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Stakeholder-informed modelling of debris mitigation strategies to support evidence-based policymaking and operator decisions

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Abstract

The scale and cadence of space activities today are expected to have long-lasting impacts on the Low Earth Orbit environment. Debris evolution models exist, but there remains a gap between environmental modelling outputs and how they translate to guiding and informing operational and regulatory decision-making. This work addresses this gap by linking orbital environment evolution to decision-relevant objectives and by integrating stakeholder engagement within the modelling process. We leverage an integrated simulation framework to evaluate mitigation strategies as controllable policy levers. A simplified one-dimensional density-based debris evolution model is used to capture the dynamics of active satellites, inactive objects, and fragments across discretised altitude shells. The debris model is combined with a state-dependent linear feedback controller that dynamically optimises debris mitigation measures to achieve prescribed space sustainability targets. This paper focuses on investigating the calibration of post-mission disposal measures under different operating scenarios. A structured stakeholder workshop involving satellite operators and policymakers was conducted to introduce the integrated simulation framework and demonstrate its functionalities based on some preliminary results from initial simulations. Participants then co-developed and refined the operating assumptions for these scenarios for a second round of simulations. Finally, results from this second round of simulations were discussed, and participants helped to validate the interpretability of the outcomes and the operational feasibility of the mitigation actions. This iterative and collaborative process proved helpful in connecting technical modelling outputs with practical policy and operational decision-making contexts, and provides a model for how stakeholder input can be integrated into model- and evidence-based decision-making to support space sustainability goals.

1. Introduction

The rapid growth in the scale and frequency of space activities is expected to have long-term consequences for the Low Earth Orbit (LEO) environment. Increasing launch rates and the deployment and replenishment of large satellite constellations are changing both the magnitude and spatial distribution of the operational population. As orbital regions become more intensively used, interactions between active spacecraft, inactive objects, and debris become increasingly relevant for assessing the sustainability

of space activities, raising questions about whether current mitigation practices will remain sufficient under future traffic conditions and which additional measures may be required. Understanding these effects has motivated the development of several evolutionary models of the space environment by research institutions and academia [1–3]. By simulating the orbital population under different assumptions on future traffic, spacecraft operations, disposal, collisions, and remediation, these models provide a scientific basis for assessing alternative sustainability strate-

gies. Such evidence contributes to the development and assessment of debris-mitigation guidelines and regulatory frameworks by international, regional, and national organisations [4–6]. Satellite operators, however, occupy a distinct position within this process. They are among the main actors determining the evolution represented by environmental models and are also directly affected by the resulting policies and regulations. Their decision-making context differs from that of population-level environmental analyses: alongside safety and sustainability requirements, operators must account for mission objectives, technical capabilities, operational constraints, and business considerations. Conversely, environmental models generally address the cumulative and long-term consequences of individual activities on the orbital environment as a whole. Consequently, measures that appear effective from an environmental perspective must also be considered in relation to their operational feasibility, costs, and implications for individual missions and operators. Stakeholder involvement is therefore valuable not only within regulatory processes, but also within the scientific analyses supporting them. Interaction between operators and researchers can help bridge these perspectives and address questions such as: Which environmental measures and thresholds are meaningful for both operators and policy-makers addressing space-sustainability-related issues? Which model assumptions and scenarios are most likely to provide decision-relevant insights? How can model outputs be translated into information that supports operational and regulatory decision-making? This paper addresses these questions through an ongoing collaboration between Secure World Foundation and Politecnico di Milano within the ERC-funded GREEN SPECIES project. A feedback-controlled evolutionary model of the LEO environment [7, 8] is combined with an iterative stakeholder-engagement process. Discussions with satellite operators inform the definition and refinement of modelling assumptions, metrics, and scenarios, while the resulting analyses provide the basis for subsequent discussion. Rather than focusing on the individual scientific results, this work examines how this iterative process can connect environmental modelling with operational perspectives. The modelling framework used during the activity and the iterative procedure of stakeholder engagement are defined in Section 2, while Section 3 describes the activities performed so far, with final conclusions in Section 4.

