

GENERATIONAL EVOLUTION OF EXPLOSION PROBABILITY: INVESTIGATING THE INFLUENCE OF MITIGATION MEASURES

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Explosions represent a significant source of debris. Mitigation measures such as passivation have been introduced to reduce this type of fragmentation events. This paper presents a rigorous analysis of the evolution of explosion probability throughout the different time periods. The effects of factors such as the orbital and the physical parameters and the launch date on the explosion probability can be studied. Two groups of orbiting objects are investigated: Payload and Rocket Body. Payloads launched after mitigation measures proposed display a significantly lower explosion probability. The same effect cannot be found for Rocket Bodies, pointing to possible regulatory gaps. Orbital and physical parameters are also considered in this work. The newly developed explosion probability matrix outperforms literature models on orbital and mass distribution. The p-matrix developed in this work can be used in long term debris simulations and can serve for updating Active Debris Removal prioritisation based on intrinsic explosion risk. The effect of mitigation measures on long-term space debris evolution is also studied.

INTRODUCTION

The first satellite breakup in 1961 increased the total number of objects around the earth instantaneously by 400%.¹ Today, nearly 1/3 of all breakup events are due to explosions. While the main source of space debris is still coming from collisions, explosions pose a serious risk of creating many fragments, which then in turn increase the collision risks. To quantify the severity of an in-orbit breakup, Letizia et. al (2017)² presents the ECOB index (Environmental Consequences of Orbital Breakups). The ECOB has the structure $p \times e$, where p indicates the probability of an object breakup and e the severity of that breakup. The severity of the breakup is influenced by the mass of the spacecraft, its semi-major axis and the inclination. The probability p is estimated by normalising the number of events with the number of objects launched in the same time period. This work demonstrated the major role explosion probability plays in long term environment evolution. In recent years mitigation measures to combat space debris have been introduced. Specifically, passivation is meant to lower explosion risks by burning left-over fuel or emptying the batteries. Besides passivation, Active Debris Removal (ADR) is a popular mitigation measure for the future. Studies have shown that to stop the exponential growth of space debris, about 5 objects per year would have to be removed from the environment.³ The effect of these mitigation measures are

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subject to investigation in this work. Other studies model explosion probability as a fixed rate per object class, based on the time spent in orbit. This does not consider when the object was launched. Starting from the ECOB index, the THEMIS (Tracking the Health of the Environment and Missions in Space) approach was developed in Colombo et. al (2023)⁴ by Politecnico di Milano to build a software tool to evaluate the environmental impact of a mission on the space environment. In THEMIS, the probability of explosion is modelled with two statistical indicators from survival analysis:⁵ the Nelson-Aalen model⁶ and the Kaplan-Meier⁷ indicators that evaluate the probability of explosion based on statistical data. This approach is also implemented in Politecnico di Milano's long-term debris evolution model COMETA (Continuum Mechanics for debris Environment Analysis),⁸ which will be used in this paper for analysis. Similarly, Hawkins et. al (2025)⁹ use survival analysis to extract explosion probabilities as a function of days in orbit, separated by object class. Manis et. al (2025)¹⁰ derives a time-dependent explosion model based on a parametric rate function. Considering only the days spent in orbit ignores passivation efforts and technological advancements. This work aims to answer three main research questions.

- How do the different models developed for explosion probability compare?
- What effect did passivation measures have on the explosion probability?
- What are the influences of orbital geometry and mass on the explosion probability?

Our here presented study presents a rigorous quantification of how explosion risk evolves across different regulatory and technology areas using the ESA DISCOS database¹¹ to retrieve the object characteristics. Explosion events caused by outside actions such as anti-satellite tests, deliberate explosions and collisions are excluded. These explosion events are not caused by an intrinsic explosion risk or influenced by mitigation measures such as passivation. An overview of the explosion categories as defined in the ESA DISCOS database can be found online.¹² To identify eras of interest, important milestones in space debris mitigation are considered. For preliminary analysis, the eras displayed in Fig. 1 are defined.

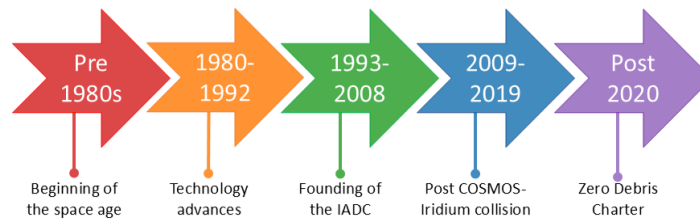


Figure 1: The timeline used for separation of explosion events in different launch eras. Important events in space debris mitigation history were used as an indicator.

