6. END-OF-LIFE OPERATIONS HISTORY

Post mission disposal mitigation measures are specifically aimed at reducing the long term interference an object in the space environment could have on the two protected regions, LEO_{IADC} and GEO_{IADC}. These mitigation measures are associated with time criteria, i.e. so-called orbital lifetimes or clearance of orbital regions, and hence require evaluating the long term evolution of orbits. For both protected regions, different mitigation measures imply different end-of life operations. The reported years for payload clearance of LEO_{IADC} goes up to 2023, for rocket body clearance of LEO_{IADC} goes up to 2024, and for payload clearance of GEO_{IADC} goes up to 2024.

6.1. End-Of-Life Operations in Low Earth Orbit

Due to the presence of atmospheric drag in the lower levels of the LEO region, a natural cleansing of space debris from these regions occurs. A payload or rocket body operating in the LEO Protected region, with either a permanent or periodic presence, shall limit its post-mission presence in the LEO Protected region to a maximum of 25 years from the end of mission, or significantly shorter [9]. This limit by itself will not lead to a long-term reduction in the amount of space debris, as will be shown in Section 7.2, but is an important step towards limiting the space debris growth rate in LEO_{IADC} [14]. In this context, there is also growing consensus that stricter mitigation practices need to be implemented globally, and in 2023, ESA released its Space Debris Mitigation Standard and associated policy [3, 4]. Among the measures introduced by this Standard, was the reduction of the post-mission maximum lifetime limit from 25 down to 5 years. Specifically, the Standard requires that the orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions: first, that the orbit lifetime is less than 5 years; and secondly, that the cumulative collision probability from end of life until re-entry with space objects larger than 1 cm is below 10^{-3} [3]. While this is only binding for ESA projects, one goal of the Zero Debris Approach is to lead by example, and thus compliance to both the 25- and 5-year thresholds is reported on here, in Sections 6.1.2 and 6.1.3 respectively. Various Standards provide an order of preference for methodologies for achieving compliance to these mitigation measures (respectively the so-called *25-* and *5-year rules*) i.e. controlled re-entry, accelerated natural orbital decay, etc.

For catalogued objects, the orbital activity of a payload or rocket body can be derived and the orbital lifetime estimated. This method is preferred over direct investigation, intelligence, of communication with the owners of a payload or a rocket body, which could increase the accuracy of the prediction, but it might be unbalanced as the request for such data might not be answered nor can all owners be clearly identified and approached. As some rocket bodies have been found to perform direct re-entries before they can be considered catalogued objects, additional asserted objects are used as to make sure that such positive cases are correctly considered in the resulting statistics. The methodology to determine the end of the operational phase of an object in LEO employed here is described in depth in [24].

For satellites without orbit control capacity (OCC), i.e. no propulsion system, or for satellites that never exhibited any orbit manoeuvre otherwise, the assessment of the mission end is not possible from orbit information alone. Therefore, a statistical approach is pursued for those objects. The source of the statistics for mission lifetimes are the *measurable* missions with orbit control capacity. Observed mission lifetimes are processed into histograms by mission category, e.g. science, communications, military, etc. They are then applied to generate missions lifetime estimations for the objects without orbit control capacity of the same category.

The boundaries between having an orbital control capacity or not is not always clearly defined by the underlying technology. This is because the effects observed by the space surveillance system may not be reliably discerned in all cases. Impulsive manoeuvres, multi-revolutions use of electrical propulsion, and large drag sail deployments are reliably picked up and hence objects exhibiting those features are categorised as having OCC.

On the other hand, smaller orbital changes, such as drag sailing, where the change in ballistic coefficient is smaller than the error margin or the orbit determination capacity of the space surveillance system, are not picked up. However, the most important metric w.r.t. the implementation is to remove an object from LEO_{IADC} within the maximum lifetime limit, which is measured independently of the OCC categorisation.

In order to estimate the orbital lifetime of an object after reaching its end of life, the general processes as laid out in Standards [13, 3] are followed. To apply these processes to all catalogued objects, a Ballistic Coefficient (BC) needs to be estimated for each of them. The BC estimation is based on least root-mean-square orbit fitting during the longest periods free from estimated manoeuvres, generally after end of life is reached in case of OCC classified objects. In case this can't be achieved, the BC is defined based in the available physical properties in DISCOS.

The lifetime is then assessed for each object by propagating the last orbital state, at the end of 2024, until re-entry in combination with a long-term space weather forecast [25]. The introduction of a 5-year lifetime limit necessitates a probabilistic approach to lifetime estimation that considers the variability of solar activity, a key driver of orbit evolution in LEO, over a full 11-year solar cycle. Therefore, objects with an estimated lifetime of between 5 and 50 years (to ensure robust assessment to both the 5- and 25-year thresholds) are assessed probabilistically by uniformly sampling the solar cycle. In practice, this involves varying the start epoch of the propagation with yearly steps over the 11-year solar cycle. The lifetime used for compliance assessment is then taken to be the median for circular orbits, while the significant influence of the atmosphere on the spread in orbital predictions for eccentric orbits (> 0.3) is captured by using the 90^{th} percentile, according to [3]. The used values and obtained results are stored in DISCOS and distributed on request [10]. The process itself is subject to a significant amount of stochastic assumptions which are described in [26]. Hence, the reported orbital lifetimes are procedurally defined and need to be understood as a *current* best-estimate that can vary between different versions of this report, as discussed in Section 6.1.4.

In case of payload objects, at least one calendar year without orbit control actions needs to pass for an object to be classified as reaching end-of-life unless it performs a controlled re-entry. This is done to mitigate the implications of the detection algorithm described above, and to avoid a potentially large amount of reclassifications in subsequent editions of this report as some operators implement less frequent actions near the end-of-life. In practice, this means that the reported years for the payload clearance of LEO_{IADC} goes up to 2023 instead of 2024.

It is important to note that for this report, where conformance to a time-limitation guidelines is to be evaluated, the categorisation of each object becomes fixed after 25 years. Unpredicted events, such as increased solar activities or missions which actively remove large pieces of space debris, will thus be accounted for only when they materialise.

Relocations from LEO_{IADC} into orbits with a perigee altitude above 2000 kilometres are no longer viable end-of-life debris mitigation practices [9]. While such relocations where relatively rare for Payload objects and only a minor historical entry in the dataset of this section, they have been more commonly used to raise the perigee of Rocket Bodies when, e.g. eccentric destination orbits such as GTO were targeted.

Human spaceflight (HS) related missions are analysed separately, as they skew results in terms of mass and count affected. These missions include crew vehicles as well as cargo payloads, but not the rocket bodies that bring them into orbit.

Throughout this section, *Stage* is used as synonym for *Rocket Body*.

The end-of-life behaviour of space objects can be categorised in seven behavioural classes to illustrate disposal success rates:

- *NCWO: (Not Compliant WithOut attempt)* the lifetime limit is not met by the mission orbit and no disposal action has been taken;

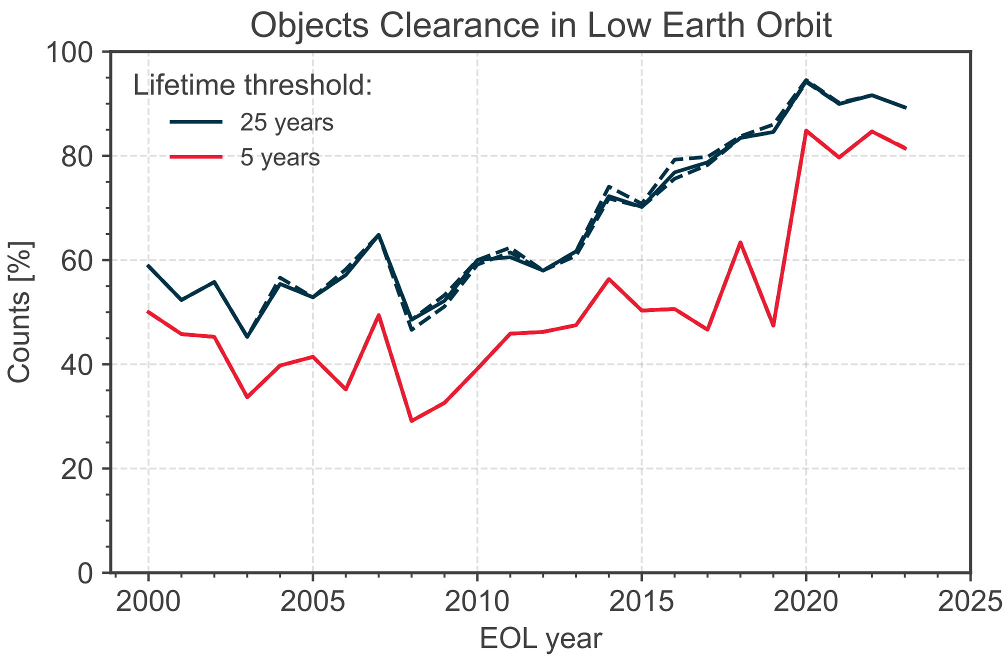
- *NCWFB: (Not Compliant With attempt False Before)* the lifetime limit rule is not met by the mission orbit, a disposal action has been attempted but it was unsuccessful or insufficient;
- *NCWTB: (Not Compliant With attempt True Before)* the lifetime limit rule was met by the initial mission orbit, a disposal action has been attempted but it was unsuccessful or the mission orbit was otherwise altered, and the new orbit is not compliant;
- *CWFB: (Compliant With attempt False Before)* the lifetime limit rule is not met by the mission orbit, but a disposal action has been taken and was successful;
- *CWTB: (Compliant With attempt True Before)* the mission orbit allowed to meet the lifetime limit, but a disposal action has been taken nonetheless;
- *CWO: (Compliant WithOut attempt)* the mission orbit allowed to meet the lifetime limit, no action was taken (nor needed);
- *CD: (Compliant With Direct Re-entry)* a controlled re-entry has been performed.

In summary, clearance of the LEO protected region by payloads and rocket bodies will be presented as *Naturally Compliant* if injected into an orbit that fulfils the 25- or 5-year lifetime measure, *Successful Attempt* when compliant after an attempt to reduce its orbital lifetime, *Insufficient Attempt* when not compliant but having attempted to reduce its orbital lifetime or *No Attempt* when not compliant with no attempt at all. It should therefore be noted that ‘disposal’ here is defined according to lifetime and does not include passivation aspects, which, as discussed in Section 1.3, cannot currently be reliably derived from observational data.

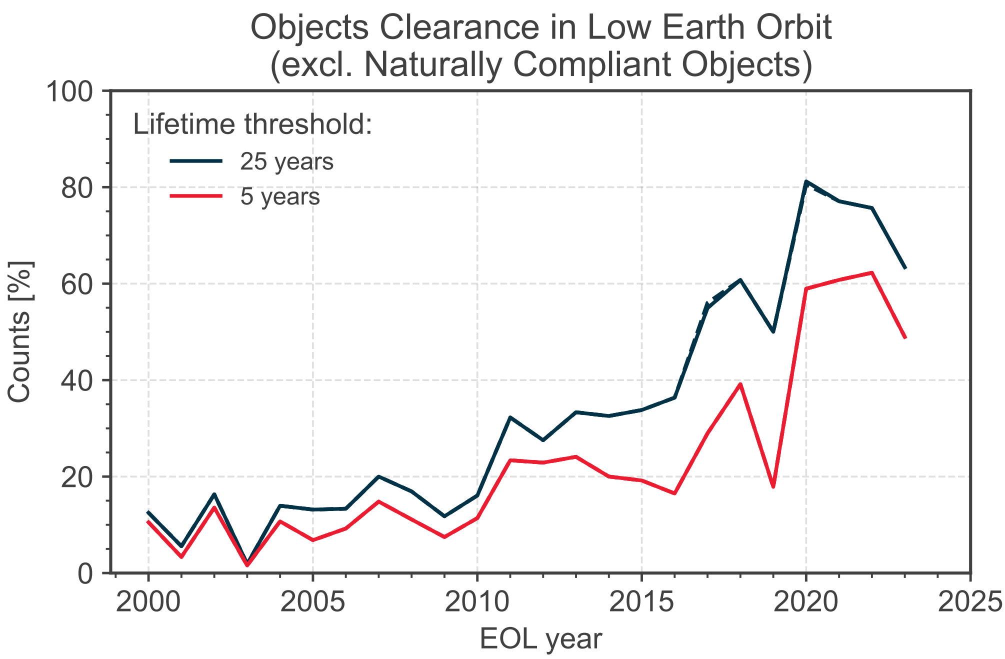
6.1.1. Evolution of compliance shares

In Figures 6.1 - 6.3, we show the share of compliance (in terms of space object count) for payloads and rocket bodies for the two lifetime limits (25 years and 5 years). Here, adherence is achieved by a *Successful Attempt* as defined above, as well as *Naturally Compliant* for the plots including naturally compliant space objects where no action was needed or taken. The solid lines represent the compliance share using the median (or 90^{th} percentile for objects with eccentricity > 0.3) lifetime, according to [3], while the dashed lines represent the compliance share for the 25^{th} and 75^{th} percentiles of the lifetimes.

More details on the levels of adherence to each of the 25 and 5 year lifetime limits are given in Sections 6.1.2 and 6.1.3 respectively.

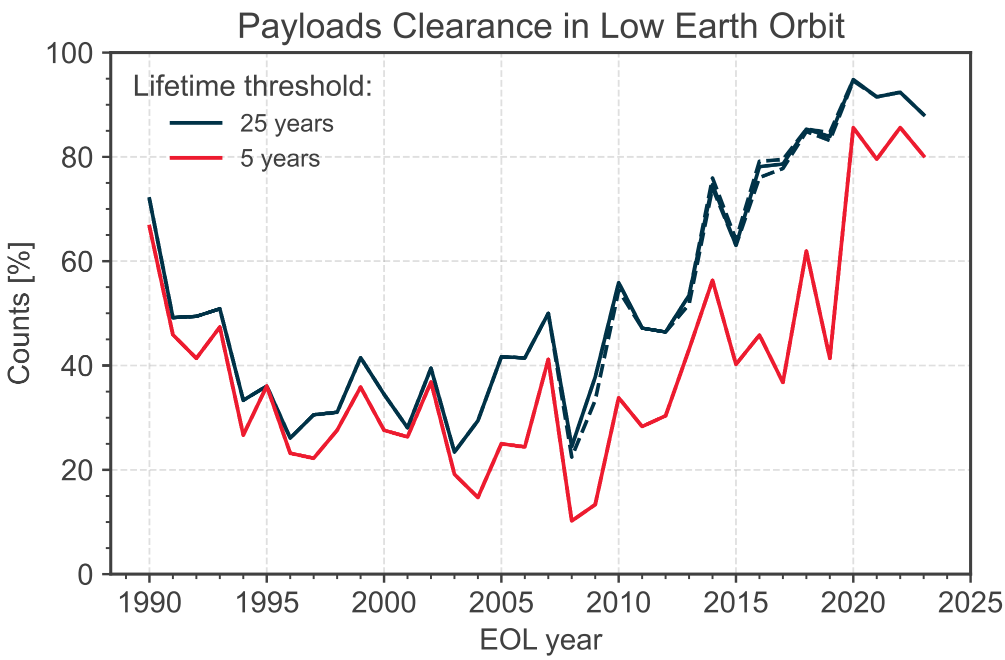


(a) Relative clearance of LEO_{IADC} by payloads.

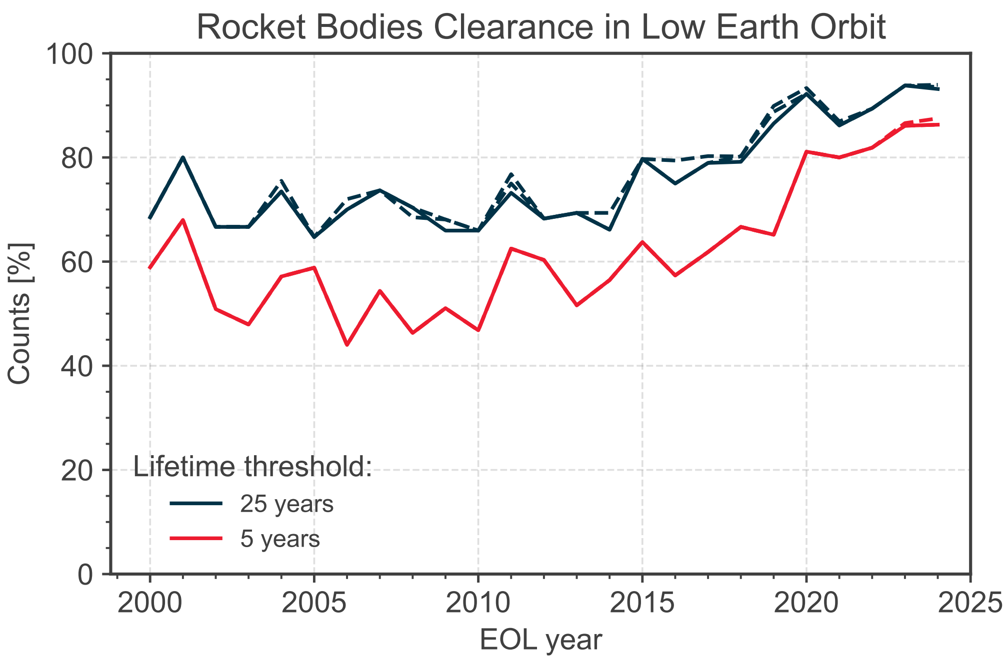


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.1: Trend of adherence to clearance of LEO_{IADC} over time to 5 and 25 year lifetime limits by share of space object count, excluding space objects associated with human spaceflight, including (top) and excluding (bottom) naturally compliant space objects where no action was needed or taken.

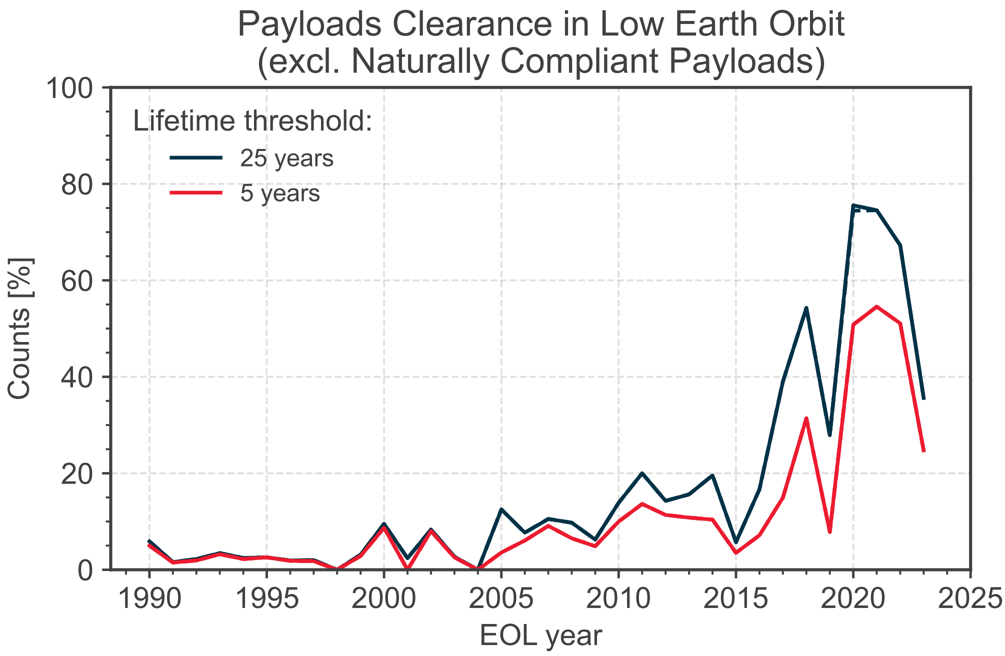


(a) Relative clearance of LEO_{IADC} by payloads.

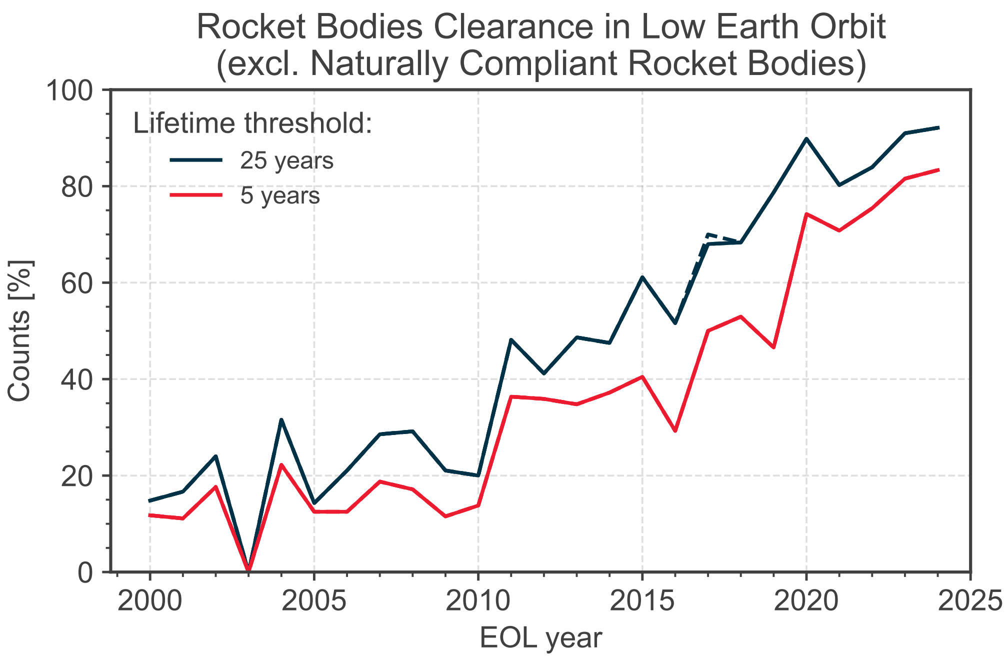


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.2: Trend of adherence to clearance of LEO_{IADC} over time to 5 and 25 year lifetime limits by share of space object count, excluding space objects associated with human spaceflight.