2. Methodology

2.1 Modelling framework

The modelling framework has been developed within the GREEN SPECIES project, which investigates the use of control strategies to support the long-term sustainable evolution of the orbital environment. A central objective is the development of an actively controlled space object population model in which mitigation actions can adapt to the evolving state of the environment. The framework is intended as a scientific decision-support tool rather than as a direct prescription of operational requirements. Only its main features are summarised here; the complete formulation and other applications are provided in [7, 8]. A density-based formulation describes the LEO object population as a continuous flow evolving under environmental perturbations, sources, and sinks. The domain extends from 200 to 2000 km altitude and is discretized into concentric spherical shells with a uniform thickness of 25 km. The population includes active and inactive payloads, constellation spacecraft, rocket bodies, and trackable fragments larger than 10 cm. Representative physical and operational properties, including lifetime, mass, and cross-sectional area, are defined at species level. The temporal evolution of each population species' density n is governed by the continuity equation (1).

$$\frac{dn}{dt} = \dot{d} + \dot{l} + \dot{p} + \dot{c} + \dot{e}, \quad (1)$$

The model accounts for atmospheric drag ($\dot{d}$), launch traffic ($\dot{l}$), Post-Mission Disposal (PMD) through satellites' relocation at lower altitudes ($\dot{p}$), collisions ($\dot{c}$) and explosions ($\dot{e}$). Future traffic is introduced through species-specific annual launch rates. At end of life, active objects become inactive and successful PMD can relocate them to the first lower shell compatible with a prescribed re-entry-time requirement. Collisions are represented statistically according to [7, 9, 10], accounting for interactions within and between species and the associated generation of fragments, while fragment-fragment collisions are neglected. Explosions are represented through prescribed annual rates. The reduced-order model is coupled with a dynamics-informed feedback controller. The control action is obtained by minimising the quadratic performance index in equation (2), where $\mathbf{e} = \mathbf{y} - \mathbf{y}_t$ is the tracking error with respect to the reference, and $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{S}_f$ are positive-definite weighting matrices. Matrix $\mathbf{A}$ penalizes deviations from the desired target, whereas $\mathbf{B}$ penalizes the control effort $\mathbf{u}$ and $\mathbf{S}_f$ is an additional penalization of the target at the end of the simulation time ($t_0 - t_f$). The control problem is solved using the State-Dependent Riccati Equation (SDRE) approach

described in [7, 8].

$$J = \frac{1}{2} \mathbf{e}^T \mathbf{S} \mathbf{f}(t, \mathbf{x}) \mathbf{e} + \frac{1}{2} \int_{t_0}^{t_f} (\mathbf{e}^T \mathbf{A}(t, \mathbf{x}) \mathbf{e} + \mathbf{u}^T \mathbf{B}(t, \mathbf{x}) \mathbf{u}) dt \quad (2)$$

For the applications considered here, PMD compliance is the control variable. The controller adjusts its value throughout the simulation according to the evolving orbital population and prescribed target, producing a time-dependent mitigation profile that represents a compromise between environmental performance and control effort. These solutions should not be interpreted as directly applicable requirements; rather, they provide ideal mitigation trajectories whose trends and sensitivity to alternative assumptions can support discussions on practical mitigation strategies.

2.2 Stakeholder engagement framework

A multistep engagement process was adopted to solicit input and feedback from stakeholders, so as to ensure that the model and results would be operationally relevant, and that the findings and insights were useful in policy and operational decision-making. Feedback was sought and incorporated at various stages of the modelling process, including simulation setup, assumptions refinement, and results analysis. The overall process is shown in Fig. 1.

The process begins with the initialization of the modelling framework to establish the baseline structure, objective functions, and scenario parameters that would underpin the subsequent analysis. This framework is then subjected to a first round of stakeholder validation: a set of focused, one-on-one consultations with key stakeholders aimed at testing whether the model’s assumptions, objectives, and simulated scenarios reflect real-world conditions. This work focused on engagement with operators, as the non-publicly disclosed operational data (e.g., PMD success rates, Collision Avoidance Manoeuvres (CAMs) efficiencies) were deemed to be the largest information gap.

After confirming the framework’s general validity, a set of simulations are conducted to produce preliminary results and policy insights, which then forms the basis for a second round of stakeholder engagement: a structured workshop that invites stakeholders to interpret the simulation outputs, discuss their policy implications, and identify areas warranting further study.

This process is designed to be iterative. Shortcomings identified by stakeholders during Stage II prompt revisions to the model’s assumptions and setup. Unanticipated findings, new research questions, or changing circumstances — regulatory shifts, new technologies, evolving operator

