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Space capacity management and its interaction with space traffic management

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ABSTRACT

The management of the finite capacity of near-Earth orbital space requires both scientific and technical as well as policy and regulatory approaches to deal with all the aspects of the issue. In this chapter these various aspects have been analysed. This paper summarises the activities carried out within the working group on Space capacity management mandated by the International Astronautical Federation Space Traffic Management Technical Committee.

First, a scientific and technical understanding of what is meant by this limited capacity, how to quantify it, and how to measure its use is discussed. Several metrics are discussed to highlight the importance of a concerted framework for the definition, computation, monitoring, and allocation of the space environment capacity. Then need for a transparent methodology and a mechanism to ensure the review and approval of the proposed capacity is discussed. The policy and regulatory aspects of space capacity management, under the existing international legal framework for space activities, are also covered. The paper gives recommendations to reach a shared understanding on how space environment capacity should be uniquely defined as a first step towards the management of this capacity and to reach an international consensus about the metrics that should be used.

1. Space capacity quantification

The Earth's orbital space environment constitutes a finite resource that is being used by an increasing number of governmental and non-governmental entities. While the increasing use of space holds out great promise for humanity, it also raises several concerns. The growing congestion in orbit, the proliferation of space debris, the increasing complexity of space operations, the interference with astronomical observations, and the emergence of large constellations of satellites are raising concerns about the safety of space and security of space operations and indeed about the long-term sustainability of outer space activities itself. These concerns are aggravated by certain behaviours that appear not to show due regard for other users of this shared domain, such as the introduction of non-trackable objects in orbit, or the intentional creation of long-lived debris, such as through the destructive kinetic testing of anti-satellite weapons.

Since the early days of the space age, States have regarded space as a common good, accessible to all nations to use, and whose use was

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rivalrous and non-excludable. But as the domain is rapidly becoming more congested, especially with the advent of very large satellite constellations, we are beginning to witness a "tragedy of the commons" [1], the situation that arises when common goods are overused by society, which leads to the destruction of the resource, to everyone's detriment. This means that the Earth's orbital environment and spectrum need to be considered as finite resources that have to be managed in a rational manner to allow equitable access to all current users and also with due regard to the needs of future generations.

The leading international forum to discuss questions of international cooperation in space activities is the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS). In 2019, following an eight-year process, the Committee adopted a set of 21 voluntary, non-binding UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities ('COPUOS Long Term Sustainability (LST) Guidelines') [2]. These guidelines comprise a collection of internationally recognized measures for ensuring the long-term sustainability of outer space activities and for enhancing the safety of space operations. They address the policy, regulatory, operational, safety, scientific, technical, international cooperation, and capacity-building aspects of space activities, and apply to all phases of a space mission, including launch, operation and end-of-life disposal [3].

While the LTS Guidelines contain elements that would be foundational building blocks for the creation of a future Space Traffic Management (STM) framework, they do not address the crucial question of the carrying capacity of the orbital environment itself. The LTS Guidelines do, however, recognise the Earth's orbital environment as a finite resource, so they open the door to a reflection on how to manage such a resource (and therefore to the concept of capacity). In this regard, it is instructive to repeat here the definition of space sustainability contained in the preamble of the LTS Guidelines:

The long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations [4].

The order-of-magnitude increase in the number of active satellites expected over the coming decade raises the question about the need of an international space traffic management framework, improved coordination among regulators, and some internationally agreed mechanism upon which States can manage and coordinate their utilization of shared orbit and spectrum resources. Regulators confronted with licence applications for space systems currently have no way of evaluating the impact of a proposed space system on the space environment itself, or on the safety of space operations. For this, they have to turn elsewhere to technical studies being performed by several groups around the world, which are described in this chapter.

