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Analysis of possible definitions of the space environment capacity to pursue long-term sustainability of space activities

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Abstract

The ability of space activities to benefit Earth and its people is now threatened by the increasing density of objects in orbit. If no mitigation measures are taken, the population could reach a level in the future at which collisions would continue to increase the number of debris in orbit, even without new launches. Addressing the need for space sustainability means preventing negative trends from becoming norms and ensure that outer space can be used for many years to come. The expansion of space activities offers opportunities to expand access to the benefits of space applications on Earth, but it poses new challenges to maintaining a safe operational environment in space. Space may seem vast, but the orbits around Earth in which satellites reside are a limited natural resource. Like the Earth's non-renewable resources (i.e., minerals and fossil fuels), these unique orbital regions, that are now essential for humanity, exist in nature in a limited way because their regeneration involves the passage of many years.

The topic of sustainability is not a new one, and many studies have been conducted on the Earth's resources over the years. From what has been done and is being done for this problem on Earth, we take the cue to analyse and address a possible application in the space field as well. Particularly, the concept of capacity of an ecosystem is investigated and related to the space debris environment.

In this work a debris evolution model, based on MISSD (Model for Investigating control Strategies for Space Debris) developed by in Somma et al. (2017), is built. The model is a source-sink debris evolutionary model based on a set of first order differential equations, which describe the injection and removal rates of objects in several altitude bands. Explosions and collisions generate fragments via the standard NASA breakup model, while drag, the only natural sink mechanism, is computed through a piecewise exponential model of the atmospheric density. The post mission disposal is the other significant removing mechanism considered in the model.

The evolutionary model is used to study the future trends of the space environment and different definitions of capacity are investigated to find a sustainable future scenario. Various possible thresholds were assumed and checked; values derived from studies of the limits of space environment as well as techniques used on earth regarding limitations of CO_2 and other harmful agents in different domains.

Keywords: environment capacity, space debris, evolutionary model, mitigation guidelines

Acronyms/Abbreviations

CSI	Criticality of Spacecraft Index
DISCOS	Database and Information System Characterising Objects in Space
ECOB	Environmental Consequences of Orbital Breakups
ITU	International Telecommunications Union
MISSD	Model for Investigating control Strategies for Space Debris
PMD	Post Mission Disposal
SSR	Space Sustainability Rating

1. Introduction

Since the start of the space age in 1957, the number of space objects residing in space has increased exponentially. Especially in the last decade, there has been an abrupt increase in space activity also due to the increasing presence of the private companies. This general growth of space economy has led to the overcrowding of specific orbital regions around the Earth, such as the Low Earth Orbit (LEO) region, intensified by the presence of a considerable number of space debris.

Several challenges, first and foremost the increasing density of objects in orbit, is threatening the ability of space activities of benefit of Earth and its people. Some experts predict the population will reach a level at which it becomes self-sustaining, the so-called "Kessler syndrome" [1]: collisions would continue to increase the amount of debris in orbit, even without new launches, in an uncontrollable way. Space may seem vast, but the orbits around Earth in which satellites reside are a limited natural resource. As the Earth's non-renewable resources (i.e., minerals and fossil fuels), these unique orbital regions, that are now essential for humanity, exist in nature in a limited way because their regeneration involves the passage of many years.

To avoid such an escalating behaviour, various guidelines to minimise the creation of new debris have been developed based on simple principles: prevent on-orbit break-ups, remove large objects from populated regions and limit the objects released [2]. Unfortunately, the current debris mitigation guidelines have a major limitation: they are formulated by considering single objects and not the overall space environment.

Over the years, with the purpose of assessing the criticality of individual objects with respect to their contribution to the space debris environment, several formulations of space debris indices have been developed, such as the Environmental Consequences of Orbital Breakups (ECOB) [3] index and the Criticality of Spacecraft Index (CSI) [4]. They are defined in such a way as to start from the knowledge of high-level information about the space object, such as its mass and the orbital parameters, in order to evaluate their potential detrimental effects on the debris environment over both the short-term and the long-term [5],[6].

The space debris indices could be used to scale the requirements for a mission such that a certain environment criticality is not achieved. However, this is not sufficient to control the overall environmental effect.

Therefore, to abandon the singular nature of the indices, the concept of the capacity of the space environment, also linked to that of space traffic management, has been introduced in recent years by Krag et al. [7] and Letizia et al. [8]. The main scope of these studies is to develop a system to launch only what the environment can handle proposing an inverse approach, w.r.t. the one of the debris indices, to tackle the question: how much capacity does the environment offer? Recent studies are extending the definition of capacity from the LEO environment to the whole space environment, including MEO, HEO, and GSO regions, for a comprehensive evaluation of the space environment capacity evolution [9].

Since there is still no available definition of the environment capacity with a wide consensus, different approaches to define it can be envisaged; from the capacity limit associated with a physical quantity to a more economical oriented definition. In any case, to define the capacity of the space environment, it seems necessary to find and/or define a quantity or a parameter that can be representative of the environment in general and not strictly related to the characteristics of a specific object in orbit. A not easy task as the various definitions of space debris indices has shown. A satisfactory description of the space environment and of the interaction between orbiting objects is complex and influenced by many factors that are often complicated to model and include.

The purpose of the mission capacity constraint is not to limit access to space, but to guarantee this possibility for future generations. The aim is to prevent the worsening of the actual negative trend and not reach a condition of cascading collisions events, which would jeopardize the use of outer space for many years to come.

The capacity, in general, is defined as the maximum amount that something can contain, but the concept takes on various nuances depending on the field in which it is used. Since the 'space environment capacity' concept is still quite new, a generally accepted and unambiguous definition of it is not available yet. Therefore, different approaches to define the environment capacity in the space sector are practicable.

For example, a purely technical definition of the capacity limit could be based on the imposition of a threshold for a physical quantity. At the same time, with the increase in private space activities, the economics of a mission are becoming increasingly important and a definition that is not purely based on technical but also on economic considerations could more useful.

Nevertheless, for all these efforts to be productive, the definition of the capacity constraint must be done with a widespread consensus among space fairing nations. In this work, the two general principles from which the available definitions of space environment capacity [7],[8] were derived are analysed and compared with the purpose of identify their advantages and disadvantages. The dependence of the results obtained on simulation times and initial conditions are analysed with particular interest.