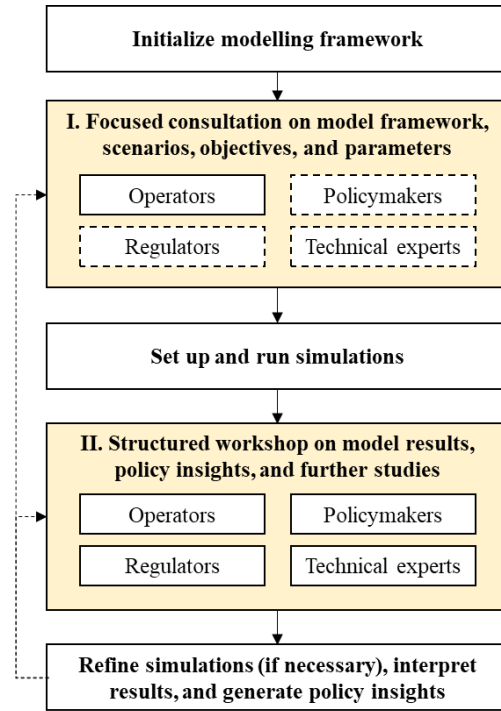


Fig. 1: Stakeholder engagement framework, with solid lines showing engagement conducted as part of the work for this paper, and dotted lines showing possible future engagement with a wider group of stakeholders on different research questions.

practices — can likewise trigger updates to scenarios and parameters. The analyses presented at the current conference represent the latest iteration of this continuing process.

3. Stakeholder-informed analysis and engagement

The scientific framework was embedded in the iterative stakeholder-engagement process illustrated in Fig. 1. Initial scenarios and environmental targets were identified within the Secure World Foundation–Politecnico di Milano collaboration.

3.1 Initial design of scenarios and targets

As described in Section 2.1, application of the controlled evolutionary framework requires the definition of both an objective representation of the desired state of the environment and a set of assumptions describing its future evolution. These choices were therefore made with particular attention not only to their scientific significance, but also to their potential relevance to operator decision-making and policy discussions. Existing metrics and in-

indices used to characterise the orbital environment were reviewed [11–14]. A candidate metric should be compatible with the species-based statistical model and be influenced through the available control actions. Particular attention was given to metrics that are already relevant to satellite operators or that have been adopted, discussed, or associated with quantitative thresholds in existing guidelines, standards, and policy frameworks. Preference was also given to metrics that could be related directly to risk or economic consequences, providing a more tangible interpretation of environmental changes. The main considerations used in this assessment are summarised in Table 1.

Two objective functions were selected for the initial analyses. The first is the cumulative collision probability experienced by a representative satellite over its mission life-cycle, including encounters with active and inactive objects and trackable fragments. It is defined as in equation (3), where Op includes the collision probability P_c during the operational phase, PMD the contributions of the disposal operations and $Fail$ the P_c of failed PMD. The last two terms are weighted based on the success probability of PMD β_r . The objective function is computed for a representative payload satellite [8].

$$P_c = \int_{Op} P_{ci} + \beta_r \int_{PMD} P_{ci} + (1 - \beta_r) \int_{Fail} P_{ci}, \quad (3)$$

This metric connects population-level environmental evolution with the risk experienced by an individual mission and is directly relevant to mission design and compliance assessment. Quantitative collision-probability requirements are included, for example, in NASA and ESA requirements [5, 6], with a threshold equal to 10^{-3} cumulative collision probability over a satellite lifetime defined in [6].

The second objective is the residual annual collision rate after accounting for collision-avoidance effectiveness. It is evaluated according to equation (4), using representative spacecraft assumptions consistent with the cumulative collision-probability metric.

$$RRes = (1 - \beta_{CAM}) ACR, \quad (4)$$

It represents the statistical collision risk remaining despite the assumed ability of active spacecraft to perform CAMs, with β_{CAM} reliability scaling the total Annual Collision Risk (ACR), including encounters with active and inactive objects and trackable fragments. As collision risk and collision-avoidance capabilities are fundamental considerations in mission design and operation, this metric provides a complementary representation of the environmental burden experienced by active spacecraft.

The initial analysis focused on the calibration of PMD compliance under different assumptions concerning future launch traffic and PMD re-entry requirements. Future launch traffic represents one of the major sources of uncertainty in long-term evolutionary modelling [15]. Changes in launch cadence and mission architectures, including the emergence and continued development of large constellations, can substantially alter both the magnitude and spatial distribution of the future population. Exploring different traffic assumptions was therefore considered necessary to assess how the mitigation effort identified by the controller depends on the evolution of space activity. Two launch cases were defined. In L1, non-constellation launch activity stabilises at recent levels, whereas in L2 it follows an exponential growth assumption; announced constellation deployments (as of 2024) and subsequent replenishment are included in both cases. The PMD re-entry time limit was selected as the second scenario dimension because of its direct relevance to recent developments in debris-mitigation practices and requirements. Post-mission disposal represents one of the most established measures available to limit the accumulation of inactive spacecraft in the orbital environment, while the maximum time allowed for disposal and re-entry has been the subject of considerable discussion and regulatory evolution in recent years [4, 6, 16, 17]. Two PMD cases were also considered: P1 applies a 5-year re-entry limit, while P2 uses a 25-year benchmark. The resulting four scenarios were initialised from the 2025 population and propagated over 50 years, with the controller determining the PMD compliance profile associated with each environmental objective. These initial scenarios constituted the scientific baseline subsequently presented to satellite operators during the first round of stakeholder engagement.