The concept of orbital carrying capacity, at least from a pre-theoretic (i.e., non-technical and intuitive sense) may serve as an incentive to cooperative global astronautical activity, and to ensure the long-term sustainability of spaceflight. That is, the idea that there may be a limit to the number of spacecraft a given orbital region can carry may encourage policy-makers, spaceflight operators, and other stakeholders to work together. However, that idea must not be used (or abused) in a way that may exclude spaceflight actors (current, new, or future) from engaging in spaceflight activities (i.e., from orbit insertion of the spacecraft). Various factors may impact a characterization of carrying capacity, such as scale of spacecraft, operational capabilities, etc. Other more complex and quantitative factors impacting a characterization may include quantity (of satellites)-dependent risk probabilities of fragmentation events. In other words, the capacity may be characterised as a prescribed limit beyond which is projected (under certain assumptions, criteria, etc.) to raise the risk of in-situ collision and environmental sustainability damaging phenomena. In any case, such characterizations, or senses, of capacity, should be explored with care so as not to impose an exaggerated restriction on our ability to push the boundaries of peaceful and globally beneficial space-faring activities.

Current debris mitigation guidelines have two main limitations: (1) they are not derived from a definition of a sustainable environment (top-down), (2) they are not linked to the actual dynamics of the debris environment (bottom-up). In practice, this means that it cannot be ensured that well known mitigation practices (e.g., 25-year rule with 90 % implementation rate) are still relevant in a new space era with launch traffic trends and spacecraft characteristics significantly different from the ones in place (or even expected) when such guidelines were drafted [5].

The concept of capacity applied to the space environment tries to respond to these gaps; as such it should (1) offer a link to desired environment trend, (2) be measurable. The first point is already not trivial in terms of definition and scope. Firstly, the "orbital capacity" can be intended as the number of objects compatible with a sustainable environment. Within this definition, according to some authors [6], a sustainable environment is only possible where a zero-growth rate of the debris population is achieved; for others [7], the capacity is defined considering an acceptable population growth rate, similarly to what is done in the climate change world with the 2-degree target. The analysis of such environment trends often relies on long-term simulations of the environment that relies on the definition of several parameters (e.g., launch traffic, break-up rates, disposal behaviour), which are difficult to predict (especially in the time horizon of 100–200 years typically adopted) and require a certain level of abstraction to be applicable on the whole space object population. For this reason, a consistent set of hypotheses and assumptions is essential for any attempt of evaluating the space debris environment as a whole that wants to collect a general technical consensus. Other definitions of orbital capacity are present in literature [8], where the focus is on active objects (especially constellations). In the rest of the document, the first definition (i.e., whole environment) will be applied as more general, whereas the second one is briefly treated in Section 4, which focuses on implementation considerations for space traffic management. Finally, further definitions of orbital capacity (and related management mechanisms) can be derived by taking inspiration from other fields where capacity concepts exist such as biology, where target thresholds are defined such as climate change, and where coordinated exploitation mechanisms are defined such as CO_2 emissions, fisheries, and frequency management through International Telecommunication Union (ITU) [9,10]. In particular, the comparison with other domains could be fruitful to learn not only on the level of abstraction introduced in these global modelling efforts, but also on the policy framework that such mechanisms require.

On the second requirement for a capacity concept (i.e., be measurable), several metrics have been proposed and will be reviewed in more detail in Section 2. In general, such metrics can be defined at the environment level (e.g., population growth) or at a single object level (e.g., number of objects, number of performed collision avoidance manoeuvres, flux, fragmentation risk) and aggregated to provide a single score representative of the global environment status. In all cases, a methodology should be defined to allow for monitoring (i.e., ideally, independent assessments are possible with inputs mostly coming from available catalogues and models. However also operator-provided data would be very preciuos) and, potentially, for traffic management (e.g. having the possibility of deriving actionable measures to be applied to space missions).

2. Space capacity metrics

It is clear that in order to regulate the space object population there should be the introduction of metrics of capacity. How can we design the indicator to define what is the maximum capacity of given orbits? How can we define the maximum capacity? These metrics should serve the needs of all space actors. Depending on the actors, the concerns are different, and it is the role of these metrics to find a common ground that would ensure a long-term use of outer space as per the UN LTS definition.