The topic of sustainability is not a new one, and many studies have been conducted on the earth's resources over the years. In the final part of the work, a preliminary study about what has been done and is being done for the sustainability problem on Earth, to address their possible application in the space field, is reported. In particular, three different concepts of capacity used on Earth, such as carrying capacity and seating capacity, are analysed and some considerations on the relationship with the space environment are included in the discussion.

2. Debris evolutionary model

A good understanding of the future of the space environment is crucial to properly evaluate the effect of mitigation actions. For this reason, a debris evolutionary model has been developed in the first part of the work.

A simplified deterministic evolutionary model has been selected to describe the population variations, as the focus is the environment capacity and the long-term development of the population. The debris evolutionary model of the LEO region is a multi-bin, multi-species deterministic source-sink model.

2.1 Model description

The model is based on the deterministic (Model for Investigating control Strategies for Space Debris) MISSD model developed by Somma et al. [10] at the University of Southampton. It is a multi-bin and multi-species deterministic source-sink model, based on a set of first order differential equations, which describe the injection and removal rates in several altitude bands within the LEO region.

Inside each altitude bin, five object species interact as reported in the Fig. 1. The five species are payloads (PL), rocket bodies (RB), mission-related objects (MRO), collision fragments (C) and explosion fragments (E) that summed give the total number of objects.

Fragments are generated by explosions and collisions. Their number can be calculated using the NASA standard break-up model [11] for the two phenomena. Drag is the only natural sinking mechanism considered in the model and is calculated using a piecewise exponential model of atmospheric density, assuming that all objects have circular orbits. Finally, Post Mission Disposal (PMD) is the other meaningful removal mechanism considered in the model.

The model is based on several simplifying assumptions, such as objects have circular orbits and no solar activity. For what concern the natural perturbations drag is the only one included in the model. Another simplifying hypothesis is that collisions may only occur within the same altitude shell and objects can decay by only one shell at each time step. To avoid the introduction of errors, it is important to select the time step accordingly.

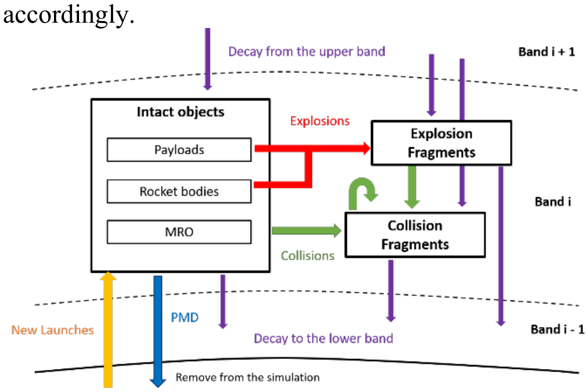

Fig. 1. Schematics of object species in one of the altitude shells [5].

2.2 System governing equations

The model uses a system of nonlinear first-order differential equations to handle the population derivatives. It uses three different equations to better simulate the addition or removal of each object type based on their nature (intact objects, explosion fragments and collision fragments). The equation for intact objects is the same for all three species (payloads, rocket bodies and MROs).

The system of differential equations represents the core of the model. The goal is to simulate the behaviour and the interactions of objects within and among each species based on their characteristics. At each time *t*, the model evaluates the total number of objects N_T in each altitude bin as the sum of the components of the different species:

$$N_T(h_\eta, t) = N_{PL}(h_\eta, t) + N_{RB}(h_\eta, t) + N_{MRO}(h_\eta, t) + N_C(h_\eta, t) + N_E(h_\eta, t) \quad (1)$$

where the index η relates to the number of evenly spaced altitude shells h_η in which the LEO region is divided.

Following the same principle, the time derivative of the total population in each altitude shell is expressed as the summation of the five derivative terms: collision $\dot{C}$, natural decay due to drag $\dot{D}$, explosion $\dot{E}$, launches $\dot{L}$ and mitigation actions $\dot{M}$.

The number of objects in each altitude band, for each species is finally computed solving the differential equations with an explicit Euler method [10].

$$\dot{N}(h_\eta, y, t) = \dot{C}(h_\eta, y, t) + \dot{D}(h_\eta, y, t) + \dot{E}(h_\eta, y, t) + \dot{L}(h_\eta, y, t) + \dot{M}(h_\eta, y, t) \quad (2)$$

where *y* indicates the cross-dependency of the term with other object species. From now on, the subscript of the discrete altitude shells η has been dropped for clarity.

The Eq. (2) can be rewritten for the five species and applying some simplifications, a system of five equations is obtained. Collision and drag terms are common in all equations, while explosions remove intact objects and generate explosion fragments, as can be seen from Table 1. The launch term adds new objects in the intact population, while the mitigation term removes objects from this latter species.

Table 1. Derivative contributions for each object species

	$\dot{C}$	$\dot{D}$	$\dot{E}$	$\dot{L}$	$\dot{M}$
PL	X	X	X	X	X
RB	X	X	X	X	X
MRO	X	X		X	X
C	X	X			
E	X	X			

2.2.1 Collisions

The collisions derivative $\dot{C}$ consists of two terms:

$$\dot{C}(h, y, t) = C_R(h, y, t)\, n_f(y) \quad (3)$$

where C_R is the collision rate and n_f is the number of fragments involved in each explosion for the different species.

The number of fragments n_f is computed as the number of fragments generated during each collision using the NASA standard breakup model [11]:

$$n_f(y) = 0.1\, L_C^{-1.71}\, M^{0.75} \tag{4}$$

assuming L_C equal to 0.1 m, while M is defined as the sum of the mass (in kg) of both objects.

To simplify, only impacts between intact objects are assumed to be capable of resulting in a catastrophic collision, while collision with and between fragments will cause non-catastrophic collisions. In first analysis, this latter category is considered negligible.

The collision rate C_R among species i and j, based on analytical laws derived from the kinetic theory of gases [12], is computed at each time step as [13],

$$C_{R_{ij}}(h,y,t) = p(h)\,\sigma(y_i,y_j)\,\frac{N(h,y_i,t)\left[N(h,y_i,t)-\delta_{ij}\right]}{1+\delta_{ij}} \tag{5}$$

where δ_{ij} is a Kronecker's delta (equal to one if both indexes are equal or to zero if the indexes are different), σ is the squared sum of the two object radii r_i and r_j (also known as square of the impact parameter),

$$\sigma(y_i,y_j) = \left(r_i + r_j\right)^2 \tag{6}$$

and $p(h)$ is the intrinsic collision probability per unit of time in a specific altitude shell [12] and it depends only on the altitude band:

$$p(h) = \pi\frac{v_r(h)}{V(h)} \tag{7}$$

where $v_r(h)$ and $V(h)$ are respectively the average relative velocity in the same shell and the volume of the altitude shell.