3.2 First round of operator engagement

Before the workshop, the initial scenarios were discussed through individual meetings with representatives of different types of satellite operators, including operators of large constellations and smaller satellite fleets, as well as consultants working with satellite operators. They are not identified here to maintain anonymity. The meetings focused on both the reasonableness of the modelling assumptions and the operational relevance of the selected scenarios, metrics, and mitigation strategies from an operator perspective. Several recurring considerations emerged:

- **Future traffic scenarios.** Operators suggested investigating the effect of specific planned large constellations.

Table 1: Trade-off between candidate environmental metrics considered for the controlled analyses.

Metric	Model implementation	Targets / thresholds	Operator relevance	Risk / cost interpretation
Cumulative P_c over a representative satellite lifetime	Directly derived from the modelled population	Existing mission-level requirements / thresholds	Directly related to mission risk and compliance	Direct risk interpretation
Number of conjunction avoidance manoeuvres	Derived from encounter rates and CAM assumptions	No unique general threshold	Direct measure of operational workload	Related to operational effort and cost
Number of inactive objects	Direct model state	No established general threshold	Indirectly related to operational risk	Indirect risk interpretation
Spatial density per shell	Direct model output	No established general threshold	Describes local orbital congestion	Indirect risk interpretation

- **Operational risk metrics.** CAM rate was identified as a useful complement to aggregate collision-risk metrics, as it provides a more direct indication of the operational workload associated with congestion.
- **PMD strategies.** Constellation operators highlighted that direct re-entry is commonly preferred to relocation-based disposal.
- **CAM capabilities.** Collision-avoidance effectiveness was considered a potentially influential assumption and one that could benefit from greater specificity across spacecraft populations and encounter types.
- **Broader sustainability indicators.** Participants highlighted the importance of inclusion of environmental impacts beyond debris-related indicators (e.g. light pollution or human casualty risk).
- **Remediation strategies.** Active debris removal was identified as an additional mitigation option of interest for future analyses.

The feedback was analysed according to its relevance and feasibility within the modelling framework. Some of the suggestions that could be incorporated within the workshop time-frame were implemented in the next analysis iteration, while others were retained as directions for future development.

3.3 First update and workshop activities

The first modification concerned PMD for constellation spacecraft. The initial model represented disposal through relocation to the first compliant orbit at lower altitude as in equation (5), where objects at end of life in a shell

volume ($\int_{V_{t_L}} \frac{\dot{n}_{i_l}(t_l)}{1 \text{ year}}$, with t_l lifetime after launch) become inactive and disposable through relocation at a lower altitude, compliant with the re-entry time requirement, with success probability β_{rl} . However, operator discussions highlighted the importance of direct re-entry, especially for constellations. The model was therefore extended through the additional term in equation (6) to distinguish the two disposal strategies: part of the objects at end of life are disposed through relocation PMD as before (α_{rl} fraction of satellites), while the remaining satellite ($1 - \alpha_{rl}$) do controlled re-entry with success probability β_{re} .

$$\dot{p} = (1 - \beta_{rl}) \int_{V_{t_L}} \frac{\dot{n}_{i_l}(t_l)}{1 \text{ year}} \quad (5)$$

$$\dot{p} = [(1 - \beta_{rl})\alpha_{rl} + (1 - \beta_{re})(1 - \alpha_{rl})] \int_{V_{t_L}} \frac{\dot{n}_{i_l}(t_l)}{1 \text{ year}} \quad (6)$$

For the workshop analyses, 90% of constellation spacecraft were assumed capable of direct re-entry, while the remaining fraction followed relocation-based disposal. PMD compliance within the control framework was consequently differentiated between the two strategies.

A second modification concerned the representation of operational collision burden. Following operator feedback, the expected CAM rate was introduced as an additional proxy for environmental risk in each altitude shell, considering encounters with both active and inactive objects. It is computed as the collision probability in [7, 9, 10], assuming circular impact area with 1 km diameter. This metric provides a more direct and readily interpretable quantity from an operational perspective, as it relates the state of the orbital environment to the frequency of actions that may be required during spacecraft operations at different altitudes.