Spacecraft operators are mostly concerned about the safety of their missions and their operability (too many collision avoidance manoeuvres would hinder the operation). Flexibility in orbit selection is also important. Therefore, they want to ensure a low collision risk during the operational lifetime. The scientific community is trying to better understand how the population of space objects will evolve over the long term, which would help to understand how many objects can be added in a specific orbit while defining the number of objects to be removed and after how long. What should be the maximum [mass/chemical composition/object mass/year?] threshold of an object allowed to enter the atmosphere in order to perform a direct re-entry? When do all the rocket exhaust plumes and satellite re-entries start to have a measurable impact on the composition and chemistry of the atmosphere? [11].

If we extend the discussion to space sustainability, the community of astronomers have raised concerns regarding interference with astronomical observations in both optical and radio domains. While there exist technical solutions and observation scheduling strategies to mitigate such interferences from observations, there are still concerns to save the "dark sky" and consider these as part of the heritage of all humankind that should be saved for future generations.

The general public is also becoming more and more educated about space sustainability issues in general and are asking questions about the use of outer space. Even if in general, the urgency to act is more related to climate change, the dependency of our current economies on space assets, combined with the awareness of sustainability questions, makes the public question the choices made by governments and commercial actors on the ways they use space and the impact of their activities on the space environment. Are large constellations of 1000s satellites for connectivity an acceptable use of limited orbital capacity? Should only missions for public good be launched? Do national security requirements justify the launch of missions that are not respecting guidelines for space sustainability?

Regulators and policy makers are trying to find ways to translate these concerns into regulations and incentives. The launching states are liable for the activities of their national and commercial operators. Their role is challenging, as they need to both regulate the launch, exploitation of orbital space and spectrum, while ensuring that they secure competitive access to a constantly fast-growing market. Space is also considered as a common good and regulators should also exchange information with their peers in the context of the UN COPUOS. As mentioned in Section 1, the discussion and decision process can be very long and runs the risk of being outpaced by technological and operational developments. Moreover, the cultural context and perception of the use of space is changing, which makes the process of defining common metrics even more challenging.

To conclude, the space community is not yet in a situation to define a list of parameters to track the evolution of the space population as we see in the climate change debate, however we can see different initiatives and the following section will present them.

As the need for regulating space occupancy is emerging, a metric for space carrying capacity is required. Not many studies exist on the definition of capacity metric. Krag et al. [12] proposed the number-time product as the fragment-years that are available for consumption by human space activity in Low Earth Orbit (LEO) for the next 200 years. Its definition is based on the number of fragments larger than 10 cm derived from the long-term debris simulations; the total available capacity is defined as the time integral of the difference in number of fragments between a space debris evolution scenario and a reference one over a time window of 200 years. Letizia et al. [7,13] proposed to use a different metric instead of the fragment-years, namely a risk metric (also indicated as space debris index) that can be aggregated across all objects in orbit to quantify which share of the environment capacity is already in use and which could be used by future missions. The specific metric used in the work measures the potential risk generational associated to single missions considering the likelihood that they are involved in fragmentations (i.e., collisions and explosions) and the severity of such fragmentations quantified as the increase in collision probability for active satellites.

