumed to be 100% successful such that no explosions were permitted within the projection period.

In addition to these characteristics, the top 50 statistically most concerning derelict objects in LEO, identified using the DAMAGE model in [9], were subject to catastrophic collisions over a 5-day period from 1 January 2038. These fragmentations represented the environmental ‘crisis’ that was the feature of the hypothetical scenario. Whilst it might be argued that such a scenario is not plausible, it is one that is often depicted in media and characterised as a form of ‘Kessler cascade’ or ‘chain reaction’. The derelict objects chosen for fragmentation were identified by ranking objects using 10 metrics, each representing different aspects of the hazard posed to the orbital object population, including [9]:

- The average number of collisions across all Monte Carlo runs involving the object
- The average collision probability × mass of the object
- The average collision probability × the number of fragments generated
- The average number of collisions involving the

fragments of the object
- The average collision probability of fragments of the object × mass of the objects impacted by the fragments

The derelict objects that were ultimately selected featured near the top of all 10 of the ranking lists produced by DAMAGE and were found to be broadly consistent with the top 50 objects identified by the other authors of [9].

We adopted a 2 × 2 trial design to be able to efficiently detect the effect on the outcome of one factor (the post-mission disposal) of the level of the other factor (the fragmentation of the 50 derelict objects – i.e. the presence of the stressor). This design led to four simulation cases:

1. No PMD, no stress
2. No PMD, with stress
3. PMD at 90% success rate, no stress
4. PMD at 90% success rate, with stress

As mentioned, computational models of the space debris environment can provide many different statistics describing the evolution of the space debris population and its impact on the environment. To simplify our analysis, we chose to focus on a single statistic, the average cumulative number of catastrophic collisions, which was reported by DAMAGE as a function of time and altitude. The resulting performance measure, $Q(t, h, s)$, was then the change in the average number of catastrophic collisions because of the post-mission disposal behaviour,

$$Q(t, h, s) = N_1(t, h, s) - N_2(t, h, s) \qquad (1)$$

where $N_1(t, h)$ is the cumulative number of catastrophic collisions at time t and altitude h in the case when PMD is implemented (with a 90% success rate), $N_2(t, h)$ is the cumulative number of catastrophic collisions at time t and altitude h in the case when PMD is not implemented, and the parameter $s = \{0,1\}$ indicates the presence of the stress test. Eq. 1 thus provides two outputs, $Q(t, h, 0)$ and $Q(t, h, 1)$ for each time t and altitude h evaluated, from the four simulation cases listed above.

The expectation from Eq. 1 is that the performance measure, $Q(t, h, s)$, is negative because the introduction of post-mission disposal should reduce the number of catastrophic collisions compared with the case where no post-mission disposal is carried out. If the effectiveness of post-mission disposal is compromised by the stress test, then the results will ideally show that $Q(t, h, 1) > Q(t, h, 0)$. For all other cases where $Q(t, h, 1) \leq Q(t, h, 0)$, we will be able to assume that the post-mission disposal is resilient to the stress test.

Here, 50 future projections of the 10 cm and larger debris populations from 1 February 2018 to 1 February 2218 were performed using DAMAGE. Simulations were conducted using 16 PC cores and were completed in 5 days.

3 RESULTS

For context, the evolution of the average number of objects ≥ 10 cm in the LEO orbital object population is shown in Fig. 5 for the four simulation cases. The cumulative number of catastrophic collisions in each of the simulation cases, from which the performance measures were derived, is shown in Fig. 6.

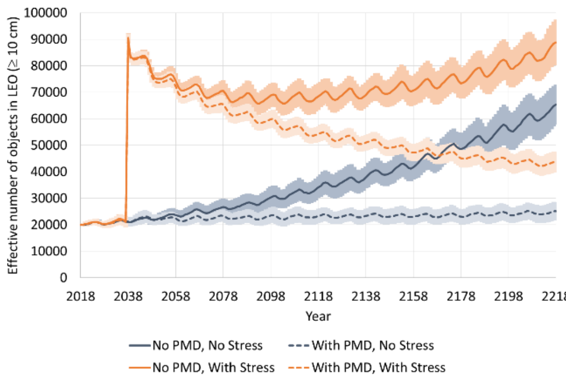

Figure 5. Effective number of objects predicted by DAMAGE for the four simulation cases. The shaded areas represent the 1-sigma variation.

The near-simultaneous fragmentation of the 50 statistically most concerning derelicts on 1 January 2038 increased the average number of objects by approximately 350% and the rate of occurrence of catastrophic collisions by a factor of 4 initially. Nonetheless, Fig. 5 shows that the subsequent response of the population to the stressor was a reduction in the number of objects, rather than an increase, as many fragments decayed out of the LEO region due to the effects of atmospheric drag. Indeed, the much mentioned ‘chain reaction’ of collisions was not obviously apparent despite the substantial ‘trigger’.

