EMISSARY – ENVIRONMENTAL MANAGEMENT INITIATIVE FOR SPACE SUSTAINABILITY THROUGH ADAPTIVE REGULATORY POLICY

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ABSTRACT

Over the past decade, the use of Low Earth Orbit (LEO) has increased rapidly. With this increase in use comes an increase in the associated impacts. To manage these impacts, tools such as models and metrics are needed to help us understand the broad and varied impacts of space activities on diverse perspectives of space sustainability. This work presents a description and example of the systems dynamics model EMISSARY, which encompasses lessons from Earth-based applications of threshold-based concepts for protected resource management. These lessons include a rejection of traditional, singular carrying capacity metrics in favour of multiple qualitative and quantitative metrics that track acceptable conditions in the complex system. By this interpretation, focus shifts from 'quantifying use' to 'quantifying the impacts of use' in a way that acknowledges the many interconnections and trade-offs that exist between different perspectives of space sustainability.

1 INTRODUCTION

As of March 2025, more than 10,000 active payloads are in Low Earth Orbit (LEO), 7,000 of which belong to a single satellite communications company that started launching in 2019 [1]. This statistic reflects a significant escalation in our use of the LEO environment to provide various services to users on Earth. These satellites provide valuable services across various sectors including Earth observation and other activities that serve to contribute towards the achievement of many sustainability goals on Earth [2]. However, these space activities can also have negative impacts on various areas of sustainability including, but not limited to: changes in the radiative forcing of Earth's atmosphere [3-5], emission of potentially ozone-layer damaging substances [6, 3, 5], re-entry risk to human life [7], oceanic pollution due to toxic materials [8, 9], electromagnetic interference with astronomical observations [10-14], economic sustainability concerns (e.g. 'economic Kessler syndrome' and the economic waste of debris in orbit) [15, 16], impacts on indigenous communities and other cultural impacts [17]. As such, policy tools that are capable of limiting the negative impacts of space activities could be useful for maintaining the broader sustainability of space activities.

In this work, a system is defined as a bounded structure of interconnected elements that produce spatial or temporal behaviour. Specifically, the term 'space system' in this paper is used to refer to the multiple, interlinked systems associated with the use of the space environment. As such, encompassed within the space system are a broad set of elements (including physical, in-space elements and non-physical, Earth-based or related elements) that are affected by space activities. The general concept of carrying capacity encompasses the idea of use-related limits in a system to achieve a pre-defined definition of sustainability in the system. The concept of carrying capacity has been identified as a potentially useful tool for managing activities in the space system and their impacts. The need to limit types of use to manage the negative impacts of space activities has been identified by multiple international research groups including the Inter-Agency Space Debris Coordination Committee (IADC) with their recognition of the relationship between the number of spacecraft and the negative impacts on the space environment [18], and the International Astronomical Union's Centre for the Protection of Dark and Quiet Skies (IAU CPS) through their recommendation to minimise the number of satellites in orbit to minimise the negative impacts of observational astronomy [19]. Therefore, threshold-based tools relating to use limits such as carrying capacity are highly relevant and potentially useful for use in managing activities in the space system.

Despite identifying the usefulness of threshold-based concepts for limiting the use-related impacts of activities, important debate exists regarding the appropriate definition and subsequent use of thresholds for effective management of space activities. Multiple interpretations and models have been derived for the application of thresholds for space activity management. Examples of such approaches include definitions of an orbital carrying capacity through assessments of numerical instabilities in the populations of orbiting objects [20, 21]. Some other examples determine a number of active satellites based on assessments of collision risk related to satellite

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constellation architecture [22, 23], and others assess the evolution of debris over time such as [24] and [25], which derives a debris-index using a risk-based metric[26, 27]. Whilst a range of approaches exist, all the examples given attempt to distil the evaluated information into a single threshold to be used to inform future management actions. Single metrics can be incredibly useful from a communications perspective and for providing simplified management objectives to work towards, but such approaches can be limited as they often do not sufficiently capture the complexities of problems that are inherent to complex systems [28-30]. Fortunately, extensive, specific advice regarding the use of threshold-based concepts for complex system management exists in the literature. This literature is often presented with respect to terrestrial protected resource management such as national parks [31, 32], biodiversity management [33], species conservation [34, 35] and many others. However, many useful lessons and inferences can be extracted and adapted for application to the management of space activities. These lessons are used to formulate the underlying approach to the Environmental Management Initiative for Space Sustainability through Adaptive Regulatory Policy (EMISSARY) model presented in the sections below.

2 EMISSARY

2.1 Concept

The following sections describe the concept behind the approach for EMISSARY. Descriptions of initial methods of modelling in EMISSARY are outlined, although future iterations reflecting the development of this model are to be expected.

2.1.1 Systems dynamics modelling

The definition of space sustainability adopted by the United Nations (UN) is:

"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." [36]

In this definition, multiple notable distinctions are made. Firstly, the use of the term 'equitable' rather than 'equal' acknowledges the existence of trade-offs in the space system arising from the varied needs of different types of space users. Secondly, sustainability is tied to the ability of actors to use space to achieve their purposes, where the type of use is not defined explicitly. The recent official UN recognition of astronomers as space users [37] further validates the variety of different perspectives and impacts arising from space activities need to be considered in space sustainability assessments. Furthermore, this terminology advocates for sustainability to be measured in clear relation to a user's ability to conduct their activities, rather than in purely environmental terms. Finally, reference to the requirement for the needs of current and future generations to be met acknowledges the dynamic, time- and spatially-persistent nature of both space activities and their impacts. With these inferences, this definition of space sustainability describes a space system that is complex, dynamic, and involves a variety of users with different needs. As such, metrics aiming to quantify the sustainability of the space system must also be able to reflect these characteristics.

Furthermore, a growing literature base is revealing a large breadth of impacts resulting from space activities beyond the generation of space debris alone. These impacts are seen in both orbital and Earth environments and affect physical, economic, societal, and cultural systems. Specific assessments of the trade-offs relating to space sustainability activities are also emerging, with recognition of the economic consequences of various debris mitigation and remediation methods [38], assessment of the impact of recommendations designed to reduce the impact on optical astronomy on the collision risk for satellites in orbit [39], the impacts of atmospheric changes on the debris population [21] and investigations into the links between economics, policy and space debris [40]. However, the volume of research into these space activity-related trade-offs is relatively modest compared to the breadth of research into specific areas of space sustainability such as space debris.

An acknowledgement of the broad and complex impacts of space activities above, alongside the UN definition of space sustainability, lends well to the interpretation of the space system as a complex system. In system dynamics modelling, a complex system is a system of many interconnections whereby delays and feedbacks can produce non-linear behaviour that is often unpredictable without numerical modelling. The goal of illustrating a system is to describe how connections produce certain responses over time. The function of each individual system determines which responses are depicted. Fig. 1 (adapted from [41]) represents the space system as a complex system of systems. A system of systems is a very broad system containing smaller systems that each have their boundaries and functions but are each connected. This identification of the function of a system is an important part of drawing the boundaries of a model. For example, in Fig. 1, the purpose of the model was to demonstrate how space activities are connected to elements outside the immediate space environment and how these feedbacks may ultimately affect space activities in the future through regulations and policies. As such, illustrative connections between atmospheric impacts, economic impacts and light and radio pollution impacts were depicted. However, as the purpose of the model was not to provide an exhaustive list of