The concept of carrying capacity in other environment fields was reviewed by Trozzi et al. [9] and summarised in the following. The carrying capacity of an environment is the maximum population size of a biological species that can be sustained in that specific environment, given the resources available [14]. This is different from the concept of population equilibrium, which may be far below an environment's carrying capacity. The logistic equation or similar shaped functions are often used in biology and other contexts as for example the modelling of the carbon dioxide (CO_2) emissions from fossil fuel combustion during research on emission trends and on their further values [14]. However, Trozzi et al. [9], by using a simplified sources and sinks space debris model, showed that applying different space capacity definitions or different aggregated space debris indices and different hypotheses in evolutionary models can lead to widely varying results in terms of absolute values of capacity and assigned capacity allocation. Lewis et al. [6] analysed the deep time issues that arise from the enduring nature of the space debris problem and highlighted the need for tools to tackle multi-millennial timescales of debris hazard. Moreover, using model-based approaches they showed the importance of properly modelling in-orbit explosions and launch traffic rate as they highly affect the exponential behaviour. All these works highlight the importance of a concerted framework for the definition, computation, monitoring, and allocation of the space environment capacity.

A recent initiative was initiated in answer to a call from the World Economic Forum (WEF) to propose a score representing the sustainability of a mission looking at the alignment with international guidelines. In answer to this call, the Space Sustainability Rating was proposed to encourage a more responsible behaviour toward mission design and operational concepts that are compatible with a stable evolution of space. The approach combined, in a unique indicator, different modules to capture different aspects of sustainability in space, considering both the impact on other operators and on the environment globally, looking both at short- and long-term effects [16].

On the technical point of view, the work by Kawamoto et al. [17] analyse how many constellation satellites can be put in each altitude band compared with the population background, not only in terms of the number of objects in the long-term evolution, but also in terms of short-term collision avoidance numbers and collision rates with non-trackable small debris. Similarly, the work by Kunstadter et al. [18] applies the definition in Ref. [15] and a Particle-in-a-Box (PIB) model to derive the maximum number of derelict objects for different altitude shells compatible with a no-growth scenario. Colombo et al. [19] developed a Life Cycle Assessment approach to measure the space debris index considering not only the risk for in orbit collisions and explosions, but also the casualty risk on ground during re-entry, and an indicator of the orbit slot used as a resource, measured based on the revenue that slot procures. Moreover, the European Space Agency (ESA) has initiated a project to develop the THEMIS tool as a platform, available to the whole community, to measure the space debris impact of a single mission on the space environment and to measure the share of space capacity used by a mission [20]. An improved continuum approach by Giudici et al. [21] is used to implement the space debris index formulation in Letizia et al. [22], which is defined as a risk indicator composed by a probability term and an effect term, which considers the contribution of fragmentations on the sustainability of the space environment. The approach is used in to evaluate the impact that already in-orbit satellites including large constellations have on the space environment [23].

While a capacity measure is needed, the resulting challenge is to define indicators and thresholds. From an operational point of view, the number of Collision Data Messages (CDM) could be used to quantify the risk in each orbit slot. Additionally, the number of Collision Avoidance Manoeuvres (CAMs) gives information on the threshold of collision probability accepted by the satellite operator, even if this is highly operator dependent as different operators can have different reaction thresholds. For example, in Polli et al. [24] the mean collision probability related to a shell crossing event was used to evaluate the risk for a passage of a de-orbiting or injecting satellite within the thin region of space populated by constellation's satellites and therefore to assess the environmental impact of the replacement of every approved constellation. Ghelani [25] proposed a congestion-tipping model for Earth orbits that shows that the risk posed by undetectable debris could bring the congestion-tipping period to around 100 years.

Most of the metrics mentioned above rely on common parameters in their assessments such as the size (i.e., mass or cross-sectional area) of spacecraft and its orbital altitude. Some formulations consider the activity status of spacecraft and their ability to perform collision avoidance manoeuvres. Further aspects that can be considered include data sharing [26], spacecraft design (e.g., robustness to failure), concept of operations (e.g., station keeping strategy, disposal approach).

