Parameterizing Large Constellation Post-Mission Disposal Success to Predict the Impact to Future Space Environment

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ABSTRACT

Future large constellations are being proposed that may include hundreds to thousands of satellites, spread across multiple orbit altitudes in LEO, some of which are already highly populated. The long-term hazard to the safe operational space environment's utility posed by these new constellations is not fully understood. The magnitude of debris generated via explosions and collisions with other space objects will be significantly influenced by the constellation characteristics, and the post-mission disposal (PMD) policy followed by these satellite operators.

This study models the future orbital environment for debris based on different levels and types of space activity and PMD success rates. The future constellation model (FCM) utilized in the study consists of numerous constellations representative of proposed systems. These constellations manifest a wide range of characteristics relevant to their impact on the future debris environment, including mission and disposal orbits, satellite counts, masses, and areas.

The PMD success rate is varied across scenarios from 70% to 100%. Unsuccessfully disposed satellites are modeled to either remain in their operational orbit after end-of-life or along the ascent or disposal paths. Given the satellite count, size, mass, and replenishment cadence of each constellation, and varying PMD success rate, each scenario is parameterized to simple undisposed object metrics. By parameterizing in this way, the environment impact of scenarios with different satellite counts and physical characteristics are compared on a normalized plot.

1 INTRODUCTION

This study investigates parameters to act as simple-to-calculate indicators of satellite activity effects on the future debris environment. They can be easily computed for any large constellation scenario and acts as an analog to "level of activity". These include undisposed mass per year (UMPY), a parameterization based on the satellite mass, constellation size, and PMD success rate, undisposed satellite count per year, and undisposed cross-sectional area per year.

Scenarios are modeled and analyzed in a Monte Carlo simulation using the Aerospace Debris Environment Projection Tool (ADEPT), with all populations within a scenario interacting simultaneously to generate collisions. Accounting of the resultant debris for a scenario is done in post-processing, enabling many combinations of constellation traffic to be examined. The result of parameterizing the scenarios shows a correlation between UMPY and the future space environment impact. Constellation altitudes, planned disposal duration, satellite sizes, and total satellite counts also contribute to the results, but are often second-order effects compared to the simple UMPY metric. Parametrization over a wide range of characteristics enables general observations about the relationship of satellite operator behavior to debris environment evolution.

The future constellation model (FCM) utilized in the study consists of numerous constellations representative of proposed systems. These constellations manifest a wide range of characteristics relevant to their impact on the future debris environment, including mission and disposal orbits, satellite counts, masses, and areas. The constellations are maintained for the entire duration of the simulation time. This is done to model "levels of activity" rather than the lifetime of individual constellations. Understanding the effects of different levels of activity on the near-Earth environment provides more general insight into the effectiveness different mitigation approaches. The scenarios are modeled and analyzed in a Monte Carlo simulation using the Aerospace Debris Environment Projection Tool

(ADEPT). The simulations used for this study are identical to those in [1].The details of the modeling are discussed in more detail in the following sections.

2 AEROSPACE DEBRIS ENVIRONMENT PROJECTION TOOL (ADEPT) OVERVIEW

ADEPT simulation process generates representations of the future orbital population. The model includes orbit trajectories and sizes for a complete set of Earth orbital objects. Early versions of ADEPT are described in [2] and [3]. More recent enhancements and a detailed description of the of ADEPT are described in [1] and [4]. In brief:

1. The ADEPT model starts with an initial population model (IPM) that includes all the known catalog objects and modelled objects that represent unknown and subtrackable (<10 cm) objects on orbit.
2. A future launch model (FLM) that includes the FCM and extends out 200 years is added to the IPM
3. Ephemeris for this population is generated by long-term propagation using the mean-element code MEANPROP (Draper Semi-Analytic Orbit Propagator [5].
4. Future random collisions are generated using an orbit trace crossing method (OTC).
5. The fragmentation modelling code IMPACT [6] is used to generate fragments from explosions and collisions.
6. Fragments are fed-back into the process at step (3) to generate multiple generations of feedback collisions and fragments, as needed

Downsampling, as described in [4] is used to keep the overall count of objects to process to a computationally tractable number while maintaining population distributions. The PMD failure approach is briefly covered in [1].

3 POPULATION MODEL

Detailed descriptions of the IPM and FLM are presented in [1] and [4]. This study uses the same methodology described there to develop the IPM and FLM, where the FLM replicates recent historical launch traffic for different orbital regimes: geosynchronous (GEO), continuously replenished constellations (CRC), and non-CRC & non-GEO, (NONCRC, basically all satellites that are not in the CRC and GEO populations).