2.2.2 Natural decay

The decay rate $\dot{D}$ is constituted by two terms: the first one refers to the number of objects that decay from the upper altitude shell into the current one, the second term indicates the objects decaying from the current into the lower altitude shell:

$$\begin{aligned}\dot{D}(h_\eta,y,t) = &+\frac{B(h_{\eta+1},y)}{\tau(h_{\eta+1},y)}N(h_{\eta+1},y,t)\\ &-\frac{B(h_\eta,y)}{\tau(h_\eta,y)}N(h_\eta,y,t)\end{aligned} \tag{8}$$

where $N(h_\eta)$ is the number of objects in the relative altitude shell, τ is the characteristic residence time and B is a ballistic coefficient.

The ballistic coefficient B is a scaling factor of the residence time and is defined as

$$B(y) = c_D\,\overline{\left(\frac{A}{m}\right)}(y) \tag{9}$$

where the average area-to-mass ratio of each species is assumed constant for each altitude shell and over time. The drag coefficient c_D is assumed equal to 2.2, evaluated with a flat plate model [10].

The residence time, τ, is the time required for an object to decay from the upper to the lower boundary of each altitude shell. It can be evaluated a priori as

$$\tau(h) = \frac{1}{\hat{B}}\int_{h_\eta}^{h_{\eta+1}}\frac{1}{\rho(z)\sqrt{\mu_E(z+R_E)}}dz, \tag{9}$$

where $\rho(z)$ is the atmospheric density at altitude z, μ_E and R_E are the Earth's gravitational parameter and radius, respectively. $\hat{B}$ is a unitary normalised ballistic coefficient to have coherent physical dimensions. Consequently, the residence times does not depend on the species, just on the altitude shell.

The profile for the atmospheric density adopted is derived from the CIRA-72 model with an adjustment in the atmospheric density ρ so to have a piecewise continuous formulation [14]. It follows:

$$\rho(h) = \rho_0\,exp\left(-\frac{h-h_0}{H}\right), \tag{10}$$

where ρ_0 is the atmospheric density at reference altitude h_0, h the object altitude and H the scale height. Above 1000 km, the density follows a single exponential law.

2.2.3 Explosions

The explosion derivative $\dot{E}$ consist of two terms:

$$\dot{E}(h,y,t) = E_R(h,y,t)\,n_E(y) \tag{11}$$

where E_R is the explosion rate and n_E is the number of fragments of each explosion.

As simplifying hypothesis, only payloads and rocket bodies can explode and generate fragments. Explosions are generated at each time step in a single altitude shell in a random manner with different fixed yearly explosion rates E_R for payloads and rocket bodies.

In the derivative equation, for their n_E term is equal to minus one while for explosion fragments, the value of n_E is computed a priori using the NASA standard break-up model [11]. The number of objects of size equal or larger of $L_C = 0.1\ m$ created is assumed constant and can be computed as:

$$n_E(y) = 6\,L_C^{-1.6} \tag{12}$$

2.2.4 Launches

New payloads, rocket bodies and MROs are inserted into the altitude shells via the launch term $\dot{L}$ as function of both of altitude shell and time. Its current implementation uses yearly average values as a reference for launch traffic and new objects released per launch.

The subdivision of the launched objects into the altitude shells is assumed proportional to the population distribution of the species obtained from the Database and Information System Characterising Objects in Space (DISCOS) database. This is a quite strong assumption, because it assumes that the future use of the space will remain the same as now, which is not necessarily the case.

2.2.5 Mitigations

The mitigation removal rate $\dot{M}$ is not function of the object species, since launches only occur for intact objects. The removal rate is computed as:

$$\dot{M}(h, t_{PMD}) = p_c\, \dot{L}(h, t_{PMD}) \tag{13}$$

where p_c is the percentage level of compliance with the post-mission disposal guidelines [2] and the term t_{PMD} corresponds to the future time when the objects (launched at the time t) will be removed from the simulation. This time is equal to the sum of the current time t, the satellite operational life t_{SOL} (assumed of 8 years), and the residual lifetime t_{SRL} established by the mitigation guidelines equal to 25 years [2].

The drawback of the approach is that keeps the objects in the same shell and then completely removes them from the simulation after a certain time.

3. Results

3.1 Validation case

For the validation case, we consider an "ideal mitigation scenario" because based on optimistic hypotheses: it assumes no new explosions (which means that the passivation effectiveness is equal to 100%, and existing debris objects do not explode), and 90% of compliance with post mission disposal strategies after an operational lifetime of 8 years.

The projection period starts in 2009 and terminates after 200 years, with an integration time step of 0.05 years. The validation case is a business-as-usual scenario, i.e., a scenario for future patterns which assumes that there will be no significant change in the activities, such as space traffic and in the characteristics of the objects launched.

The initial population (see Table 3) and the average physical characteristics of the objects within it were computed from 16812 objects extracted from the MASTER 2009 dataset [15] and split into 36 evenly spaced altitude shells. The study considers only objects bigger than 0.1 m.

A mean yearly launch profile was also obtained from 537 launches in an 8-year interval between 2005 and 2012 reported in Table 2. The subdivision of the objects of the different species into the altitude shells is assumed proportional to the population distribution of the species obtained from the DISCOS database.

Table 2. Statistics on LEO-residing object launched by type in period 2005-2012

Object type	Total objects	Yearly average
Payloads	361	45.125
Rocket bodies	101	12.625
MROs	75	9.375
Total	537	67.125

The model was validated against the results of MISSD from the study of Somma et al. [15], where a similar set of assumptions is adopted. In Table 3 the results of both MISSD and the presented model are listed to have a direct comparison of the results. The initial population is the same for both models.

What can be noticed from the results in Table 3, the increases of the number of objects for the total population were slightly different, with total population more numerous in MISSD than in the current model for an increase of the 43.6% and of the 38.1%, respectively.

For what concern the collision fragments, they are more numerous in the model whereas largely different results are obtained in the case of intact objects.

Table 3. Comparison of the numerical results obtained with MISSD (and presented in Somma et al. [15]) with the model results.