EXPLOSION PROBABILITY MODELS FOR SPACE ORBITING OBJECTS

This work uses terminology from survival analysis. This is a tool to analyse the time until a specific even of interest occurs. It comes from the medical context, where it is used to quantify quantify the time to death (in this context: time to explosion). A comprehensive overview can be found in Clark et. al (2003).¹³ The main quantity referenced in this work is the survival function

$S(t)$. It represents the probability that an object remains intact at least until a time t . It is connected to the cumulative probability $P(t) = 1 - S(t)$. In this work three different models are compared. The first one is the model based on the Kaplan-Meier estimator, as included in the THEMIS and COMETA models, developed by Politecnico di Milano in Colombo et. al (2023),⁴ which from here on is referred to as the "PoliMi model". The Kaplan-Meier estimator is a stepwise, non-parametric approximation of the survival function, based on observational data. It is defined as seen in Eq. 1.

$$S_{KM}(t) = \prod_{i: t_i \leq t} \left(1 - \frac{d_i}{n_i}\right), \quad (1)$$

where d_i describes the number of deaths at time t_i and n_i the number of subjects that have survived until t_i . As a second model, the cure mixture model approach modelled by Hawkins et. al (2025), referred to as "ESA model" is investigated. The ESA model applies a cure-fraction to the population. This means that only a certain % of the population is given the ability to explode. The survival curve can be calculated with Eq. 2.

$$S_{ESA}(t) = (1 - p) + p \cdot S_0(t), \quad (2)$$

where S_0 describes the survival curve obtained by only those objects that have exploded. After a certain time this goes towards zero and the survival curve stabilizes at the p value. Finally, the parametric rate model from Manis et. al (2025),¹⁰ referred to as "NASA model" is considered. Here, it is assumed that explosions follow a non-homogenous Poisson probability. The probability of surviving up to a time t can be described by Eq. 3.

$$S_{NASA}(t) = \exp \left[- \int_0^t \lambda(u) du \right] \quad (3)$$

The λ hazard rates are determined by a maximum likelihood (MLE) fit to the observed explosion times, separated by object class. The resulting survival curves for each model can be seen in Fig. 2.

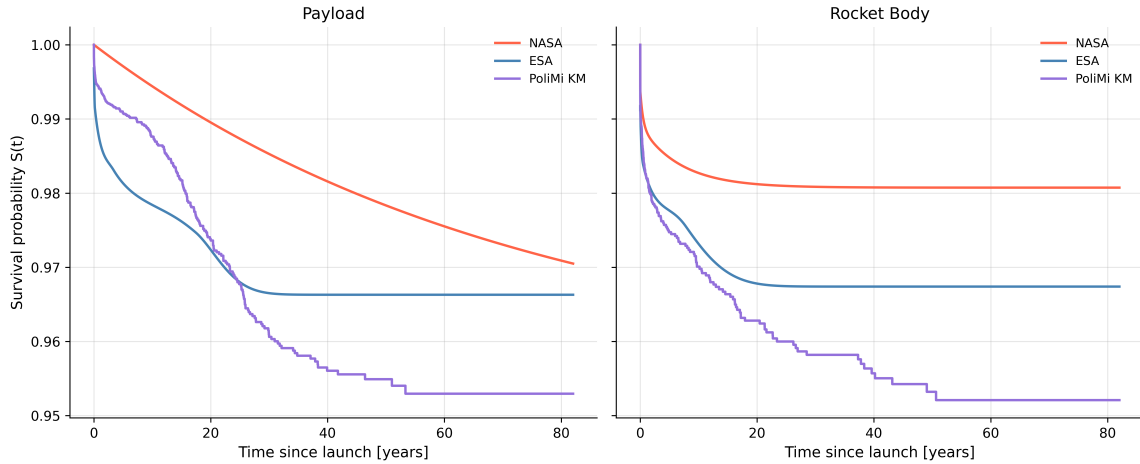


Figure 2: Survival probability of Payloads (left) and Rocket Bodies (right) over the span of 80 years for the different models

For the PoliMi model, the step function structure of the Kaplan-Meier approach can be observed. The ESA survival function displays a stark drop in the beginning. This is due to the fact that most

objects explode early in their lifetime (see also **HISTORICAL ANALYSIS**). The NASA model shows a much slower and more continuous decay rate. The ESA and NASA model plateau, reflecting that some objects may never explode. For the Payload objects this plateau happens after the 80 years plotted here. When considering explosion events in the context of space debris modelling there are two questions that need to be answered: with what probability p can the object explode and if it explodes, when does it explode? All models approach the first question in a similar way. In the long term simulation, Bernoulli sampling based on the object type is used to decide whether an object will explode. The probability p of explosion is slightly different across the different models. The NASA and ESA model consider a constant explosion probability by object class. The PoliMi model defines a time-dependent explosion probability, based on the survival curves. The explosion probability can be defined as $P(\Delta t) = S(t_1) - S(t_2)$. Since the THEMIS framework evaluates the explosion probability at each time step, this formulation is useful when considering the explosion probability of a single mission. As the survival curve stabilises, the explosion probability decreases and eventually goes towards zero. In this way, the PoliMi model answers both the questions of if and when with the same survival curve. ESA and NASA instead will always have constant explosion probabilities. In the following Tab. 1 the main assumptions of each model are summarised.

Table 1: Comparison of explosion models.

Model	Method	Payload	RB	Timing model
PoliMi ⁴	Kaplan-Meier	$P_{PL}(t)$	$P_{RB}(t)$	Bernoulli trial using $\Delta S_{KM}(t)$
ESA ⁹	Cure-mixture	0.0337	0.0326	Explosion-only survival curve $S_0(t)$
NASA ¹⁰	Poisson & parametric rate fit	0.044	0.019	MLE fit with fast/medium/slow decay modes

ESA and NASA report slightly different explosion probabilities due to slightly different data sources. Furthermore, NASA has divided the rocket bodies into two separate categories: Russian Sistema Obespecheniya Zapuska units and other rocket bodies. Furthermore, these methods do not take the effect of mitigation measures into account. The reduction of explosion probability is a question of investigation in the here presented work. By analysing historical data, the influence of parameters such as altitude, mass, and launch era on the explosion risk can be quantified. This raises a key question: is explosion risk primarily driven by object-specific characteristics, or by technological and regulatory generation?