(a) Relative clearance of LEO_{IADC} by payloads.



(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.3: Trend of adherence to clearance of LEO_{IADC} over time to 5 and 25 year lifetime limits by share of space object count, excluding naturally compliant space objects where no action was needed or taken, and space objects associated with human spaceflight.

6.1.2. Compliance to a 25-year lifetime limit

6.1.2.1. Evolution of compliance shares

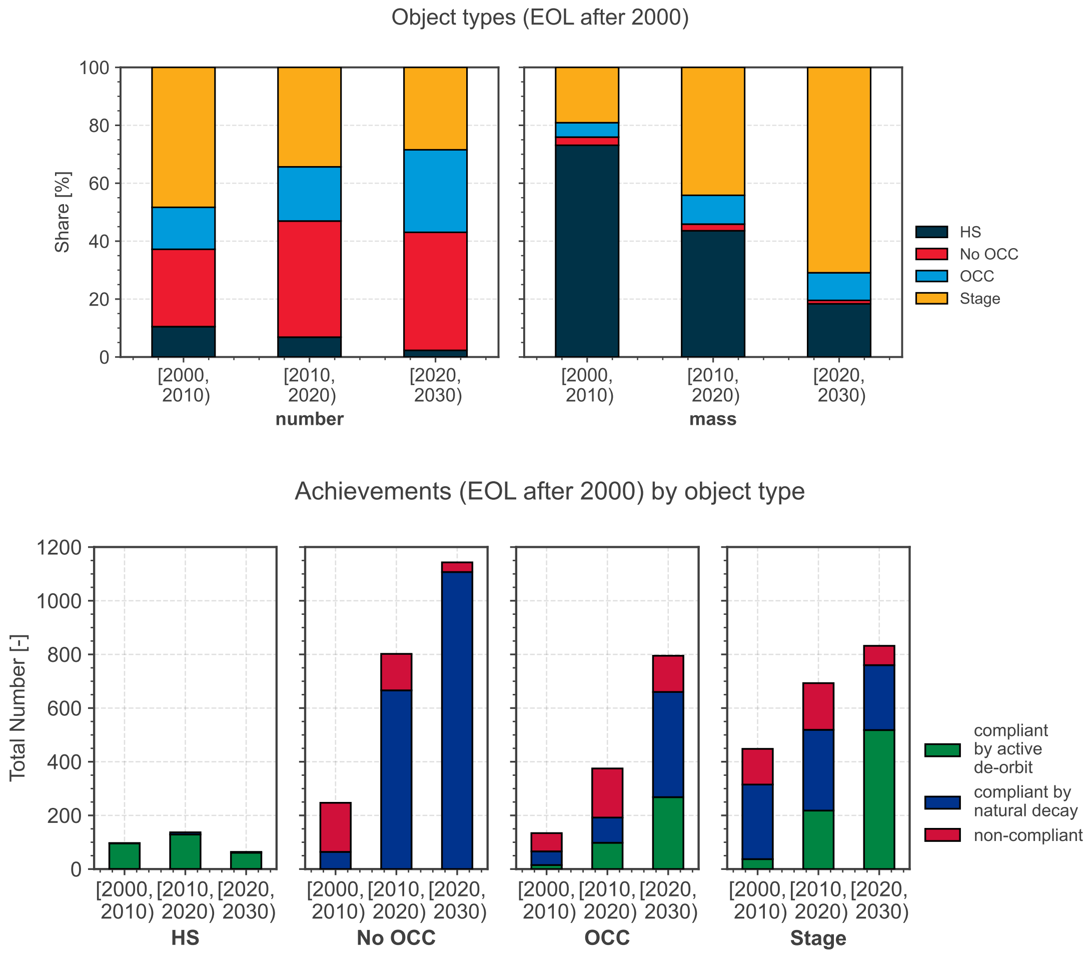


Figure 6.4: Share of payloads and rocket bodies in terms of mass and number (top) and compliance in terms of clearing the LEO protected region (bottom). The reported years for payload clearance of LEO_{IADC} goes up to 2023, for rocket body clearance of LEO_{IADC} goes up to 2024, for a lifetime limit of 25 years.

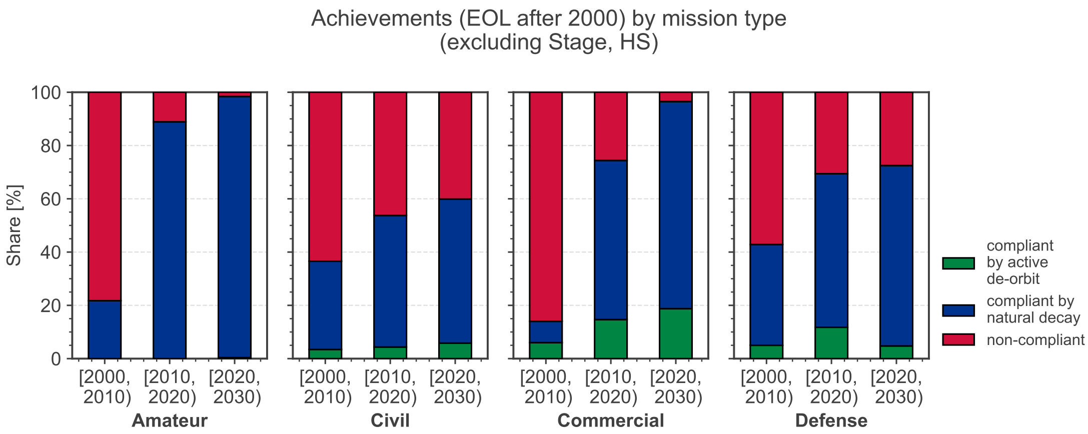


Figure 6.5: Share of compliance in terms of clearing the LEO protected region by mission type, for a lifetime limit of 25 years.

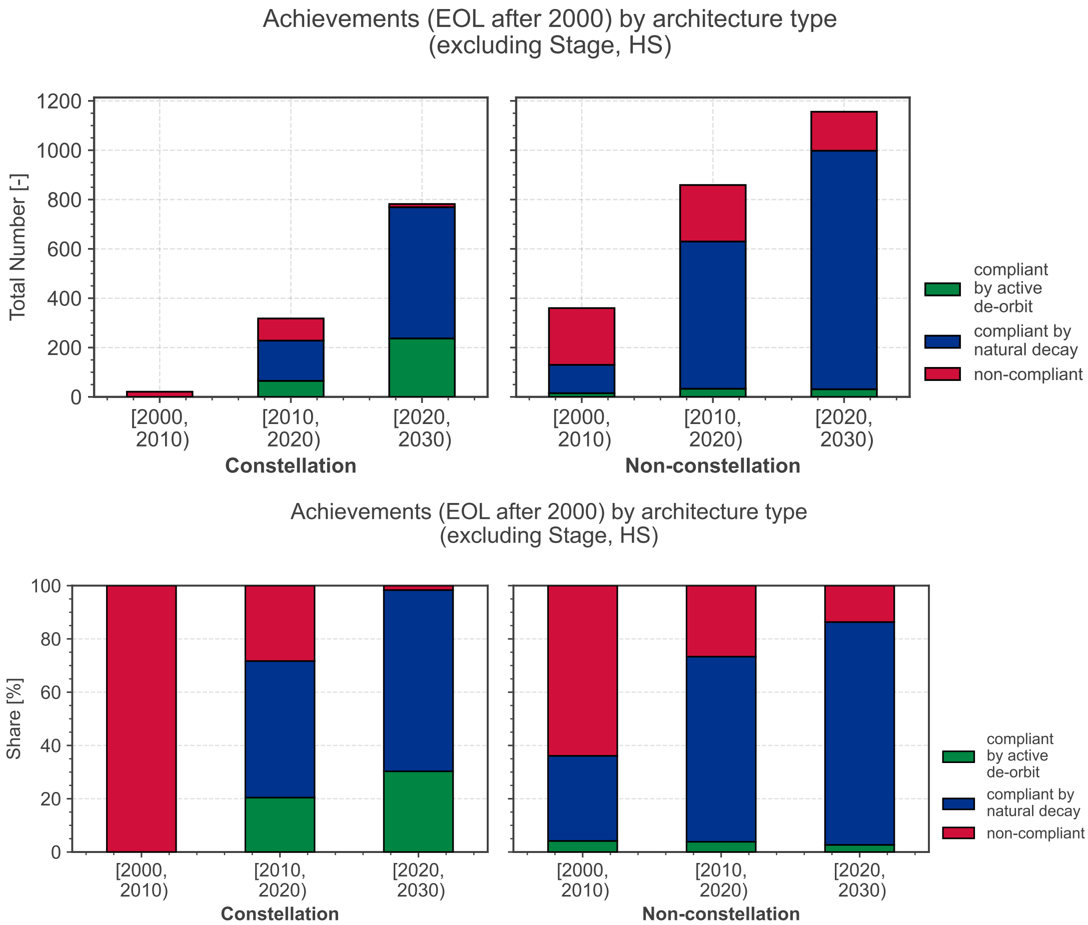
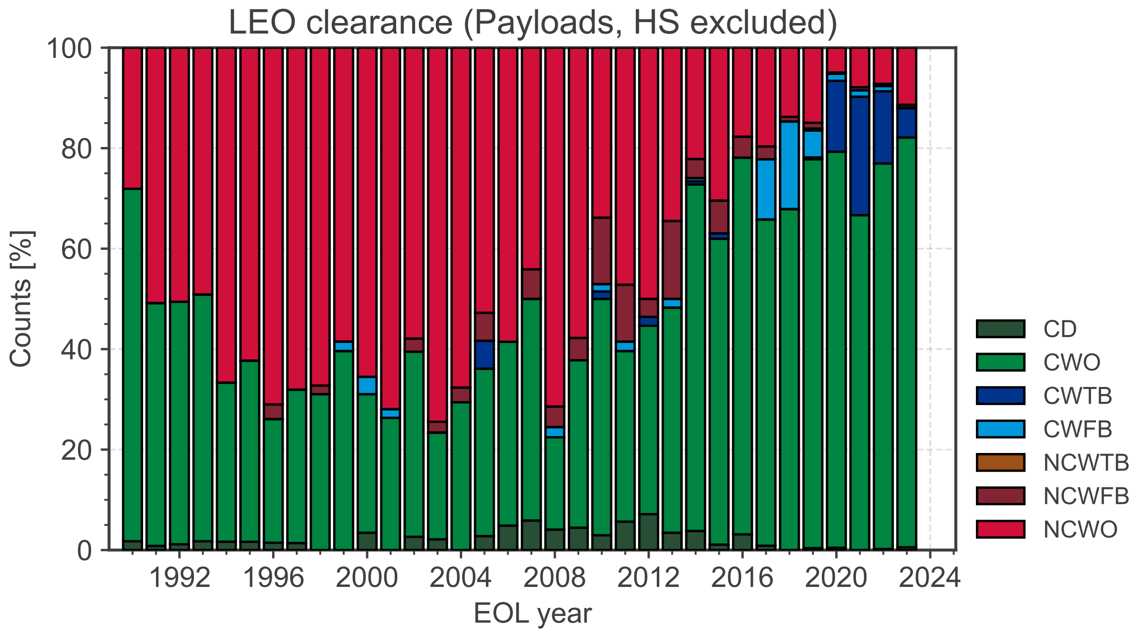


Figure 6.6: Compliance in terms of clearing the LEO protected region for constellation and non-constellation objects, in absolute numbers and in relative share, for a lifetime limit of 25 years.



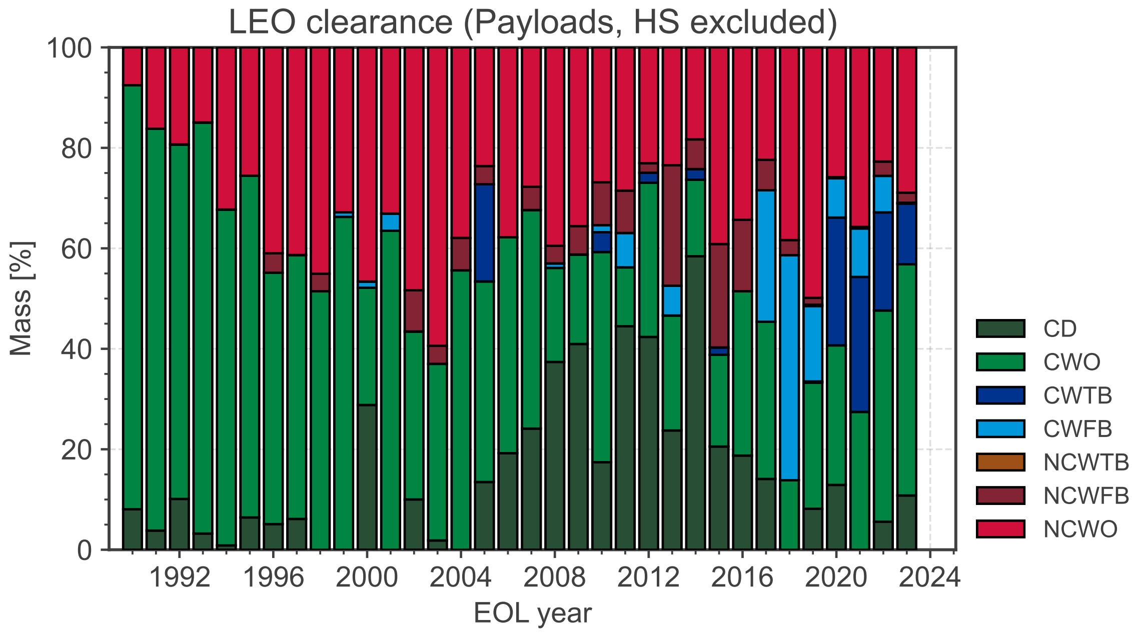


Figure 6.7: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for payloads in LEO, excluding objects associated with human spaceflight by end-of-life year, for a lifetime limit of 25 years.

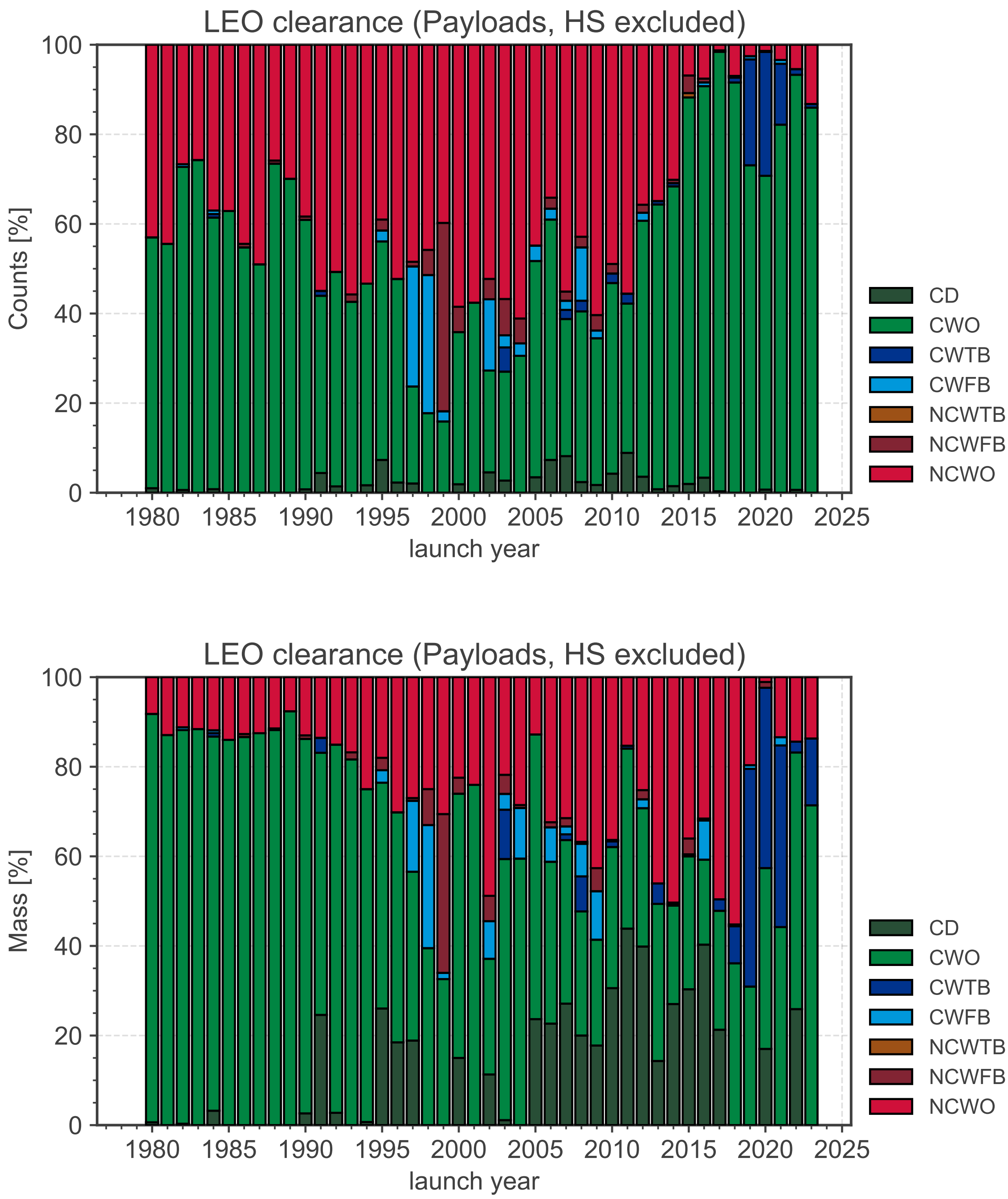


Figure 6.8: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for payloads in LEO, excluding objects associated with human spaceflight by launch year, for a lifetime limit of 25 years.

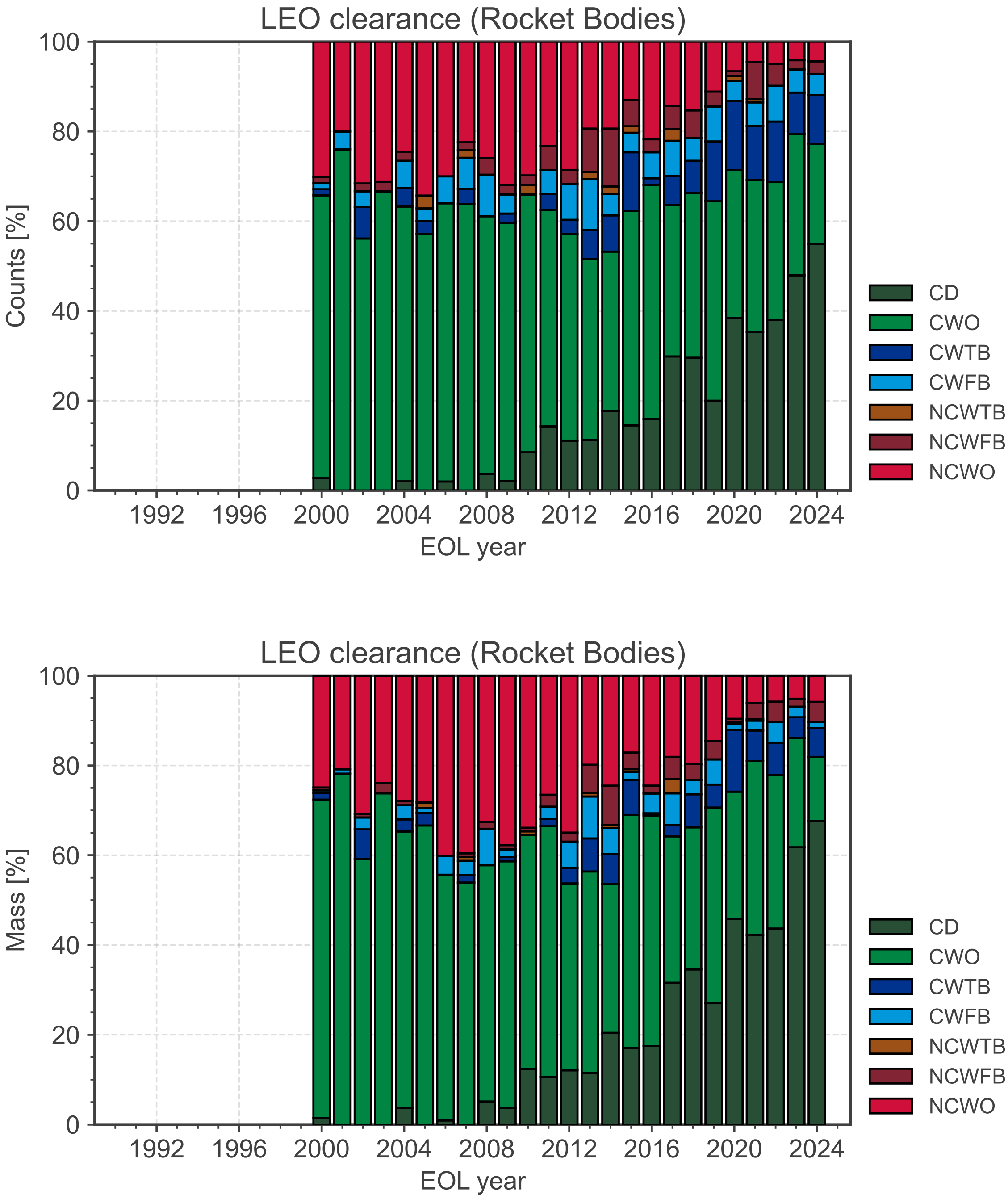
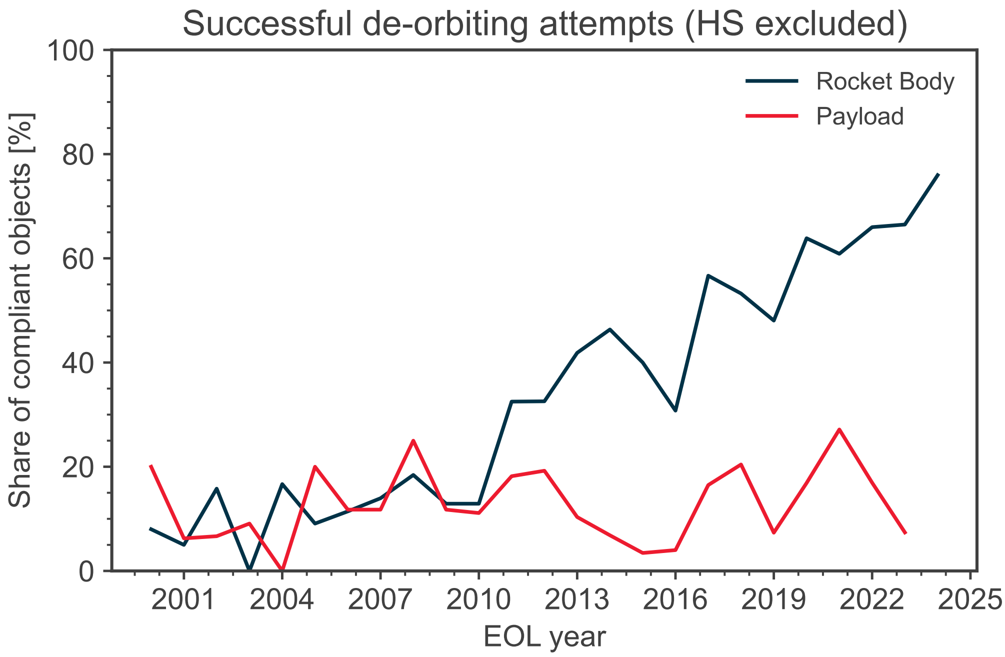


Figure 6.9: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for Rocket Bodies in LEO by end-of-life, i.e. launch year, for a lifetime limit of 25 years.