	MISSD	Validation case
Object class	Final population	Final population
Intact objects	5103 (+52.7%)	3478 (+4.1%)
Collision Frag.	14973 (+2155.0%)	15952 (+2331.7%)
Explosion Frag.	4243 (-66.9%)	3778 (-70.5%)
Total	24139 (+43.6%)	23208 (+38.1%)

The differences in the results obtained are thought to be due to certain assumptions considered in the choice of this validation case. For the sake of simplicity, unlike in Somma et al. [15] in which different mean values of the physical characteristics are assumed in each shell, the characteristics of the objects have been assumed constant not only over time but also for all altitude bands, as already mentioned. To obtain more precise results it would be appropriate to add a differentiation of the characteristics not only by species but also by altitude band. This certainly affects the population as both the collision term and the decay term are closely linked to the average mass of the band.

3.2 Results updated to 2020

For the next chapter, it is interesting to study the evolution of the population with more up-to-date data, also to see how different initial conditions affect the results of the simulation.

In this second test case, the projection period started in 2020 and terminated after 200 years, with an integration time step of 0.05 years. The initial population (see Table 6) was computed from 15452 objects [16] and split into 36 evenly spaced altitude shells. The average physical characteristics of the objects (see Table 4) were updated and derived from ESA's Annual Space Environment Report [16] and the characteristics of the collision and explosion fragments are assumed the same. Since the division between collision and explosion fragments is not clearly stated, all fragments are assumed to be of explosive origin at the beginning of the simulation (at time zero).

For payloads and rocket bodies the distribution is proportional to that of the specific species taken from DISCOS database (updated to 8 February 2021). Instead, for simplicity, MROs are assumed proportional to the distribution of rocket bodies, while collision and explosion fragments are assumed to follow the distribution of payloads.

Table 4. Statistics on LEO-residing objects by type in the initial population for the population of 2020 [16].

	Average mass (kg)	Average diameter (m)	Average area (m^2)	Average area/mass (m^2/kg)
PL	1771.0	1.8512	4.5458	0.0025
RB	1284.5	3.8189	11.7599	0.0091
MRO	5.8	0.3736	0.3893	0.0671
C	2.7	0.3149	0.6987	0.2587
E	2.7	0.3149	0.6987	0.2587

For what concern the launch profile, a total of 491 LEO-residing objects launched in an 8-year interval, between 2009 and 2016, can be identified [15]. The statistics on LEO-residing object launched by type are reported in Table 5 and it can be seen that the majority of objects (about 60\%) consist of payloads.

As already done for the objects composing the initial population, the subdivision of the launched objects into the altitude shells was assumed proportional to the current population distribution of the specific species.

Table 5. Statistics on LEO-residing object launched by type in period 2009-2016

Object type	Total objects	Yearly average
Payloads	301	37.625
Rocket bodies	110	23.750
MROs	80	10.0
Total	491	61.375

The evolution of the orbital population for each species and total spatial density are shown in Fig. 2 and Fig. 3, respectively. Some relevant numerical data for this scenario are listed in Table 6.

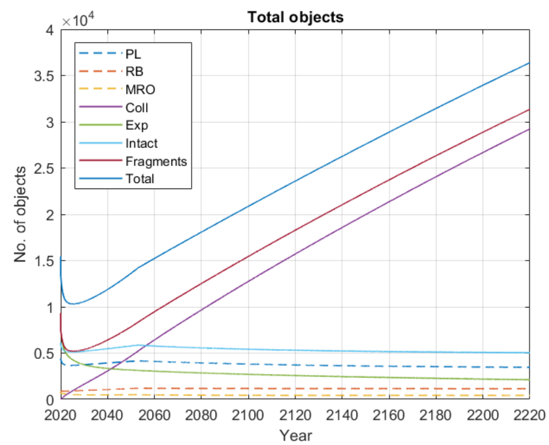

Fig. 2. The evolution of the total population and of the different species of object in LEO for each species for the 2020-2220 time interval.

The initial 2020's population of payloads is more than double the one of 2009 and has a much higher average mass. Since the number of collision fragments generated are proportionally dependent on the mass of the objects involved, the fragments created in a catastrophic collision in this more recent scenario have a higher characteristic length than in the validation case.

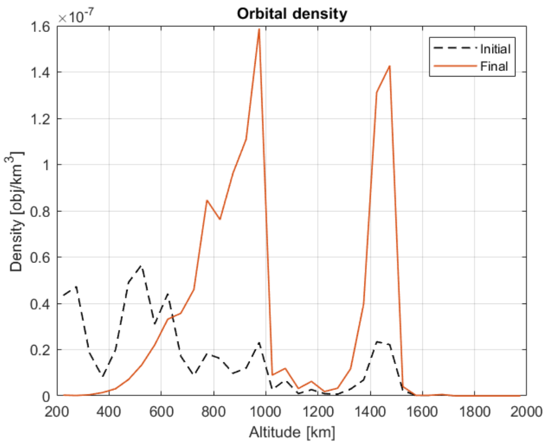

Fig. 3. The total spatial density of objects in LEO for the initial and final population of the 2020-2220 time interval

Table 6. The orbital population of the five species in the updated case at the initial and end time.

Object class	Initial population	Final population
Payloads	4410	3466 (-21.4%)
Rocket bodies	885	1152 (+30.2%)
MROs	821	424 (-48.4%)
Intact objects	6116	5042 (-17.6%)
Collision Frag.	0	29229 (-)
Explosion Frag.	9336	2115 (-77.3%)
Total	15452	36386 (+135.5%)

From the study of the current situation, we can identify as the region with the major orbital density peak at the beginning of the projection period the one below below 700 km. In particular, the highest peak is reached around 500 km, an area in which the launches of certain constellations have been concentrated in recent years. Another even lower peak is present at around 350 km. Over time the natural drag prevented the build-up of the population at altitudes lower than 750 km, as can be clearly seen in Fig. 3.

During the time simulation, the orbital density increases in magnitude and the peak shifts towards higher altitudes, creating two very close peaks in the 750-800 km and 950-1000 km ranges. This migration of peaks to higher altitudes occurs mainly because of the absence of the decaying effect of the atmospheric drag at higher altitudes. In addition, continuous launches in the region contributed to the formation of these new high-density regions. A third region with high orbital density exists in the 1400–1550 km region, as depicted in Fig. 3, already present in the trend at the beginning of the simulation. The main cause of the peak is due to an explosion more than four decades ago, showing how detrimental such events are to the space environment.