HISTORICAL ANALYSIS

To properly quantify the effect of orbit, mass and launch era on the explosion probability, an historical analysis of the explosion events is performed. This section describes the necessary data preparation and the results from the analysis.

Data preparation

For the analysis the ESA DISCOS¹¹ database is used. For this analysis two categories of orbiting objects are considered: Payloads and Rocket Body. The mission related objects are counted together

with the corresponding category. The 15 largest constellations are filtered out as described in.¹⁴ Explosions in constellations have so far rarely been reported yet. Only the Starlink constellation has had two explosions so far.¹⁵ A technical fault in a constellation satellite would have an immense impact on the environment, due to the large amount of satellites. Consequently, for this analysis, constellations are filtered out. The DISCOS database provides both an overview of the objects in space and the explosion events. For the survival analysis one large file is created matching the explosion events to the catalogued objects by using the DISCOS ID. For a real object it is possible to explode multiple times; however, in the context of survival analysis an object is dead once it has exploded once. There are two possible ways to handle this: consider only the first explosion event or keep all explosion events. Since for space debris modelling the number of explosions is most important, all explosion events are kept. In practice this means that in a simulation context the explosions are more spread out throughout the objects. The time until explosion (in days) is calculated by comparing the launch epoch to the explosion epoch.

Further parameters of interest are the mass of an object, the orbit type and the launch era. These parameters are not available for all objects catalogued in DISCOS. While the launch era information is complete, not all objects have information about their mass or their target orbit. Therefore, the analysis is divided into two steps: first only an analysis based on the time spent in orbit is considered, then the objects without orbital information are filtered out to get a conditional explosion probability. This slightly reduces the dataset but allows to analyse the effect of the orbit on the explosion probability. The orbit is defined by altitude and eccentricity. Objects with an eccentricity exceeding 0.6 are classified as highly elliptical orbits (HEO). For the remaining objects, classification proceeds by altitude: below 2,000 km as low Earth orbit (LEO), between 2,000 km and 35,786 km as medium Earth orbit (MEO), between 35,786 km and 45,000 km as geostationary orbit (GEO), and anything else as other. For reference the data used for all further analysis is presented in Tab. 2. The explosion probability is defined as seen in Eq. 4.

$$p = \frac{\text{Explosion Events}}{\text{Total Objects}}. \quad (4)$$

Table 2: Explosion Statistics by Object Type

Type	Total Objects	Objects Exploded	Explosion Events	Explosion Probability
Payload	11708	281	336	0.0287
Rocket Body	7549	198	203	0.0269

The effect of mitigation measures

To quantify the effect of mitigation measures, the explosion events by launch era are investigated. In Fig. 3 an explosion probability matrix for payload and rocket bodies by launch era is presented. The figure also shows how many objects were launched in each era for each category, excluding constellation launches. Payload explosion probability is highest for objects launched during the cold war era in the 1980s and drops sharply after the formation of the IADC in 1993. Investigating the data in more detail demonstrates that a large portion of the explosions recorded for objects launched in the 1980s comes from COSMOS satellites.

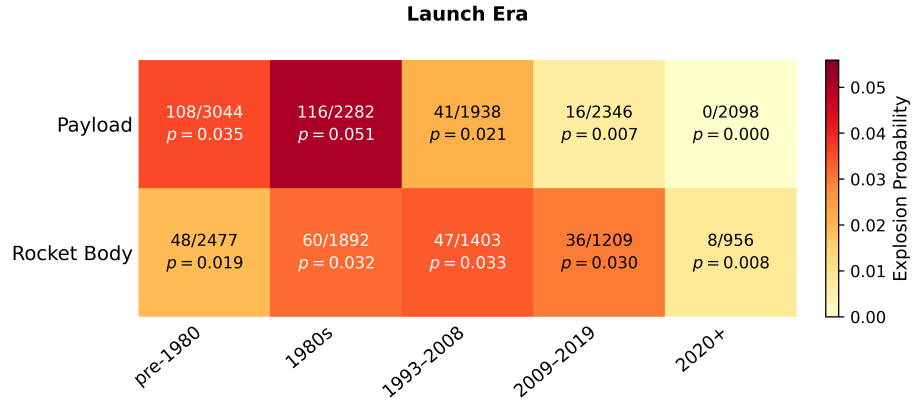


Figure 3: Explosion matrix by launch era

For objects launched after 2020 it is possible that the objects have not exploded "yet". An analysis of explosion events by days spent in orbit, as shown in Fig. 4, shows that most objects explode within the first 2000 days (≈ 5.5 years) of their lifetime. Still, the 2020+ panel includes very recently launched objects.