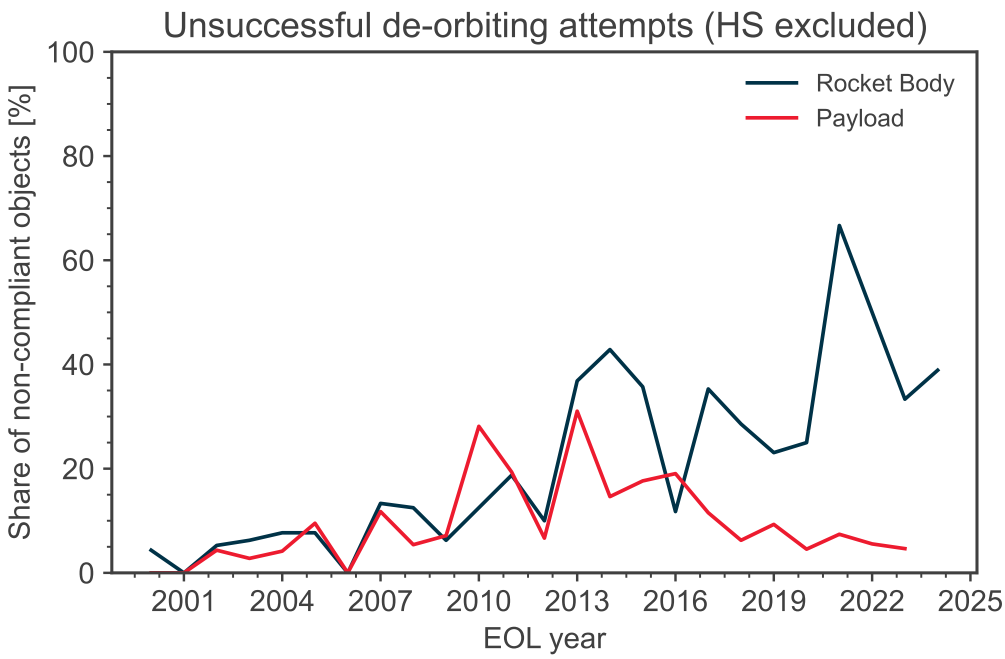
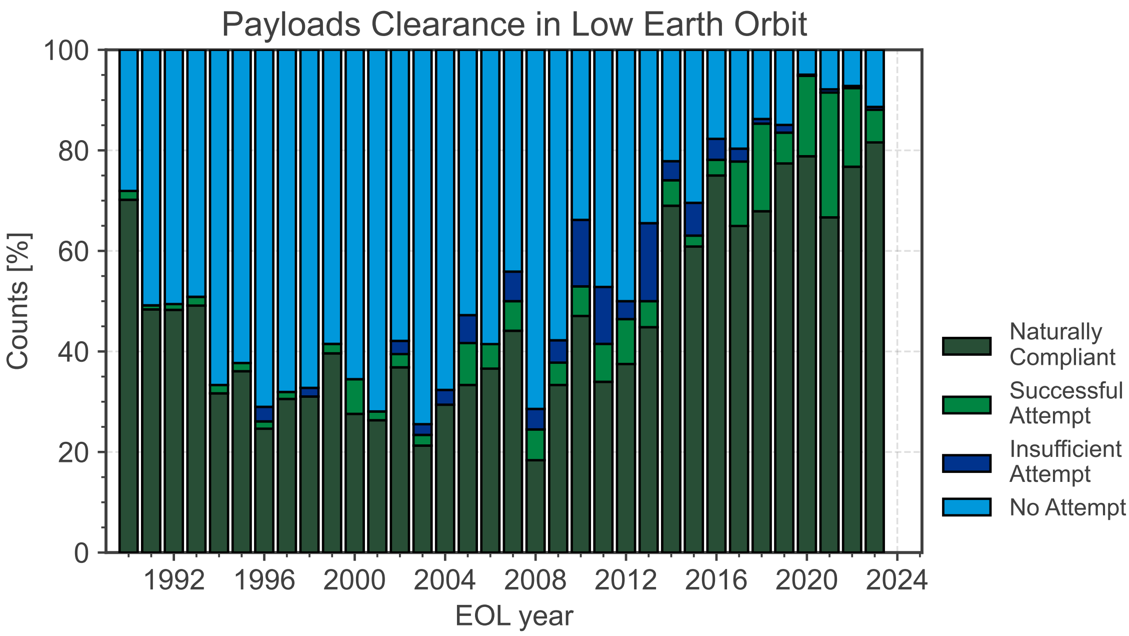
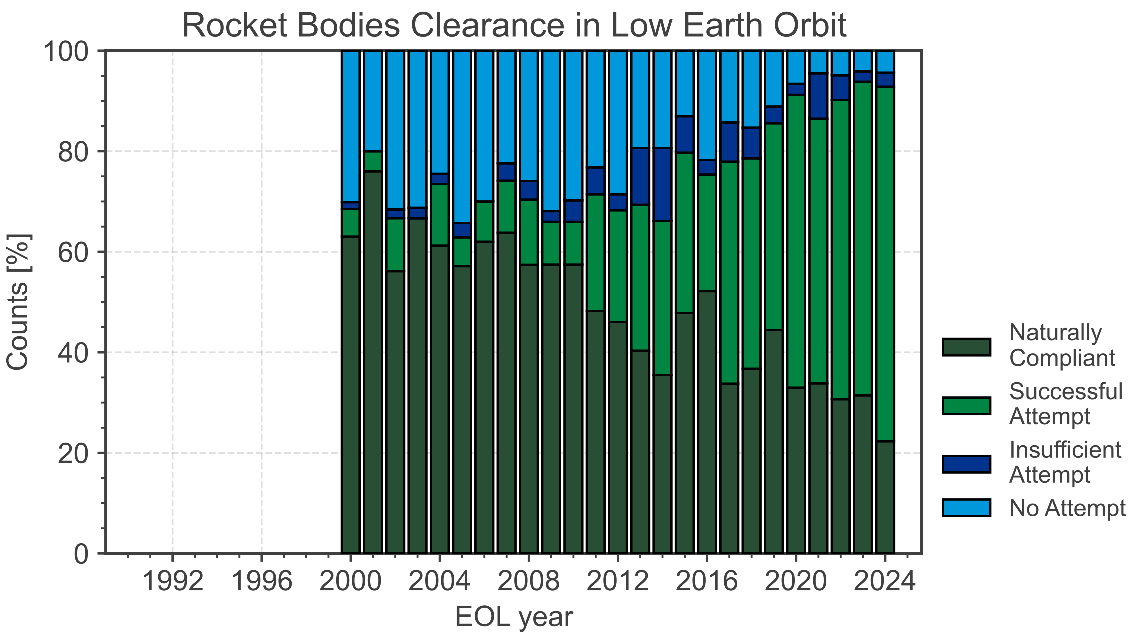


Figure 6.10: Relative shares of success w.r.t. compliance (top) and non-compliance (bottom) over time, excluding objects associated with human spaceflight, for a lifetime limit of 25 years.

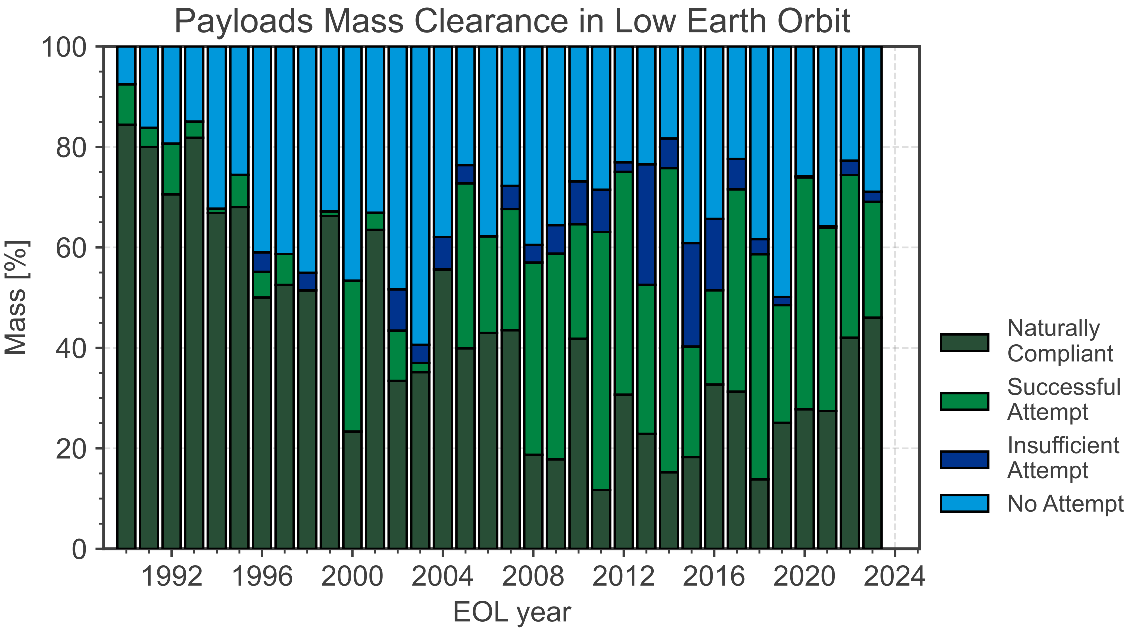


(a) Relative clearance of LEO_{IADC} by payloads.

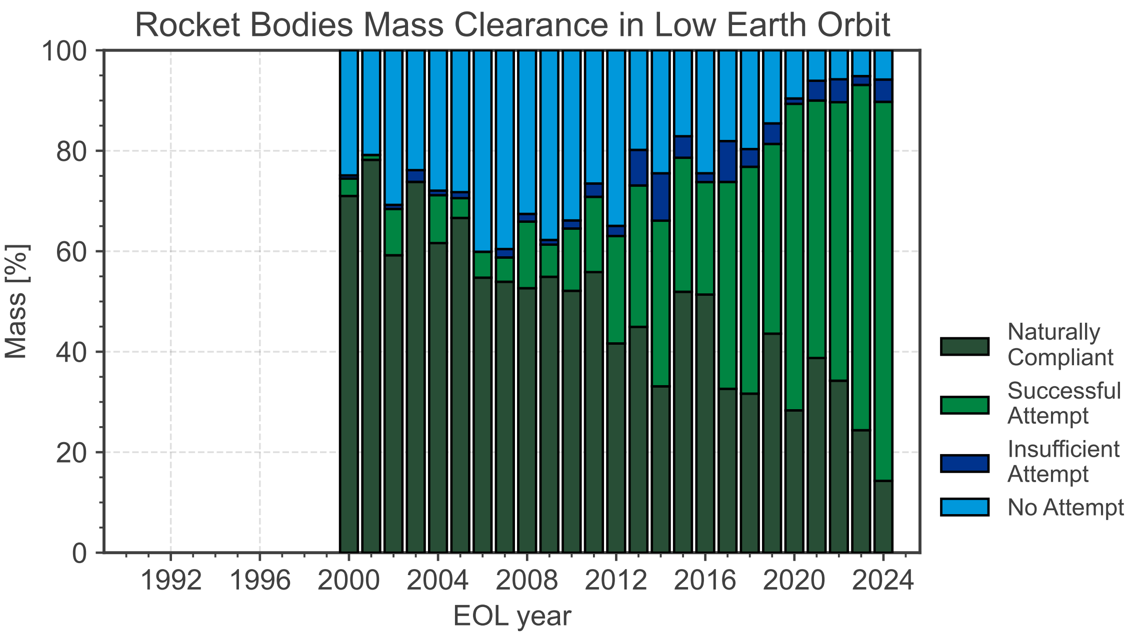


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.11: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, for a lifetime limit of 25 years.

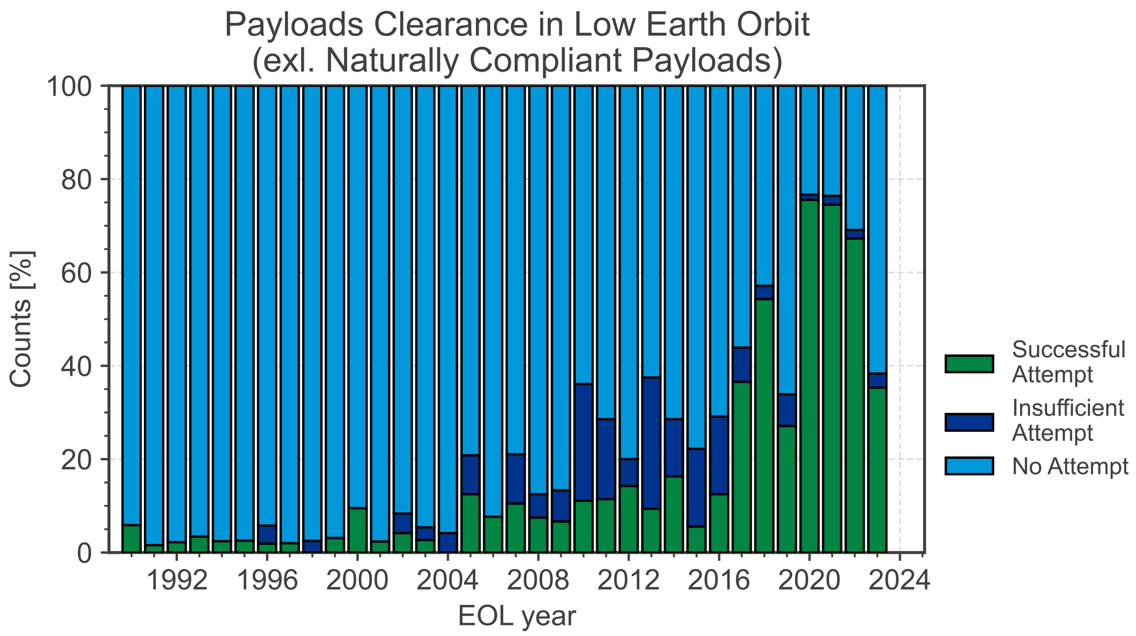


(a) Relative clearance of LEO_{IADC} by payloads.

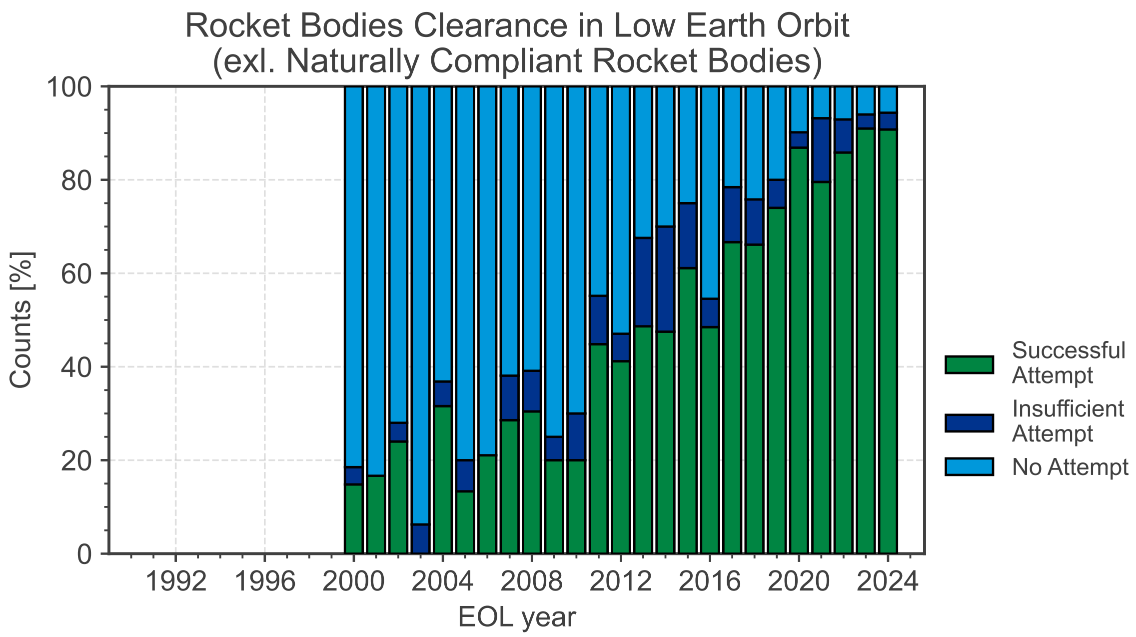


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.12: Trend of adherence to clearance of LEO_{IADC} over time in terms of mass, for a lifetime limit of 25 years.

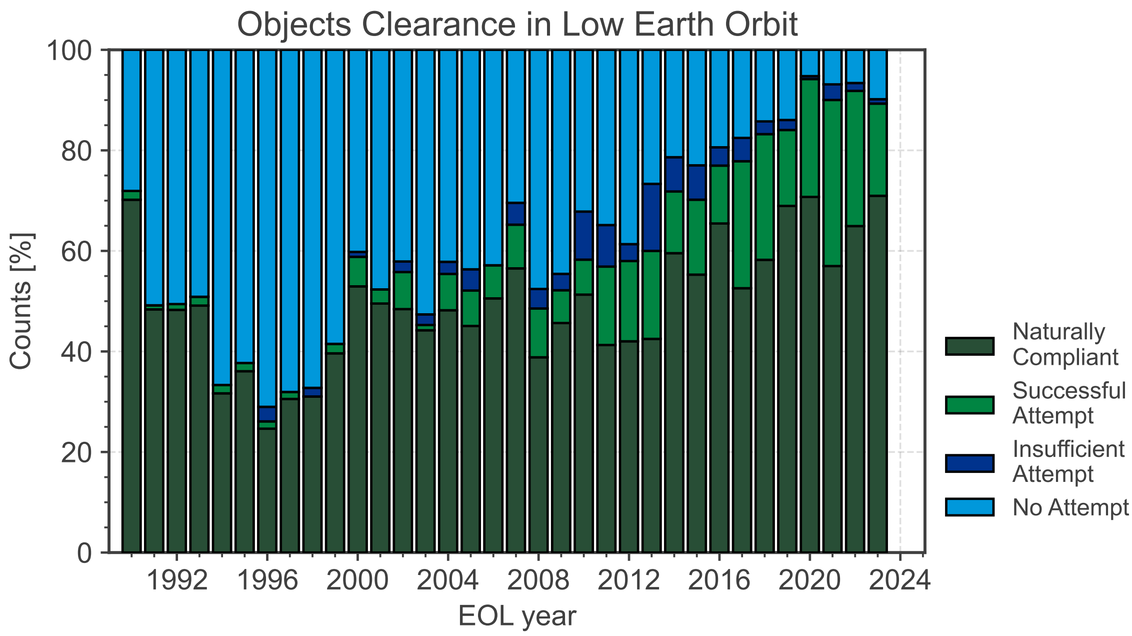


(a) Relative clearance of LEO_{IADC} by payloads.