In parallel, the preliminary discussions informed an interactive questionnaire activity designed for the workshop. The objective was to extend the engagement beyond the initial operators and collect broader feedback on modelling assumptions, operational priorities, sustainability metrics, and future scenarios.

3.4 Workshop results and emerging discussions

The revised analyses were presented at the Second Space Capacity Allocation For The Sustainability Of Space Activities Workshop. The workshop brought together space operators, regulators, and researchers from the space debris and space law communities to discuss current advances in space capacity modelling and management, with the broader objective of progressing towards internationally agreed approaches for modelling space capacity and defining acceptable thresholds. It also provided an interdisciplinary platform for discussing space sustainability and capacity management from technical, legal, and economic perspectives, while considering the different factors that affect the sustainable use of the space environment. Rather than discussing the numerical results comprehensively, selected outcomes are reported here because they generated particularly relevant discussions with participants. Examples are presented for the cumulative collision probability objective defined in equation (3). Fig. 2 shows the cumulative collision probability experienced by a representative spacecraft across altitude for the scenarios in Section 3.1. The results highlight that mission-level risk at a given oper-

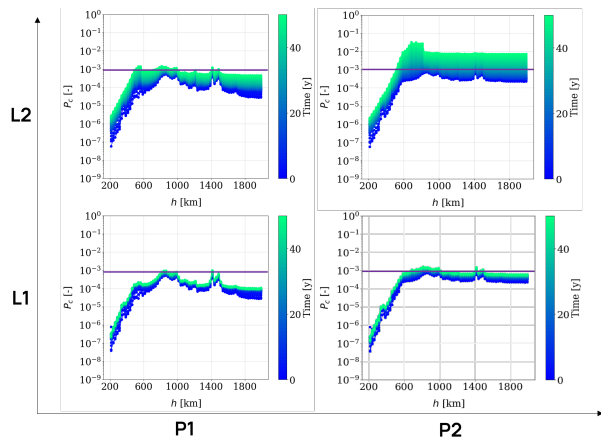


Fig. 2: Temporal evolution of the cumulative collision probability altitude profile for the scenarios in Section 3.1. The horizontal line identifies the 10^{-3} threshold.

ational altitude can also be affected by population changes

elsewhere in the environment. In particular, successfully disposed spacecraft traverse and may accumulate within lower disposal regions, contributing to the cumulative probability experienced by missions originating at higher altitudes. This effect is particularly visible for the 25-year PMD cases, where accumulation around the first compliant disposal region makes the disposal phase a major contribution to cumulative collision probability in the higher orbital shells that converge to similar values. Under the 5-year requirement, this accumulation is reduced and the contribution from the operational phase becomes comparatively more important, with peaks corresponding to highly populated operational regions. These results prompted discussion on whether PMD requirements based on a single maximum re-entry time fully capture the environmental consequences of disposal. A compliant manoeuvre can reduce the long-term persistence of a spacecraft while still transferring it to an already congested region. Participants therefore highlighted the importance of considering local congestion within disposal regions when evaluating PMD effectiveness and, potentially, when defining disposal requirements, since the consequences of individual disposal decisions are not necessarily confined to the orbital region in which the corresponding missions operate. Figs 3 and 4 report the corresponding distributions of relocation-based PMD and direct re-entry operations, respectively. Higher

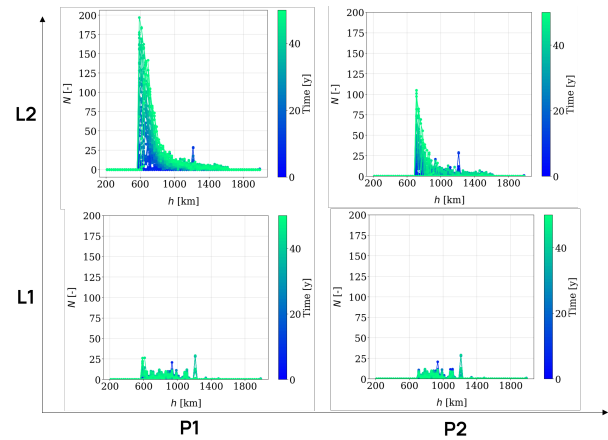


Fig. 3: Temporal evolution of the relocation PMD operations altitude profile for the scenarios in Section 3.1.

launch activity in L2 results in more spacecraft requiring disposal. In the 25-year cases, congestion around the disposal region can become sufficiently significant that the controller limits relocation actions that would further increase the local population at that altitude. This illustrates how the environmental effectiveness of PMD depends not