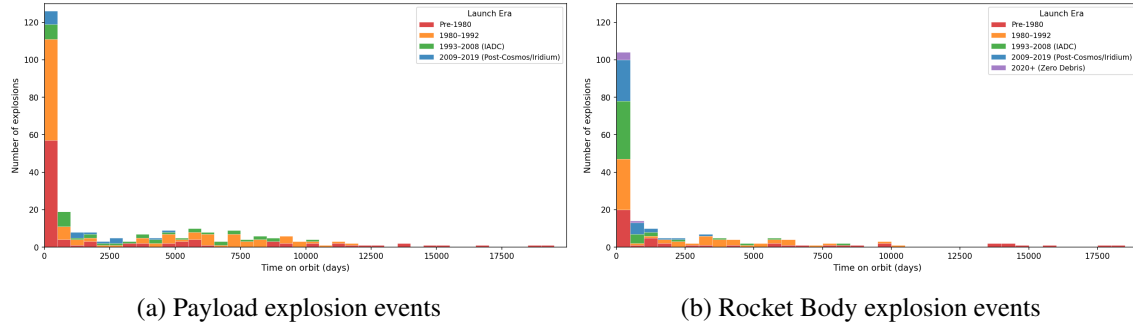


Figure 4: The raw explosion counts depending on the days spent in orbit. They are further divided by launch era to investigate generational effects.

Looking at payload objects and only considering the average explosion probability pre 2008 ($p_{\leq 2008} = 0.036$) and the explosion probability between 2009-2019 ($p_{2009-2019} = 0.007$) the reduction of explosion probability by 80% is notable. For rocket bodies instead there is even a slight increase of 7.1% ($p_{\leq 2008} = 0.028$, $p_{2009-2019} = 0.030$). The most recent rocket body explosions are mainly made up by rockets coming from China (17/36 between 2009 and 2019). These explosions are classified as a propulsion event, but no further information is available. It might be that they have a technical problem with their rockets, or that they do not use passivation measures. In a report submitted to the United Nations Committee in June 2026 the Chinese Space Agency said it complies with all post-mitigation guidelines.¹⁶ A study done by LeoLabs¹⁷ states that China uses bigger rockets than most nations. This could mean more fuel is stored, which in turn increases the explosion risk. The same study also reports a pattern of abandonment of Chinese rockets in low Earth orbit. In the end, the exact cause for these explosions remain unknown. In conclusion, the analysis shows that the assumption of a 90% reduction of explosion probability is

very optimistic. Rocket bodies still explode at the same rate. This needs to be considered in space debris environment simulations and also poses the question of how rocket body explosion can be mitigated.

The effect of orbit and mass

Besides the launch era, the effect of the orbital region and the mass of the object is investigated. As previously mentioned, here only the data for which orbital region and mass are known are investigated. Each panel shows both the explosion events and the total number of objects that are in the category. The results are presented in Fig. 5.

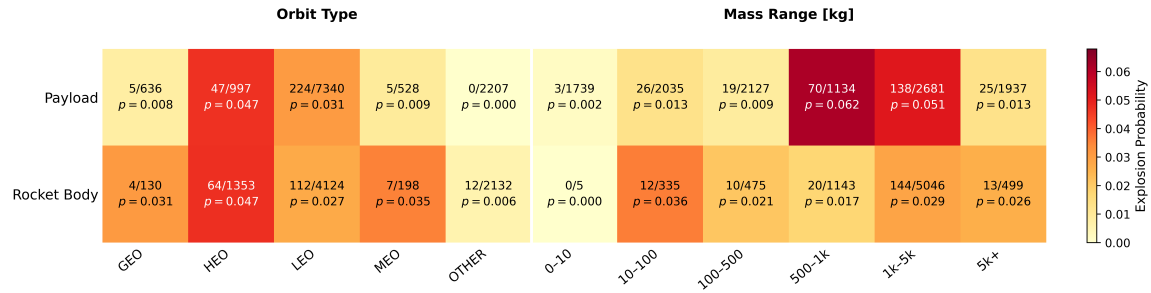


Figure 5: The probability of explosion based on orbit type (left) and mass range (right)

In terms of orbit the HEO region shows the highest probability of explosion for both payloads and rocket bodies. This could be due the fact that highly elliptical orbits spend more time in the Van-Aalen Belts and are thus exposed to more radiation. The trajectory further means very different temperature regions. LEO is a highly populated orbit, exposed to atmospheric drag and thermal cycling. GEO being the lowest orbital region in terms of explosion probability could be due to the fact that there is a strong incentive to passivate the vehicles at the end of life, since there is limited slot availability. In terms of mass, payloads with mass ranges between 500-5000 kg show the highest explosion probability. These payloads probably have the highest energy stored in terms of residual propellant. Furthermore, they might also consist of large legacy spacecrafts, which were launched before passivation measures were introduced. Interestingly, objects larger than 5000 kg show a reduced explosion probability. They might have received a more careful end-of-life planning. The analysis in terms of launch era, orbit type and mass range show significant differences in historically observed explosion probability depending on these parameters. Especially for payloads the difference is notable. Rocket bodies show a more or less consistent explosion probability across all different parameters, the main increase being in HEO. The effect of an explosion on the environment is highly dependent on orbital region and mass. The differences observed here give a strong indication that not all objects should be assigned the same explosion probability. In the next step, an extended explosion model is developed and compared with the already existing models.