While the general drivers for capacity are shared in the community (i.e., large inactive objects with long orbital lifetime are especially detrimental), several issues arise when attempting to define a specific number or threshold. For example, analyses often rely on simulations where the minimum size of objects need to be specified and/or where some types of fragmentations are accounted for (e.g., catastrophic collisions, where the spacecraft is destroyed). While these assumptions can be justified, a sensitivity analysis of the proposed thresholds to such model parameters is usually not available and it may be a required step to build consensus in the technical community on a modelling approach. Moreover, capacity metrics have the limitation of validation only against models, which are affected by several uncertainties. Some possibilities exist to partially validate against catalogues, or CDMs and objects Two Line Elements (TLEs) could offer a real snapshot of the in-orbit situation.

In conclusion, a transparent methodology needs to be developed to seek for global consensus and implementation in countries' regulatory approach.

3. Coordination of the space capacity

The environment capacity should be uniquely defined, reaching an international consensus about the metrics that should be used. It may be necessary to distinguish between global and local capacity. The former would correspond to the capacity of all the Earth orbits, while the latter would define the capacity of specific orbital regimes, shells, or inclinations.

The definition of a space capacity should lead to acting against overcrowding the space environment, since this would prevent further space exploration and exploitation. Hence, the local and global threshold that should not be exceeded should be defined by international entities, as it has been done with Space Debris Mitigation guidelines and requirements, by entities such as IADC and the UN COPUOS. To maintain space usage under the maximum capacity, a slot capacity allocation system could be put into place, like the one that is in place for telecommunication frequency allocation. The slot allocation should take into account both the global and local threshold and could be based on the metrics mentioned in Sections 1 and 2. To this end, the need for mechanisms to ensure the review and approval of the proposed capacity use would arise.

In terms of Article VI of the Outer Space Treaty, States are responsible for the authorization and continuing supervision of space activities conducted by non-governmental entities under their jurisdiction and/or control [27]. This treaty obligation is normally codified in national legislation that is implemented by the relevant national regulatory authorities. In addition to such legally binding treaty obligations, States may also choose to codify non-binding principles or guidelines, such as space debris guidelines or LTS guidelines in their national regulatory practices.

Many national regulatory offices are quite small, both in terms of the number of officials and budget and other resources dedicated to the regulatory functions; this means that they have limited capability to process new licence requests and meet Article VI obligations. In the past, the number of licensing applications per year was limited, and the regulators could keep pace with the flow of new licensing applications. Moreover, regulatory oversight often peaked in the period leading up to the issue of a licence and then tapered sharply in the operational and post-operational phases. However, the accelerating pace and volume of space activities is starting to strain the capacity of some states to exercise their regulatory functions. Moreover, with the growing congestion in orbit, it becomes more important to implement the Article VI provisions for continuing supervision.

In addition to this, the web of possible relationships among space actors is now vastly greater and more complex than it used to be, and national regulators are facing challenges with chain-of-custody issues and phenomena such as regulation shopping. If we are to avoid a fragmented governance system, with different standards of behaviour in one common, shared domain, we will need to improve our cooperative governance of space activities and inter-regulator coordination.

The emergence of STM is going to add a further layer of complexity to the licensing process and continuing supervision processes. There are several questions that arise, such as.

1. What will be the environmental burden of a given space system on the domain?
2. What do we mean by carrying capacity. How do we define it in an operationally useful way?
3. How does capacity vary with the size, number, distribution, manoeuvring capabilities and/or function of space objects?
4. What is the carrying capacity of the orbital environment, and will the addition of the proposed system to what is already there be within that carrying capacity?
5. Is the proposed capacity use a rational and equitable use of the limited orbital resource? Who decides this and what are the criteria used to reach such a decision?
6. Will conditions be imposed on a licensee to ensure that the allocated capacity is vacated after the end of licensed operations, or sooner if the mission fails? How will such conditions be enforced?
7. Will the period of validity of the licence be limited, or will it be indefinite, as long as the allocated capacity is "used" in some way? What constitutes "use"?
8. Could an operating licence be transferable from the licensed operator to another operator?

These are important questions to consider because when a State licences a space system, it is essentially allocating a fraction of the limited shared orbital carrying capacity to one of its national space activities, and it is accepting international liability for that system on behalf of the nation's taxpayers.