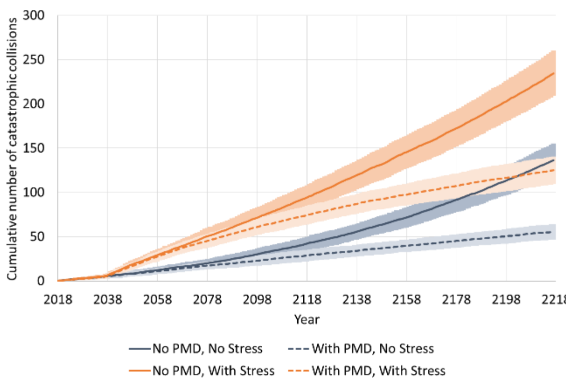

Figure 6. Cumulative number of catastrophic collisions predicted by DAMAGE for the four simulation cases. The shaded areas represent the 1-sigma variation.

Fig. 6 also shows that the high catastrophic collision rate observed in simulation case 2 (without PMD and with the stressor) was still reached even without the presence of the stress test if post-mission disposal was not implemented. Conversely, the widespread implementation of post-mission disposal at a success rate of 90% in simulation case 4 enabled the catastrophic collision rate to ultimately reach the same, reduced level as observed in the corresponding case without the stressor. These results highlight the substantial benefits of post-mission disposal (and certainly support calls to increase compliance with the IADC guideline). However, a more detailed assessment using the performance measure was undertaken to ensure that this intervention was resilient to the selected environmental crisis and to quantify any hidden consequences.

3.1 Detailed analysis

The change in the number of catastrophic collisions as a function of time and altitude, $Q(t,h,0)$, is shown in Fig. 7. These results indicate that, without the addition of the stressor, the widespread adoption of post-mission disposal was able to reduce the number of catastrophic collisions at all altitudes above 600 km throughout the projection period.

The benefits of post-mission disposal were greatest at altitudes between 700 km and 800 km, where the current debris spatial density in LEO is at its greatest and where non-linear (exponential) population growth is predicted to occur if no interventions are implemented. However, post-mission disposal was observed to be detrimental at altitudes between 400 km and 600 km, in line with expectations arising from the results presented in [3] and [4], although the variation across the Monte Carlo runs (Fig. 6) was greater than the increase in the number of collisions seen at these lower altitudes. Whilst the increase in the number of catastrophic collisions here was far outweighed by the decrease at altitudes above 600 km, there could be potential consequences for space systems operating in this lower LEO region.

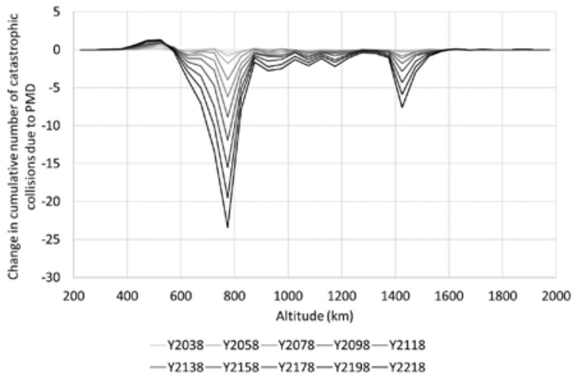

Figure 7. Change in the number of catastrophic collisions without the presence of the stress test as a function of altitude and year, $Q(t,h,0)$.

The corresponding change in the number of catastrophic collisions as a function of time and altitude in the presence of the stressor, $Q(t,h,1)$, is shown in Fig. 8. These results show the same general trends as observed in Fig. 7.

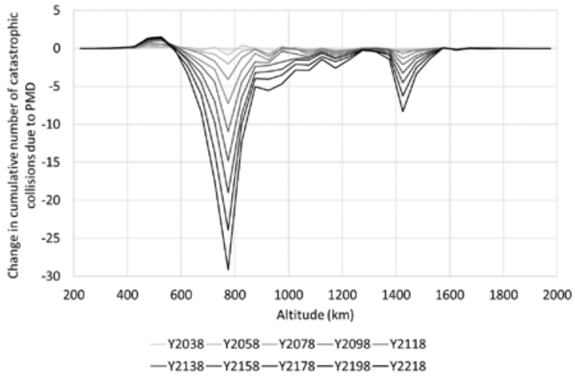

Figure 8. Change in the number of catastrophic collisions in the presence of the stress test as a function of altitude and year, $Q(t,h,1)$.

The evaluation of the resilience of post-mission disposal was based on whether $Q(t,h,1) > Q(t,h,0)$. Consequently, Fig. 9 shows the values of $Q(t,h,1) - Q(t,h,0)$ at 20-year intervals and all altitudes, which should be negative if the post-mission disposal is robust to the simulated environmental crisis. The figure indeed reveals that this is generally the case. Although there are instances (in time and altitude) where $Q(t,h,1) > Q(t,h,0)$, these occurrences could be due to the variation across the Monte Carlo runs. At altitudes between 650 km and 1000 km, the stressor ultimately improved the effectiveness of the post-mission disposal. That is, post-mission disposal prevented more catastrophic collisions in this region when the catastrophic collision rate was artificially increased. This is, in fact, a very positive outcome of the stress test.