EXTENDED EXPLOSION MODEL

The historical analysis demonstrated that for payloads, orbit, era and mass play a significant role when estimating the explosion probability. The challenge is to translate these findings into a statistically relevant explosion probability. Combining five different launch eras, five different orbital regions and five different mass classifications into one explosion probability matrix would

result in combinations with very sparse objects and elements, making the results not statistically robust. Consequently, for the further analysis only mass and orbit are considered when assigning an explosion probability to an object. To simplify, only three mass ranges are considered: light, medium and heavy objects. In terms of orbit LEO and non LEO objects are split. While the HEO region historically showed a higher explosion probability, adding this as a dimension together with the mass bins produced very sparse bins. Validating the p-matrix against historical data showed better results when not including HEO. The sample size here is the limiting factor. The signal is not strong enough to improve forecasting accuracy. Additionally, empirical Bayesian smoothing is applied to stabilize estimates in sparsely populated cells. The explosion probability per cell is defined as seen in Eq. 5.

$$p_{cell} = \frac{n_{cell}^{expl} + \alpha \cdot \bar{p}}{n_{cell}^{total} + \alpha} \quad (5)$$

where $\bar{p}$ is the mean explosion probability and $\alpha = 80$ is the smoothing strength. Cells with few observations are shrunk towards the class mean, preventing extreme estimates from small samples while leaving well-populated cells unaffected. In this way, a 2x3 explosion probability matrix for each object class is created, as can be seen in Fig. 6.

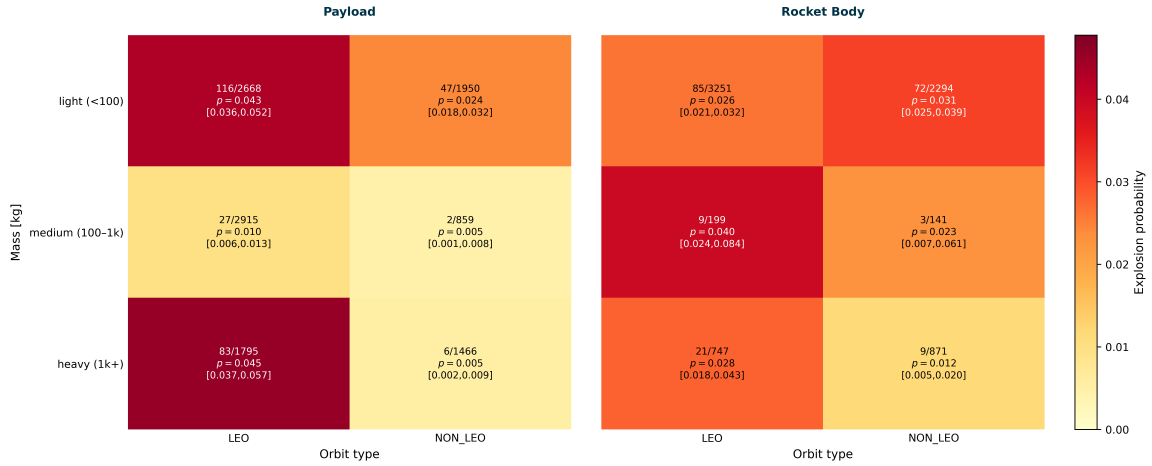


Figure 6: The p-matrix created for the simulation, combining the effect of LEO and non-LEO orbits with three mass ranges. Payloads are presented on the left side and rocket bodies on the right.

After deciding if an object has the ability to explode the explosion time is based on the $S_0(t)$ survival curve of exploded objects, separated by payloads and rocket bodies. In this way a cure model is assumed, where the cure fraction depends on the object characteristics.

MODEL COMPARISON

The launch traffic from 1990-2023 is considered to compare the different models. A stand-alone explosion module is run 50 times, where for each model there is a Bernoulli trial to decide if the object can explode. If it explodes an explosion time is sampled from the survival curves presented in Fig. 2. The main differences here are the explosion probabilities p , that decide if an object can explode. For the ESA and NASA model these are static values, as presented in Tab. 1. The PoliMi

model calculates the explosion probability for each object at each time step. The newly developed p-matrix uses the characteristics of the object to assign an explosion probability $p(\text{orbit}, \text{mass})$. Then, depending on the shape of the survival function an explosion epoch is assigned. The p-matrix uses the survival curve of the exploded objects per class. For all of these models, the values are compared to the actual historical explosion events. The first thing to investigate is the projected explosions per year compared to the historical data. This result is presented in Fig. 7. In Fig. 7 the

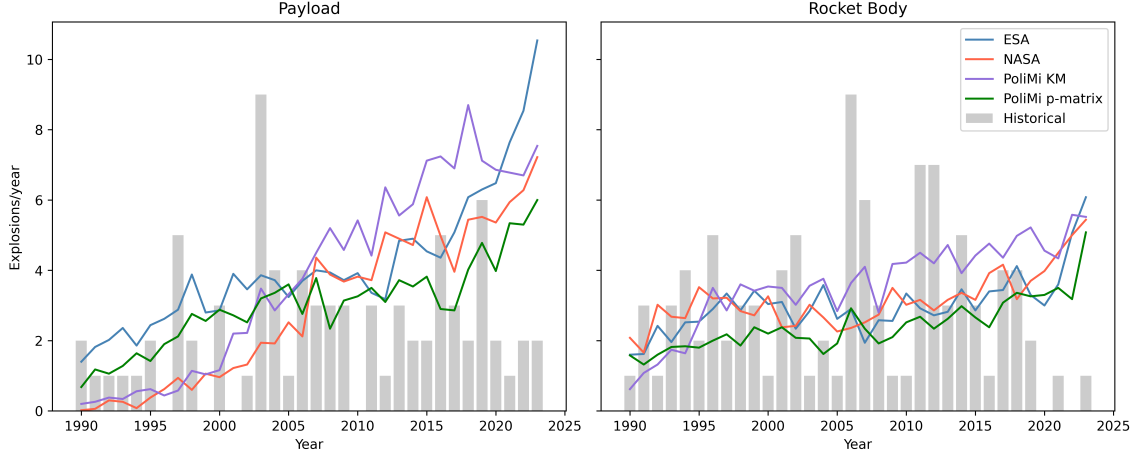


Figure 7: The historical number of explosions per year compared to those predicted by the different models for payloads (left) and rocket bodies (right).