3.3 Sensitivity analysis

Moreover, a sensitivity analysis with different launch rates and different levels of compliance of post-mission disposal manoeuvres has been carried out choosing as reference case the updated results one. The main scope of this analysis was to try distinguishing the effects caused by the variation of some relevant parameters from other behaviours that are always present.

The analysis of the sensitivity of the results to the level of PMD compliance was chosen because the model is based on an optimistic level of compliance derived from the IADC mitigation policy [2] but which does not correspond to which, however, does not correspond to the current level of compliance.

The level of compliance with PMD measures has a non-linear effect on the population at the end of the simulation. The biggest benefits occur when increasing compliance from a low value. However, the efficiency of the method decreases with increasing compliance, so that even at 100% compliance, the final population is still above the initial one.

The launch rate for the three species of intact objects was extrapolated from historical data, an average over the number of launches carried out in previous years. However, these values are changing considerably in recent years and a study of its effect is necessary.

The 'no-launches' scenario was the most optimistic case, and it was the only one in which the final total population was smaller than the initial population.

Concerning the population evolution, the results suggest that the number of objects in the final population is not linearly proportional to the launch rate parameter. A non-linear relation between the final population and the variation of launch traffic is identified and it is due to the increasing number of both targets and newly generated fragments that act as projectiles.

4. Space environment capacity

As anticipated, the studies have often focused on the single object and the best way to describe its criticality, but there is a need of recognising that the space is in fact a finite resource, which requires time to regenerate naturally. Once the importance of the issue is understood, some questions about possible limits arise spontaneously. Among the first to come to mind are surely: "how much capacity does the environment offer?" and "how much of this capacity is still available?". As already introduced, these are some of the common questions from which we start when studying the capacity of the space environment.

Someone already tried to answer by defining the 'space environment capacity'. Two interesting definitions of available capacity can be found: the number-time product definition by Krag et al. [7] and the cumulative index definition by Letizia et al. [8].

4.1 The number-time product definition

According to Krag et al. [7], a suitable parameter to measure the capacity is a number-time product based on the number of fragments bigger 10 cm derived from the long-term propagation of the trend of object with ESA-DELTA [17]. In particular, the total available capacity is defined by the curve resulting from the difference between the trend in the number of fragments in two different scenarios over a period of 200 years.

The first scenario is based on the assumption of a business-as-usual scenario with a 90\% probability of successful for PMD manoeuvres, the other without additional launches.

The total available capacity is then defined as the integral of the difference curve over the chosen time window. According to the concept proposed in the paper, this would correspond to the fragment-years that are available for “consumption” by human space activity in LEO for the next 200 years.

Nonetheless, to apply the definition, a measure of the debris environment criticality is required, and it should be comparable to the quantity used for the environment capacity definition. Consequently, the index chosen to measure the criticality of an object should also be able to describe the amount of environment capacity that the mission would consume.

For this reason, the Fragment-Year Index has been defined in such a way as to respect the need of compatibility with the definition of capacity [7]. For a better evaluation, it is recommended the use of more sophisticated approaches in the definition of the criticality of spacecraft [7].

4.1.1 More scenarios

Two other cases are studied in addition to the results of the work of Krag et al. [7]. In the following part, the definition of ’space environment capacity’ through the quantity of the number-time product is recalculated using the results obtained from the debris evolutionary model developed and presented in Chapter 2. The deterministic model has a low computational cost, so it allows us to have a global idea and to study different scenarios and the effect of different quantities in an easier way.

Specifically, the two cases analysed are:

A. Same inputs and new model: the inputs of Krag et al. [7] are used as initial condition for the evolutionary model developed in this thesis,
B. Updated inputs and new model: the initial conditions used for simulating the evolution of the fragments are updated to 2020,

and then the capacity is calculated as described in the work of Krag et al. [7] from those results in both cases. A comparison of the characteristics of the three cases is reported in Fig. 4

Krag et al.	Case A	Case B
Starting from 2009	Starting from 2009	Starting from 2020
Model: **ESA-DELTA**	Model: **debris evolutionary model**	Model: **debris evolutionary model**
Launch traffic between 1990 and 1998 (about 330 launches)	Launch traffic between 2005 and 2012 (about 530 launches)	Launch traffic between 2009 and 2016 (about 490 launches)

Fig. 4. Summary of the major characteristics of the case used in Krag et al. [7] and of Case A and Case B.

The evolutionary model is used to calculate the evolution of the number of objects larger than 10 cm in the two scenarios required by the definition. The procedure must be repeated for both cases listed above. Following the same procedure described in Section 4.1, the available capacity is calculated from the integral of the difference of the two curves for both the cases.

Details of the results obtained for cases A and B, as well as their graphical representations, are given below in Fig. 5 and Fig 6. Then they are compared with each other and with the results already obtained by Krag et al. [7] in Table 7 which show how variable the quantity can be.

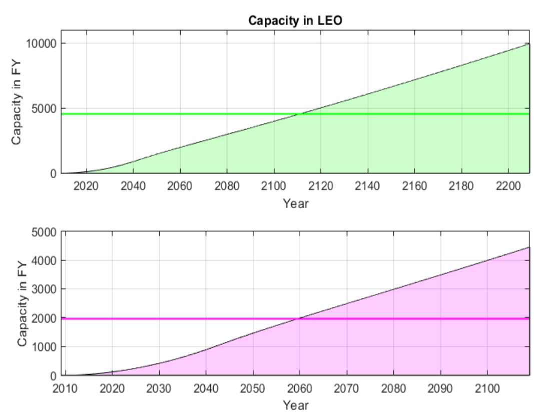

Fig. 5. Case A: the total capacity in LEO from 2009 for propagation times of 200 years (top) and 100 years (bottom), and the average fragment-years per year in both cases.

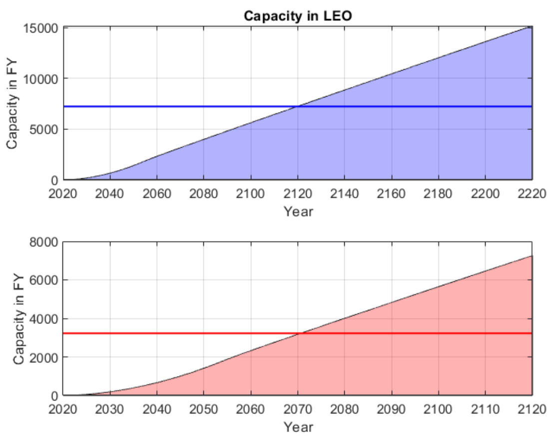

Fig. 6. Case B: the total capacity in LEO from 2020 for propagation times of 200 years (top) and 100 years (bottom), and the average fragment-years per year in both cases.