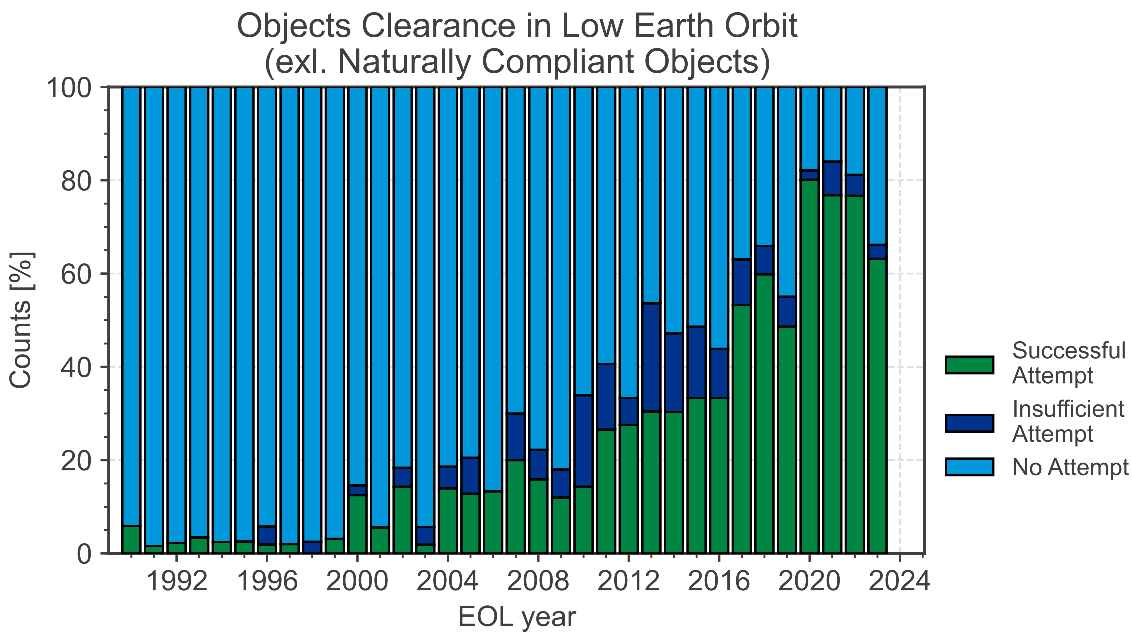


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.13: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, excluding naturally compliant objects where no action was needed or taken, for a lifetime limit of 25 years.



(a) Relative clearance of LEO_{IADC}.



(b) Relative clearance of LEO_{IADC} excluding naturally compliant objects where no action was needed or taken.

Figure 6.14: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, considering payloads and rocket bodies together, for a lifetime limit of 25 years.

6.1.2.2. Evolution of behavioural classes per mass breakdown

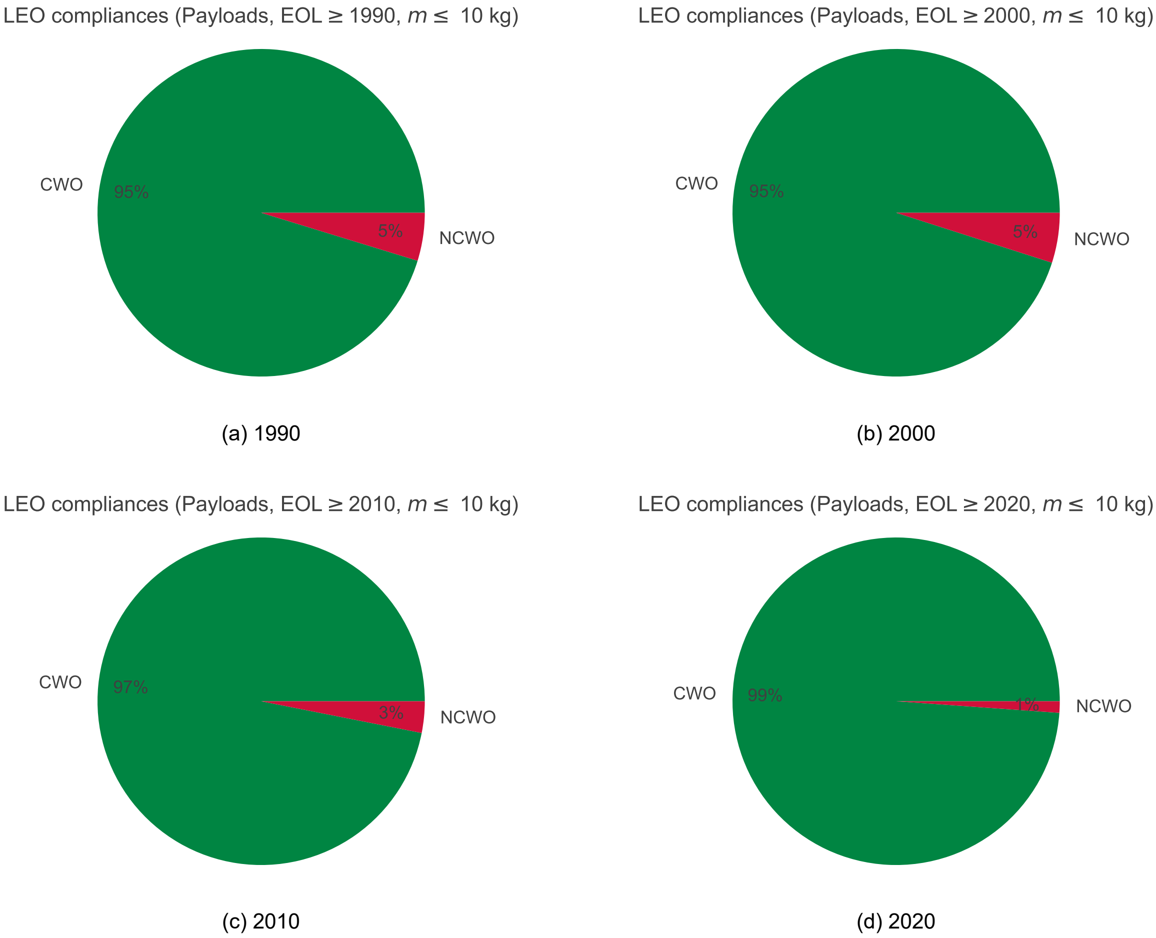


Figure 6.15: Breakdown per decade of observed behavioural classes for payloads with a mass below 10.0 kg, for a lifetime limit of 25 years.

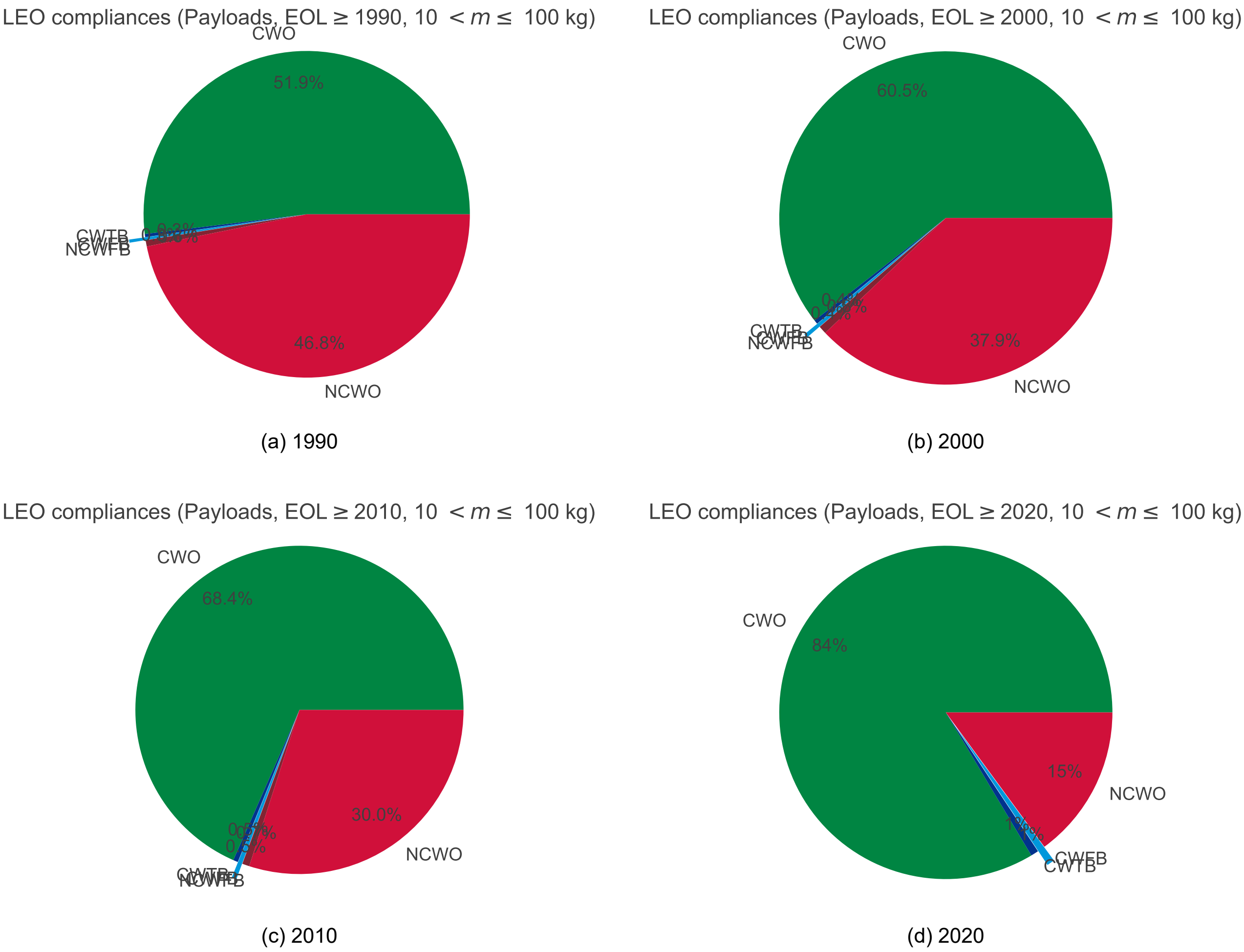


Figure 6.16: Breakdown per decade of observed behavioural classes for payloads with a mass between 10.0 and 100.0 kg, for a lifetime limit of 25 years.

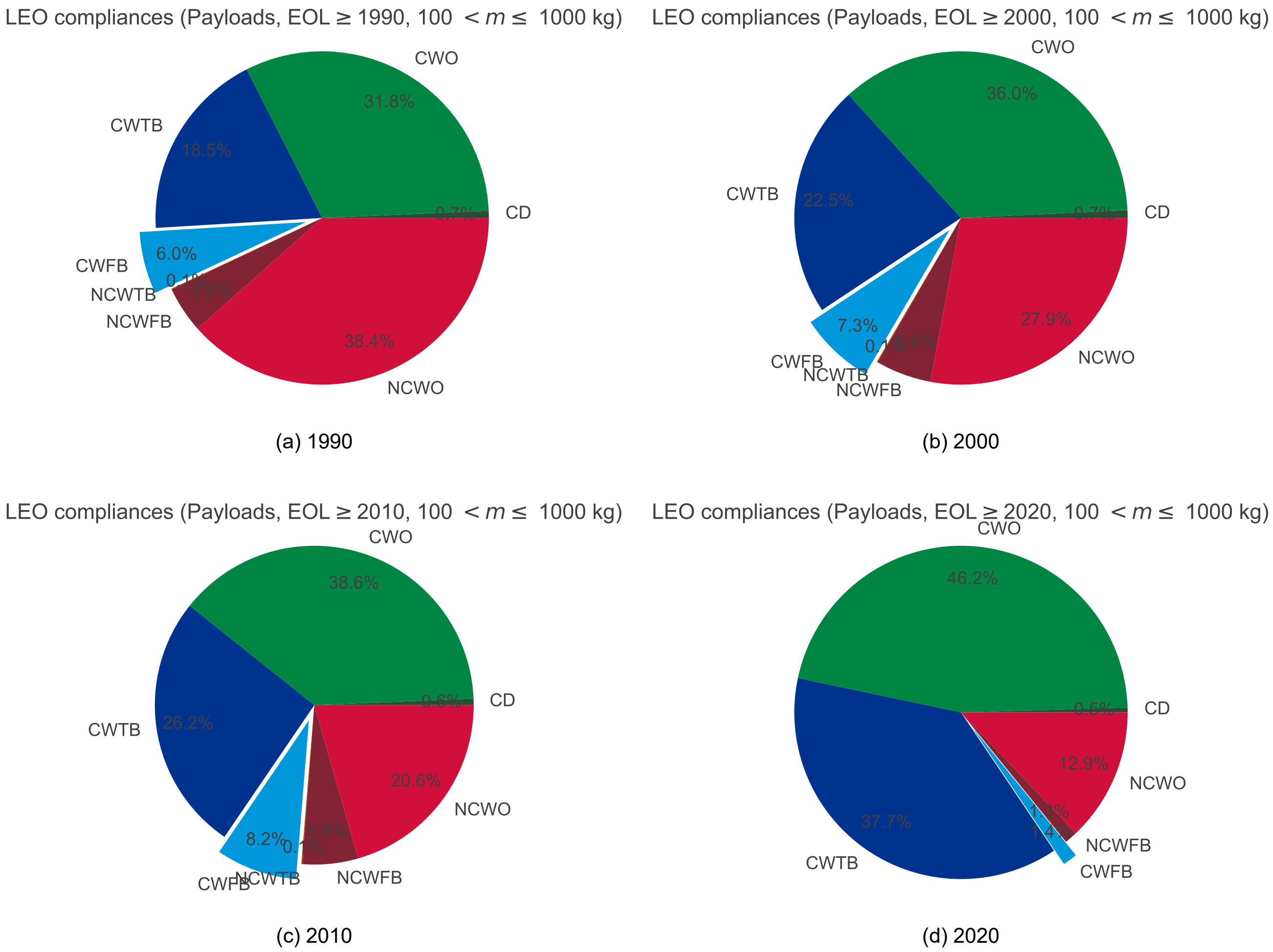


Figure 6.17: Breakdown per decade of observed behavioural classes for payloads with a mass between 100.0 and 1000.0 kg, for a lifetime limit of 25 years.

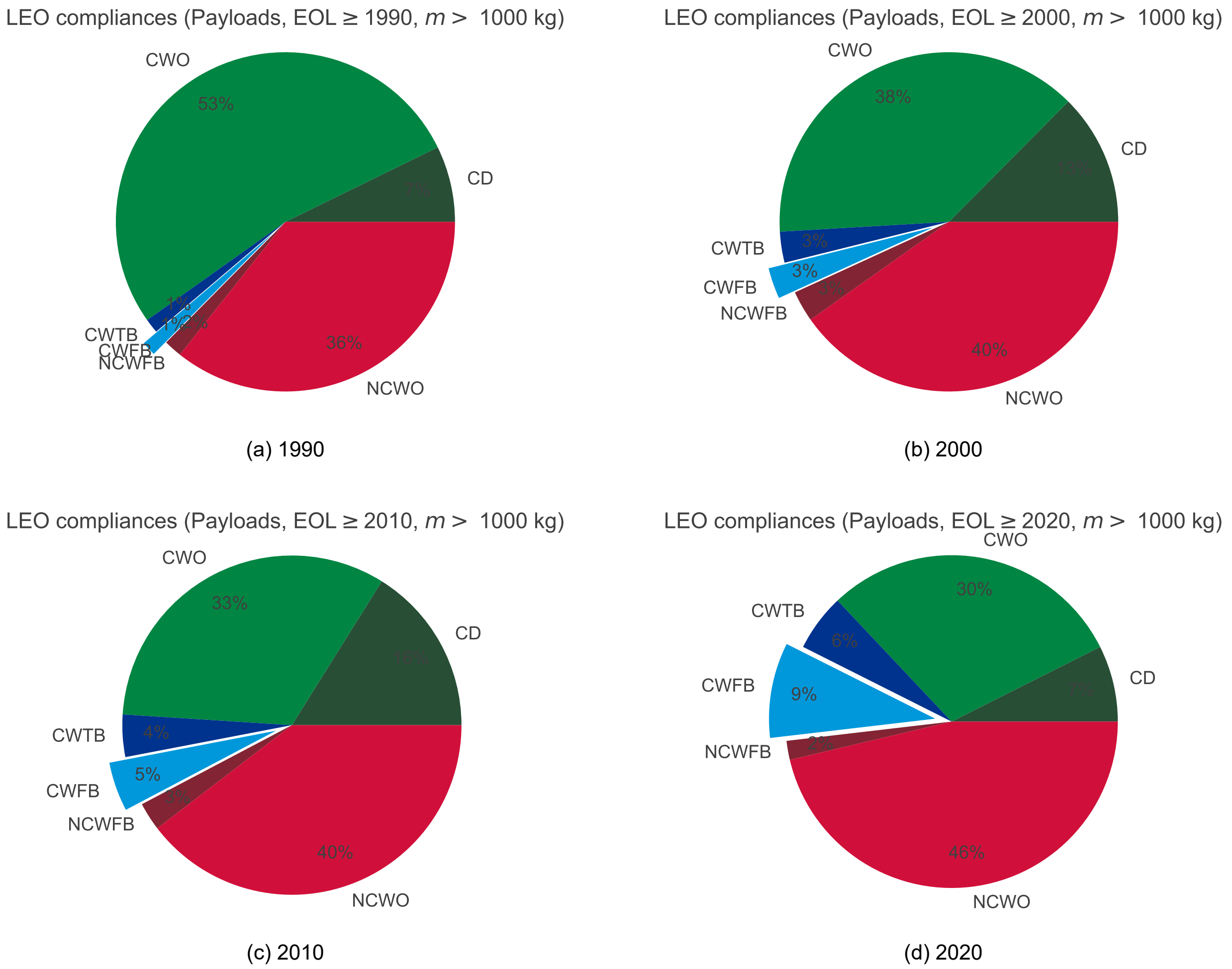
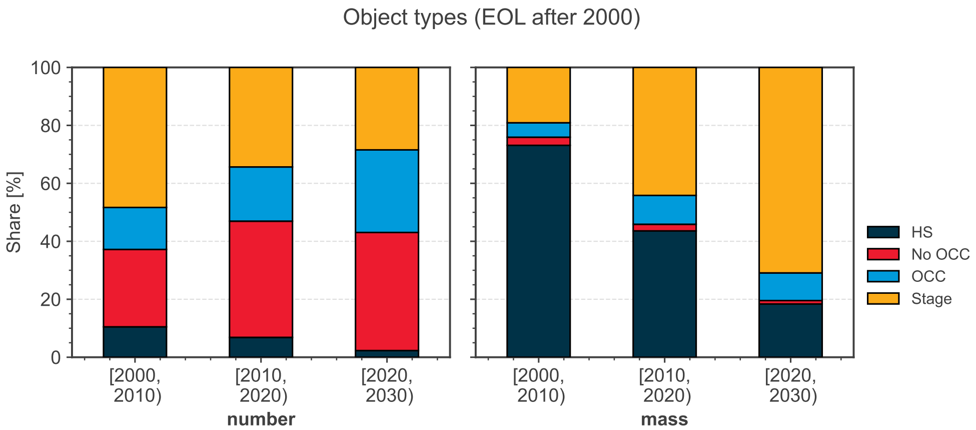


Figure 6.18: Breakdown per decade of observed behavioural classes for payloads with a mass above 1000.0 kg, for a lifetime limit of 25 years.

6.1.3. Compliance to a 5-year lifetime limit

6.1.3.1. Evolution of compliance shares



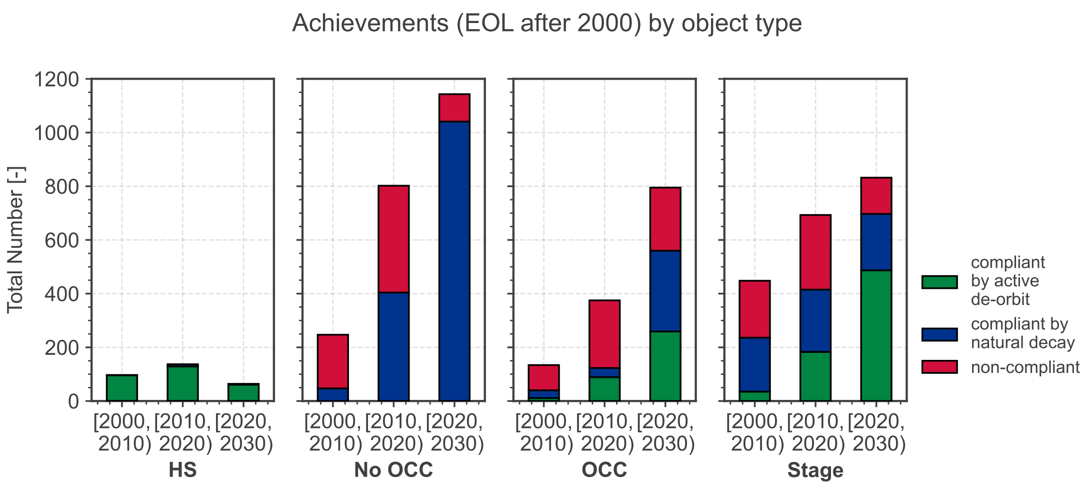


Figure 6.19: Share of payloads and rocket bodies in terms of mass and number (top) and compliance in terms of clearing the LEO protected region (bottom). The reported years for payload clearance of LEO_{IADC} goes up to 2023, for rocket body clearance of LEO_{IADC} goes up to 2024, for a lifetime limit of 5 years.