4. Space capacity in the context of space traffic management

Due to declining costs, satellite and launcher size evolutions, an increase in the pace of space activity is happening, adding objects to already crowded orbits. The exponential increase of the space object population is increasing the complexity of the operational aspects of space activities. Although access to space is in principle regulated by international and national law, once in orbit the physical reality determines the consequences that a single object has on all its orbital neighbours. The increased number of close approaches that have to be managed - including multiple encounters, debris versus debris events, close approaches between active satellites in which the lack of rules of the road impose needs for coordination, etc.- reveal the need for a more holistic strategy in the management of the space operations, as well as the urgency in implementing new measures, both in technological aspects (e.g. active debris removal, on-orbit servicing, etc.) and policy aspects (e.g. regulatory frameworks, cooperation among stakeholders, interoperability, etc.).

The way space traffic is organised today differs depending on the nature of the orbit. This is clear when comparing LEO vs geostationary Earth orbits environment.

In LEO, each operator tends to select their mission orbit focusing uniquely on their mission outcomes, with little to no analysis of how this selection impacts the space capacity of the selected orbit or its close environment. In terms of traffic management, collisions between operational spacecraft are not avoided "by design". This means that operators need to deal, not only with non-operational objects but also with operational satellites. While the orbits of the first ones are well-characterised in advance by all operators (those that are big enough to be tracked), for operational satellites this is not necessarily the case. This is due to artificial events changing the natural evolution of the operational-objects in space such as station-keeping, orbit raising or de-orbiting manoeuvres, which are not, in most cases, openly shared in advance with the rest of the space community. Additionally, the lack of the so-called "rules-of-road", increases the operations complexity as well as the probability of space debris generation, which negatively impacts space capacity. The not complete adherence to post mission disposal strategies is one of the greatest contributors to space debris creation and reduction of orbital capacity in LEO. Lowest altitudes provide natural compliance of the 25-year deorbiting rule, due to the effect of atmospheric drag. Nevertheless, there is a region (above 600–700 km depending on the object features) where the natural decay does not happen fast enough, and the current success of disposal actions is still not sufficient.

Moreover, as the number of spacecraft in orbit is drastically increasing due to the advent of large constellations, the maximum of 25 for re-entry time after the end-of-operation may not be sufficient anymore and should be decreased. All in all, space capacity in the LEO environment can still be limited by enhancing post mission disposal guidelines adherence and traffic organisation [5].

In Geostationary orbit (GEO) post mission disposal adherence and traffic management is different as the number of operational satellites is smaller and the level of successful disposal (in %) is higher than in LEO (when comparing with non-natural compliant objects). In terms of traffic, each operator continues to be focused on its mission outcome but also respecting its longitude window. This was made possible by a regulation (managed by the ITU) that indirectly drove the accepted GEO "capacity" today. This implementation ensures that collisions between operational satellites are avoided "by design". Due to the dynamics in GEO, the management of space traffic can be organised by means of one degree of freedom, the longitude. The same strategy cannot be directly applied to the LEO and Medium Earth Orbit (MEO) environment since more degrees of freedom in terms of orbital elements need to be considered [28]. Nevertheless, it can be used as an example of how a certain level of traffic organisation affords, by design, collision avoidance between operational artificial satellites. How to apply this philosophy in the LEO environment, minimising the impacts on the interests of each space actor, is a problem that still needs to be solved.