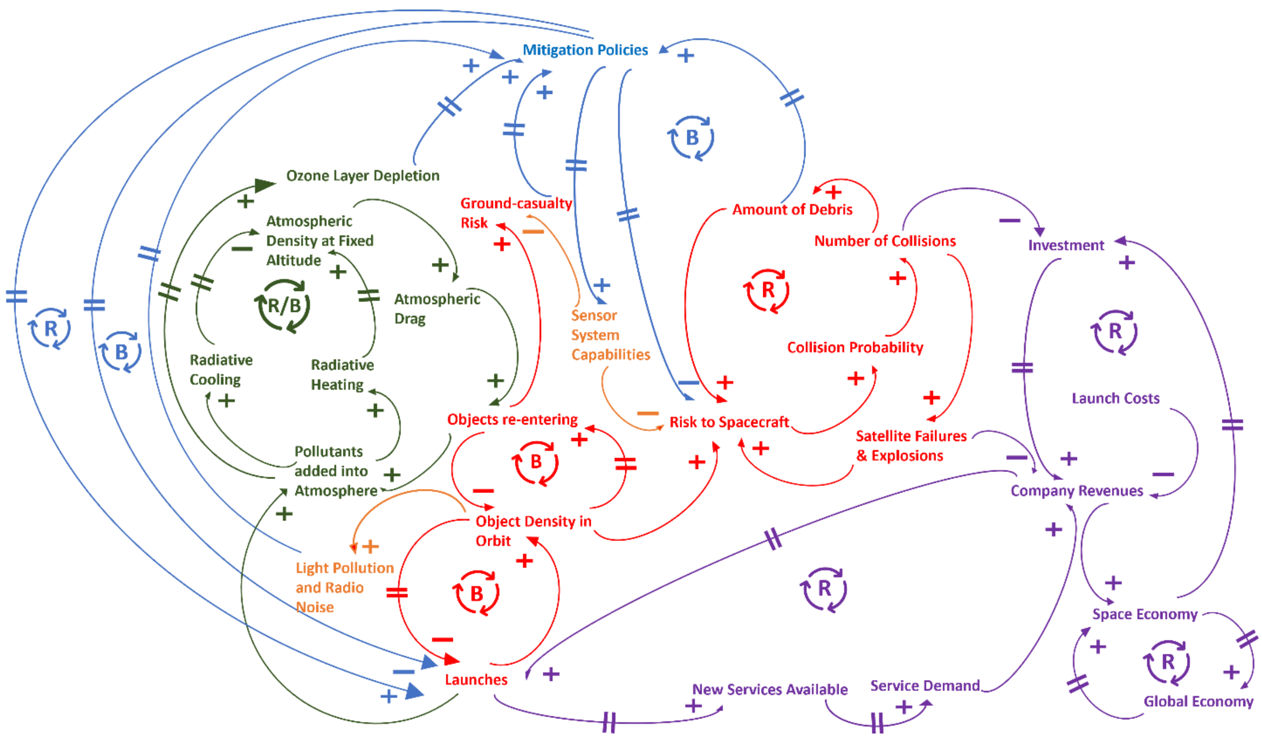

Figure 1 - Causal loop diagram adapted from [41] illustrating the connections between a broad variety of elements associated with the space environment and space activities. This diagram acts as a guiding framework for EMISSARY. Coloured sections indicate discrete systems that have been historically considered only in isolation, with red representing the space environment, green representing Earth's atmosphere, purple represents economic factors and orange represents sensor systems.

connections, there are other examples of potential regulatory feedbacks that exist that are not included in Fig. 1. One such example includes connections to pollution related to the re-entry of space objects into terrestrial or oceanic environments.

In Fig. 1, the arrows represent causal relationships between the linked elements in the causal loop diagram, with symbols '+' and '-' representing the polarity of the relationship. A positive polarity '+' indicates that a change in the first element will elicit a change in the same direction in the following element (e.g. a decrease in the first will also produce a decrease in the second). A negative polarity '-' indicates that a change in the first element will produce a change in the opposite direction for the second (e.g. an increase in the first produces a decrease in the second). Feedbacks are closed loops of connections that can produce reinforcing behaviours (denoted by 'R') whereby a behaviour is amplified, or balancing behaviours (denoted by 'B') whereby the behaviour in that loop tends towards some stable value. Delays in the system are denoted by '//' and show where a particular relationship acts on a relatively long timescale compared with most connections in the system.

Representing complex systems using systems dynamics modelling techniques can be very useful for providing insights into system behaviour. Understanding this behaviour is essential for developing effective and efficient management techniques for achieving sustainability goals. This is because ignorance of the multiple impacts of actions creates further vulnerabilities and risks in the system through unintended consequences and unaccounted costs [33]. By understanding how the system behaves, leverage points can be identified in the system. Leverage points are points in a complex system where a small change can produce a large impact elsewhere in the system [42]. Designing management actions that target these leverage points can be an effective way to influence change in a complex system. When identifying these leverage points, it is also useful to identify which actors in the system have control over them and therefore retain the power to influence large change in the system. Conversely, identifying leverage points outside the sphere of control of any actors is also useful for identifying areas of risk in the system. Both of these aspects are necessary for designing appropriate management actions for a complex system. However, a good understanding of how these leverage points influence wider system behaviour is also needed as the effects of using them in complex systems can often be counter-intuitive [43].

System archetypes are a system dynamics tool which allows for the identification of common patterns of responses in a system that have common solutions. By

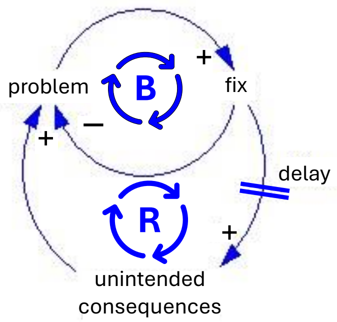

Figure 2 – diagram of the 'fixes that fail' archetype. The 'problem-fix' loop contains a balancing feedback whereby an increase in the fix causes a short-term reduction in the problem. The 'fix - unintended consequences – problem' loop is reinforcing, where the fix increases the problem over a longer timescale.

identifying these archetypes, it may be possible to predict the occurrence of problems in the system before the impacts are observed because the root causes of issues in the system can be identified. Additionally, by identifying these archetypes, unwanted responses can be identified in a system without performing simulations. For example, in the 'fixes that fail' system archetype shown in Fig. 2, a fix is enacted to produce short-term benefits that reduce the magnitude of a problem. However, the fix also produces unintended consequences that act on longer timescales and counterproductively amplify the problem. Unintended consequences can occur when impacts of actions within the system are not fully understood or not represented in the process leading to the development of the fix. This archetype is particularly relevant when short-term fixes are applied continuously to alleviate symptoms of a problem instead of applying fundamental solutions that address the underlying cause(s) [44], or when solutions to be applied in interconnected systems are formulated without considering the interconnections and trade-offs in the system. Such an approach can reduce the strength of the unintended consequences feedback loop and has been advocated for by international organisations tackling similar complex problems such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in their assessments of appropriate management of global biodiversity issues [33].

Reference [33] advocates for non-siloed approaches to sustainability assessments and the development of management mechanisms, whereby interconnections resulting in trade-offs and the broad range of impacts are considered. The need for non-siloed approaches is also echoed by many other existing applications of complex system management on Earth, with notable examples including: the World Economic Forum which recognises interconnected economic, environmental, geopolitical, societal and technological risks in its annual global risks report [45], the Dasgupta Review [46] assessing the economics of biodiversity, and the common notion of the 'three pillars of sustainability' [47] which recognises the need for environmental, economic and social considerations to achieve sustainability. The United Nations University - Institute for Environment and Human Security (UNU-EHS) Interconnected Disaster Risk report [48] also clearly identifies space debris as one of six interconnected tipping points. It cautions against attempts to reduce risk in one area without considering the connections with the others.

However, when it comes to the development of guidelines and mechanisms to support space sustainability in international fora, siloed approaches are currently being used. This means that whilst research is being conducted into the impacts of space activities in a variety of different areas and perspectives, very little research exists that assesses the multiple perspectives and trade-offs at once. This includes research used to inform guidelines and policies for space sustainability. For example, the IADC Space Debris Mitigation Guidelines [49] used space debris evolutionary models to make recommendations regarding the post-mission disposal (PMD) of objects in orbit, but did not perform research to assess the impact that these recommendations may have on the Earth's atmosphere. Additionally, the IAU CPS used brightness models to make recommendations to satellite operators to reduce the impact of satellites on observational astronomy [19], but did not perform studies to assess the impact that these recommendations may have on the operating conditions for satellite operators in the orbital environment. Each of these is an example of a siloed approach to the formulation of management actions in a complex system. This is a direct contradiction to the advice regarding effective management approaches for complex systems presented previously in this paper.