As in [1], the FCM is a collection of proposed and notional future large constellations with hundreds or thousands of satellites spread over multiple LEO altitude shells. As of the writing of this paper, OneWeb, SpaceX, and Planet Labs have had successful launches of their proposed systems and continue to fill out their constellations.

Table 1 and Table 2 show the constellation and satellite physical parameters used to populate the FCM. These are largely based on public FCC filings [7] and should be viewed as representative of the types of constellations designers are considering; what may actually fly will certainly be different than the presented values, but this serves as a good representative set of constellations to study the relative effects on the future space environment and is consistent with the idea of examining “levels of activity”.

Table 1. Orbit parameters for FCM Constellations

Const	Total sats	Altitude (km)	Inc (deg)	Planes	Sats per plane
1a	1600	1150	53	32	50
1b	1600	1110	53.8	32	50
1c	400	1130	74	8	50
1d	375	1275	81	5	75
1e	450	1325	70	6	75
2	720	1200	88	18	40
3	120	1400	89	6	20
4	112	800	98.6	8	14
5a	72	1000	99.5	6	12
5b	45	1248	37.4	5	9
6	100	651	97.9	5	20
7	30	576	97.8	5	6
8	150	500	97.4	1	150
9	60	450	55	3	20
10	140	550	97.6	7	20

Table 2. Physical parameters for FCM satellites

Const	Satellite area (m^2)	Satellite diameter (m)	Satellite mass (kg)
1	15.45	3.68	386
2	2.25	1.67	150
3	10.5	6.92	700
4	30	6	3000
5	10.5	6.92	700
6	0.16	0.50	5
7	0.75	0.70	100
8	0.16	0.50	5
9	0.35	0.77	50
10	0.16	0.50	5

Constellations labelled 6-10 are considerably smaller and at lower altitude than the others and are grouped together into a single category called Small LEO Constellations.

It's worth noting the difference between some of these constellations, as this is relevant to the results and discussion later. FCM1 is a multi-shell constellation, with far more satellites in total than the other proposed constellations. It can, however, be broken down into its constituent shells, each of which can be treated as its own constellation. Still, the first two shells would alone each be the largest constellation compared to all the rest. The satellite area and mass of FCM1 are somewhere in the middle of the pack. FCMs 3, 4, and 5 all have larger individual satellite mass, with FCM4 having the largest mass by a wide margin. Although FCM 4 has the smallest number of satellites in its constellation, the mass on orbit in FCM4 is larger than all others except for the first two shells of FCM1.

A probability-severity (P-S) metric can be used to approximately rank the various FCM constellations in terms of their likely contribution to the future debris environment [8]. P-S is used here as defined and used in [9] and [10]. The P-S value used here is defined without relative velocity or time and is given by Eq. 1.

$$\text{P-S} = \text{number*density*area*mass} \quad (1)$$

Figure 1 shows the P-S value for the examined constellations and constituent orbital shells within the larger constellation (the large circles). The absolute P-S number is not particularly relevant, but the relative ranking of one constellation's value to another's is. The currently existing Iridium, Globalstar, and Orbcomm constellations are shown for comparison purposes. Different combinations of parameters can cause high P-S. As discussed, the number of satellites and satellite mass vary greatly between FCMs 1 and 4 in particular, and the resulting P-S index for both is high compared to the other constellations.

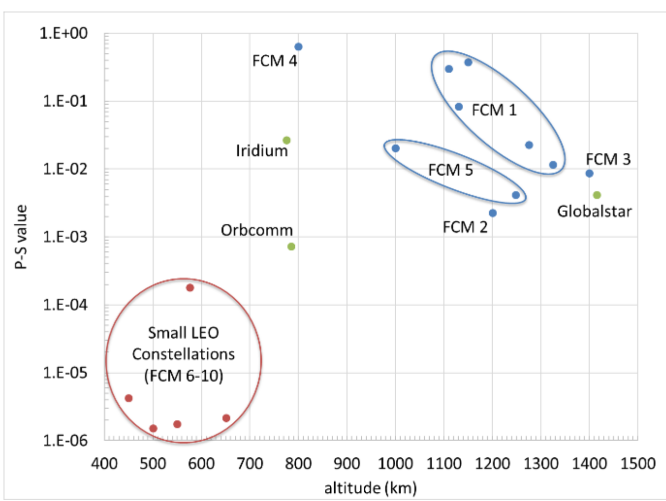

Figure 1. Probability-Severity index for examined FCM constellations along with other existing constellations

P-S is a metric that has been used in the past to parameterize constellations, but only considers the snapshot of the operational constellation, and does not account for the change in undisposed objects on orbit at different PMD rates. In general, P-S values should give us some a priori notion of which constellations will likely have more impact on the environment at a fixed PMD rate, but this study seeks to find a more direct correlation to results.