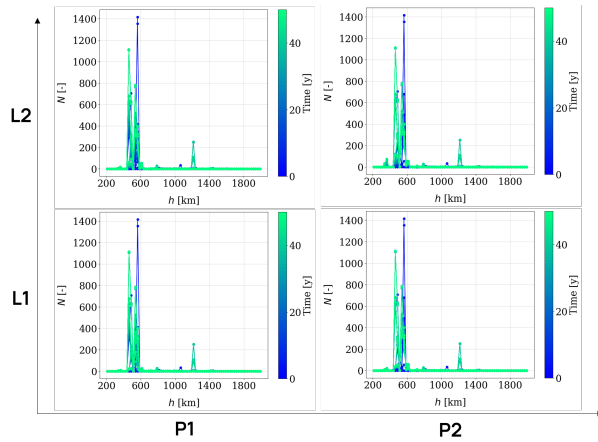


Fig. 4: Temporal evolution of the controlled re-entries altitude profile for the scenarios in Section 3.1.

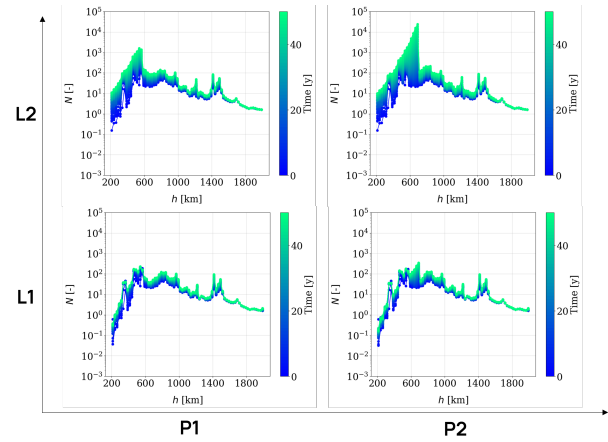


Fig. 5: Temporal evolution of the CAM rate altitude profile for the scenarios in Section 3.1.

only on the nominal compliance level, but also on the location and traffic conditions under which disposal occurs. The comparison also stimulated discussion on future traffic assumptions. Despite the simplified distinction between L1 and L2, traffic growth already produces substantial differences in environmental evolution and mitigation response. Participants therefore suggested investigating planned large constellations and emerging mission architectures more explicitly.

The operational implications of the different scenarios were further explored through the CAM-rate metric introduced following the preliminary operator meetings. Fig. 5 shows the CAM-rate distribution for a representative spacecraft in each altitude shell. Higher launch activity increases the active population and therefore the expected manoeuvre burden, while longer PMD times increase the inactive population at lower altitudes. Discussion of these results reinforced the importance of accurately representing collision-avoidance capabilities within environmental analyses. Participants identified assumptions concerning CAM effectiveness as potentially influential model parameters, suggesting that a single aggregate representation may not adequately capture differences between spacecraft populations and encounter types. Moreover, the collision-probability threshold at which a conjunction triggers a manoeuvre was identified as another meaningful quantity from an operator perspective and as a possible complement to the statistical CAM-rate metric.

3.5 Second round of engagement

The workshop discussion was complemented by an interactive questionnaire session designed partly around questions raised during the preliminary operator meetings. A total of 52 respondents participated in the interactive poll, with response rates of between 67% to 100% for different questions. Of the 52 participants who reported their professional affiliation, half identified as researchers. 17% were students, 12% were satellite operators, 6% were policymakers and/or regulators, and 16 % were civil society and other working professionals. The sample is therefore weighted towards the research community. Participants were asked to provide their perspectives on: which scenario assumptions or model parameters could most strongly affect the results; the principal barriers to PMD compliance and successful disposal; the factors, beyond fulfilment of the core mission objectives, that influence satellite operational decisions; policy mechanisms and initiatives that could support effective debris mitigation and remediation; scenarios that would be valuable to investigate in subsequent analyses; simulation time horizons useful for organisational decision-making; and sustainability aspects beyond orbital debris that should be considered in future work. Some of these questions directly followed from the preliminary operator engagement. For example, earlier discussions had emphasised that sustainability of space activities cannot be represented exclusively through orbital debris metrics. The workshop was therefore used to investigate which additional impacts participants considered relevant for future analyses. Similarly, the preliminary meetings had shown that the practical relevance of a metric

can depend strongly on how directly it maps onto quantities used in operational decisions. Examples included the preference for collision-probability thresholds associated with CAM decisions rather than conjunction frequency alone, and the broader importance of expressing sustainability measures in terms of their operational or economic consequences. Questions concerning the factors influencing operator decisions were consequently included to investigate this aspect across the broader workshop audience. The interactive session therefore served both to evaluate the assumptions underlying the analyses and to identify priorities for the subsequent modelling iteration.