In EMISSARY, sustainability is defined as a balancing of these trade-offs to maintain acceptable conditions from multiple perspectives simultaneously. As such, EMISSARY is a systems dynamics model designed to capture the interconnections and to analyse the trade-offs within the broad space system. By measuring them using quantitative metrics, an understanding of the trade-offs in relation to a more holistic definition of space sustainability can be achieved. Such a definition considers the impacts from a variety of different perspectives both within and beyond the immediate, physical space environment (i.e. all systems associated with the use of the space environment). This includes an acknowledgement that the space system is more than just the sum of its parts and an understanding of how these elements behave together is needed. EMISSARY can therefore reduce the likelihood of future unintended consequences and unaccounted for costs. The methodology behind EMISSARY is presented in the following section.

2.1.2 Sustainability in qualitative and quantitative terms

The space environment is not the first complex system requiring a framework to manage use within it. Many examples of such management exist for applications on Earth, for which multiple decades' worth of literature exists reviewing and analysing the effectiveness of such techniques. From this literature, key lessons regarding the appropriate use of threshold-based concepts such as carrying capacity for complex system management can be extracted.

Outdoor spaces are examples of complex systems in which activities need to be managed to achieve sustainable use of the environment. The first key conclusion that can be drawn from the terrestrial literature is that a carrying capacity metric that is derived from a singular perspective and distilled into a singular number is insufficient for the effective overall management of activities in outdoor spaces [28-30]. Examples of singular carrying capacities include physical equilibrium-based capacities. Some of these equilibrium-based capacities are derived using the logistic growth equation and have been used to provide insights into population dynamics of highly controlled or low-complexity systems [50, 51]. Other interpretations such as the stable equilibrium point around which multiple populations oscillate over time [52, 53] which can provide more useful insights for more dynamic systems. However, as system complexity grows to accommodate increasing accuracy and realism, these methods become less flexible, transparent, and practical [51]. Furthermore, these equilibrium approaches are designed to measure stability in a system, but stability alone is not sufficient to describe the relevant factors of importance encompassed within the UN definition of space sustainability. To capture the essence of the UN definition, an analysis of the multiple impacts of different space users is required, which is not achievable through stability analyses alone.

Instead of using singular carrying capacity metrics, many terrestrial management frameworks use multiple metrics that describe and can be used to monitor the conditions in the system rather than just system stability [29, 30, 32]. With this focus on conditions in the system, the ‘impacts of use’ in the system are measured and monitored as opposed to the ‘levels of use’ which is typically encompassed within commonly-adopted carrying-capacity approaches. In other words, the impacts that activities have in the system are quantified and used to define and monitor the sustainability of the system state, rather than defining sustainability in terms of the ‘amount of activity’ or the ‘population of users’ in the system. This perspective opens up the possibility for a range of different management actions that target the impacts of use, rather than the control of use alone. The target for regulations and other management actions therefore becomes the management of impacts from space activities that constrain the quality of conditions in the system. This is important as a threshold-based system has no value unless management organisations can develop mechanisms to limit use-related impacts [29].

The impacts of use that are important to achieving sustainability will vary from different perspectives [31]. Capturing these diverse perspectives is an important part of the approach taken in EMISSARY for achieving holistic sustainability. In other words, sustainability is measured in the context of the whole system, not just in particular parts [33]. Therefore, multiple metrics are needed that can measure the impacts that activities have on the quality of conditions in the system. These metrics either relate to the ability for different users to function when conducting their various space activities, or relate to the impacts on socio-economic or Earth systems (e.g. unacceptable impacts on Earth’s atmospheric conditions or economic impacts). It is important to consider more than just physical impacts as a degradation of sustainable conditions can occur without physical environmental damage occurring [54]. Also, thresholds informed by the social needs of users in a system are typically lower than thresholds derived from purely physical perspectives [55]. These thresholds are not stability-related but instead represent the minimum acceptable conditions that can be tolerated from the perspectives of different constituents before action is taken.

In this work, the term ‘constituents’ rather than ‘stakeholder’ is used to refer to groups of users, Earth and human systems that are influenced by the impacts of space activities. ‘Stakeholder’ was deemed insufficient due to its common association with economic investment. The term ‘constituency’ more readily allows for the inclusion of a diverse set of perspectives. Reference [56] is an example of an existing systems thinking approach that also uses this terminology. Furthermore, the term ‘actors’ is also used in this work. Actors specifically refer to individuals, groups, or organisations that have control or can influence change in the system. Actors may be individual constituents themselves (such as an individual satellite operator) or may be acting on behalf of a constituency (such as an international committee forming space sustainability policies or guidelines).

In EMISSARY, sustainability in the space system will be measured using the same structure of metrics used in many terrestrial management approaches. In these approaches, the impacts of activities on the conditions in the system from the perspectives of each constituency are monitored using factors, indicators and thresholds [32, 57, 58]. The definitions for each are as follows:

• Factors – broad, qualitative categories of importance to a constituency that define the aspects of sustainability in the system. These describe the conditions to be monitored in the system. Multiple factors may exist for each constituency.

• Indicators – quantitative, measurable indicators that directly or clearly quantify the conditions in the system. Each indicator should be clearly linked to an associated factor. Multiple indicators can be used, but each should ideally relate to a unique condition (i.e. the number of indicators should be minimised).

• Thresholds – the quantified limits of individual indicators. These represent the minimum acceptable conditions in the system, whereby management actions are conducted to avoid these being exceeded. If a threshold is crossed then the system is unsustainable from some perspective. These limits do not represent desirable conditions. Rather, they represent hard limits that must be met in a system where several needs may conflict and compromises must be made [57]. The derivation of these 'acceptable' quantitative thresholds should include qualitative, subjective inputs directly from the relevant constituencies.

Management actions such as regulatory policies act as balancing feedbacks to return indicators within acceptable thresholds. The management actions enacted should not cause other indicators to exceed their acceptable thresholds as a result. The goal should be for these indicators to remain within their acceptable thresholds in the current system state as well as future modelled system states.

Factors, indicators and thresholds are the metrics that actors monitor and use to make decisions about behaviour in the system. Management actions are taken by an actor to maintain acceptable conditions in the system from their perspective, as defined by their factors, indicators and thresholds. Depending on the actor, the management actions taken may only relate to their own behaviour or may extend as restrictions on other actors' behaviours.

The purpose of EMISSARY is to understand the trade-offs that the impacts from certain actions have on different conditions important to space sustainability, not to determine what those acceptable conditions are. As such, the determination of thresholds cannot be achieved purely using EMISSARY and requires subjective contributions directly from the constituents themselves to define quantitative 'acceptable' impacts [28, 29, 30, 32] As mentioned previously, these thresholds will likely be below limits identified via purely numerical methods or based on physical, environmental damage alone [55]. However, sufficient research should be used to evidence the choice of thresholds [57]. Where evidence does not already exist, efforts should be made to rectify this.

Furthermore, by continuously reviewing these factors, indicators and thresholds as part of an adaptive management strategy, changes in the dynamic system such as the development of new technologies, a changing user base and changing user needs can be accounted for [58, 59]. This ensures that the quantitative definition of space sustainability remains up to date in a continuously changing system and as knowledge about the system and its behaviour improves. The Conservation Standards [34] which provide a framework for addressing conservation issues are an example of a management framework that uses an adaptive strategy to tackle complex problem management.

2.2 Modelling approach example

An example model is presented to demonstrate the concepts described in this paper. The example model will demonstrate the effects that feedbacks beyond the immediate space domain have on overall system behaviour, where some leverage points outside the orbital space domain lie and how they may be used to affect the system behaviour, and how factors, indicators and thresholds are used to inform the behaviour of actors in the system.

In this example, a single satellite operator whose business goal is to deliver a certain quality of data service to paying customers is considered. The purpose and main driving factor in this model is to achieve a predefined profit goal over time. This goal is achieved by providing a target service quality over time. Satellites in this system function solely to deliver this data service. Limiting factors in the system then act to constrain the achievement of the goal. Three actors are considered in this simple example: a single satellite constellation operator, a regulatory body, and customers paying for the satellite service. This example forms a capital-resource-pollution system with foundations similar to those presented in [43]. The capital includes the satellite company's financial reserves and the satellites themselves, customers are treated as a renewable resource and space debris is the pollution component. Each of these can limit or advance the achievement of the model goal in some way and are affected by a complex network of interconnections between model parameters.