Figure 2 shows typical future environment impact results. This is the "all-FCM" scenario, which includes the initial population model (IPM), future launch model (FLM) objects that are replenishments of current activity (CRC, nonCRC, etc.), and all the proposed FCMs. All 100 Monte Carlo runs are displayed in a light gray color to show the full range of statistical variations in the ADEPT runs. On top of that, the mean and some statistical bounds at the 10th, 25th, 75th, and 90th percentiles are shown with bolder, colored lines. Here, dispA refers to PMD duration of 25 years, pmd090 refers to 90% PMD success rate. Environment impact is represented by number of >10cm objects over 200 years. Note that here and in [1] all fragments greater than 1 cm that result from breakup events are included in the analysis and can be involved in collisions as well. The spread of the Monte Carlo statistics highlights the importance of considering the variance involved in studying environment effects so far out into the future, and how that variance compares to small changes in the inputs, such as constellation sizes and PMD success rate.

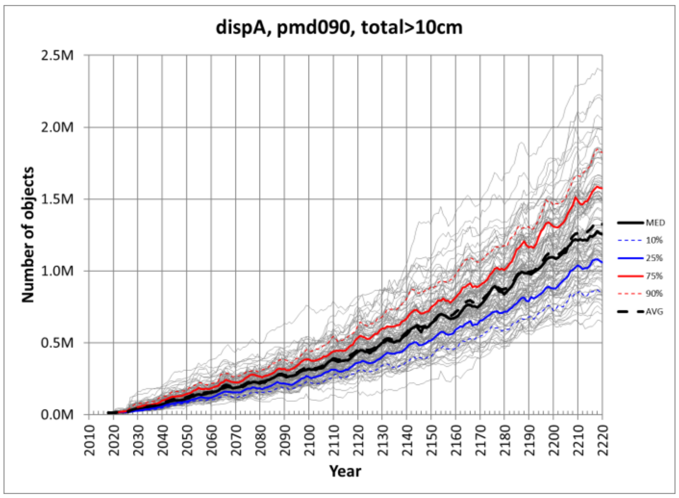

Figure 2. All-FCM scenario object count over 200 years showing 100 Monte Carlo runs and statistics

Figure 3 shows the >10 cm object count growth of the 5 separate FCM1 shells and FCM4, with 90% PMD success rate. These are all compared to the "Baseline" scenario, which is simply the impact of the IPM and FLM not including any of the FCM constellations. As expected, shells a and b are dominant over the others. The impact of FCM4 is still significant compared to the smaller FCM1 shells due to the large mass of its satellites, despite the much smaller satellite count.

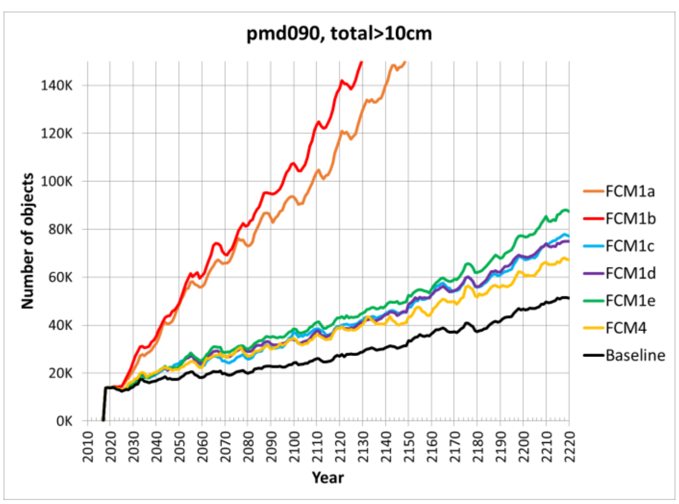

Figure 3. FCM1 shells a-e mean object count over 200 years, 90% PMD

4 PARAMETERIZING CONSTELLATION IMPACT

The goal of this study is to identify an approach to examine debris environment impact of a broad range of constellation activity levels using a single parameter to characterize the effect of that activity. Since the FCMs and historical constellations in general operate by reaching and maintaining a steady-state satellite count and configuration, this approach should be based on steady state level of constellation maintenance/activity.