explosions per year are depicted. Notably, all models predict a growing number of explosions. This is because, in this formulation, the number of explosions is predicted to scale with the number of launches. Since the explosion probability is defined irrespective of launch year and mitigation measures, with growing number of objects a growing number of explosions is expected. The historical data shows that this is not the case and the actual explosions per year are more steady. As already discussed, mitigation measures and technological advances are having a clear effect and should be considered when modelling explosions for future environment simulations. All models show very similar expected explosions per year. Besides that, also the orbital placement of the objects and the mass of the objects should be compared to the historical distributions. From this point, on the analysis is performed on both Payload and Rocket Body explosions combined. In Fig. 8 the mass distribution of the explosion events is depicted. All models place most explosions into the heavy category. Likely, most launched objects fall into that category. Additionally to the simple mass distribution, also the combination of orbit and mass is of interest. Two metrics are used to evaluate how well each model reproduces the historical explosion distribution, with the result presented in Tab. 3. The Jensen-Shannon divergence (JSD) measures the similarity between two probability distributions, ranging from 0 (identical) to 1 (completely dissimilar); it is computed separately over the orbital and mass distributions of simulated versus historical explosions. It is computed as two separate 2D distributions, measuring similarity in terms of (SMAxECC) and in terms of (SMAxmass). In this way not only the general mass distribution of the explosions, but also the distribution of fragmented mass in the correct orbits is quantified. The Earth Mover’s Distance (EMD, also known as the Wasserstein distance) quantifies the average displacement required to transform one distribution into another, here expressed in kilometres of altitude difference, making it a physically intuitive measure of orbital placement accuracy. Together, JSD captures distributional shape similarity and

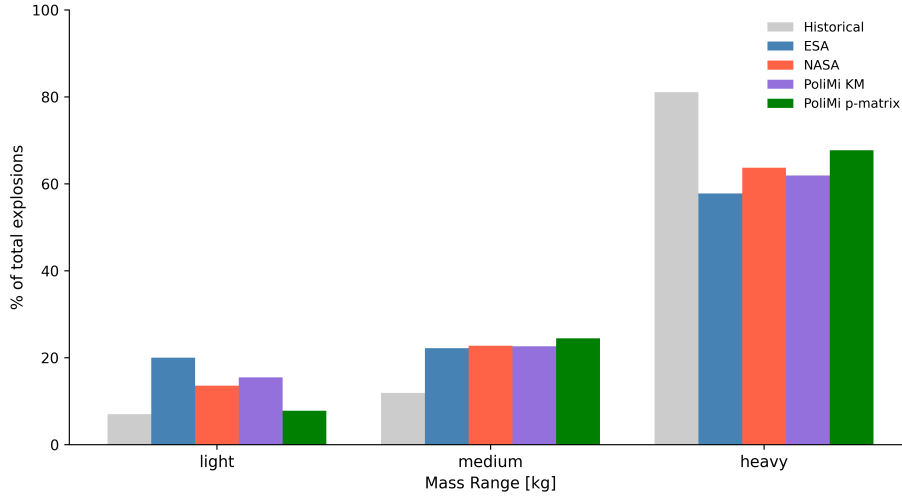


Figure 8: The mass distribution as a function of percent of the total explosions for the different models

EMD captures spatial fidelity.

Table 3: Model comparison against historical explosion data for objects launched between 1990–2025 and simulated until 2025. Best-performing value in each metric is shown in bold.

Model	Exp. (PL)	Exp. (RB)	JSD (SMA×ECC)	JSD (SMA×mass)	EMD [km]
Historical	80	99	–	–	–
ESA	140.2	102.8	0.252	0.302	2417
NASA	101.3	107.3	0.257	0.273	2963
PoliMi	131.4	122.5	0.252	0.284	2790
p-matrix	103.0	82.9	0.233	0.264	1631

While the general mass distribution in Fig. 8 showed similar results across the models, the combination of SMA and mass clearly identifies the p-matrix model as the best performer. No single model dominates the expected explosion counts: ESA most closely reproduces the rocket body total (102.8 vs. 99), while NASA best matches the payload count (101.3 vs. 80), though both overestimate payloads relative to history. PoliMi consistently overshoots both classes. In contrast, the p-matrix achieves the best distributional agreement across all three scored metrics. Its JSD of 0.233 on the SMA×eccentricity distribution indicates that it places explosions at the correct orbital regimes more faithfully than the reference models, and its EMD of 1631 km, roughly half that of ESA and PoliMi, confirms that the predicted explosion altitudes are systematically closer to the historical record. The SMA×mass score further shows that the p-matrix correctly associates the right object sizes with the right orbital altitudes, a relationship the simpler scalar-probability models cannot capture by construction. The main weakness of the p-matrix is its underprediction of rocket body explosions (82.9 vs. 99). While constructing the probability matrix, the rocket body matrix has had a few sparse bins. It might be beneficial to collapse the complexity of the rocket body matrix further.