The structure and behaviour of each section of the example capital-resource-pollution model are presented and explained in the sections below. These sections use a systems thinking technique called 'stock and flow diagrams'. In these diagrams, 'stocks' are represented by boxes and represent the accumulation of material or information in a system over time as a result of 'flows' which are denoted by taps. The strength of the inflows and outflows to a stock determines the change in the stock levels. As such, there are two mechanisms by which a stock can grow – either by increasing the inflow or decreasing the outflow, but constraints always exist in the system that act to limit the growth in some way [43]. Additionally there are also 'information elements' that represent parameters that influence the flow of information in the system, the relationships for which are denoted by smaller arrows. The clouds in the diagram also signify that there are additional elements connected to the factors depicted in the model, but that these elements are outside the scope of the model purpose and are therefore not modelled explicitly.

2.2.1 Capital model

Fig. 3 shows the capital model adapted to describe the space system example described previously. Here, the capital is encompassed within three separate stocks: monetary funds, manufactured satellites and active satellites in orbit. Each of these stocks has inflows and outflows that adjust the levels of the stocks. Delays act to affect the rate of these inflows and outflows.

The levels of the active satellite stock have to be controlled as this level directly relates to the service provided and therefore also the profits generated. The main inflow into the capital model is the investment rate that transforms available funds into satellites. This investment rate is informed by the monetary fund stock and the replenishment need of the satellites in orbit according to service maintenance and profit growth goals. The main outflow from the capital model is the depreciation rate of the active satellites. This depreciation rate is the combination of outflows describing the loss of active satellites, which are outlined in further detail in the debris model in Section 2.2.2. A change in this depreciation rate directly relates to a change in the average satellite lifetime in the model. This average satellite lifetime is used as a feedback control to adjust the flows in the capital model according to service maintenance and growth goals. For example, if the depreciation rate increases without an associated increase in newly launched satellites, the active satellite stock will decrease. This will lead to a reduction in the service delivered and therefore also a reduction in the income generated. To maintain the desired income generation, adjustments must therefore be made to generate more income. One such adjustment shown in Fig. 3 is a change in the investment rate (i.e. launching of more satellites), but other available levers also exist and will be discussed further in Section 3. The appropriate adjustment to be made to the investment rate is partially informed by the change in the average lifetime which is derived from the depreciation rate (feedback control).

Significant delays that exist in the capital model are manufacturing delays, potential launch delays that may be imposed by regulating bodies, and orbit-raising delays after launch. Delays in the system are important because they create oscillations in stock values, particularly when feedback controls are present. This is because changes occur in the system before the impacts of corrective action are observed. Due to the effects of actions not being seen immediately, this can often lead to an over-prediction of the response needed, leading to oscillations. Typically, the length of these delays and response time to system changes control the severity of oscillations in the system. However, it is important to understand the behaviour of delays in a system as the appropriate actions to reduce oscillations in the system may be counter-intuitive [43].

The money stock itself can act as a large source of delay in the system. The size of the money stock translates to an additional 'time buffer' in the system which can improve the ability of the system to recover. For example, if conditions in the system mean that income is no longer being generated and the money stock is large, the system may be able to continue for a period of time or recovery actions may be enacted to prevent the system from collapsing. However, if the stock is small, the system may crash before it can recover. Understanding the sensitivity of the model to the size of the stocks within it can also provide useful insights into understanding how

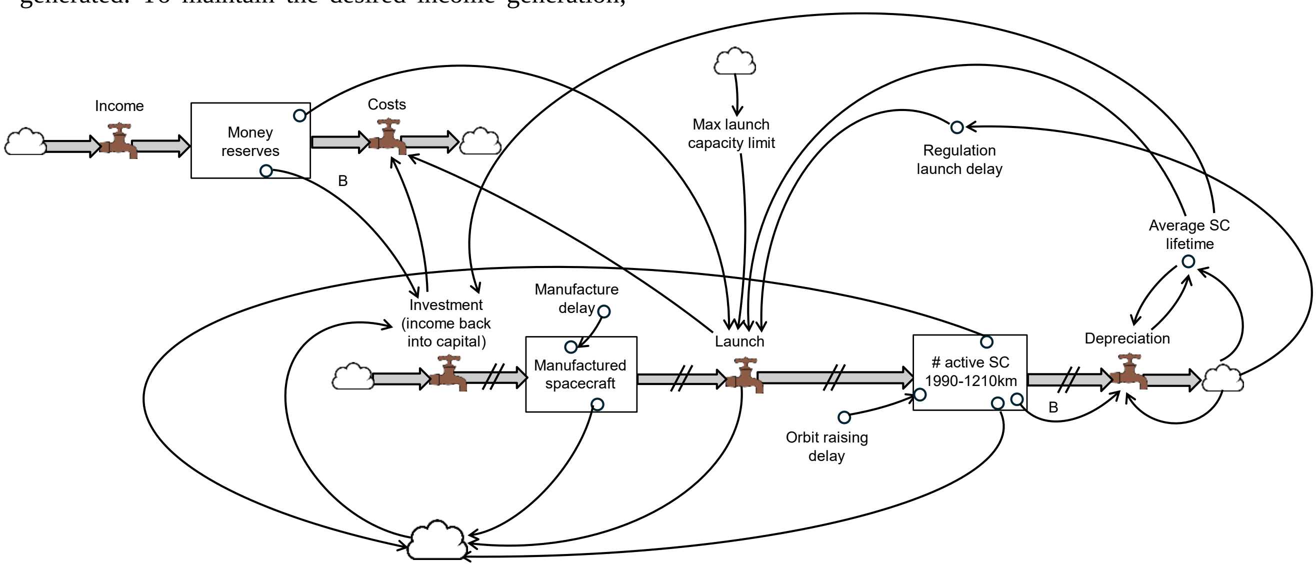

Figure 3 – Stock and flow diagram of the example capital model.

to improve the resilience of the system. In this example model, it is assumed that money passes through the system in a closed loop whereby all money generated and spent stays inside the system shown in Fig. 3. In reality, other factors such as external investment and other company costs would affect this money stock. The inclusion of these factors may be investigated in future work.

In this section of the model, the satellite operator has control over most of the elements presented. The two exceptions to this are the 'regulation launch delay' which is controlled by the regulating body, and the 'maximum launch capacity limit' which is controlled by external factors not included in this example. Additionally, whilst the satellite operator has control over how much money to spend on new satellites and launches, it does not control the manufacture and launch costs. As these elements are controlled by actors external to this model example, they are not explicitly included in Fig. 4, although these will likely be constraining factors in the model and will therefore be considered in future work.

2.2.2 Debris model

In this example, a simplified constellation operator operating without competition in a narrow altitude band of 1990-1210 km is considered. There are three stocks representing objects in the space environment: active satellites, lethal non-trackable (LNT) debris (1-10cm in size) and trackable debris (larger than 10cm in size). This section of the model is shown in Fig. 4. The following assumptions are made:

- All satellites are the same mass and size.
- Collisions occurring in the altitude band occur according to the kinetic theory of gas, where collisions only occur between active satellites and LNT debris, trackable debris and LNT, and LNT debris and LNT debris.
- All active-satellite-on-trackable-debris collisions are avoided at a fixed success rate. This is an oversimplification that may be expanded on in future work.
- Active-satellite-on-active-satellite conjunctions or collisions are not considered.
- Each active satellite has a fixed collision risk reduction manoeuvre (CAM) fuel budget over its original intended lifetime. If the CAM rate exceeds the fuel budget, then the average lifetime of the active satellites in orbit is reduced.
- All active satellites have a fixed orbit raising time during which the satellites cannot deliver services to customers.
- Failures only occur for newly launched satellites and happen at a fixed rate. This means that PMD success from the operational altitude is 100%. This does not necessarily mean that failures do not occur below the operational altitude during PMD, but these lower altitudes are not modelled in this example. Considering these lower altitudes may be done in future work.
- The flux of objects into and out of the operational altitude band due to non-satellite operator sources is zero. This means that no other satellite operators, no orbital debris flux and no micrometeoroid flux is considered in this example. Additional sources will be considered in future work.