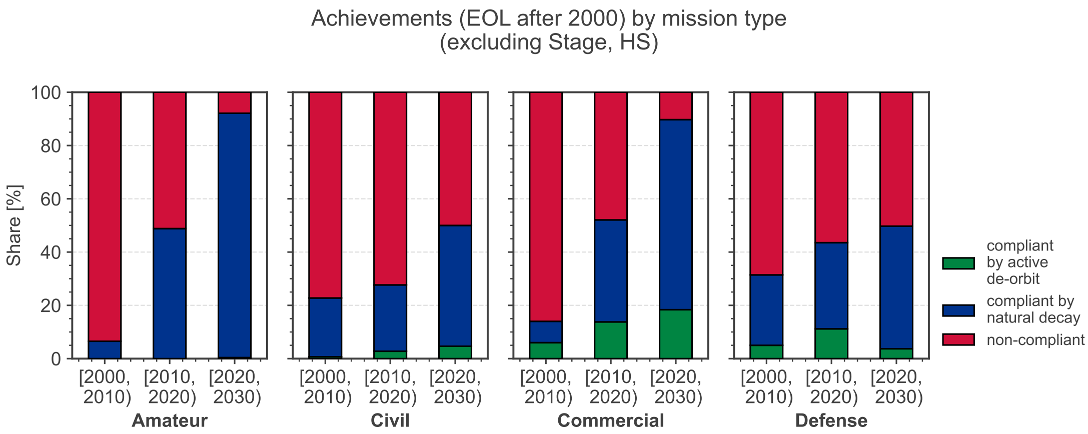


Figure 6.20: Share of compliance in terms of clearing the LEO protected region by mission type, for a lifetime limit of 5 years.

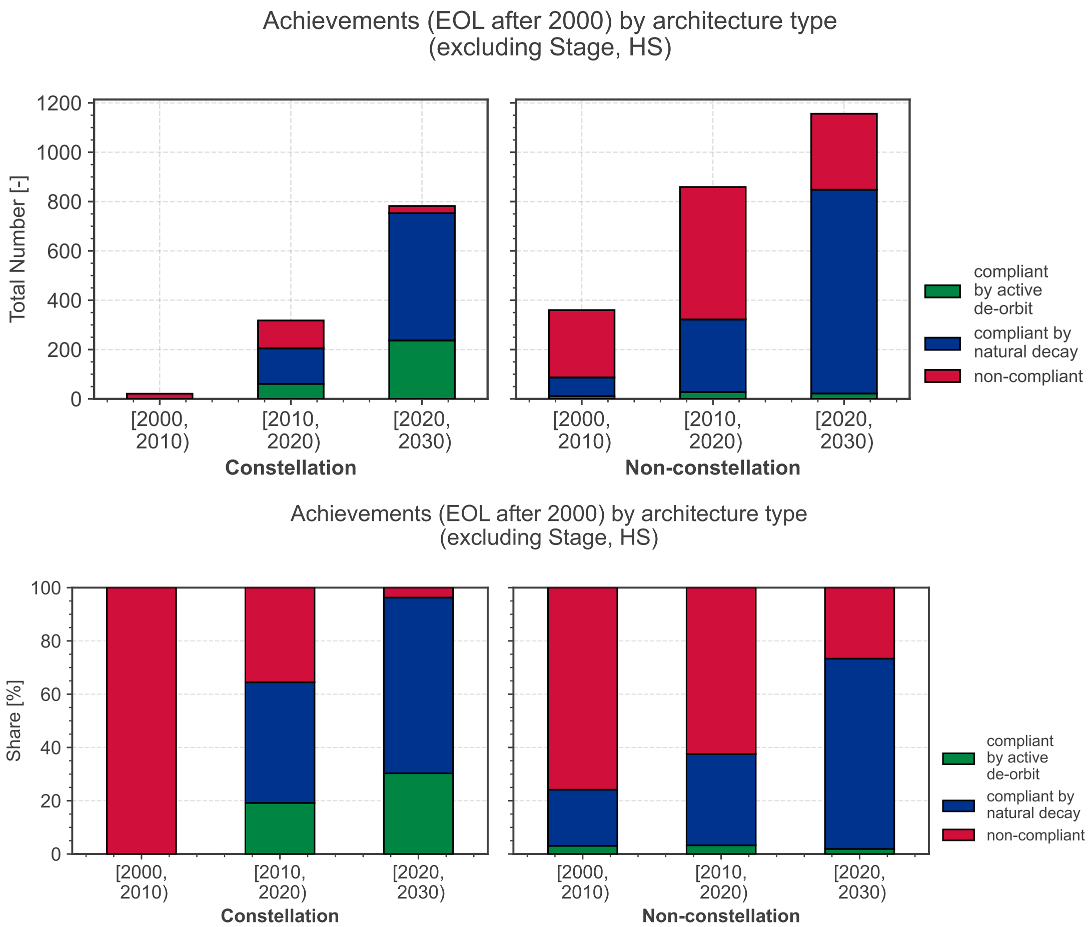
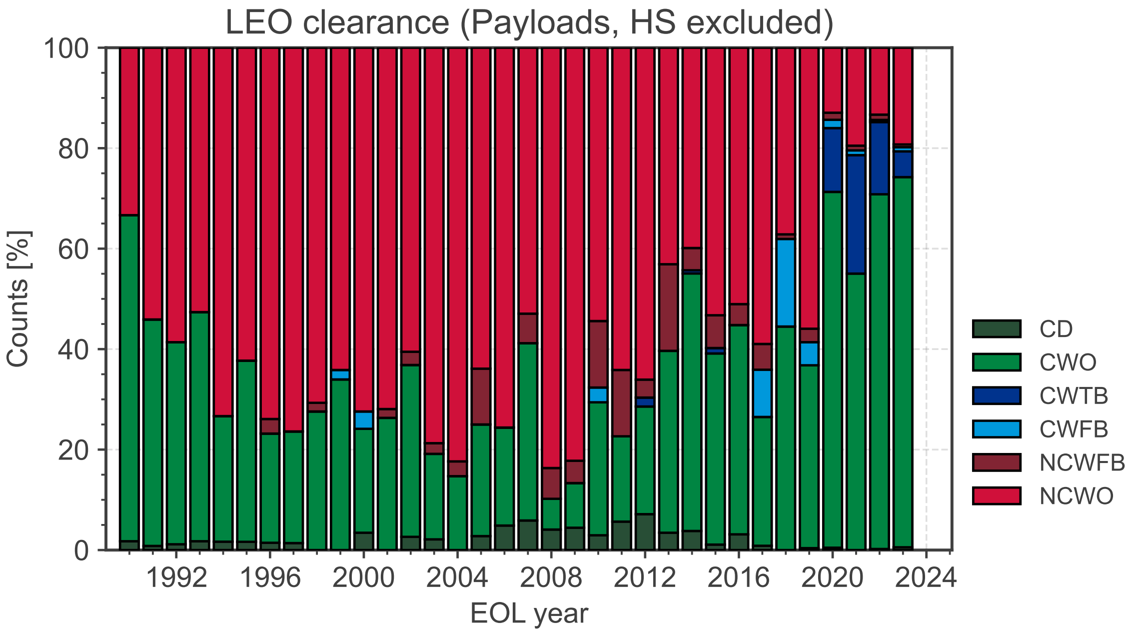


Figure 6.21: Compliance in terms of clearing the LEO protected region for constellation and non-constellation objects, in absolute numbers and in relative share, for a lifetime limit of 5 years.



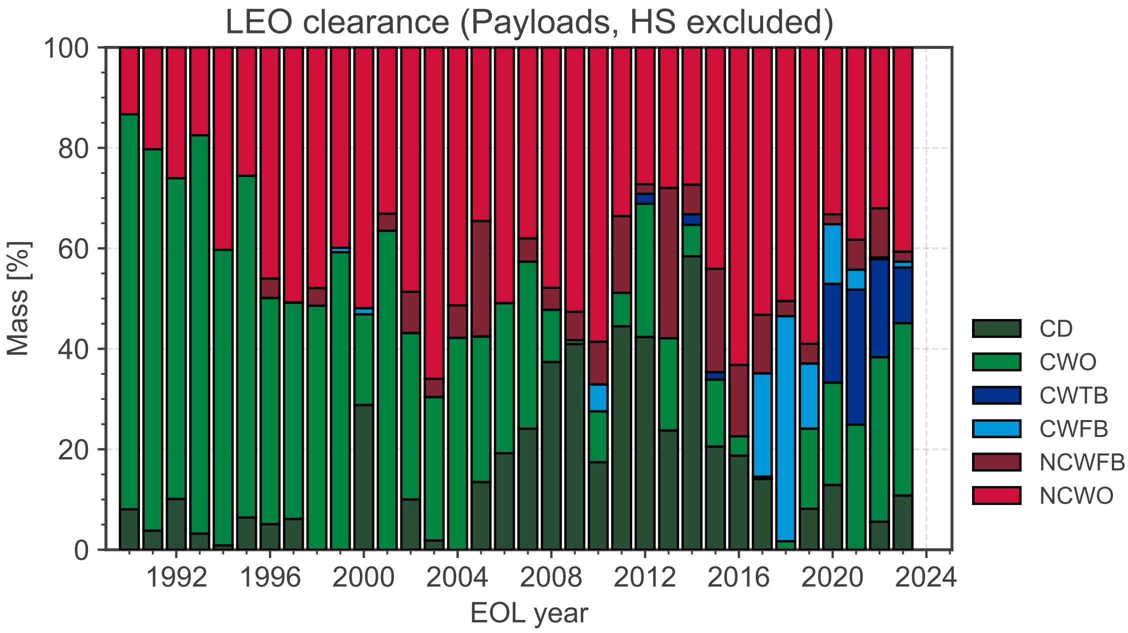
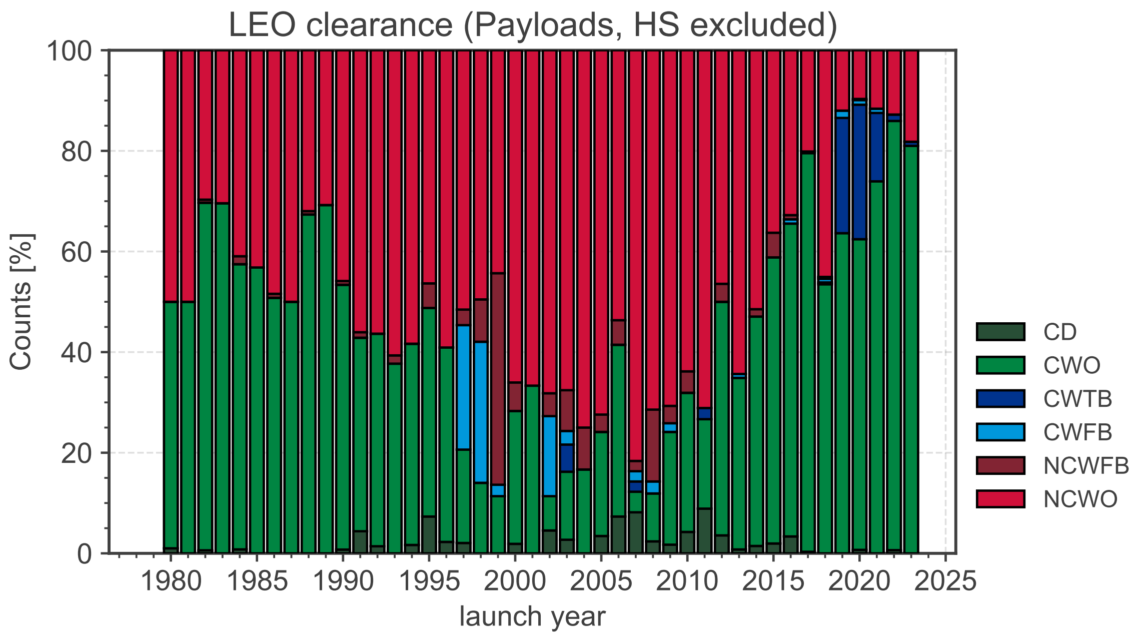


Figure 6.22: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for payloads in LEO, excluding objects associated with human spaceflight by end-of-life year, for a lifetime limit of 5 years.



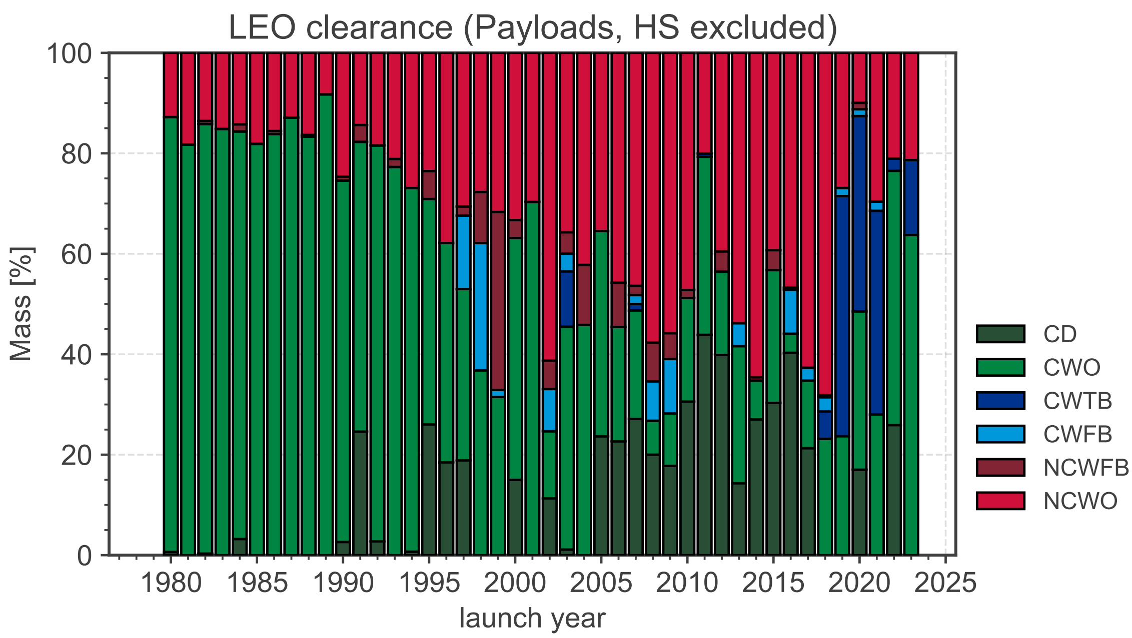
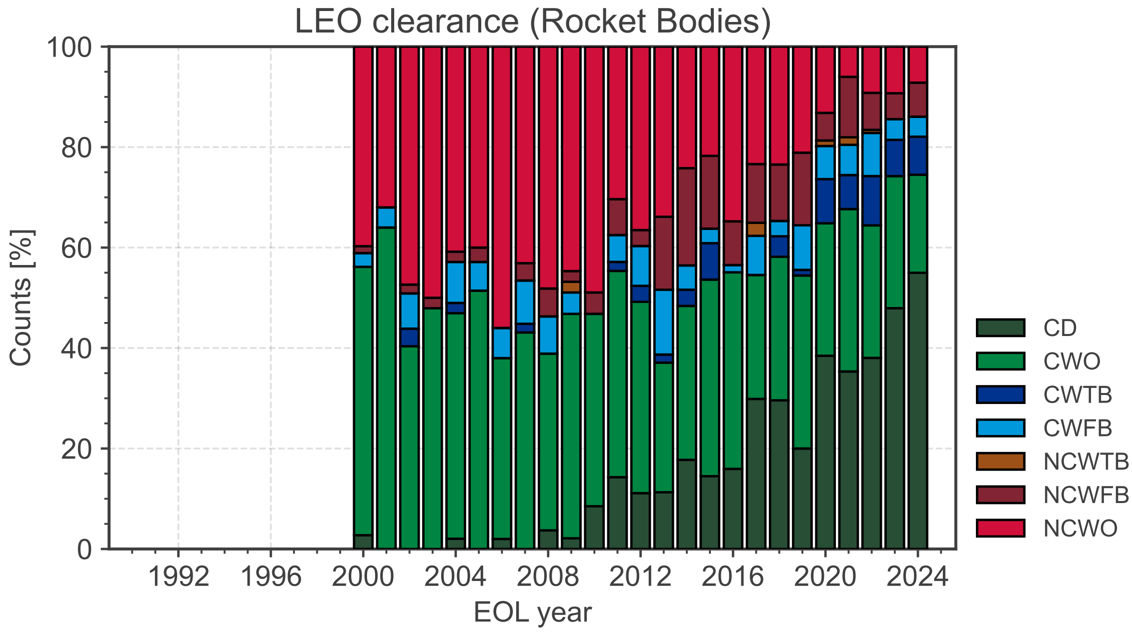


Figure 6.23: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for payloads in LEO, excluding objects associated with human spaceflight by launch year, for a lifetime limit of 5 years.



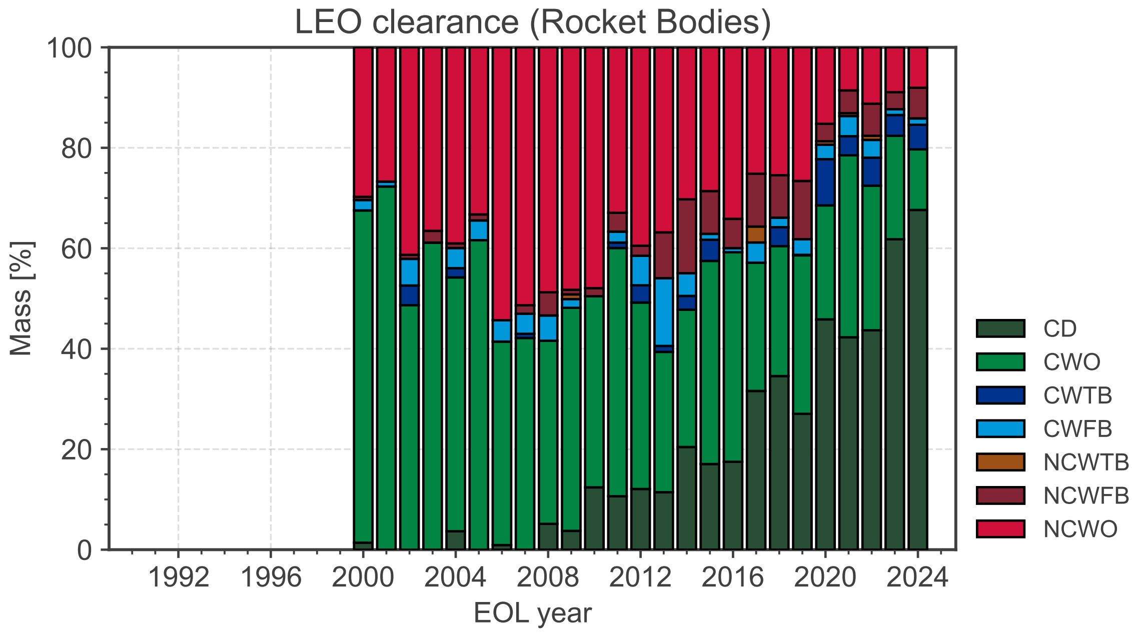


Figure 6.24: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for Rocket Bodies in LEO by end-of-life, i.e. launch year, for a lifetime limit of 5 years.