The result of the fragments trends obtained with the developed model differs significantly from that used in the first definition [7]. While the ESA-DELTA software [17] uses a deterministic model, in which the orbits of the single artificial objects are propagated for the desired time, the model developed in this thesis is subject to various simplifying assumptions, already discussed in Section 2, which lead to an overestimation of the number of fragments in orbit. This leads to a significant difference also in the available capacity, both total and annual shown in Table 7.

Table 7. Total and annual available capacity for Case A and Case B for two time spans (200 and 100 years) compared to the results of Krag et al. [7].

	Total available capacity	Annual available capacity
Time span: 200 years		
Krag et al.	400,000	2,000
Case A	910,000	4,500
Case B	1,400,000	7,200
Time span: 100 years		
Case A	196,000	1,960
Case B	320,000	3,200

If the outcomes of cases A and B are compared with each other, irrespective of the propagation time, the available capacity for a launch year in case B is greater than in case A by a factor of about 1.6. In the second case, in fact, the initial conditions as well as the greater average masses of the intact object species mean that during evolution the number of fragments created is greater than in case A. Case B therefore corresponds to an environment in which the number of accepted fragments is much higher, and consequently orbital density and collision probability will also be higher without the possibility of setting a proper limit to their values.

4.2 The cumulative index definition

Another definition of the environment's criticality has been proposed by Letizia et al. [8], and the definition of the available capacity of the space environment goes through the ECOB index [3]. The debris index can be a way to quantify which share of the environment capacity is already in use and which could be consumed by future missions, but its use is not straightforward.

In contrast to the number of objects or fragments, the ECOB index refers to a single object. To be used as a measure of capacity, it is necessary to calculate the cumulative index for all spacecrafts and rocket bodies and for a suitable period of time. At this point, the variation of the cumulative index can be taken as an indicator of the trend in the use of capacity, but a threshold is needed to properly scale the relevance of the observed variation.

The approach adopted by Letizia et al. [8] seems to find consensus in the community of experts; the application of this definition of space environment capacity can be found both in the latest ESA Space Debris Environment Report [16] and in the definition of the Space Sustainability Rating (SSR) [18].

The key to achieve sustainability in the space activities is create, implement, and support mechanisms that not only address current demands of the space environment, but also can continue to meet the demands of use for future generations.

Therefore, in a first approach, the derivation of the capacity utilisation threshold from the results of long-term simulations of a reference scenario seems a wise idea. The reference scenario should be defined with an acceptable evolution trend in mind to achieve the desired sustainability results. The capacity represents the total amount that can be managed by an environment, which can be easily translated into a constant maximum limit for the cumulative index, for example by choosing the value at the end of the simulation.

By limiting the index below a maximum threshold, it is expected that consequently the environment will evolve with an acceptable trend. To make the prescription more effective, instead of using the total capacity that is valid for such a long period, it might be useful to define the available capacity, i.e., the fraction of capacity that could be used each year.

Specifically, the approach to calculate available capacity can be divided into six steps [8]:

1. Selection of a suitable space debris index,
2. Long-term simulations of the evolution of the space environment,

3. Computation of the index for all spacecraft and rocket bodies in orbit by extracting yearly snapshots of the population from the results of the simulation,
4. Computation of the cumulative index at each time step,
5. Selection of the threshold (e.g., constant threshold equal to the allowed maximum debris index),
6. Definition of the available capacity in one launch year dividing the remaining capacity (i.e., threshold minus used capacity) by the number of remaining years of the control period.

Similar to the definition of the number-time product, the available capacity in one launch year is defined by dividing the remaining capacity (i.e., the difference between threshold and used capacity) by the number of remaining years of the control period.

The results show that the launches planned for a certain year (e.g., 2014 and 2017) may exceed the allocated capacity for that year [8]; this will affect the capacity available in the future. If the capacity for the year is frequently exceeded or a fragmentation occurs, the available capacity may be affected for the years following the event.

4.2.1 The Criticality of Spacecraft Index (CSI)

An analytical index, called Criticality of Spacecraft Index (CSI), developed to be applied to LEO objects was introduced by Rossi et al. [4]. The index depends on the background debris density, the object residual lifetime, the mass, and its orbital inclination.

Its analytical nature is one of the reasons why this index was chosen; it reduces the complexity of the computational procedure and, in this way, it is possible to reduce the required runtime and speed up operations by allowing the extension of the cases analysed. Another point in its favour is the fact that the effect of the spatial environment surrounding the object is represented by the orbital density, which at this point can be easily calculated with the evolutionary model. The use of the same model allows an easier comparison of the obtained values with the number-time product definition.

The CSI applies in principle to large, abandoned objects since an active object should be able to perform collision avoidance manoeuvres, and it is assumed useful only for large objects because they represent a threat to the environment at large if fragmented since they would generate large debris clouds. Therefore, the larger the value of the CSI of an object, the more dangerous it is to the environment.

The CSI was defined as [4]:

$$CSI = \frac{M(h)}{M_0}\frac{D(h)}{D_0}\frac{life(h)}{life(h_0)}\frac{1+k\Gamma(h)}{1+k}, \tag{14}$$

where M is the mass of the object, D is the spatial density, *life(h)* is the residual lifetime of the object, which highly depends on the altitude. The last term introduces the inclination i dependence as:

$$\Gamma(h) = \frac{1-\cos(i)}{2}, \tag{15}$$

where the parameter k is assumed equal to 0.6 since the typical flux of debris on an almost equatorial orbit is about 60% of the flux on a polar orbit. While the subscript 0 refers to the normalising values chosen arbitrarily by the authors and are reported in Table 8.

The lifetime, as a function of the mean orbital altitude h, is estimated from an average lifetime resulting from power law fit of the form:

$$\log(life) = ah^b + c, \tag{16}$$

where h is the mean altitude of the object and $a = 14.18$, $b = 0.1831$ and $c = -42.94$ are the coefficients of the fit derived assuming an average area over mass ratio of $A/M = 0.012$ m^2/kg and an average solar flux between 110 and 130 units [4].