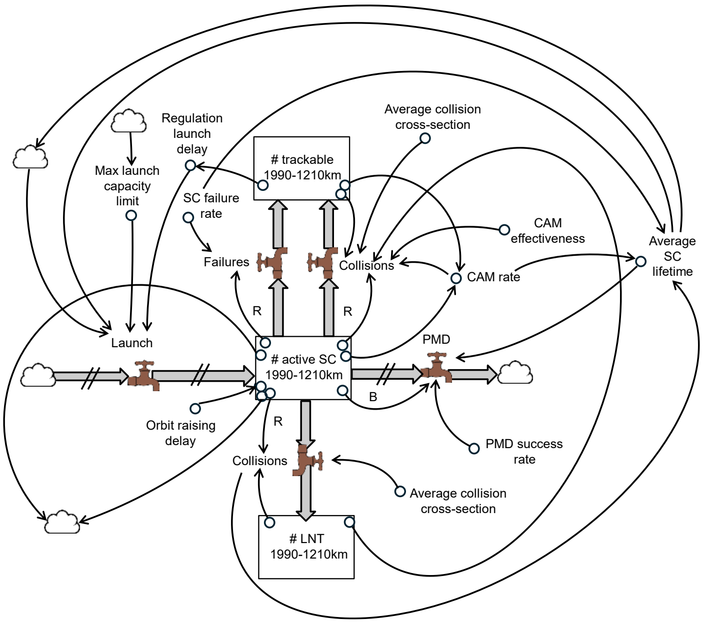

Figure 4 – Stock and flow diagram of the example debris (pollution) model.

The main focus in this section of the model is the change in the active satellite stock. Changes to this stock occur as a result of the inflow rate of launches after a delay dictated by the orbit raising time, and outflows as a result of failures, collisions, and PMD at the end of a satellite's lifetime. The sum of these outflow rates is equivalent to the depreciation rate shown in Fig. 3. All other elements shown in Fig. 4 are encompassed within the cloud connected to the depreciation rate in Fig. 3.

By replacing the depreciation rate in Fig. 3 with the debris model in Fig. 4, a capital-pollution model is described. In this model, the pollution acts as a constraint on the model via the depreciation rate of the active stock. As more new satellites are added into the environment, the pollution (i.e. debris stocks) constraint grows and increases the depreciation rate of the capital. This effect is magnified as there are no outflows to the debris stocks due to the atmospheric decay rates being negligible at this high altitude.

The failure, collision and PMD rates all act to reduce the average lifetime of satellites in the model as they represent the removal of satellites from the active satellite stock before their intended lifetime on launch. In this model, it is considered that satellites have a finite CAM budget associated with the size of their fuel reserves on launch. This means that CAM rates above the CAM budget will result in satellites requiring early PMD. As such, the CAM rate reduces the average lifetime of the satellites in orbit. This average lifetime is then associated with the replenishment rate needed to maintain the intended service delivery.

A further potential constraint in this system exists due to delays to the launch rate introduced by a regulatory body. This delay represents a regulatory example such as the 'object year' restriction proposed by the FCC, whereby a satellite company is refused approval for further launches if the cumulative lifetime of debris objects they have contributed to the space environment exceeds 100 years. This delay is only present in the system when the trackable debris stock exceeds the threshold value. This is an example of an indicator and threshold that an actor (i.e. the regulating body) tracks and uses to alter behaviour in the system. The actor hopes that by taking the management action of restricting further launches of the satellite operator, the indicator will not exceed the threshold value that describes acceptable debris environment conditions.

2.2.3 Renewable customer resource model

Customers are a renewable resource with a maximum upper limit that is represented in Fig. 5 as the 'potential customers in the market'. The customer stock describes the number of people that are paying for the satellite company's services, with changes in this stock occurring due to a rate of new customers joining and existing customers leaving after a delay determined by the contract length. The 'service quality' describes the data service provided to each customer and is tracked by the satellite operator in comparison to their desired service quality goal. The 'service value' describes the service quality compared to the data price. Customer behaviour in the model is driven by this service value. This service value is an indicator for customers and is the element against which a threshold would be associated. When the service value is above the acceptable threshold, a greater number of customers will join over the rate that leaves. When it is below, more customers will leave than will join. If the service value is high, then more customers will join and the customer stock will increase. If no changes are made in the capital-data system (i.e. the data capability and data price remain fixed) then this will lead to a decrease in the delivered service quality as the same data capability is shared amongst more customers. This leads to a reduction in the service quality, thus decreasing the customer stock by decreasing the inflow of customers and increasing the outflow. This creates a balancing feedback loop.

Additionally, whilst the customer resource is renewable,

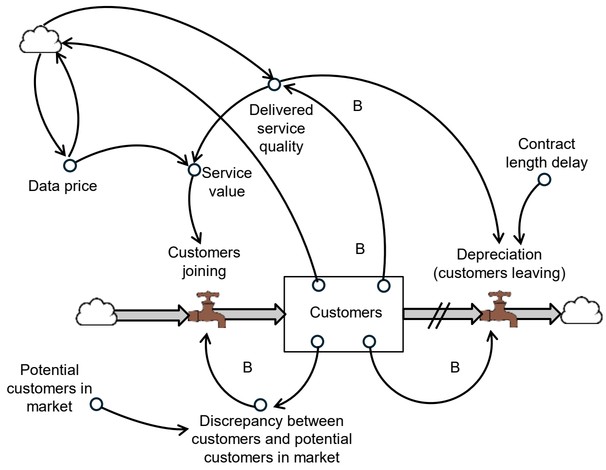

Figure 5 – Stock and flow diagram of the example customer model.

there is a finite maximum limit on the number of available customers. Hence, a balancing loop exists to describe the decrease in the rate of new customers joining as the discrepancy between the number of customers that have joined and the number of customers still in the market decreases.

Two actors have control over different elements in this section of the model. Firstly, the satellite operator has control over the contract length. By increasing the contract length delay, the satellite operator creates a buffer that decreases the variability of the customer depreciation rate, therefore improving the stability of the customer stock from which it generates income. This buffer increases the time the satellite operator has to recover from changes in the system. For example, if no contract delay existed and the service quality dropped below the acceptable threshold for customers, customers would begin to depreciate very rapidly. This rapid customer depletion would lead to an equally rapid decline in income and therefore potential crash of the system. By introducing this delay, the satellite operator introduces a time buffer within which it can recover from the expected impacts of a drop in service quality. It is assumed that the contract length has no influence on the joining rate of customers, although this may be changed in future work. Furthermore, customers may be able to leave before the contract delay if the service quality drops below the levels required by their contracts. This consideration has not been included in this example, but may be included in future work. Indirectly, the satellite operator also has control over the service quality as it controls the number of active satellites stock, and over the service value as it controls the data price. Changes to these values would alter the inflow and outflow rates of customers. Alternatively, the act of joining or leaving after a fixed contract delay is the only point of control that customers have in the system.

2.2.4 Full example model

Fig. 6 presents a combination of all of the previous model sections discussed. Feedbacks, connections and delays act throughout to connect the model together. As such, changes in one part of the model will result in changes in other parts of the model. Due to the delays and feedbacks, the effects of changes throughout the whole system will likely be non-linear and unpredictable without numerical modelling. However, by isolating parts of the model, smaller-scale relationships and behaviours can be analysed to provide useful insights. One example such includes the identification of system archetypes. Numerical modelling of this model will be performed in future work.

In the capital-resource model presented in [43], the purpose of the capital is to harvest the resource. Alternatively, in this model, the purpose of the capital (satellites) is to generate data, which is later 'harvested' by customers which are the resource. The data stock represents the finite amount of data capacity that a single satellite can generate, whereby the data capability per satellite is fixed. Therefore, the 'data' stock is linked directly to the active satellite stock by the 'data generation' inflow and the outflow 'sale' is driven by the customer model.

By acknowledging the purpose of satellites to generate and deliver valuable data to customers, thereby creating profit for the satellite company, the value of satellites can be included and analysed in model behaviour in addition to the potential harm that they create through debris generation (pollution).