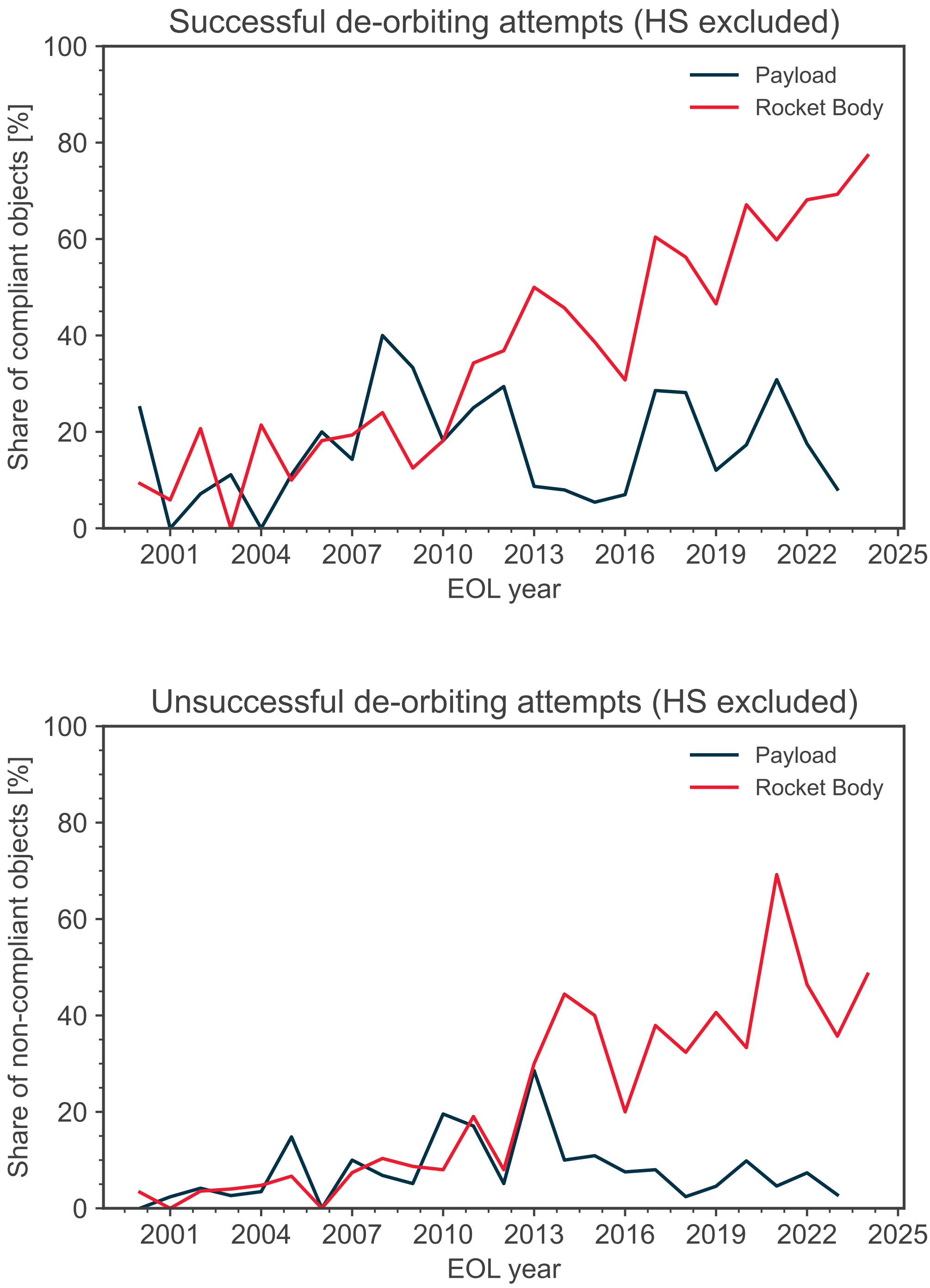
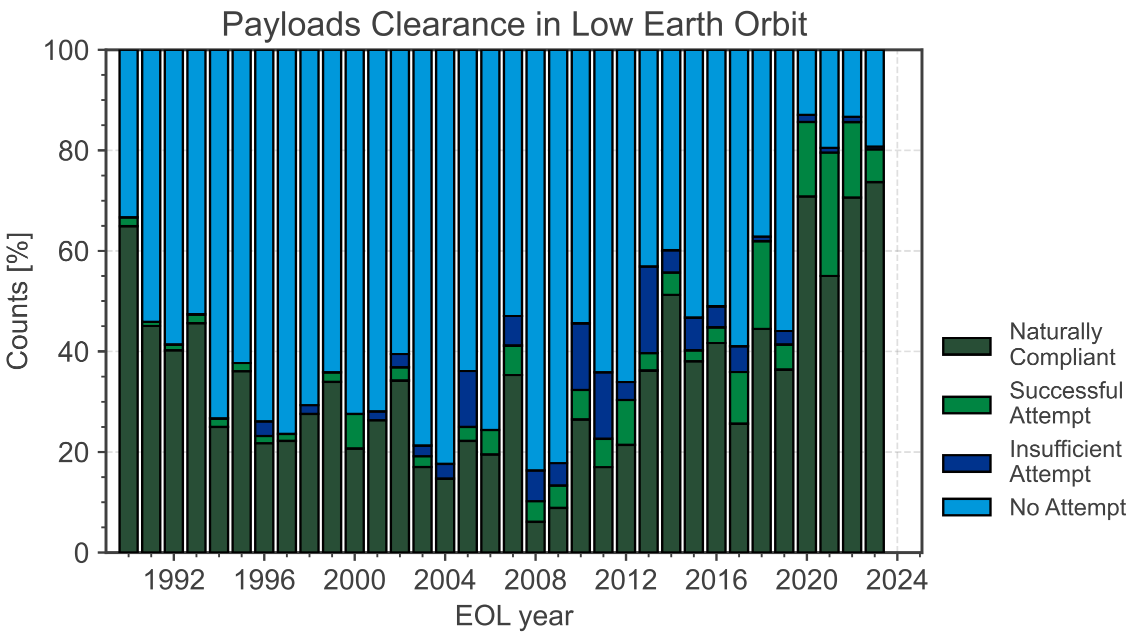
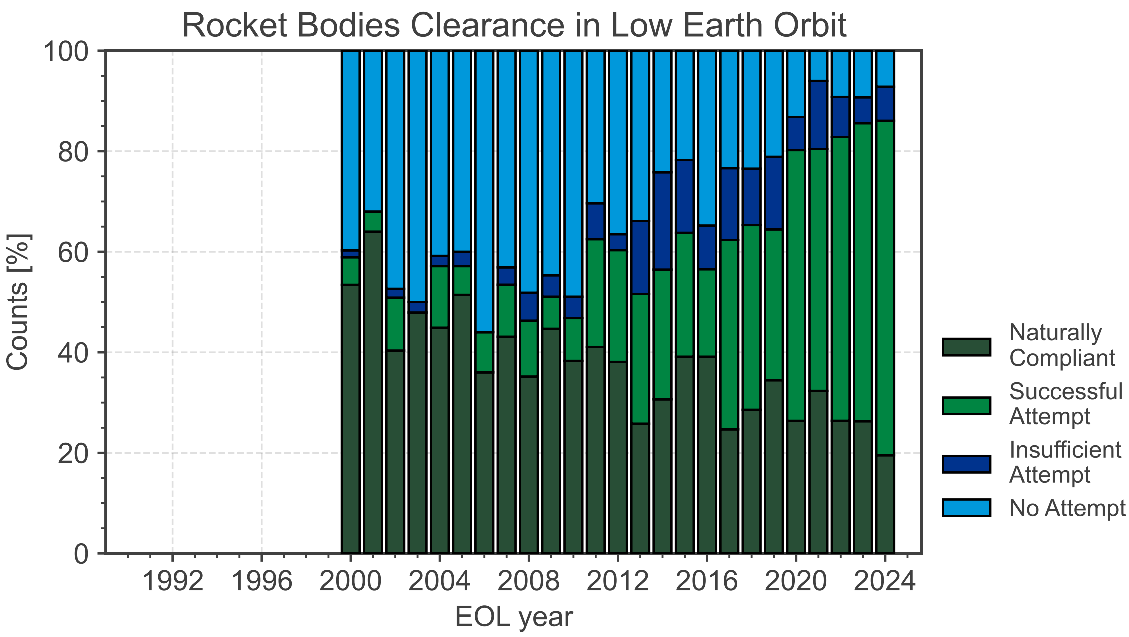


Figure 6.25: Relative shares of success w.r.t. compliance (top) and non-compliance (bottom) over time, excluding objects associated with human spaceflight, for a lifetime limit of 5 years.

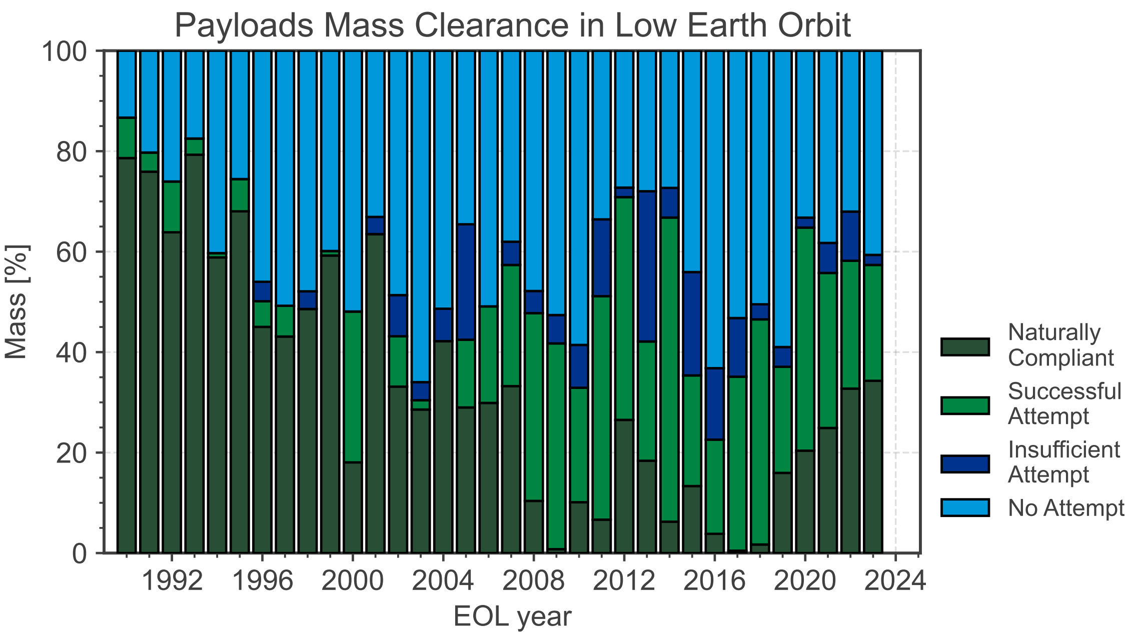


(a) Relative clearance of LEO_{IADC} by payloads.

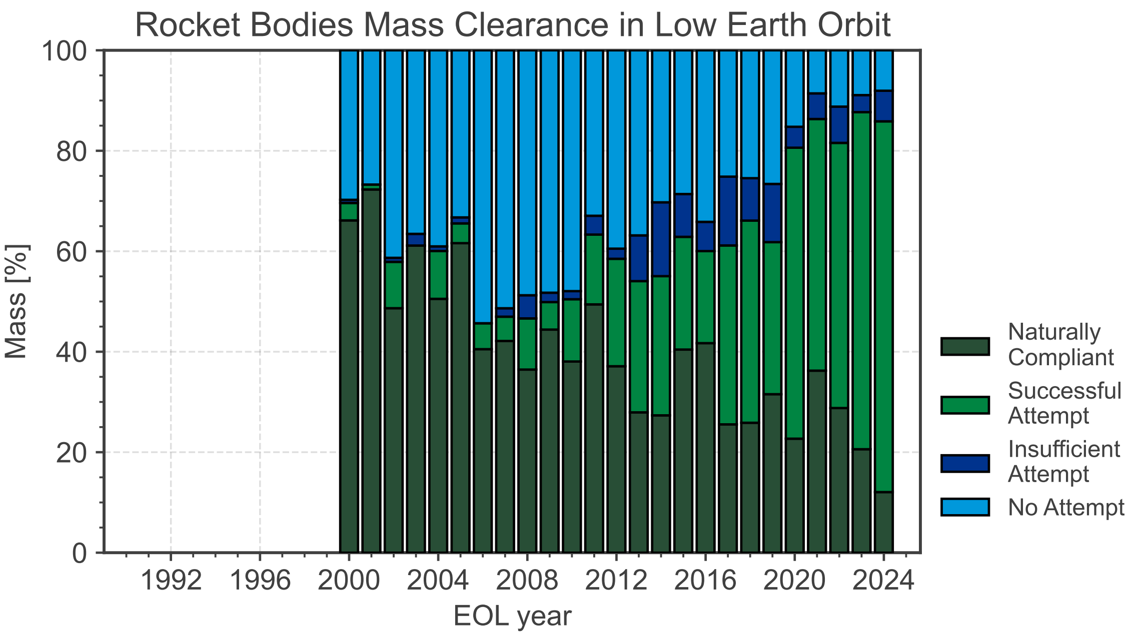


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.26: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, for a lifetime limit of 5 years.

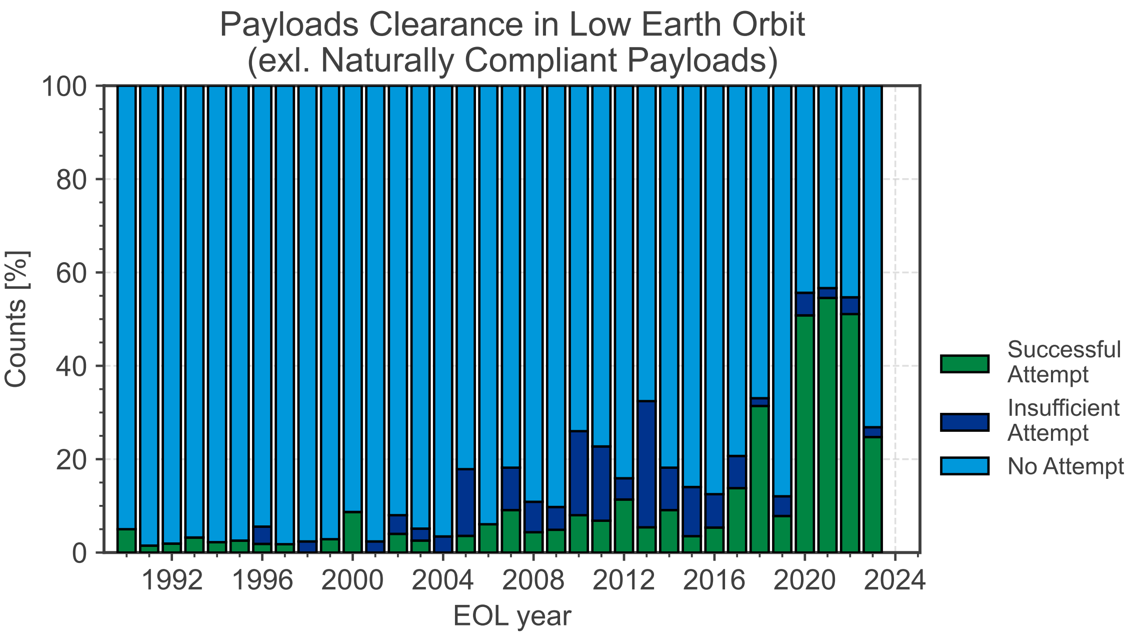


(a) Relative clearance of LEO_{IADC} by payloads.

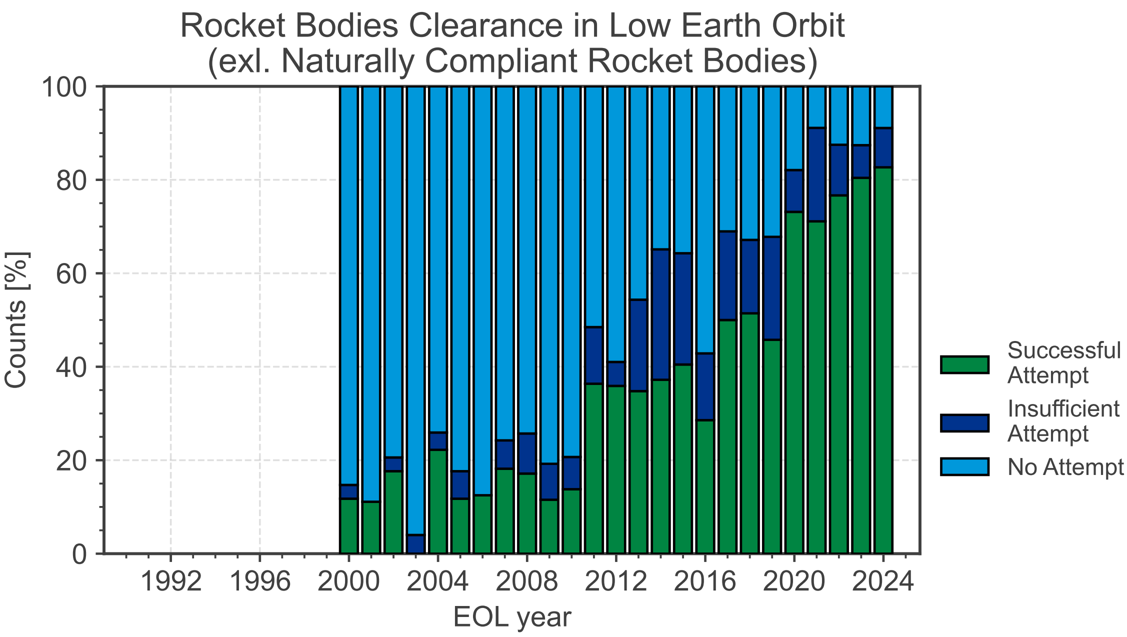


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.27: Trend of adherence to clearance of LEO_{IADC} over time in terms of mass, for a lifetime limit of 5 years.

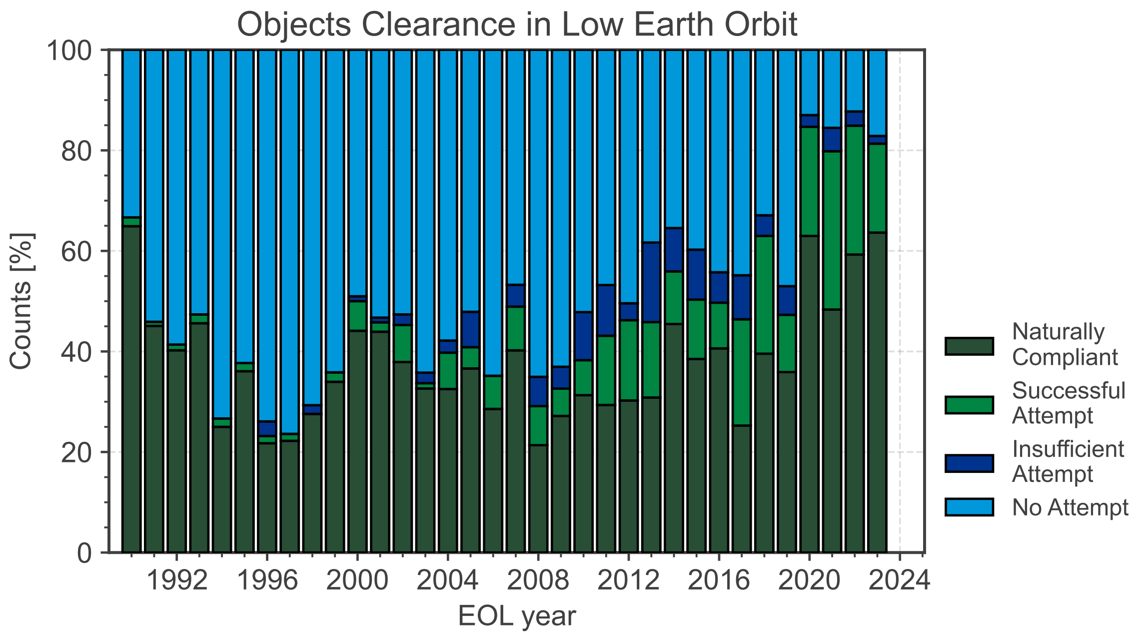


(a) Relative clearance of LEO_{IADC} by payloads.

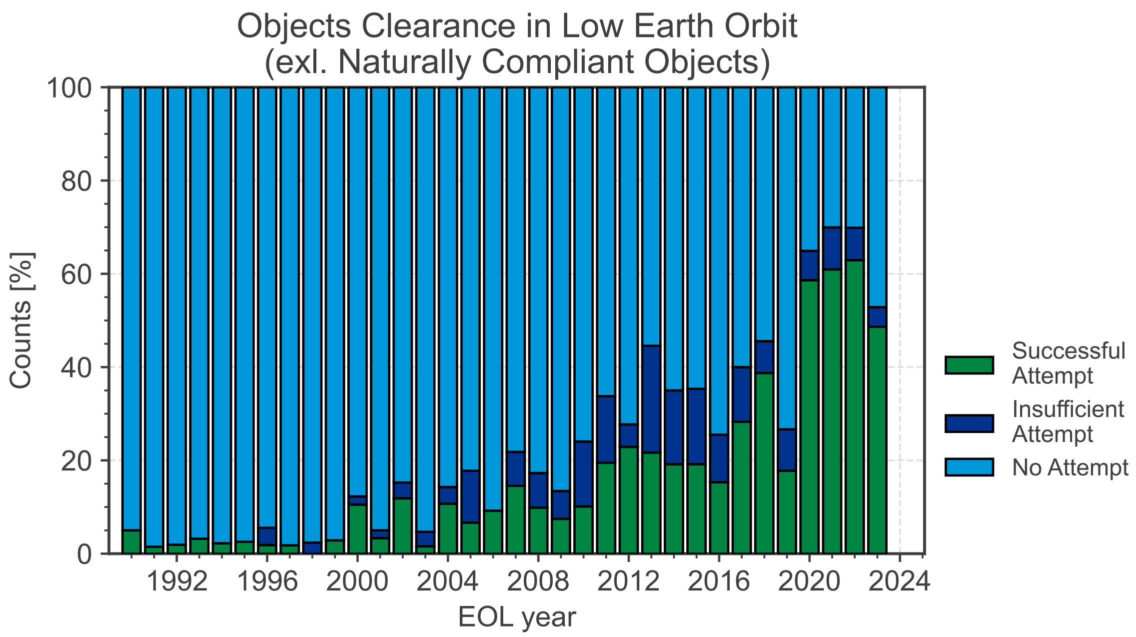


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.28: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, excluding naturally compliant objects where no action was needed or taken, for a lifetime limit of 5 years.



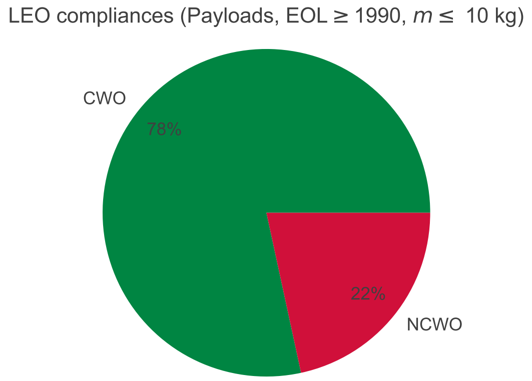
(a) Relative clearance of LEO_{IADC}.



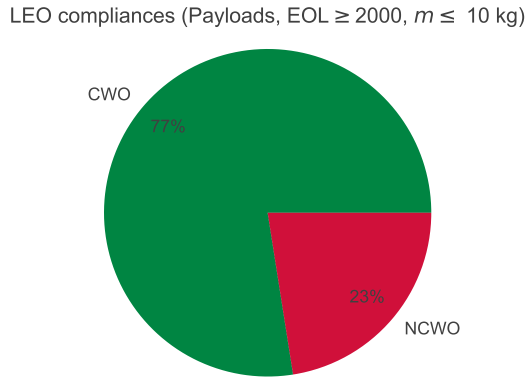
(b) Relative clearance of LEO_{IADC} excluding naturally compliant objects where no action was needed or taken.