A summary of the workshop results is as follows.

- **Drivers of operational decision-making.** When asked to select the top three factors (apart from fulfilment of core mission objectives) that affect satellite operational decisions, respondents pointed to mission cost (75%), regulatory compliance (64%) and manoeuvre frequency or cost (53%). Direct risk metrics such as collision probabilities, conjunction rates, and protection from residual risks were selected less often, from 9% to 35%. Economic and compliance considerations thus appear to mediate operational decisions more strongly than the collision risk metrics that dominate the technical literature.
- **Constraints on PMD compliance.** Participants rated six factors affecting PMD compliance and success rates on a scale from 1 (not an issue) to 5 (very significant). The highest mean score was for lack of policy mandate and support (4.3), followed by mission cost (4.0), mission design constraints (3.7) and technical capabilities and know-how (3.5). Awareness of PMD requirements scored lowest among the substantive options (2.7). This ordering suggests participants view the binding constraints on disposal performance as institutional and economic rather than informational.
- **Preferred policy instruments.** When ranking nine initiatives by expected usefulness in driving debris mitigation and remediation, participants placed international legal and liability frameworks first, a stronger national regulatory and licensing regime second, and financial penalties for non-compliance third. Financial incentives for innovative ADR technologies ranked fourth and licensing requirements on manoeuvrability fifth. Industry standards, insurance frameworks, Space Situational Awareness (SSA) initiatives and shorter PMD time limits occupied the bottom four positions. The ranking is consistent with the

PMD compliance results, in that binding legal and regulatory mechanisms were favoured over voluntary standards, information-based measures and tightening of the disposal timeline itself.

- **Implications for simulation design.** Participants identified launch rates as the assumption with the largest impact on simulation outcomes (92%), followed by PMD and re-entry success rates (70%) and CAM efficiency (53%). On usefulness of different simulation horizons (two selections allowed), half of the respondents selected less than 10 years and 46% selected 10 to 20 years, revealing a bias toward shorter planning horizons that may understate debris accumulation effects that unfold over multiple decades. Finally, when asked which scenario would be most useful to analyse next, respondents favoured accounting for regulatory differences across jurisdictions (28%), the impact of a major fragmentation event (26%) and different launch assumptions such as very large constellations (20%).
- **Impacts beyond in-orbit congestion.** An open-text question invited participants to name safety or sustainability impacts other than in-orbit congestion, that future analyses should address. 43 respondents provided 57 terms. After grouping near-duplicate responses, the most frequent themes were atmospheric and re-entry effects, including atmospheric pollution, ablation and ozone depletion (17 mentions); astronomical observation, light pollution and sky visibility (9); and cost and broader socio-economic externalities (8). Smaller clusters addressed orbital access and capacity (5), human safety and casualty risk including aviation exposure (4), space weather (3), cybersecurity and radio-frequency interference (3), and terrestrial environmental and health effects (3).

3.6 Updated analyses and future directions

Following the iterative process described in Section 2.2, the discussions generated during the workshop motivated a second update of the analyses. Participants particularly emphasised the importance of understanding how planned large-scale deployments may affect the future environment. This led to the definition of an additional launch-traffic scenario intended to explore the environmental implications of a major planned constellation. A third scenario, L3, was consequently introduced. It extends the L2 assumptions by including the planned Guowang constellation at approximately 1100 km altitude, while retaining the two PMD re-entry-time cases and the environmental objectives pre-

viously defined. Figs 6-9 report representative results for cumulative collision probability objective function, PMD distributions, and CAM rate.

The environmental effect of the additional population

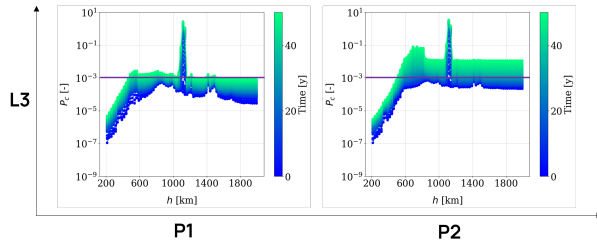


Fig. 6: Temporal evolution of the cumulative collision probability altitude profile for the L3 scenario.