Feedback controls represent opportunities for actors in the system to respond to changes in the system that cause discrepancies in relation to their goals and make adjustments intended to reduce these discrepancies. Often, many options for feedback control mechanisms exist for each actor, with each option relating to elements that are within the actor's control. In this example, achieving a desired profit is the driver for satellite operator behaviour. Achievement of this goal is

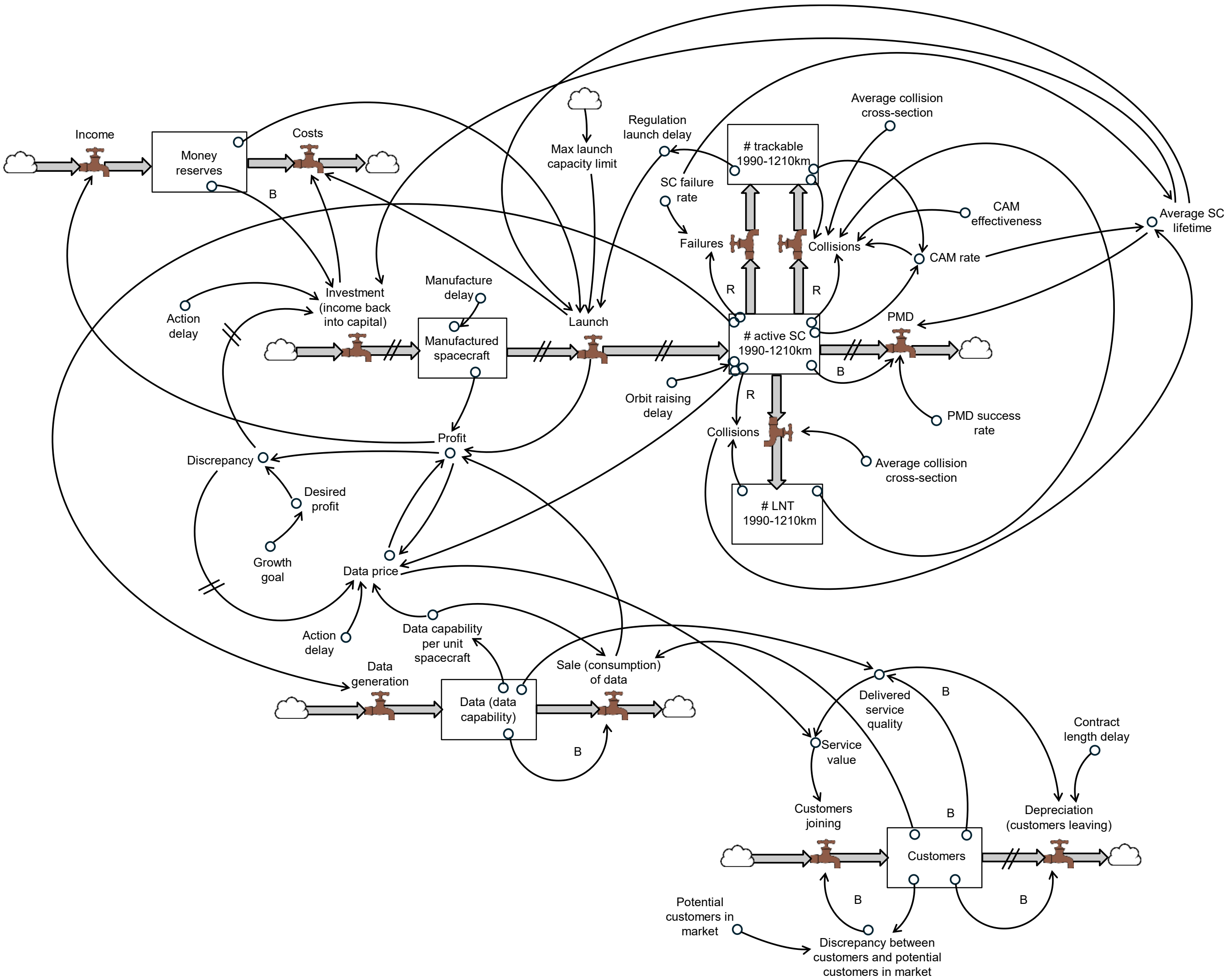

Figure 6 – A combination of all the stock and flow diagrams to form the capital-resource-pollution system for this example.

monitored by tracking the discrepancy between the actual and desired profit. However, the satellite operator cannot increase profits directly. Instead, the satellite operator can take action to reduce the costs from the capital model or increase income through the data model.

A range of potential actions exist for the satellite operator actor to take to reduce the profit discrepancy. In Fig. 6, some pre-determined examples of feedback mechanisms have been presented. These examples include: a change to the capital investment rate, thus increasing the number of satellites producing data, or an adjustment to the data price to immediately increase the income from the customers in the customer stock. These two management mechanisms are presented as examples and are likely not the only options available to the satellite operator in this scenario. The data price is considered fixed and is under the control of the satellite operator. The data price is set based on the costs associated with operating the satellite constellation and the desired uptake of customers in the customer model. It is an interesting leverage point in the system because it has direct connections into and from all sections of the model. Note that whilst the investment rate feedback mechanism acts to make changes in the space domain, changing the data price is a mechanism that acts outside of the orbital environment. This is one example of where a leverage point exists outside of the space domain model but has an indirect influence on space debris. Other mechanisms to reduce this discrepancy are also likely available to the satellite operator but are not depicted in Fig. 6. An element of further work may include an analysis of more of these potential options.

Multiple delays in the system will prevent the impact of this change from being seen immediately, and further changes in the system may occur before the corrective action takes effect. This may lead to the production of oscillations in the system. The 'action delay' is one potential method to influence the severity of oscillations in the system; the action delay represents the period of time associated with the responsiveness of actions in relation to changes in the 'discrepancy' term. In other words, having a highly responsive reaction to any change in the discrepancy could cause instability in the system. The action delay represents a period of time over which the change in the discrepancy is assessed and then action is taken if deemed necessary. This delay means that not every small change in the discrepancy produces a management response somewhere else in the model.

3 DISCUSSION

The example shown in Section 2.2 is an example of a systems model of activities performed by three example actors in the space system. By analysing systems models such as this, insights relating to potential bottlenecks, spheres of control (and therefore areas of risk), driving behaviours, existing leverage points and potential opportunities to introduce new leverage mechanisms can all be identified. An analysis of some of these discussion points follows in the section below.

3.1 General discussion

The purpose of building and analysing a model such as the example shown in Fig. 6 is not to predict the most likely future state of the space system. Rather, its purpose is to help build an understanding of the relationships in the holistic space system, where this knowledge can be used to help inform future actions with an awareness of the complexity and breadth of the potential impacts and trade-offs. Understanding these impacts and trade-offs is important because, as depicted in the causal loop diagram in Fig. 1, these impacts in other areas can affect space activities at a later time via various feedbacks. The high density and breadth of interconnections in the space system make trade-offs unavoidable. However, if these trade-offs and impacts are well understood then appropriate mitigation and other management actions can be taken to account for them. This assessment cannot be performed effectively by taking purely siloed approaches to formulate management actions, where a lack of consideration of the diverse trade-offs and impacts from actions results in negative unintended consequences and unaccounted for costs [33]. As such, understanding these impacts is essential not only for minimising the negative impacts that these activities have within and outside of the immediate space domain, but also for improving the overall resilience of the space industry and the space environment.

Identifying where leverage points exist in the system is important for understanding which management actions can be taken to produce the maximum positive change towards a specific goal. As outlined by [42], there are 12 broad categories of leverage points in a system, where actions are taken to: alter parameters, change the size of buffers, alter the structure of stocks and flows, change the length of delays, adjust the strength of negative feedback loops, derive more gain from positive feedback loops, modify information flows, change the rules of the system, change the system structure, change the goals of the system, change the mindsets that have caused the creation of the system in its current form, and finally to influence actors in a system to transcend their own personal paradigms. Each of these leverage points has a different level of effectiveness in a system and a different ease of difficulty to enact. For example, modification of parameters in the system is the easiest leverage point to access but is also often the least impactful [42]. With reference to the earlier example, changing the data price to reduce a profit discrepancy may be helpful in the short-term for the satellite operator, but as it doesn't address the root cause of the problem it will likely have limited success. Often, the leverage points that are most effective will address the root cause of a problem. In the example presented in this paper, this could be through the introduction of a sink to the debris stocks via an active debris removal (ADR) actor operating in the system. This would be an example of altering the system structure and would be significantly more difficult to achieve than the easier to access parameter changing leverage option.