In addition to the steady-state characteristics of the constellations and their satellites, one other factor that is known to heavily influence a constellation's impact is its PMD success rate. As PMD success rate decrease, more inactive satellites are left on orbit beyond the 25-year requirement [11], often in undesirable locations close to operational orbits. The amount of satellites and total mass on orbit over time are directly related to the PMD success rate.

Figure 4 shows a comparison of the environment effects of FCM2 at varying PMD success rates. The pmd100 case is the impact of only the FCM2 operational constellation and its successfully disposed objects that will re-enter within 25-years. As the success rate drops, disposed satellites accumulate on orbit for longer, and significantly increase collision events. The impact of varying PMD is studied further, including discussion on statistical uncertainties, in [1].

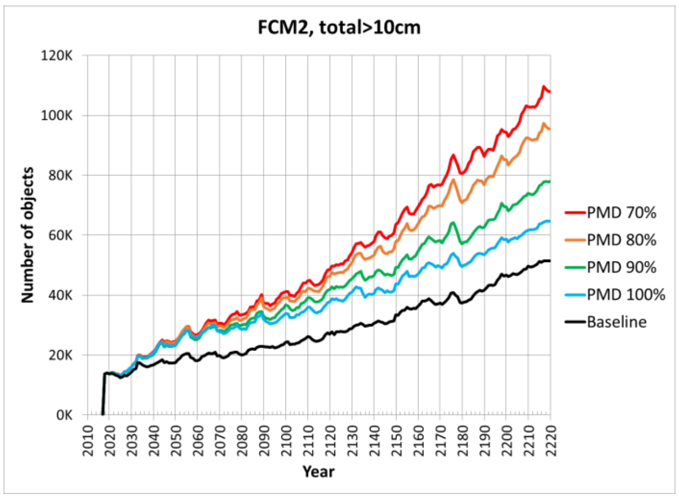

Figure 4. FCM2 mean object count over 200 years for PMD success rates of 70%-100% vs. Baseline scenario

4.1 Candidate Parameterization Metrics

Using the constellation and satellite characteristics, several metrics were examined to identify which might correlate best with effect on the environment. The simplest approach is to look at the number of undisposed satellites per year, agnostic to their mass, area, or orbit. Figure 5 are scatter plots of the final count of >10cm objects after 200 years for numerous constellation scenarios. Each pair of blue and red dots are the 25th and 75th percentile of the Monte Carlo runs for a single scenario, showing the middle 50% results after 200 years. At a zoom level that includes all scenarios in the study (out to >300 undisposed satellites per year), there appears to be a somewhat quadratic relationship. At a more reasonable level of PMD success rate with fewer total constellations (<50 sats/yr), the relationship is more linear, but correlation isn't very good (R^2 = 0.334, 0.319 for 25th/75th percentiles, respectively).

Another metric considered is undisposed satellite area per year. The area of a satellite is directly related to its probability of collision, so larger satellites will collide more often with other objects [12][13][14][15]. Figure 6 plots are similar to Figure 5 but with undisposed satellite area per year as the independent variable. In the "reasonable" linear range (undisposed area <120 m^2/yr), the correlation is starting to look much better (R^2 = 0.598, 0.493) than with number.

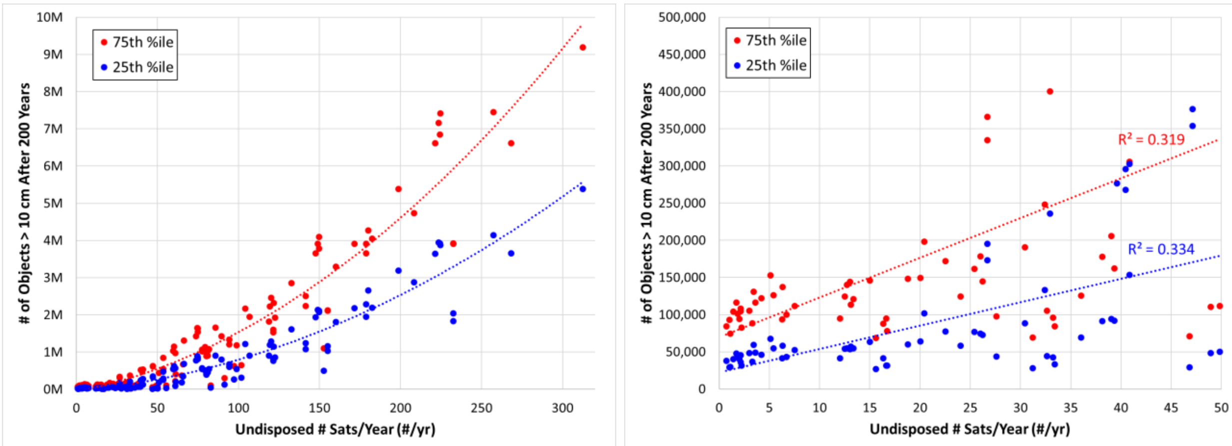

Figure 5. (a) # of objects >10 cm after 200 years vs. undisposed satellites per year (b) # sats/yr <50