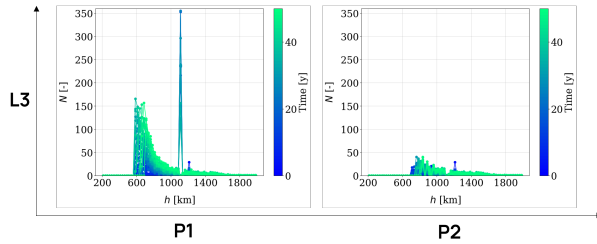


Fig. 7: Temporal evolution of the relocation PMD altitude profile for the L3 scenario.

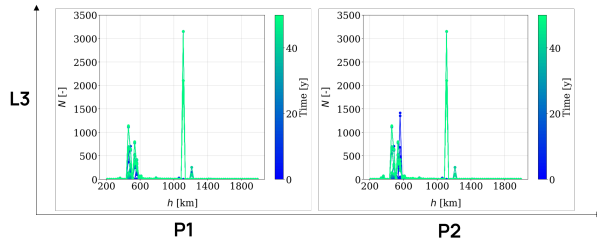


Fig. 8: Temporal evolution of the controlled re-entries altitude profile for the L3 scenario.

is clearly visible, with a new peak in cumulative collision probability around the constellation operational altitude. These results should not be interpreted as predictions of the risk associated with a specific constellation: the current model does not explicitly represent constellation-specific orbital configurations, collision-avoidance strategies, or other detailed operational practices. Instead, the scenario is intended to investigate how a large-scale addition to the

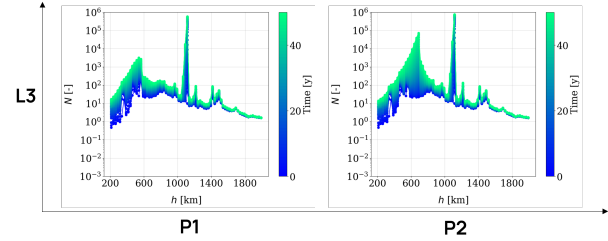


Fig. 9: Temporal evolution of the CAM rate altitude profile for the L3 scenario.

population may influence aggregate environmental trends. The larger constellation population substantially increases the number of spacecraft requiring disposal. Under the adopted assumptions, 90% of constellation spacecraft can perform direct re-entry, while the remaining fraction is relocated. When applied to a very large population, however, even small disposal failure rates or relatively small fractions of relocated spacecraft can result in significant additional populations in disposal regions. The controller responds to the associated congestion by limiting relocation actions, while unsuccessful disposal increases the inactive population and affects collision probability beyond the constellation's operational altitude. Similar effects are visible in the CAM-rate distributions.

This analysis illustrates one potential use of the framework for operators: investigating how planned activities interact with the surrounding environment and how apparently small fractions of unsuccessful or alternative disposal outcomes scale when applied to large populations. Although simplified, these analyses illustrate how the consequences of individual compliance decisions accumulate across multiple missions and orbital regions. More broadly, the results highlight the value of considering future developments from both individual and environmental perspectives. Operators naturally assess the implications of design and operational choices at mission level, whereas environmental models focus on their cumulative effects across the orbital population. The analyses presented in this activity provide a means of connecting these viewpoints by explicitly linking individual mitigation actions to the aggregate environmental burden they are intended to control. By combining scientific modelling, stakeholder engagement, and iterative scenario development, the activity seeks to strengthen the connection between environmental analyses used to inform sustainability policies and the operational realities of the actors who will ultimately implement them. The engagement campaign remains at an early stage, and the iterative process in Fig. 1 will continue through addi-

tional discussions, scenarios, and sustainability indicators. The present conference represents the next stage of this process, providing an opportunity to further evaluate the relevance of the assumptions and results and identify priorities for subsequent analyses.

4. Conclusions

This work presented an ongoing collaboration between Secure World Foundation and Politecnico di Milano aimed at integrating satellite-operator perspectives into model-based analyses of the long-term sustainability of operations in the LEO environment. The activity combines a feedback-controlled evolutionary model with an iterative engagement process in which stakeholder input contributes directly to the definition and refinement of modelling assumptions, metrics, and scenarios. The first iterations produced concrete changes to the scientific investigation, including the representation of direct re-entry for constellation spacecraft, the introduction of CAM rate as an operational metric, and the analysis of planned large-constellation traffic. Discussions also highlighted broader issues concerning congestion in disposal regions, collision-avoidance assumptions, and the relationship between mission-level mitigation requirements and aggregate environmental outcomes. The activity remains ongoing, and further engagement will be used to refine the modelling assumptions and expand the scenarios and sustainability indicators considered. More broadly, the approach provides a basis for strengthening the connection between scientific environmental modelling, operational realities, and evidence-based policy development for long-term sustainability of space activities.

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