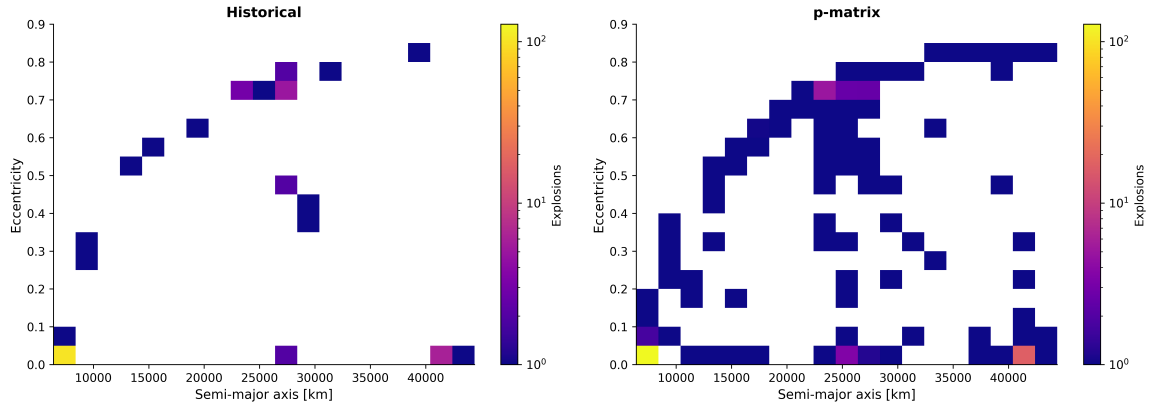


Figure 9: Historical (left) and p-matrix (right) explosion distributions in SMA-ECC space

Fig. 9 compares the historical and p-matrix explosion distributions in the SMA–ECC space. Both panels share the same logarithmic colour scale, allowing direct comparison of explosion counts across orbital regimes. The historical distribution is sparse and highly concentrated: the dominant cluster appears at low eccentricity and low SMA, corresponding to LEO objects, with a secondary concentration at $e \approx 0.7$ – 0.8 and $SMA \approx 20000$ – 28000 km, consistent with Molniya-type highly elliptical orbits. A small isolated cluster near $e \approx 0.0$ and $SMA \approx 42000$ km corresponds to GEO. The overall sparsity reflects the limited number of observed historical fragmentation events. The p-matrix prediction reproduces the three main clusters correctly, which is reflected in its low EMD of 1631 km. However, it spreads probability more broadly than the historical record, populating intermediate SMA and eccentricity bins that are empty historically. The model assigns non-zero explosion probability to all objects regardless of orbital slot, which historically is not true. With the main clusters reproduced, the p-matrix is the best candidate to model future explosions.

IMPLEMENTATION IN COMETA

After the validation of the p-matrix against historical data the p-matrix is implemented in the long-term debris evolutionary model COMETA.⁸ This model operates in LEO, so the separation by orbit type will not have an effect here. Instead, what these simulations show is the extrapolation of the current passivation success in long-term debris evolution. Two different scenarios are considered. The first scenario reflects what has been assumed so far: no mitigation measures implemented, just the p-matrix is used to determine the explosion probability and the new launches are expected to explode with the same rate as the older objects. The second scenario implements a passivation effect as a tunable parameter. In this way, the application of mitigation measures and their effect can be assessed in long term simulations. The explosion probability is reduced or increased by X%. The explosion probability is calculated as shown in Eq. 6. The ability to define passivation success rates is also described for the DELTA model by ESA,¹⁸ but no result of the effect of different rates on the environment are presented.

$$p_{exp} = (1 - X)p_{matrix} \quad (6)$$

The simulation runs between 2025-2050, using an 8-year historical launch traffic for Payload and Rocket Bodies from 2016-2024. Constellations are not considered. Collisions are possible between active objects and debris objects, but no intact-intact collisions are considered. A post-mission

disposal of 25 years is assumed with a 90% success. Previous studies have investigated the effect of passivation measures^{19–21}, which demonstrated that passivation alone cannot stop the exponential debris growth. This study specifically studies the effect of the passivation success observed in the historical analysis: Payload passivation success is set to 80%, for Rocket Body a negative effect is assumed. The explosion probability for rocket bodies is set to -10%. For each scenario 20 simulations are performed. The results are presented in Fig. 10.