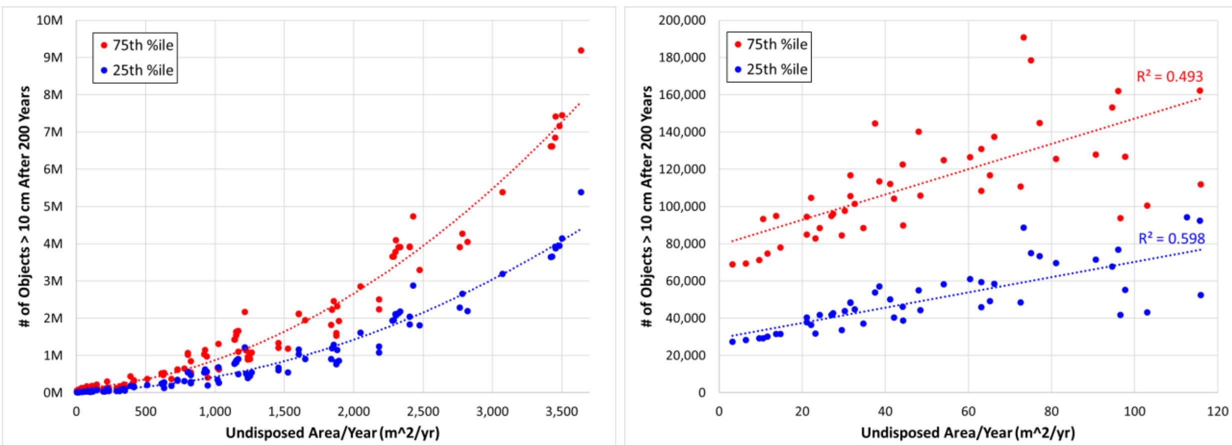

Figure 6. (a) # of objects >10cm after 200 years vs. undisposed satellite area per year (a) area/yr <120 m^2

4.2 Undisposed Mass Per Year (UMPY)

A metric based on mass was also considered as mass is included in many probability-severity calculations and affects the environment [12][13][14][15]. Consider that collision energy is influenced by the mass of the colliding objects, and more fragments will result from a collision between more massive objects. Although object count and size are more indicative of how many and often collisions occur, the number of resultant fragments will increase with mass.

Undisposed Mass Per Year (UMPY) is a function of the number of satellites in the constellation, the lifetime of each satellite, spacecraft mass, and PMD success rate. It essentially states how much mass per year is left in non-compliant disposal orbits that can pose a collision hazard in LEO, agnostic to the actual undisposed satellite count, size, density, shape, or altitude. UMPY is defined by Eq. 2.

$$UMPY = \frac{n_{sats} \times mass}{PMD \times lifetime} \tag{2}$$

Where n_{sats} is the number of satellites, mass is in kg, PMD is success rate in %, and lifetime is in years. Figure 7 plots are similar to Figure 5 and Figure 6 but with UMPY as the independent variable. Correlation of object count vs. UMPY (<10,000 kg/yr) to a linear trend is strongest of the candidate metrics (R^2 = 0.662, 0.663).

Table 3 shows the UMPY formula inputs and UMPY for the FCM constellations in this study. The PMD success rate is set to a minimum of 90% but is adjusted upward in FCM1 to ensure UMPY does not exceed 10,000 kg. This shows how PMD success rate can be used to control UMPY. Note that FCM1 has a top row that sums the multiple altitude shells together. This is significant, as it shows that the impact of multiple constellations can be combined by simply adding the UMPY value together, as is done with FCM5 and Small Constellations as well.