Table 8. Normalising values of the Criticality of Spacecraft Index [4]

	Normalising values
M_0	10,000 kg
h_0	1,000 km
$life(h_0)$	1468 years
D_0	maximum spatial density at the beginning of 2009 from ESA-MASTER (v. 8: 5.629 x 10^{-6} objects/km^3)

4.2.2 The CSI as a measure of the capacity

The purpose of the current study is to find a way to quantify which share of the environment capacity is already in use and which will be consumed by future missions using the debris index proposed by Rossi et al. [4], not to compile a ranking of catalogued objects to find out which one is the most dangerous.

Indeed, as suggested by Letizia et al. [8], the variation of the cumulative index over a long-time span can be taken as an indicator of the trend in the use of capacity.

In order to calculate the cumulative index, the index formula must be applied to a multitude of objects and the results summed up. The list of all payloads and rocket bodies launched in the LEO region (updated to 8 February 2021), obtained from the DISCOS database, is filtered to leave only objects still in orbit in the list. While the spatial density is calculated with the debris evolutionary model developed (see Section 2).

Fig. 7 shows the resulting cumulative index evolution for payloads, rocket bodies and the sum of the two contributions, while the numerical values are reported in Table 9. The portion of the total cumulative index due to payloads remains more or less constant during the whole simulation time.

Table 9. Some important values of the cumulative CSI during the simulations with a time span of 200 years.

Cumulative CSI	Min value	Max value	Mean value	Increase factor
Total	131.6	733.7	434.6	5.58
Payloads	64.9	360.3	211.9	5.55
Rocket bodies	66.7	373.4	222.7	5.60

The total cumulative index increased by a factor of 5.58 over the 200 years of simulation. Similar increase factors characterise the two species of intact objects considered in the study, payloads, and rocket bodies.

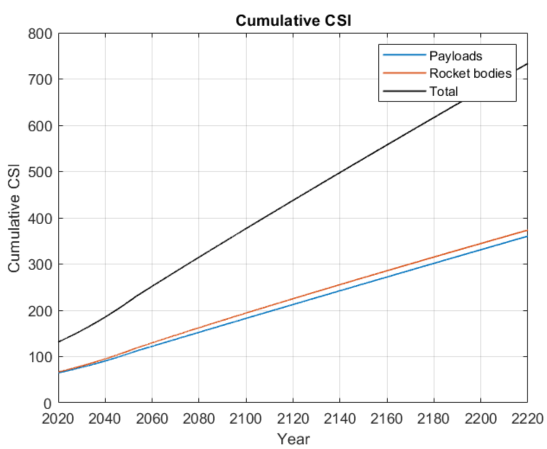

Fig. 7. The cumulative CSI for the overall set of payloads and rocket bodies over a time span of 200 years.

To use the cumulative CSI as indicator of the management of the capacity, to proper scale the relevance of the observed variation of the index, a threshold should be defined. The easiest way is to define a constant threshold for the capacity and the most immediate choice is the maximum cumulative index for the sum of payloads and rocket bodies.

Given the value of the growth factor of more than 5, this choice is allowing and justifying a considerable growth in the cumulative index and thus a remarkable variation in environmental conditions.

Similar to what was done before in Section 4.2, the available capacity in one launch year is defined by dividing the remaining capacity by the number of remaining years of the control period and the values obtained are reported in Table 10. The remaining capacity is finally computed as the difference between threshold and used capacity in that moment.

Table 10. The available capacity evaluated with the cumulative CSI.

Cumulative CSI	Available capacity
Total	3.01
Payloads	1.48
Rocket bodies	1.53

An example of the results that it is possible to obtain with the above method is shown in Fig. 8, where the markers represent the capacity consumed with the launches of each year and the red dashed line represent the allocated capacity evaluated for the complete catalogue. The results present a very different situation from the one in Letizia et al. [8], where the used capacity approach the imposed threshold.

The values of capacity consumed in one launch year in the period between 2018 and 2020 are far less than that of the available capacity. This shows how the results largely depend both on the type of index selected in the definition of capacity, and on the evolution of the term linked to the environment.

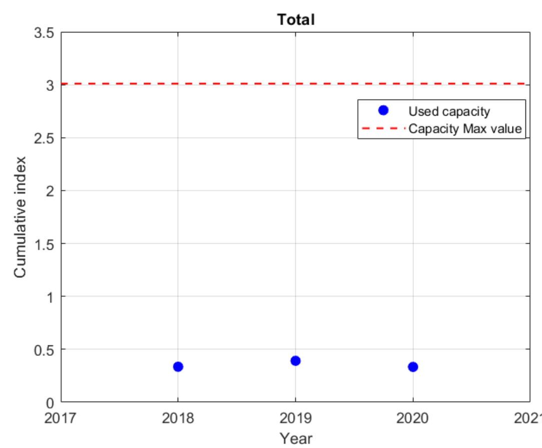

Fig. 8. The allocated capacity (dashed lines) evaluated with the cumulative CSI and used one per year (markers) for the total set (both payloads and rocket bodies).

5. Comparison of the capacity definitions

5.1 Correlation between the two quantities

After having studied in more in depth the two definitions of environment capacity, it would be interesting to make a comparative analysis of the definitions and possible relationships between the results of the cumulative CSI and those of the capacity defined as a number-time product.

Fig. 9 shows graphically the trend of the total cumulative index (in blue) compared to the trend of the available capacity in fragment-years, as well as the trend of the one for payloads (in red). To analyse the relationship between two variables, the degree of correlation between the two variables, which is expressed through the Pearson correlation index, was evaluated. The degree of correlation is very high, very close to 1 as Table 11 shows, so the two trends could be linked through a linear dependency indicating a predictive relationship.

Table 11. The correlation coefficients of the total cumulative CSI and the payloads cumulative CSI with respect to the available capacity computed as number-time product.

	Correlation coefficient
Capacity vs Total CSI	0.9996
Capacity vs Payloads CSI	0.9997

The existence of a correlation does not imply any statement about the nature of the relationship between the two variables, much less the attestation of a cause-effect relationship. It affirms the tendency of a variable to vary with greater or lesser approximation as a function of another. The high level of correlation could be due to the common causes of the variations: the capacity is calculated from the number of fragments in orbit, and they strongly affect the orbital density, which is present in the formulation of the index.