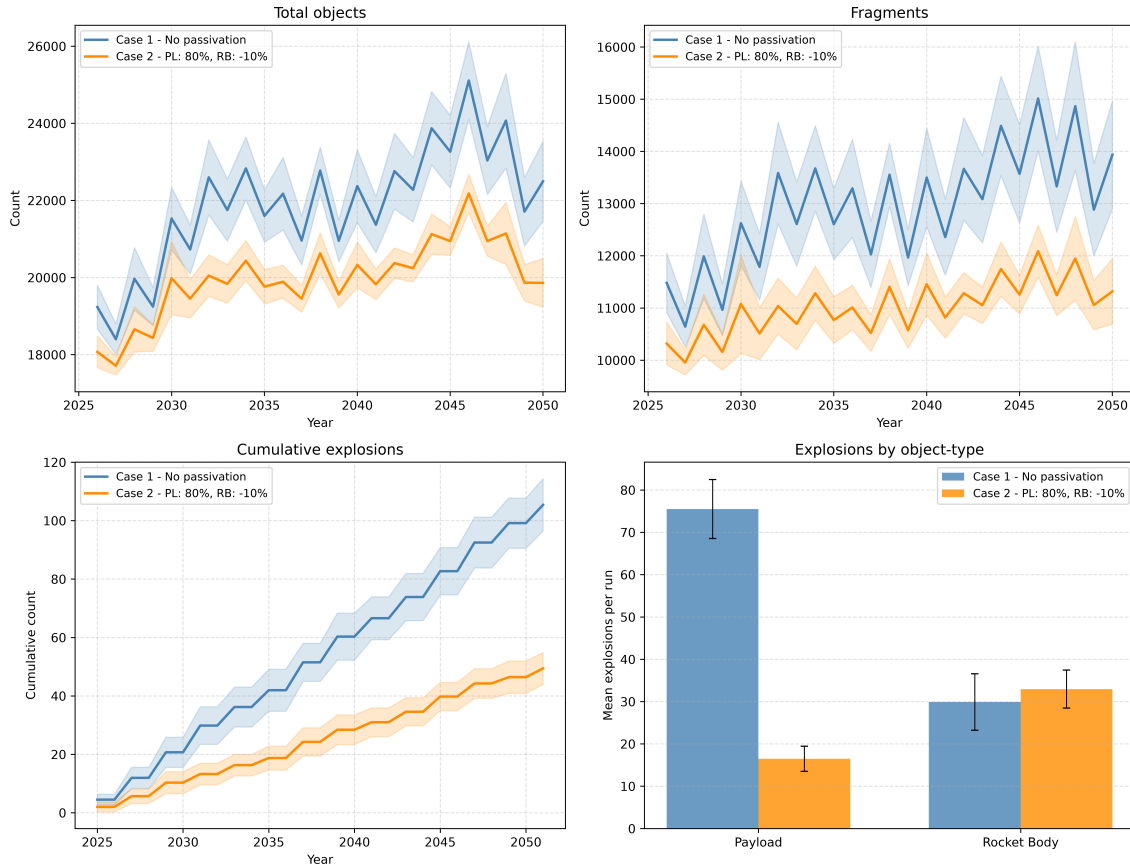


Figure 10: The effect of passivation measures demonstrated in COMETA. Displayed are the total objects (upper left), the number of fragments (upper left), the number of explosions (lower left) and the explosions by object type (lower right).

The simulation results presented in Fig. 10 demonstrate the substantial impact that passivation has on the future environment evolution. Depending on the success of passivation the number of fragments changes drastically. A higher passivation success rate reduces the occurrence of on-orbit explosions, thus leading to a slower growth of the debris population over time. This trend is reflected in the total number of objects (upper left) and the lower fragment count (upper right). The extrapolation of the current success of passivation measures with an 80% passivation success for Payloads and -10% increase for rocket bodies can be seen in the lower right corner. Since rocket bodies store a large amount of residual propellant, improving passivation success for these would improve the space debris environment further. These results highlight that passivation is one of the most relevant post-mission mitigation measure for limiting long-term debris generation. While it

cannot prevent collision-induced fragmentations, it reduces the future debris population and thus mitigates the risk of cascading fragmentation events.

OUTLOOK AND CONCLUSION

This work offered a comprehensive comparison of explosion probability models developed by the different entities. The literature model all perform similarly, with slightly different assumptions on the probability of explosion and the time of explosion. None of the models consider orbit or mass, even though this directly impacts debris generation. The introduction of a p-matrix, which describes probability as a function of mass and orbit regimes has significantly improved the capabilities to predict orbital and mass distribution of exploded objects, especially for Payloads. The effect of these explosions in different orbit and mass regimes is subject of future studies. In particular, the THEMIS framework will be used to investigate how these characteristics influence the index of a mission. The comparison of historical explosion events to those generated by the models in Fig. 7 demonstrated that simply assuming explosion probability scales with launch rate is not correct. A passivation success of X% is introduced and implemented in the long-term debris environment model COMETA. The historical analysis performed in this work showed that for Payloads a reduction of about 80% is realistic. Rocket bodies instead even displayed a higher explosion probability in recent years. This result suggests passivation efforts have been more successful for Payload objects. This might point to a regulatory gap, where mitigation guidelines can still be improved. To quantify the effect of passivation on the long-term environment evolution two simulations were performed: one without any passivation measures and one with passivation measures mirroring the historical findings. The difference in environment evolution, displayed in Fig. 10, highlighted the importance of passivation measures. Historically, with Payloads we are on a good path with implementing passivation measures and thus reducing explosion risk. In future works different passivation success rates will be investigated and its effect will be compared to the effect of post-mission disposal success. The formulation of a p-matrix could also be useful for ADR prioritisation strategies, as these often rely on physical object characteristics. Objects that were launched in a pre-passivation era pose a higher risk of explosion and should therefore be removed earlier. In Borelli et. al (2025)²² a ranking framework for active debris removal candidates based on environmental, economic, operability and mission related characteristics is developed. This framework could be extended with the explosion probability based on launch era and the sensitivity of the index to the explosion probability could be investigated.

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