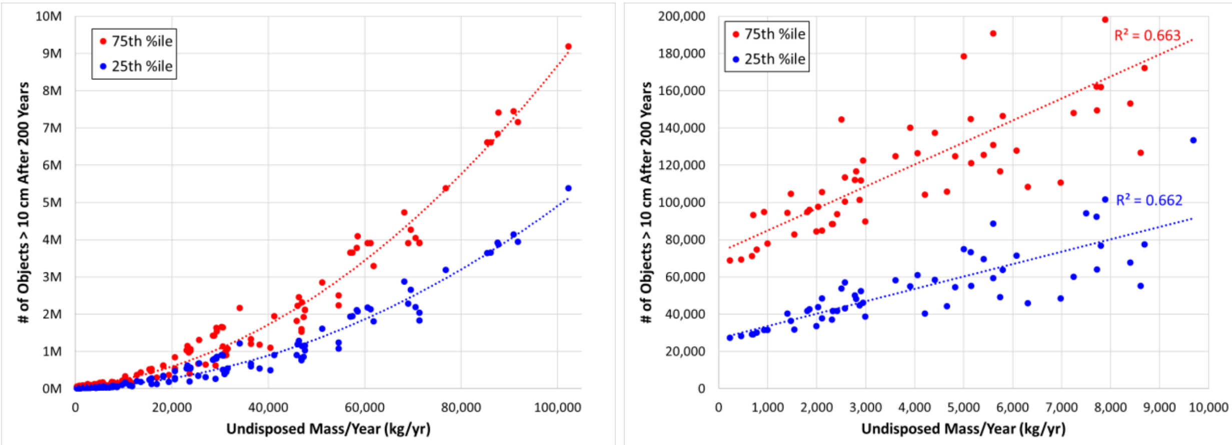

Figure 7. (a) # of objects >10cm after 200 years vs. undisposed mass per year (UMPY) (b) UMPY <10,000 kg/yr

Table 3. UMPY for the FCM Constellations with PMD success rate for UMPY <10,000 kg

Const	Total sats	Mass (kg)	Lifetime (years)	PMD Success	UMPY (kg)
1*	4,425	386	6	0.97	8,540
1a	1,600	386	6	0.91	9,264
1b	1,600	386	6	0.91	9,264
1c	400	386	6	0.9	2,573
1d	375	386	6	0.9	2,413
1e	450	386	6	0.9	2,895
2	720	150	6	0.9	1,800
3	120	700	12	0.9	700
4	112	3000	16	0.9	2,100
5*	117	700	9-12	0.9	770
Small*	480	5-100	2.5-5	0.9	225

5 RESULTS & DISCUSSION

Figure 7 results capture the impact of all the scenarios tested, including all FCMs with a 70% PMD success rate. UMPY is >100,000 kg/yr in that worst case, which would not be sustainable, as the number of >10cm objects grows to >1 million on average, two orders of magnitude more objects than the current environment. Instead we focus on the more realistic future scenarios where UMPY is <10,000 kg and the relationship is approximately linear.

One clear utility of this approach is that it shows a much better correspondence with the effects on the environment, as represented by number of objects, than using only number of constellation satellites. Even in the case of number of undisposed satellites per year (Figure 5b), which already contains more information than number of satellites in a constellation, there is still not as good a correspondence with number of objects in the environment at 200 years as with UMPY. The consequence of this is that using a value of UMPY or other similar parameter as a dividing line between acceptable and unacceptable behavior will be more likely to result in the desired response in the debris environment regardless of other details of the constellations. If there is some agreement amongst policy-makers on what is an acceptable number of objects in LEO after 200 years, this figure can be referenced to determine what UMPY value is likely to achieve that acceptable level with some statistical confidence. This can be applied to single large constellations, but in practice the entire set of large constellations should be considered together.

Figure 8a shows the relationship between UMPY and PMD success rate for a set of FCMs and combinations of FCMs. The takeaway is that for many constellations, the 90% PMD success rate limit is enough to keep UMPY below 10,000, but for FCM1 it would need to be set to 97% to achieve that limit. Figure 8b shows FCM1 UMPY at PMD of 97%, 98%, and 99% as vertical lines crossing the object count vs. UMPY plot. Any other UMPY limit could be selected, and any combination of FCMs could be analysed in the same way.