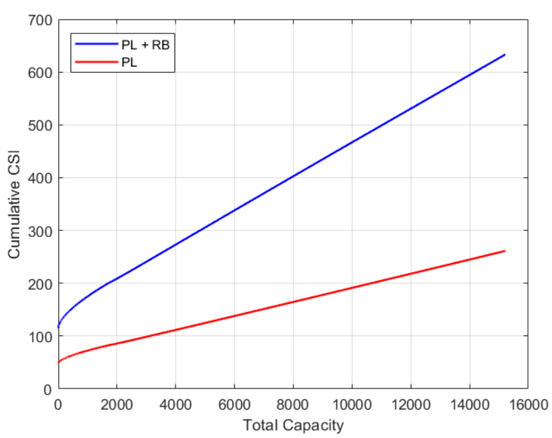

Fig. 8. Comparative image of the evolution of the total cumulative index (blue) and of the cumulative index of payloads (red) with the capacity defined as a number-time product with time.

5.2 Discussion on the two definitions

In conclusion, it is possible to identify pros and cons for both the definitions of available capacity that are been presented in this work.

The number-time product definition is simple and immediate in the meaning, with a more practical quantity that quantify the capacity. Moreover, it is possible to have lower computational times, using the evolutionary model

On the other hand, it has a high level of variability with respect to different quantities such as the launch profile, the propagation time and the model used. The differences in the final values that were found and are reported in Table 7, demonstrate the dependence of the capacity defined according to the "years-fragments" definition on the assumed future space activity and the way it is calculated but also on the propagation time. This significant dependence on propagation time and other quantities suggests that it may be necessary and beneficial to investigate capacity definitions that are less dependent on the arbitrary simulation time.

The cumulative index definition has the same problem of high variability due to the dependence on the launch profile, the propagation time and the model used to evaluate the orbital density.

Moreover, it has a higher computational cost and requires periodic re-computation of the long-term environment simulation to adapt it to the real evolution of the environment and, therefore, also the cumulative index for all the payloads and rocket bodies should be re-evaluated and a new available capacity computed. All these additional cons balance the greater ability of this definition of representing the environment with more sophisticated quantities than in the number-time product definition.

In short, both the definitions of capacity may not be enough to set a real limit because of its high level of variability. Perhaps the imposition of a threshold for a relevant quantity that does not depend on various simulations could eliminate the problem even though it would complicate the calculation of the final capacity.

6. The concept of capacity in other fields

The capacity is, by definition, the maximum amount or number that something can contain. Since its meaning can take on various nuances depending on the field in which it is used, in the following section some of the capacity concepts that seem to be most relevant and useful in the discussion for the definition of 'space environment capacity' are discussed more in detail. Three concepts of capacity have attracted the attention during the work: the carrying capacity, the Environmental Capacity, and the seating capacity.

The carrying capacity concept is born to describe the evolution of the population size of biological species. A more rigorous definition of it has been offered by Monte-Luna et al. [19]: 'the limit of growth or development of each and all hierarchical levels of biological integration, beginning with the population, and shaped by processes and interdependent relationships between finite resources and the consumers of those resources'.

The effect of carrying capacity on population dynamics may be modelled with a logistic function, used to describe the population growth, and has already been adopted in different context, such as in the modelling of the carbon dioxide (CO_2) emissions from fossil fuel combustion [20]. In contrast to biological populations, the space population is not self-regulating, but some similarities in the behaviors can be found, for example, launches can be seen as births and reentries as deaths.

The parameters representing the equation and the carrying capacity can be obtained from the fitting of real data describing the particles emission of, if the number of data is not sufficient, the carrying capacity can be calculated from thresholds for correlated quantities.

The approach of defining a threshold for some representative quantities of the problem could be useful also in the case of the definition of the space environment capacity. As already mentioned, a maximum acceptable collision probability could be imposed as a general boundary, also considering the repercussions on the number of collision avoidance manoeuvres.

From the definition of the carrying capacity of a species the concept of Environmental Capacity is derived to be applied to the assessment of the impact of potentially harmful substances released into the marine environment. The Environmental Capacity is defined as "a property of the environment and can be defined as its ability to accommodate a particular activity or rate of activity ... without unacceptable impact" [21].

The basic premise of the report is that only a certain level of a contaminant will produce an unacceptable effect on the environment or its various uses; hence, the environment has a finite capacity that can be quantified, to accommodate wastes.

Moreover, the definition of quality criteria is already a widespread practice that could be necessary and useful also in the space field, contributing to a sustainable development of the space environment and related activities.

Another interesting example is the concept of seating capacity. The seating capacity of enclosed spaces is the number of people that can be seated in a specific space, based on assigning a slot of space to each person.

An application of this underlying idea can already be found in the space field: the slot licensing in Geostationary Orbit (GEO) protected region [22]. Specifically, the licensing is needed for the allocation of satellites and their communication frequencies in highly competitive areas in order to regulate the population.

The good results obtained with this approach in the GEO region led to think that just as every operator in space must acquire a license for radio-frequency slot even in the LEO region, it may be necessary to expand the licensing regime to the orbits themselves.

Synchronising capacity allocation with mission proposal issues through the International Telecommunications Union (ITU) would benefit both processes, as already suggested by Krag et al. [7] and Letizia et al. [8]. The operators need to provide information on the spacecraft, the operational orbit, and the expected reliability in the implementation of mitigation measures to obtain an evaluation of the capacity consumption and so the approval for launch.

7. Conclusions

The aim of this work was to investigate the possible definitions of space environment capacity, necessary to promote the sustainable development of space activities. Furthermore, it was found interesting to examine possible connections and similarities with situations and definitions already used on Earth.

The comparison of the two definition of space environment capacity available in literature leads to the individuation of common problems such as the high variability of the results and the absence of direct control over other significant quantities, for example the collision probability or the orbital density.

Is it possible to overcome such limitations? If yes, how?

First, one of the options could be to change the way the threshold is defined and, taking inspiration from the carrying capacity evaluation, a threshold for a significant quantity can be selected. From this value, the corresponding limit in the terms needed by the type of definition is derived.

Otherwise, the use a completely different method to control the environment could be hypnotized. For example, the idea of introducing the licensing for orbits as is already done in GEO is not linked to the environment capacity definitions studied in this work.

Further studies are needed to validate the hypotheses done in this work and to draw more conclusions on the subject.

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