Figure 6.29: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, considering payloads and rocket bodies together, for a lifetime limit of 5 years.

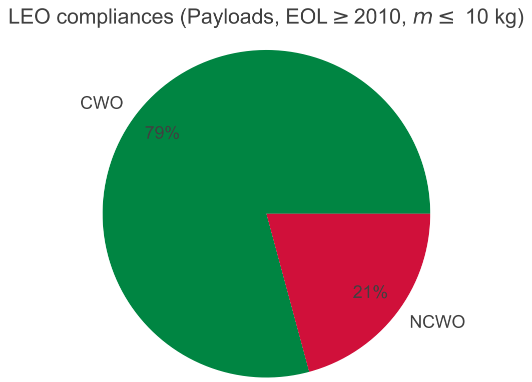
6.1.3.2. Evolution of behavioural classes per mass breakdown



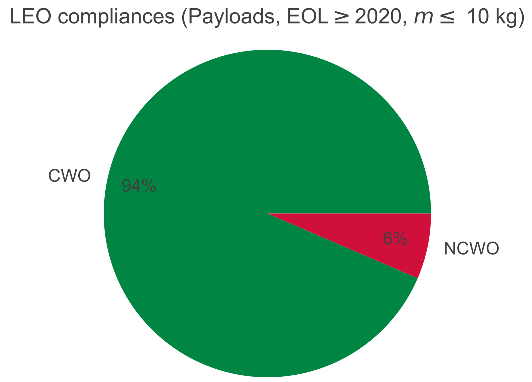
(a) 1990



(b) 2000



(c) 2010



(d) 2020

Figure 6.30: Breakdown per decade of observed behavioural classes for payloads with a mass below 10.0 kg for a lifetime limit of 5 years.

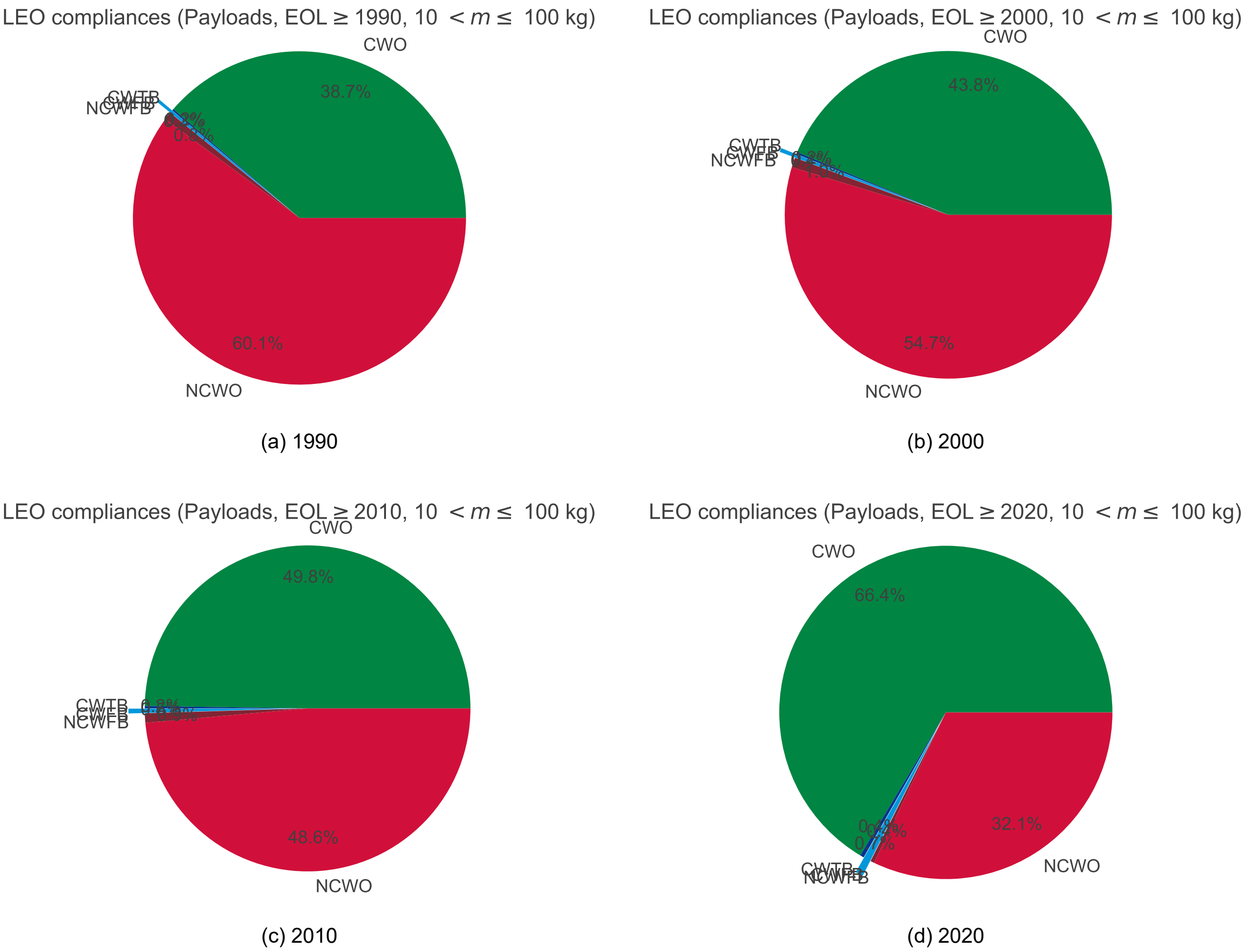


Figure 6.31: Breakdown per decade of observed behavioural classes for payloads with a mass between 10.0 and 100.0 kg for a lifetime limit of 5 years.

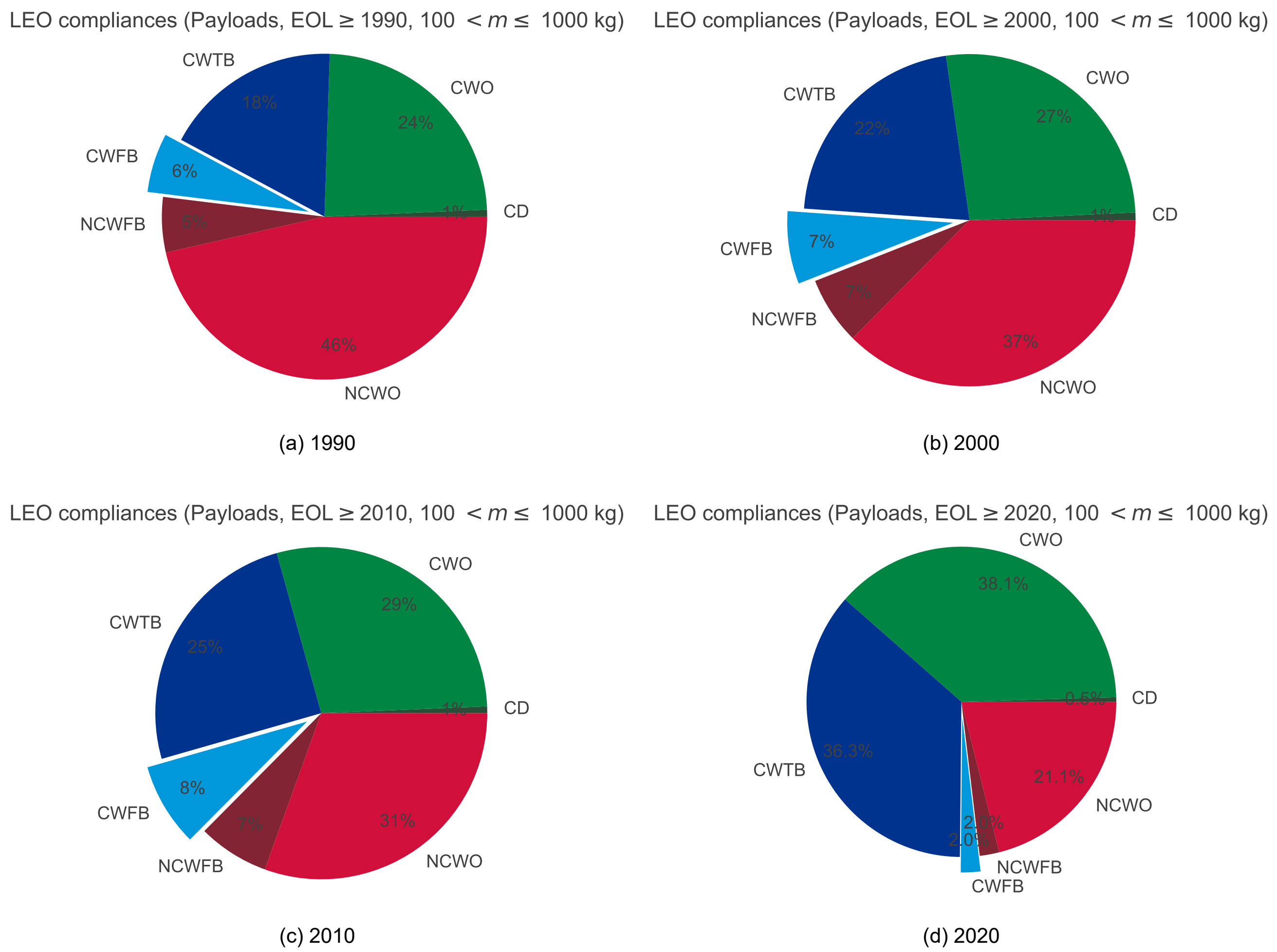


Figure 6.32: Breakdown per decade of observed behavioural classes for payloads with a mass between 100.0 and 1000.0 kg for a lifetime limit of 5 years.

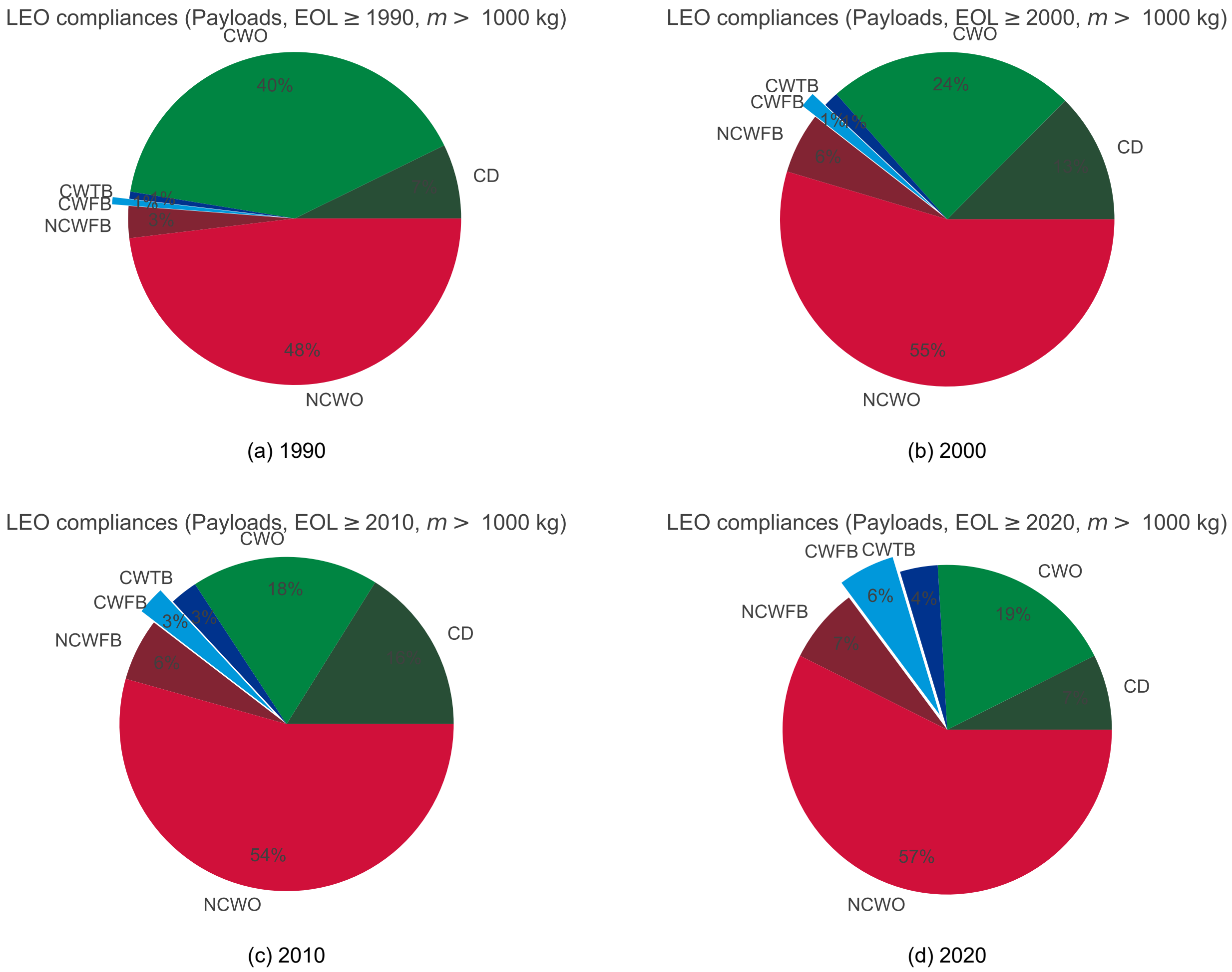


Figure 6.33: Breakdown per decade of observed behavioural classes for payloads with a mass above 1000.0 kg for a lifetime limit of 5 years.

6.1.4. Robustness of the evaluation of compliance shares in LEO

The following analysis shows how the compliance classification has changed over the different editions of the report, considering that each edition is based on a *current* best-estimate of the residual orbital lifetime and reclassification can take place. Fig. 6.34 shows the share of successful re-/de-orbit attempts for payloads according to the different report editions. As mentioned in Section 6.1, in case of payload objects, as in the case in Fig. 6.34, at least one calendar year without orbit control actions needs to pass for an object to be classified as reaching end-of-life, so the report issued in a given year covers up to the end of two years before the release year (e.g. the report issued 2017 covers until the end of 2015). Note that for this visualisation (and for the purpose of the comparison), re-orbits are still considered as successful attempts.

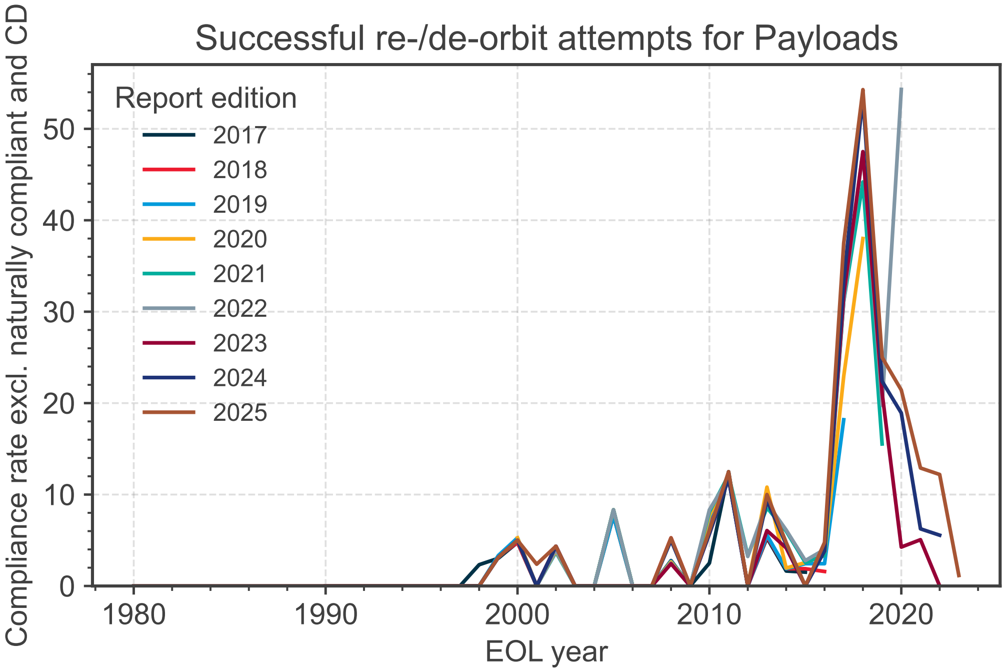


Figure 6.34: Successful re-/de-orbit attempts for payloads according to the different report editions, for a lifetime limit of 25 years.

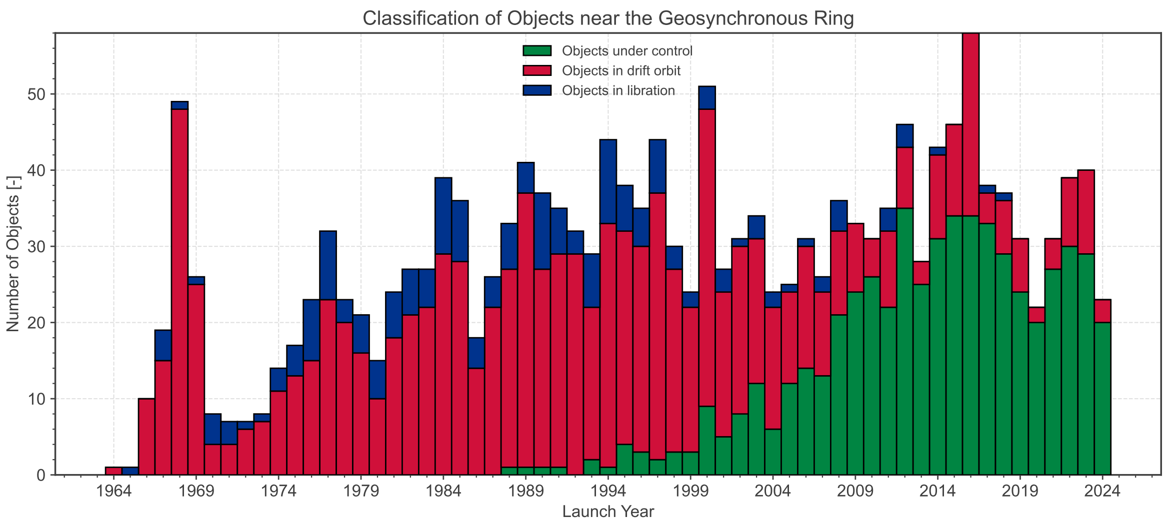
6.2. End-Of-Life Operations in Geostationary Orbit

Unlike in LEO, no natural sink mechanism is available for the GEO protected region by which objects could leave. The solar radiation pressure on the objects will also make long term predictions subject to non-negligible uncertainties. A payload or rocket body operating in the GEO Protected Region, with either a permanent or periodic presence, shall be manoeuvred in a controlled manner during the disposal phase to an orbit that lies entirely outside the GEO Protected Region. There are different ways of ensuring that this condition is met. For example, the launch procedure for Rocket Bodies can be adapted to ensure that the release of the payloads no longer takes place directly within the geostationary orbit but below. In this case, the payload has to climb the last part into GEO_{IADC} but the launcher remains on a GTO trajectory that does not intersect the GEO protected region. For payloads within the GEO protected region, the mitigation measure has been refined, i.e. the so called IADC formulation [8], to ensure that a disposal occurs in a graveyard orbit with minimal interference. At least one of the following two conditions should be met:

- The orbit has an initial eccentricity less than 0.003 and a minimum perigee altitude ΔH (in km) above the geostationary altitude, in accordance with equation:
  1. ΔH = 235 + ($1000 C_r A/m$);
  2. where C_r is the solar radiation pressure coefficient (dimensionless);
  3. A/m is the ratio of the cross-section area (in m^2) to dry mass (in kg) of the payload.
- The orbit has a perigee altitude sufficiently above the geostationary altitude that long-term perturbation forces do not cause the payload to enter the GEO Protected Region within 100 years.

In summary, clearance of the GEO protected region by payloads will be presented as *Successful Attempt*, i.e. the payload clears GEO_{IADC} in-line with the formulation above, *Insufficient Attempt* when the payloads attempt to clear the GEO_{IADC} but does not reach the criteria in the IADC formulation, and *No Attempt* otherwise. An in-depth overview of the status of objects in GEO_{IADC} and description of the summarised results shown here is available via [27].

For the rocket bodies delivering payloads in or near the GEO protected region, the long-term disposal orbits are influenced by a variety of perturbations potentially including Luni-Solar, solar radiation pressure, gravitational resonances, and atmospheric drag. This implies that long-term, i.e. over 100 years [9], clearance of both protected regions by these rocket bodies is only predictable as a stochastic estimate. To assess the adherence by rocket bodies to the disposal guidelines in a first approximation, we list the amount of rocket bodies predicted to cross one or both of the protected regions within the next 100 years after launch, as a function of the total number of rocket bodies that launch payload objects with a destination orbit in GEO. In addition, for those objects crossing the LEO protected region, an object is marked as *LEO-crossing* if it crosses LEO and the permanence time in the LEO region is longer than 25 years. Objects for which no orbital data is available are marked as *Not classified*.