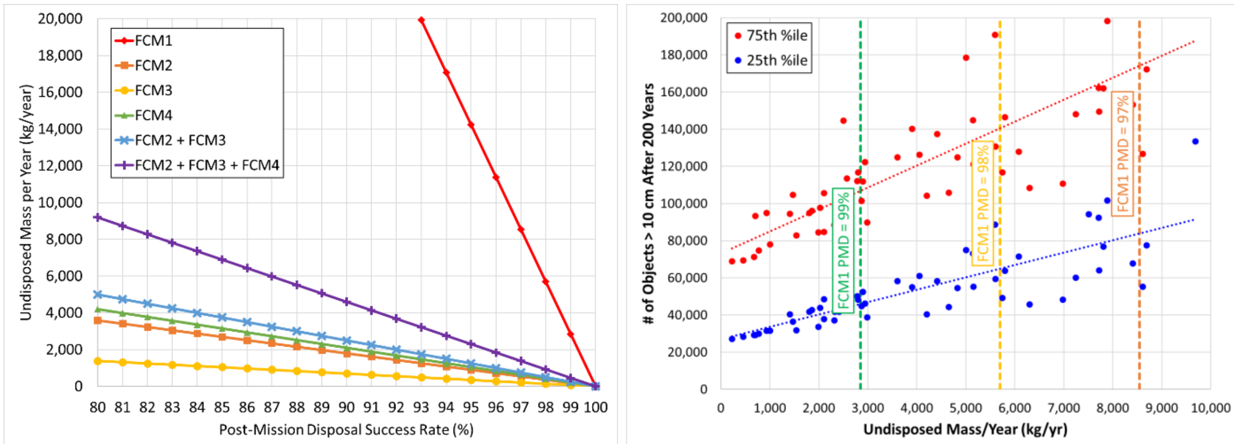

Figure 8. Comparison of UMPY vs PMD Success Rate for various FCM constellations and combinations

Figure 9a indicates where some very different cases nearly overlap. Here, the scenario with FCM3 + 4 at 70% PMD success has similar UMPY to the scenario with FCM1 shells *c*, *d*, and *e* at 90% PMD success. Although the satellite characteristics and constellation altitude and count are very different for these scenarios, UMPY values are both around ~8,000 kg/yr, and this results in a similar object count after 200 years (~150,000).

Figure 9b is a comparison of the object count of those same two scenarios over the 200-year simulation. The color bands are the middle 50% (25th-75th percentile), showing significant statistical overlap between these scenarios.

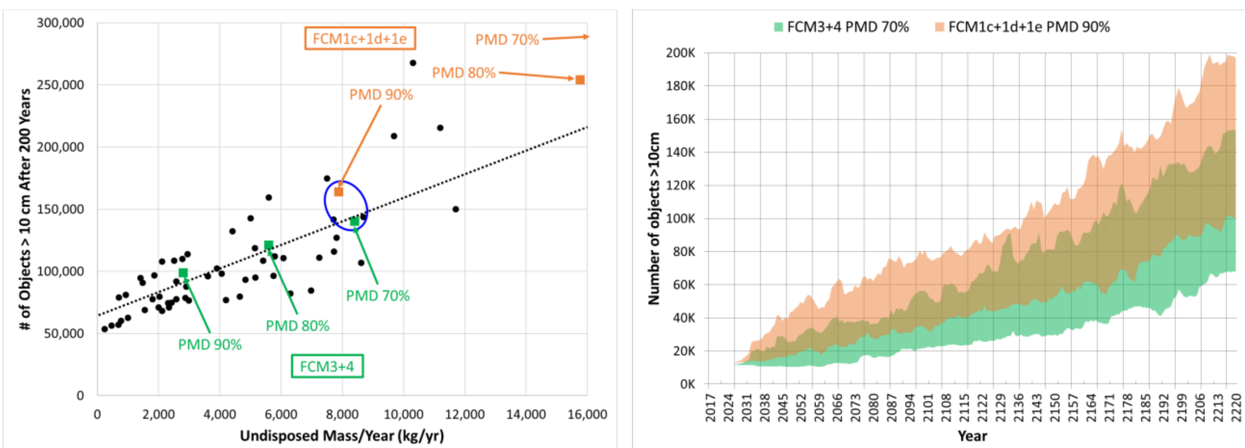

Figure 9. (a) # of objects > 10cm after 200 years with some FCM/PMD cases labeled, (b) Overlap of object count over 200 years of two different sceanrios with varying PMD success rate

Although UMPY does not account for terms like satellite area and altitude directly, these effects may be included indirectly and/or appear minor relative to the other factors. For example, satellite mass and area are correlated. In general, as mass increases area increases too so both parameters tend to move in the same direction with respect to their effect on the debris environment. This may be why undisposed mass and area show similar correlation with number of future objects. The effects of these factors may be relatively smaller, but they can be seen in the results indicating that the modeling still captures them. Figure 10 zooms in on data representing very similar scenarios vs. the mean trend line. This is the FCM1-only scenario, plus the cases that add one other FCM, at 70% PMD success rate. In each case, adding another FCM increases UMPY by the same amount as that constellation by itself. Adding the Small Constellations increases UMPY the least and adding FCM4 increases UMPY the most. All scenarios follow the trend line fairly closely, but characteristics other than mass cause some deviation from the linear trend.