One of the main challenges of LEO are orbital perturbations, which are much more prominent and dynamic than in MEO/GEO. Without station-keeping manoeuvres, satellite orbital parameters continuously drift due to natural perturbations such as Earth gravity field, atmospheric drag, and solar radiation pressure. Consequently, satellites do not fly along a constant two-dimensional orbit, but along a certain volume that varies depending on the interval of time considered for natural propagation. This concept was described in the literature as the "space occupancy" [29] The concept of Space Occupancy Range (SOR) is based on an altitude variation metric over a certain period of time. Due to the complexity of LEO environment (mainly due to the range of possible orbital inclinations and the precession of orbital planes), it seems a natural idea to use the radial displacement with respect to the Earth as one of the key parameters to "organise" space traffic and avoid collisions between operational spacecraft. The lower a satellite flies, the more the atmospheric drag will have a negative influence on the size of this altitude variation metric (increasing its range due to orbit decay). Intuitively, it seems necessary that each satellite reduces its space occupancy as much as it can so that more entities can take profit of this limited resource. When considering all perturbations, an adaptation of the concept is required in what some authors [30] have called Minimum Space Occupancy (MiSO) orbits. This can be understood as a generalisation of the frozen orbits: considering the whole set of orbital perturbations for a given orbit and by means of dedicated numerical methods, a set of initial orbital conditions is found that minimises the natural drift of the orbit.

The definition of appropriate orbital capacity metrics can contribute to a more efficient approach for space traffic management, allowing the evaluation of the integral risk over all actors in orbit [31]. A better and more accurate knowledge of the orbital capacity, and the impact of any object (or distributed space system) on this capacity [32] (depending on size, shape, manoeuvrability, disposal strategy, frequency, etc.), would allow the establishment of clearer thresholds to jointly manage the use of this limited orbital capacity and to better coordinate space operations activities. The benefits of such metrics and the associated thresholds are numerous [33], including for example.

1. Raising awareness of the actual dimension of the problem, which can be over- or under-estimated without the due transparency.
2. Incorporating the use of the metrics and thresholds as part of the licensing process?
3. Establishing premiums and/or penalties based on agreed impartial criteria to incentivize responsible and sustainable behaviour in orbit?
4. Informing decisions on the need (or not) to review the de-orbiting/re-orbiting recommendations: Is 25 years still a reasonable period for LEO? Would it make sense to have different values depending on altitude, manoeuvrability, mission? What are the needs in MEO?, etc.
5. Quantifying the benefit and impact of Active Debris Removal (ADR). Would it make sense to incentivize or even impose de-orbiting fixtures depending on the characteristics of the object? How might such policy and regulatory measures affect the market for ADR and how large would the potential annual market for ADR be?
6. Quantifying the benefit and impact of On-Orbit Servicing Missions, with similar questions to the ones associated with ADR.
7. Informing decisions about recommendations and/or obligations to minimise the harmful interference of an object with other operational objects in the environment (e.g., observability of the object, manoeuvrability, data sharing, accuracy of ephemerides, etc.)
8. Define the risk thresholds for the Probability of Collision depending on the orbital capacity?

5. Recommendations and conclusions

In recent years we have witnessed an exponential increase in the number of active satellites in Earth orbit, which is being driven by a growing number and diversity of space actors on Earth. The growing congestion in orbit due to active satellites and space debris has led to the conclusion that the Earth's orbital space environment constitutes a finite resource that must be managed rationally and equitably for the benefit of current as well as future generations. The management of the finite capacity of near-Earth orbital space requires both scientific and technical as well as policy and regulatory approaches to deal with all the aspects of the issue. In this chapter these various aspects have been analysed.

The first step toward space capacity management is to develop a scientific and technical understanding of precisely what is meant by this limited capacity, how to quantify it, and how to measure its use. Measuring the available capacity of the space environment, to drive debris mitigation guidelines to a desired environment trend. The "orbital capacity" can be understood as the number of objects compatible with a sustainable utilization of the environment. However, a consensus has not yet been reached on what a definition for sustainable environment is, in terms of population growth rate (i.e. zero-growth rate or an acceptable growth rate). The difficulty is that prediction relies on long-term simulations of the environment that depends on the definition of several parameters (e.g. launch traffic, break-up rates, disposal behaviour), which are difficult to predict. Other domains can provide a good inspiration for definitions of orbital capacity and related management mechanisms. These include examples of nature from closed ecosystems, management of climate change, fisheries, and frequency management through the International Telecommunication Union.