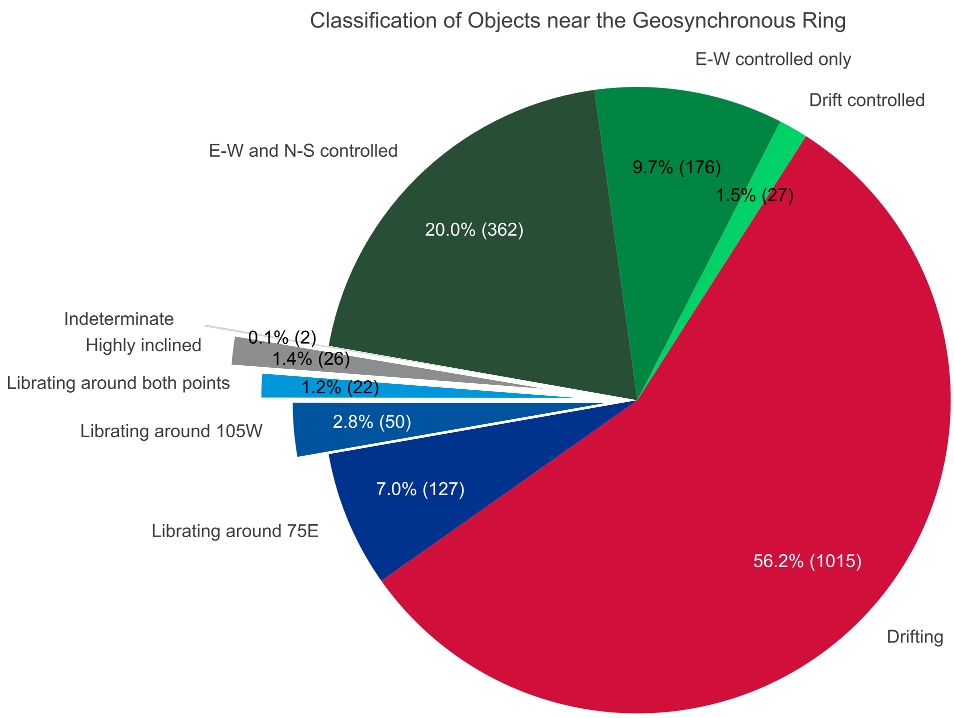
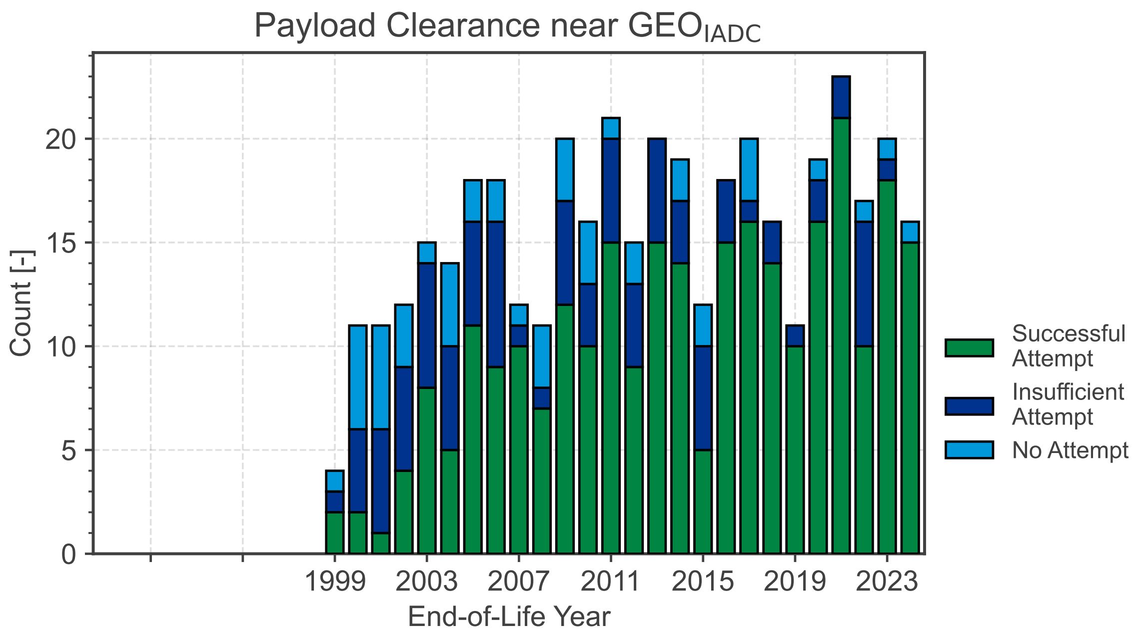
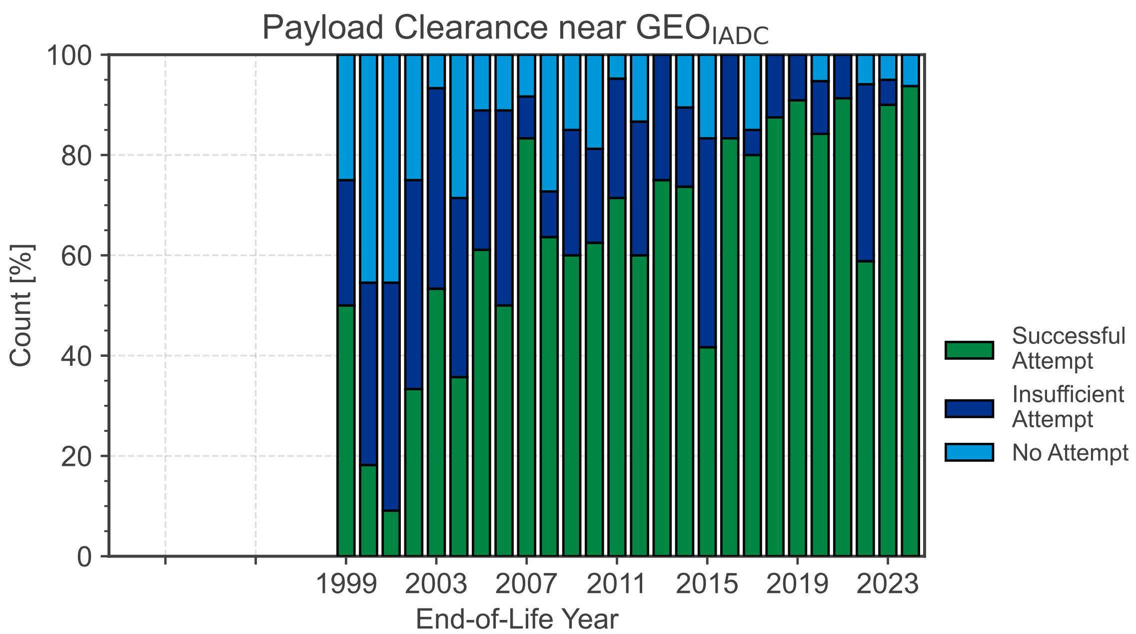


Figure 6.35: Orbital evolution status of payloads near the Geostationary orbit during 2024.

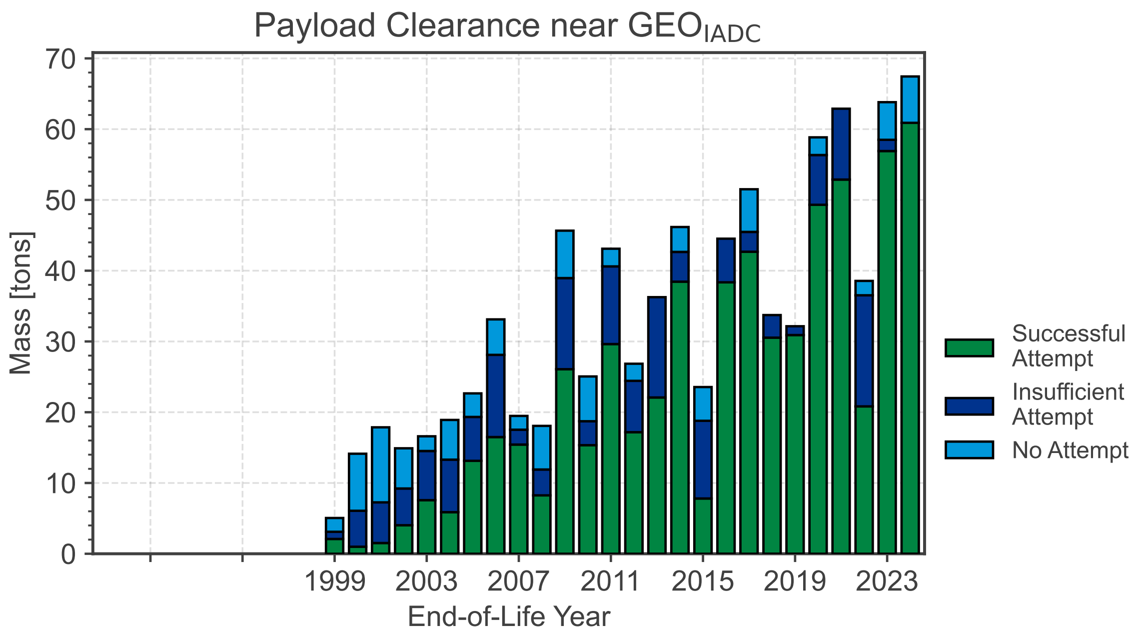


(a) Absolute clearance near GEO_{IADC}.

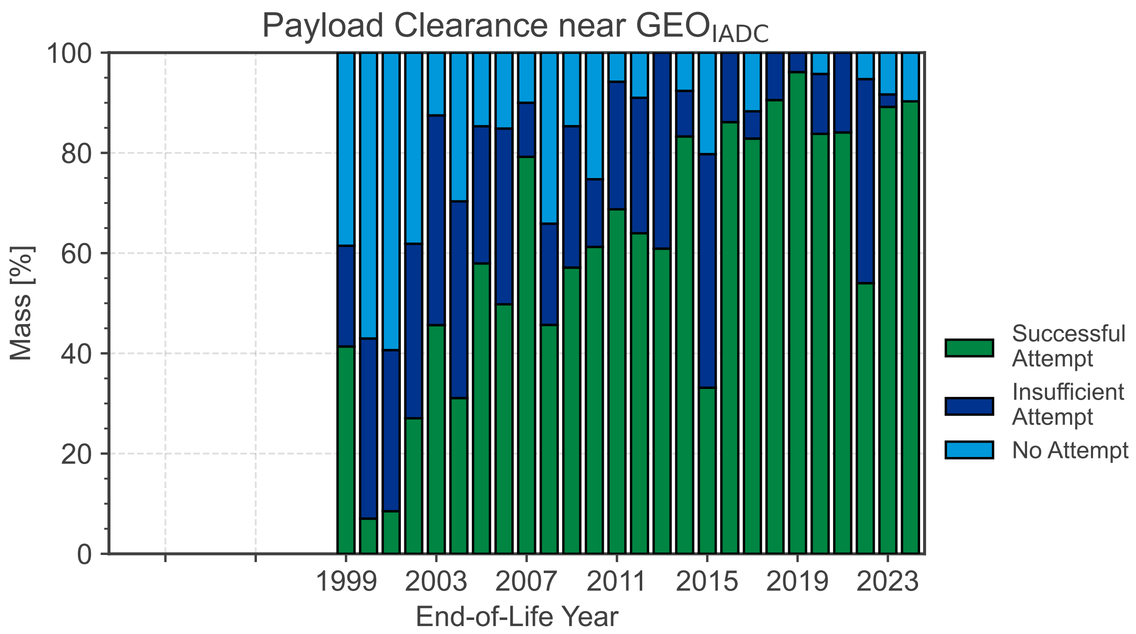


(b) Relative clearance near GEO_{IADC}.

Figure 6.36: Trend of adherence to the disposal guideline in GEO_{IADC}.

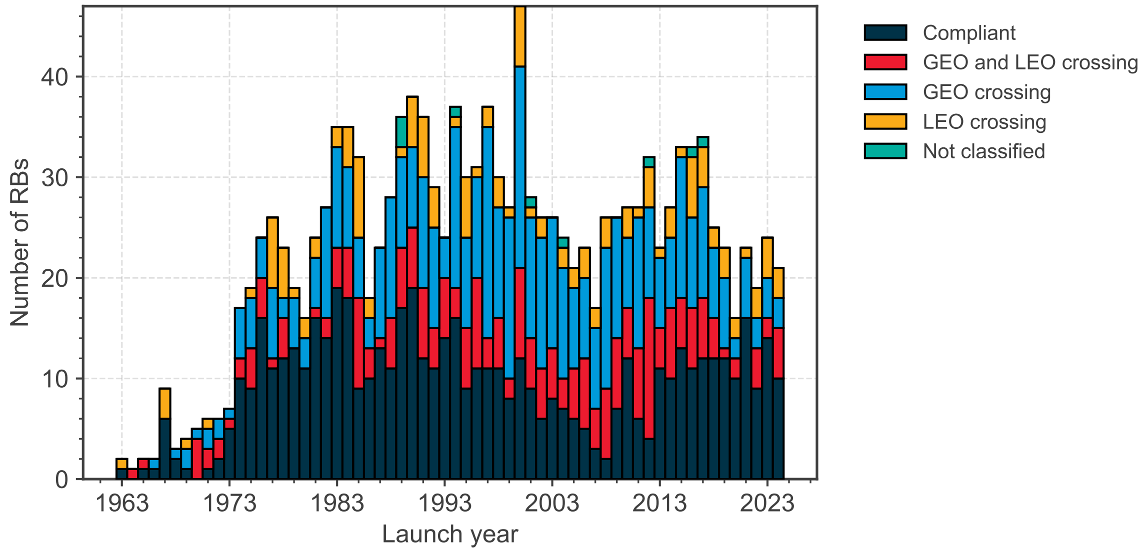


(a) Absolute mass clearance near GEO_{IADC}.

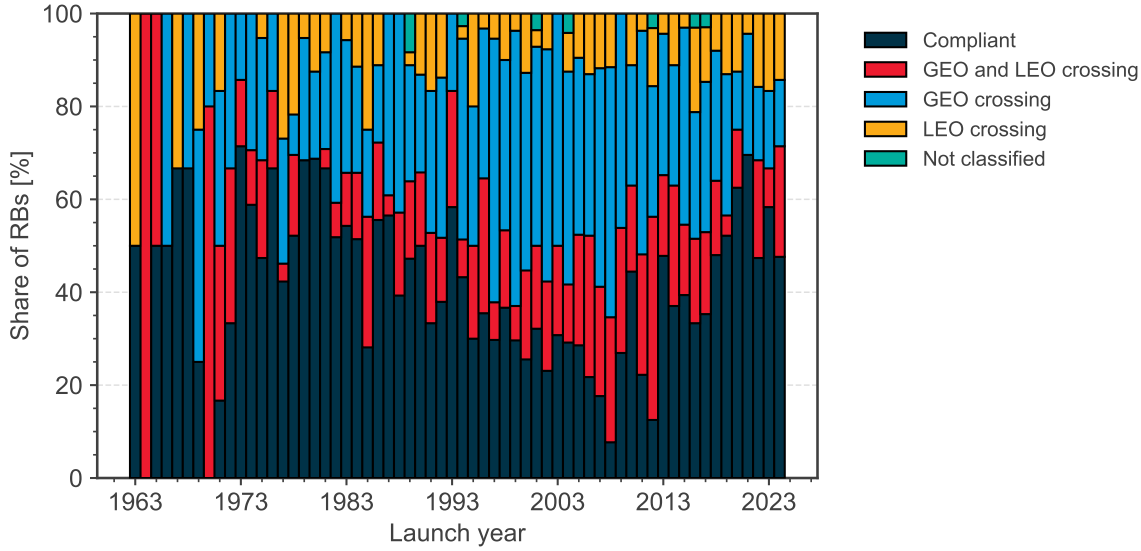


(b) Relative mass clearance near GEO_{IADC}.

Figure 6.37: Mass trend of adherence to the disposal guideline in GEO_{IADC}.



(a) Absolute clearance near GEO_{IADC}.

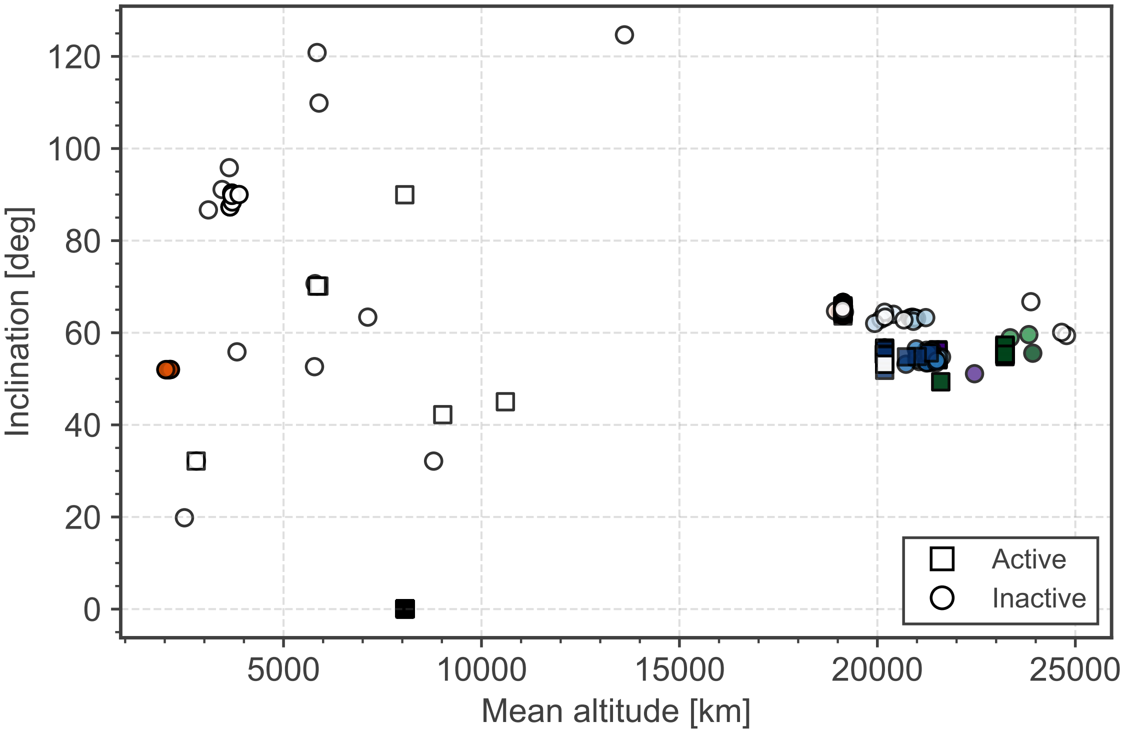


(b) Relative clearance near GEO_{IADC}.

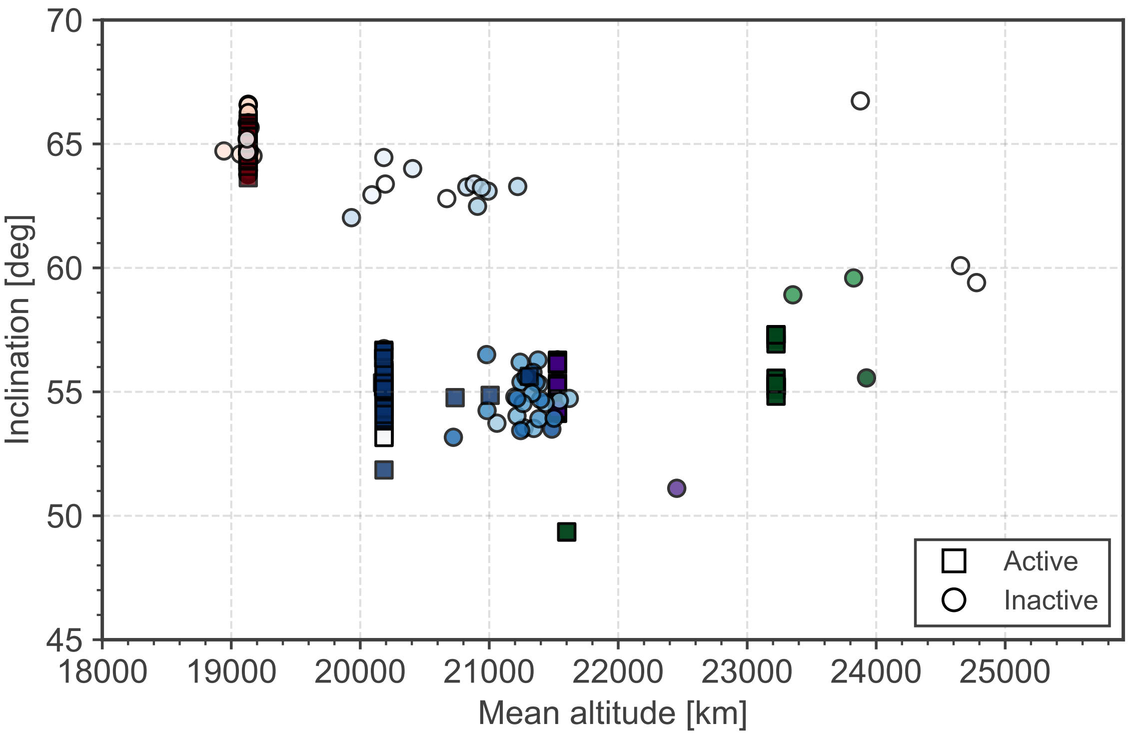
Figure 6.38: Trend of adherence to the disposal guideline for rocket bodies used to insert satellites in GEO_{IADC}.

6.3. End-Of-Life Operations in MEO

Compared to the LEO_{IADC} and GEO_{IADC} regions, MEO contains relatively fewer objects in a larger volume of space. Notwithstanding the resulting lower space debris density, the region is of importance for global navigation and communication constellations, and crossed by space objects with large eccentricity and semi-major axis orbits. Space debris mitigation guidelines call for the avoidance of space debris dense regions by means of targeted disposals, even outside the protected regions [14]. With this perspective in mind, it is instructive to show the orbital disposal behaviour of Payload objects in this region.



(a) MEO region



(b) GNSS constellations

Figure 6.39: Distribution of payloads in MEO in mean altitude and inclination, distinguishing by activity status (symbols) and constellation (colour).