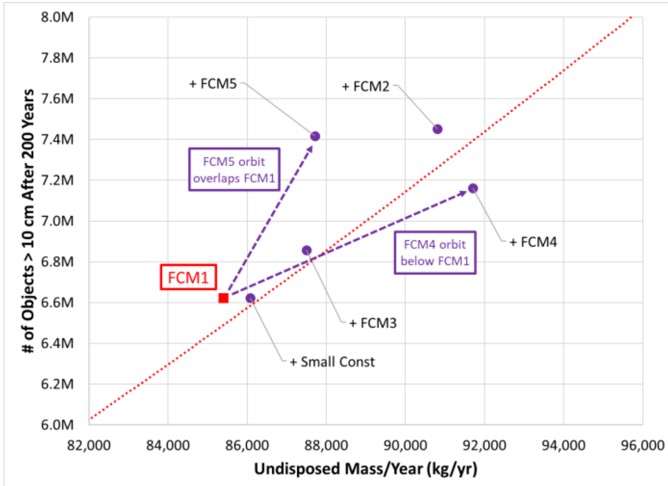

Figure 10. FCM1 plus one more FCM, zoomed-in on mean object count vs. UMPY

The most likely reason is constellation altitude overlap. Referring back to Table 1, the FCM1 shells span a range of altitudes from 1110 km to 1325 km. The only other FCMs that have altitudes that lie in that range are FCM2 and FCM5. It is possible that the higher than average impact of addition these constellations is due the overlap between the constellations' altitudes. FCM3 is well above that range at 1400 km, and FCM4 and the Small Constellations are all well below. The overlap in orbital altitude, or lack thereof, is likely influencing the future environment impact [15][16], albeit to a much smaller degree than UMPY alone.

The major impact of altitude is the amount of time that an undisposed object will remain in orbit. For satellites in lower orbits, below 600-650 km, the undisposed satellites will reenter within 25 years and so will naturally have an UMPY value of zero. For satellites that are in higher orbits, higher than 700-800 km the lifetimes are a significant portion of or more than the simulation time so which specific altitude they are in does not affect their orbital lifetime in a way that would manifest in the simulation. It is just satellites in the intermediate altitudes at which the lack of inclusion of orbit altitude in a parameter like UMPY might not completely reflect their environmental consequences. This is the case for some of the satellites in the "small constellations" group. It is useful to note that these variations form the average trend are still well within the associated uncertainties.

6 CONCLUSION & FUTURE WORK

Various future large constellation scenarios, effectively space traffic activity levels, are parameterized by computing UMPY, a measure of how much mass will be left in non-compliant disposal orbits based on PMD success rate. This parametrization enables general observations about the relationship of satellite operator behavior to debris environment evolution. The goal is to identify parameters that are more effective at "drawing a line in the sand" for defining acceptable behavior for a range of levels of activity, versus creating altogether different rules for large constellations where defining the threshold for those rules is technically, and politically, very difficult.

The number of objects on orbit after 200 years correlates well, varying linearly, with UMPY over lower ranges of activity, and quadratically at very high levels of activity. These higher levels of activity with very low PMD reliability are very likely unsustainable, so the focus for realistic future levels of activity should be in the linear range. Potentially achievable PMD success rates (undemonstrated) are 95-97%, which would enable some of the scenarios with larger levels of activity.

Constellation altitudes, planned disposal duration, satellite sizes, and total satellite counts also contribute to the results, but these are often indirectly included, or are second-order effects compared to direct UMPY parameters. The strongest second-order effect after UMPY appears to be the amount of overlap in altitude among constellations in a scenario. The parameters observed to affect future debris are consistent with observations of other studies [8], [12]-[17]. The lesser effects appear to fall within the intrinsic variability of the projections. The scenarios included in this analysis are only a small subset of the possible combinations that can be examined but are sufficient to cover the range of UMPY up to including all FCMs. Still, more work will be done to add as many scenarios as is practical, to more comprehensively understand the space of different feasible constellation configurations and their effects.

Finally, the ADEPT tool and process continue to improve and adapt to the evolving space environment and requirements. As more systems come online and enter the background population, and future FCC filings reveal entirely different levels of possible activity, ADEPT will need to be updated and rerun to keep up with the state-of-the-art. Required PMD success rate levels are also likely to be higher than previously considered, in the 95%-99% range, and the current practice of using 10% step size in PMD will be reduced to something more in line.

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