To determine if management actions are needed, actors in the system use metrics to understand the conditions of the system from their perspectives, as defined by their factors, indicators and thresholds. In response to observed divergence from the desired conditions, actors may then utilise leverage points within their control to change the conditions in the system according to their needs. Overall system management can be difficult in systems where multiple actors are utilising leverage points independently. This can be especially difficult when actors make changes to achieve their own independent goals without consideration of the impacts from the perspectives of other actors (i.e. each actor acts according to their bounded rationality [43]). However, it is important to consider that not all leverage points are available to all actors due to the different spheres of control in the system. Different actors also have influence over different scales, with regulatory bodies (especially international bodies) likely retaining the broadest reach throughout the space system as they can have various influences over a broad range of space-related elements. As such, it is important for actors to consider the whole range of potential management actions within their influence, as the most beneficial management actions with the least negative impacts and trade-offs may exist outside the immediate system in which change is desired [33].

Understanding the limiting factors in the system is also important for understanding how to grow and maintain activities in the space system. Whilst one constraint on system growth is the debris population and associated collision risk in orbit, not all of the limiting factors lie in the immediate space domain. If debris is the only limiting factor considered then management focus for satellite operators may (as an example) fall on improving the CAM success and capabilities of active satellites to counter the growing debris stocks. Whilst this increase in CAM rate would affect the average lifetime of the satellite population, without accounting for economic considerations, one may assume that the increasing replenishment need can always met. However, the inclusion of economic considerations would likely reveal that even if 100% CAM success is achieved (a theoretical scenario that is not practically achievable), the system would likely eventually collapse due to the escalating costs associated with the escalating CAM rate. Leverage points may be available to the satellite operator that could prolong the system crash. However, this economic constraint would always limit system growth due to the lack of sinks in the debris stocks at this altitude, which inevitably causes the CAM rate to increase. In this example, a powerful leverage point could be the creation of sinks for the debris stocks (i.e. ADR capabilities). Whilst this is an example of another leverage point within the physical space domain, the inclusion of ADR in this model would also require consideration of the economic models for the ADR company. The demonstration of this economic constraint numerically and the effect of including ADR into the model in Section 2.2 is a target for future work.

Furthermore, understanding the factors that drive the behaviours of actors in the system may provide useful insights to inform the most effective methods of enforcement of regulation by regulating bodies. For example, actors may be more likely to adopt management actions voluntarily if these actions are cohesive with their driving behaviour. Using the example in Section 2.2, a satellite operator may be more likely to adopt certain behaviours voluntarily if there is a clear understanding of how these actions will decrease the discrepancy in their profit goals. Otherwise, if these actions will work counter to an actor's driving goal or the relationship to their driving goal is not well understood, then non-voluntary enforcement may be required to maintain a change in behaviour in the system. This is an example of designing management mechanisms that work 'with' the existing system structure rather than acting to alter the system structure, which [42] states is harder to achieve.

4 CONCLUSIONS

The concept behind a new systems dynamics model, EMISSARY, was presented in this paper. EMISSARY uses a series of metrics to describe the sustainability of space activities in a more holistic context, modelling the trade-offs and interconnecting relationships between multiple, diverse perspectives encompassed within the UN definition of space sustainability. The intended use of EMISSARY is to support the assessment of the sustainability of space activities and management actions in this holistic context. A number of key messages presented in this paper are summarised below.

Firstly, the consideration of the holistic impacts and trade-offs of space activities from a variety of different perspectives encompassed by the definition of space sustainability adds significant complexity to assessments of the sustainability of space activities and management guideline formulation processes. However, this additional complexity should not be interpreted as a further constraint to space activities. Rather, it is the complete opposite; understanding the diverse impacts that occur over different timescales allows for the design of more resilient systems that can persist and evolve to deliver improved space services in a competitive, complex and dynamic environment. Lack of consideration of these impacts only leaves vulnerabilities in the system that may generate unexpected future harm. By understanding the impacts and trade-offs that result from space activities, management strategies can be derived that account for these impacts, rather than allowing them to evolve into unintended consequences and unaccounted for costs. EMISSARY and its underlying concepts provide a methodology with which to help us understand, assess and gain insights to aid the development of management strategies that aim to achieve holistic space sustainability.

Secondly, the extensive interconnectedness of the space system makes trade-offs as a result of space activities and management actions unavoidable. Therefore, a method to analyse and understand the scope and severity of these trade-offs is an essential part of achieving holistic space sustainability. This method needs to incorporate the use of multiple quantitative metrics used to measure the severity of these diverse impacts. These metrics are used to define the limits of acceptable compromise in a holistic space system with many different actors with equally diverse needs. Indicators are the metrics used to monitor the effect of these impacts on conditions in the system. Thresholds define the limits to compromise which allow for trade-offs to be managed appropriately. Thresholds are inputs to the EMISSARY model, not outputs.

Thirdly, a recontextualization of the goals of space sustainability to reflect a holistic definition of space sustainability may be useful for assessing the suitability of future management actions. In the holistic context discussed in this paper, space sustainability is not merely the constraint of the debris environment, nor is it the achieved by the reduction of satellites' impact on observational astronomy (or any other singularly focussed example). Whilst these examples are certainly parts of achieving space sustainability, the true goal of space sustainability is the maintenance of conditions that support the equitable access and acceptable use of space from the perspectives of all space users, both now and into the future. This switch to focus on the interconnected conditions in the holistic space system may require a management approach that is more reminiscent of the holistic assessment approaches taken by organisations such as IPBES for biodiversity and environmental threat management, rather than the more siloed approaches currently taken. The intention for EMISSARY is to provide a model concept that is capable of providing this diverse perspective of space sustainability.

Finally, the strongest leverage points for achieving outcomes cohesive with sustainability goals may exist outside the immediate environment within which change is desired. For example, strong leverage points that can positively affect space debris environment conditions may exist outside of the immediate debris and orbital environment. However, it is only possible to identify such leverage points by modelling the diverse interconnections between the physical space environment and beyond. This is a limitation of current siloed approaches used in space sustainability modelling. EMISSARY is designed to aid with the identification of these leverage points and to improve our understanding of how these leverage points may be utilised successfully as space activity management mechanisms. As such, appropriate consideration of where control lies for different actors in the system will be an important step for establishing the appropriate scope and boundaries of EMISSARY.

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6 REFERENCES

1. McDowell, J. Jonathan's Space Pages. Online at https://planet4589.org/space/stats/active.html (as of 18 March 2025).

2. Anderson, K., et al. (2017). Earth observation in service of the 2030 Agenda for Sustainable Development. Geo-spatial Information Science, 20(2), 77-96.

3. Miraux, L., Wilson, A. R., & Calabuig, G. J. D. (2022). Environmental sustainability of future proposed space activities. Acta Astronautica, 200, 329-346.

4. Ross, M. N., & Sheaffer, P. M. (2014). Radiative forcing caused by rocket engine emissions. Earth's Future, 2(4), 177-196.

5. Dallas, J. A., et al. (2020). The environmental impact of emissions from space launches: A comprehensive review. Journal of Cleaner Production, 255, 120209.

6. Ferreira, J. P., et al. (2024). Potential ozone depletion from satellite demise during atmospheric reentry in the era of mega-constellations. Geophysical Research Letters, 51(11), e2024GL109280.

7. Pardini, C., & Anselmo, L. (2024). The risk of casualties from the uncontrolled re-entry of spacecraft and orbital stages. Journal of Space Safety Engineering, 11(2), 181-191.

8. Byers, M., & Byers, C. (2017). Toxic splash: Russian rocket stages dropped in Arctic waters raise health, environmental and legal concerns. Polar Record, 53(6), 580-591.

9. De Lucia, V., & Iavicoli, V. (2018). From outer space to ocean depths: The spacecraft cemetery and the protection of the marine environment in areas beyond national jurisdiction. Cal. W. Int'l LJ, 49, 345.

10. Barentine, J. C., et al. (2023). Aggregate effects of proliferating low-Earth-orbit objects and implications for astronomical data lost in the noise. Nature Astronomy, 7(3), 252-258.