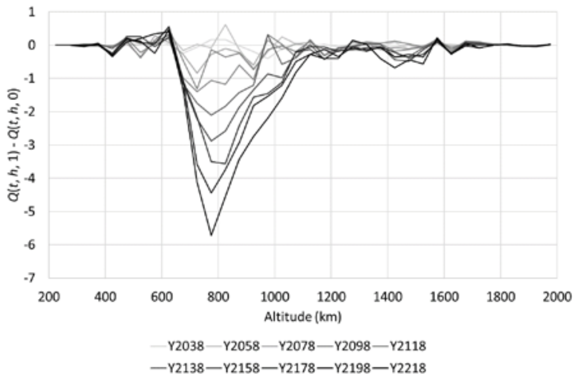

Figure 9. Impact of the stress test as a function of time and altitude.

For altitudes between 400 km and 600 km where, at worst, post-mission disposal already has the potential for a small detrimental impact on the number of catastrophic collisions, Fig. 9 does show a slight tendency for $Q(t,h,1) > Q(t,h,0)$, which may indicate a worsening of these detrimental impacts. Fig. 10 provides a close-up view of the results for this region. Recalling the caveat that the very small differences observed in this region of LEO may have been due to variations across the Monte Carlo runs, it is possible that there was a gradual worsening of the negative aspects of post-mission disposal as time progressed, although even this trend is weak. It would be, in effect, a mirroring of the finding that benefits of post-mission disposal are enhanced by this stressor in altitude regions where the intervention is already effective. That is, enhancement of the benefits of post-mission disposal above 650 km lead to worsening of unfavourable effects below 650 km. As shown in the study by Lewis [4], longer projections may provide more robust insight into this possible phenomenon.

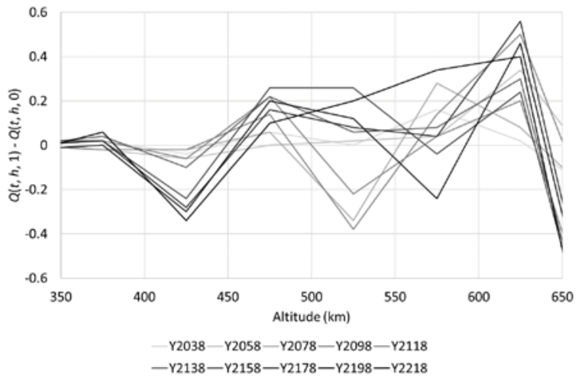

Figure 10. Impact of the stress test as a function of time and altitudes between 350 km and 650 km.

4 CONCLUSIONS

The approach using computational models to identify and evaluate some space debris mitigation guidelines may be subject to limitations because of the nature of the scenarios employed. Conventionally, interventions that aim to prevent the generation of new space debris are evaluated using ‘best case’ scenarios. Such scenarios do not account for possible environmental crises that could constrain the benefits of the intervention or introduce previously unknown deficiencies. We proposed the use of hypothetical stress tests, scenarios designed to enable the resilience of debris mitigation solutions to be assessed, to overcome these limitations.

As an example, we introduced a scenario featuring an environmental crisis resulting from the collisional fragmentation of the top 50 statistically most concerning derelicts in LEO, which was simulated using the DAMAGE debris model. This effect of this stress test was to increase the population of objects ≥ 10 cm by approximately 350% and to increase the catastrophic collision rate by a factor of 4. Our objective was to evaluate the resilience of post-mission disposal, an intervention that is outlined in the IADC space debris mitigation guidelines.

A 2 × 2 experimental design was used to evaluate the impact of the stressor on the number of catastrophic collisions reported by DAMAGE over a 200-year projection period. The results indicated that post-mission disposal remained effective at altitudes above 650 km and even provided enhanced benefits in the aftermath of the near-simultaneous fragmentation of 50 derelict LEO objects. At altitudes below 650 km, the DAMAGE results provided further evidence of unfavourable effects from post-mission disposal, even without the stressor. In this altitude region post-mission disposal appeared to increase the number of catastrophic collisions predicted. The impact of the stress test was uncertain in this region, with the possibility of a slight worsening of the unfavourable outcomes as a consequence of the multiple fragmentation events. Further work is needed, possibly using a substantially longer projection period, to fully understand any limitations of post-mission disposal at these lower altitudes.

We also propose the development of an internationally approved set of stress test scenarios, which can be implemented across all computational models used to support the development of new space debris mitigation guidelines. Ideally, this would prevent the gradual increase in complexity of guidelines (and a possible decrease in compliance) on the delayed discovery of hidden consequences or lack of resilience to substantial changes to the environment.

5 ACKNOWLEDGEMENTS

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