Several metrics have been proposed such as the fragment-years that are available for consumption by human space activity in Low Earth Orbit for the next 200 years or a risk metric that can be aggregated across all objects in orbit to quantify which share of the environment capacity is already in use and which could be used by future missions. However, applying different space capacity definitions, or different aggregated space debris indices, and different hypotheses in evolutionary models or different models for in-orbit explosions and launch traffic rates can lead to widely varying results. This highlights the importance of a concerted framework for the definition, computation, monitoring, and allocation of the space environment capacity.

In conclusion, a transparent methodology needs to be developed to seek for global consensus and implementation in countries' regulatory approach. Moreover, it may be necessary to distinguish between global and local capacity. The former would correspond to the capacity of all the Earth orbits, while the latter would define the capacity of specific orbital regimes, shells, or inclinations, which could be related to space traffic management procedures. The local and global threshold not to be exceeded should be defined by international entities, as it has been done with Space Debris Mitigation guidelines and requirements, by entities such as Inter Agency Space Debris Coordination Committee and the United Nation (UN) COPUOS. To this end, the need for mechanisms to ensure the review and approval of the proposed capacity use would arise.

Regarding the policy and regulatory aspects of space capacity management, under the existing international legal framework for space activities, States bear international responsibility and liability for the space activities of entities under their jurisdiction and/or control. These obligations derive from legally binding international treaties, as well as legally non-binding (although politically binding) soft law instruments such as UN General Assembly resolutions, and other internationally accepted standards, principles, and guidelines. The treaty obligations of States are normally codified in national legislation that is implemented by the relevant national regulatory authorities. In addition to such legally binding treaty obligations, States may also choose to codify non-binding principles or guidelines, such as space debris guidelines or the Long-Term Sustainability guidelines in their national regulatory practices. The dramatic increase in the number and nationalities of non-State actors raises challenges for national regulators regarding chain-of-custody issues and phenomena such as regulation shopping. This raises the possibility of a fragmented governance system, with different standards of behaviour in one common, shared domain, which can only be avoided through cooperative governance of space activities and improved inter-regulator coordination.

Reaching a shared understanding on how space environment capacity should be uniquely defined will be the first step towards the management of this capacity. The next step would be to reach an international consensus about the metrics that should be used. In doing so, it may be necessary to distinguish between global (i.e. all the Earth orbits) and local capacity (i.e. specific orbit regimes). These are important considerations because when a State licenses a space system, it is essentially allocating a fraction of the limited, globally shared orbital carrying capacity to one of its national space actors, and it is also accepting international liability for that system on behalf of that nation's taxpayers.

The licensing process should include regulatory considerations such as: (i) what fraction of capacity is allocated and whether this can be justified as a rational and equitable allocation of such capacity; (ii) whether conditions should be imposed on a licensee to ensure that the allocated capacity is vacated after the end of licensed operations, or sooner in the event that the mission fails, and how such conditions would be enforced; (iii) whether the period of validity of a license should be limited, or whether it should remain in force as long as the allocated capacity is "used" in some way, and specifying what constitutes "use"; and (iv) whether an operating license should be transferable from the licensed operator to another operator.

CRediT authorship contribution statement

Camilla Colombo: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Peter Martinez:** Writing – original draft, Methodology, Conceptualization. **Francesca Letizia:** Writing – original draft, Methodology, Conceptualization. **Benedetta Cattani:** Writing – original draft, Methodology, Conceptualization. **Emmanuelle David:** Conceptualization. **Diego Escobar:** Writing – original draft, Methodology, Conceptualization. **Satomi Kawamoto:** Writing – original draft, Methodology, Conceptualization. **Robert Rovetto:** Writing – original draft, Methodology, Conceptualization. **Ivan Sumelzo:** Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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