11. Tyson, J. A., et al. (2020). Mitigation of LEO satellite brightness and trail effects on the Rubin Observatory LSST. The Astronomical Journal, 160(5), 226.

12. Hainaut, O. R., & Williams, A. P. (2020). Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains. Astronomy & Astrophysics, 636, A121.

13. Kruk, S., et al. (2023). The impact of satellite trails on Hubble Space Telescope observations. Nature Astronomy, 7(3), 262-268.

14. Billot, N., et al. (2024). In-situ observations of resident space objects with the CHEOPS space telescope. Journal of Space Safety Engineering, 11(3), 498-506.

15. Adilov, N., Alexander, P. J., & Cunningham, B. M. (2018). An economic "Kessler Syndrome": A dynamic model of earth orbit debris. Economics Letters, 166, 79-82.

16. Leonard, R., & Williams, I. D. (2023). Viability of a circular economy for space debris. Waste Management, 155, 19-28.

17. Millet, I. (2025). Re-thinking Property and Pollution: Conserving the Night Sky as Natural Commons. In Demanding a Radical Constitution: Environmentalism, Resilience, and Participation in Chile's 2022 Reform Efforts (pp. 113-130). Cham: Springer Nature Switzerland.

18. Inter-Agency Space Debris Coordination Committee. (2017). IADC statement on large constellations of satellites in low earth orbit. IADC Steering Committee.

19. International Astronomical Union Centre for the Protection of dark and quiet Skies. (2023). Consolidated recommendations for low-earth orbiting satellite constellation operators to mitigate visibility impact on astronomy. IAU CPS.

20. Stevenson, M., et al. (2021). Identifying the statistically-most-concerning conjunctions in leo. In Proceedings of the AMOS Technical Conference.

21. Parker, W. E., Brown, M. K., & Linares, R. (2025). Greenhouse gases reduce the satellite carrying capacity of low Earth orbit. Nature Sustainability, 1-10.

22. Arnas, D., Lifson, M., Linares, R., & Avendaño, M. E. (2021). Definition of Low Earth Orbit slotting architectures using 2D lattice flower constellations. Advances in Space Research, 67(11), 3696-3711.

23. Lifson, M., et al. (2024). Low-Earth-Orbit Packing: Implications for Orbit Design and Policy. Journal of Spacecraft and Rockets, 1-14.

24. Krag, H., Lemmens, S., & Letizia, F. (2017, November). Space traffic management through the control of the space environment's capacity. In Proceedings of the 1st IAA Conference on Space Situational Awareness (ICSSA).

25. Colombo, C., et al. (2023). Assessment of the collision risk in orbital slots and the overall space capacity. In 2nd International Orbital Debris Conference (IOC II) (pp. 1-10).

26. Letizia, F., Lemmens, S., Virgili, B. B., & Krag, H. (2019). Application of a debris index for global evaluation of mitigation strategies. Acta Astronautica, 161, 348-362.

27. Letizia, F., Virgili, B. B., & Lemmens, S. (2023). Assessment of orbital capacity thresholds through long-term simulations of the debris environment. Advances in Space Research, 72(7), 2552-2569.

28. Mexa, H. C. (2004). The Challenge of Tourism Carrying Capacity Assessment: Theory and Practice. Routledge.

29. McCool, S. F. (2001). Tourism carrying capacity: tempting fantasy or useful reality? Journal of sustainable tourism, 372--388.

30. Lindberg, K., McCool, S., & Stankey, G. (1997). Rethinking carrying capacity. Annals of tourism research, 24(2), 461-465.

31. Manning, R. E., et al. (1995). The visitor experience and resource protection (VERP) process: The application of carrying capacity to Arches National Park. In The George Wright Forum (Vol. 12, No. 3, pp. 41-55). George Wright Society.

32. Manning, R. E. (2002, January). How much is too much? Carrying capacity of national parks and protected areas. In Monitoring and management of visitor flows in recreational and protected areas. Proceedings of the Conference held at Bodenkultur University Vienna, Austria (pp. 306-313).

33. IPBES (2024). Summary for Policymakers of the Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.

34. CMP. (2020). Open standards for the practice of conservation version 4.0. Conservation Measures Partnership.

35. CPSG. (2020). Species Conservation Planning Principles & Steps, Ver. 1.0. IUCN/SSC Conservation Planning Specialist Group: Apple Valley, MN.

36. United Nations Office for Outer Space Affairs. (2022). Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the

Peaceful Uses of Outer Space. UN.

37. UN COPUOS STSC. (2025). Conference Room Paper on the Protection of Dark and Quiet Skies for science and society. A/AC.105/C.1/2025/CRP.22/Rev.3. UN COPUOS Scientific and Technical Subcommittee Sixty-second session, Vienna, 3–14 February 2025.

38. Locke, J., et al. (2024). Cost and benefit analysis of mitigating, tracking, and remediating orbital debris. Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris.

39. Perks, M.E., Lewis, H.G., Vaidya, N. (2024). The impact of SATCON recommendations of the safety and sustainability of large constellations. 75th International astronautical congress (IAC), Milan, Italy, 14-18 October.

40. Verma, V. K., Gangadhari, R. K., & Pandey, P. K. (2023). A re-examination of the space debris problem using systems thinking. Space Mission Planning & Operations, 2(1), 28-43.

41. Perks, M. E., Lewis, H. G., & Vaidya, N. (2024). A holistic systems thinking approach to space sustainability via space debris management. Journal of Space Safety Engineering, 11(3), 532-538.

42. Donella Meadows. Leverage Points: Places to Intervene in a System. The Donella Meadows Project Academy for Systems Change. Online at https://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/ (as of 21 March 2025).

43. Meadows, D. H. (2008). Thinking in systems: A primer. Chelsea green publishing.

44. Kim, D.H. (2008). Systems archetypes I: diagnosing systemic issues and designing high-leverage interventions. Pegasus Communications, Inc.

45. World Economic Forum. (2024). Global Risks Report 2024, 19th Edition, Insight Report.

46. Dasgupta, P. (2021), The Economics of Biodiversity: The Dasgupta Review. Abridged Version. 103 pages. (London: HM Treasury).

47. Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. Sustainability science, 14, 681-695.

48. UNU-EHS Interconnected Disaster Risks 2023: Risk Tipping Points. (2023). United Nations University, Institute for Environment and Human Security.

49. Inter-Agency Space Debris Coordination Committee. (2025). IADC Space Debris Mitigation Guidelines. IADC Steering Group and Working Group 4.

50. Odum, E. P., & Barrett, G. W. (1953). Fundamentals of ecology.

51. Sayre, N. F. (2008). The genesis, history, and limits of carrying capacity. Annals of the Association of American Geographers, 98(1), 120-134.

52. Lotka, A. J. (1920). Analytical note on certain rhythmic relations in organic systems. Proceedings of the National Academy of Sciences, 6(7), 410-415.

53. Volterra, V. (1926). Fluctuations in the abundance of a species considered mathematically. Nature, 118(2972), 558-560.

54. Lime, D. W. (1973). Recreational carrying capacity: An annotated bibliography (Vol. 3). Intermountain Forest and Range Experiment Station.

55. Seidl, I., & Tisdell, C. A. (1999). Carrying capacity reconsidered: from Malthus' population theory to cultural carrying capacity. Ecological economics, 31(3), 395-408.

56. McCool, S. F., et al. (2015). Benefiting from complexity thinking. Protected area governance and management, 291-326.

57. Cole, D. N., & McCool, S. F. (1997). The limits of acceptable change process: modifications and clarifications. McCool, SF and Cole, DN, comps.(1997). Proceedings-Limits of Acceptable Change and related planning processes: progress and future directions. Gen Tech. Rep. INT-GTR-371. Ogden, Utah: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

58. Manning, R. E., & Lime, D. W. (2000, June). Defining and managing the quality of wilderness recreation experiences. In Wilderness science in a time of change conference (Vol. 4, pp. 13-52).

59. Brooks, N., & Adger, W. N. (2005). Assessing and enhancing adaptive capacity. Adaptation policy frameworks for climate change: Developing strategies, policies and measures, 165-181.