# The Theoretic Foundation for Modelling Arms Race Stability in Outer Space

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**Abstract**

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| Introduction | The accelerating dependency on space-based infrastructures across military, civilian, and economic sectors, combined with the rapid evolution of counterspace capabilities, creates a strategic environment marked by profound uncertainty and growing instability. This paper positions arms-race stability as a central component of strategic stability in outer space and develops a conceptual foundation for modelling arming behaviour of nations navigating this domain. |
| Approach | By adapting the concept of arms-race stability to the space domain and examining the key drivers of arming behaviour, this study offers a structured lens through which to assess how instability arises and how it can be modelled using System Dynamics. |
| Results | A definition of arms-race stability tailored to the space domain is proposed, followed by an analytical assessment identifying uncertainty, vulnerability, perceptions, and national strategic motivations as the dominant forces shaping competitive dynamics. To capture these interactions, the behaviours of governments, commercial actors, and innovation processes are represented through three interconnected conceptual models. These models illuminate how feedbacks, delays, and misperceptions can accelerate instability. |


**Keywords:** strategic stability, arms race model, outer space security, peace and conflict studies, space conflicts

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| Discussion | The paper concludes by outlining how these qualitative structures can be translated into a quantitative System Dynamics model, enabling systematic exploration of policy interventions and governance mechanisms. In doing so, it contributes to the broader effort of crafting shared, stable futures in an increasingly contested and strategically vital domain. |
| Use of AI | OpenAI has been used in order to shorten and rephrase texts. After using this tool, the authors reviewed and edited the results and take full responsibility for the content of the article. |

# 1 Introduction and Research Question

Outer space is rapidly emerging as a critical domain for both military and civilian applications. Its importance is growing not only due to its role in military capabilities, such as surveillance, precision targeting or command and control, but also due to its economic relevance like for navigation, global communications, Earth observation, and many more applications [1]. As the costs of accessing space decline and the dual-use character of space systems intensifies, the potential of arms races, crisis instability, and unintended escalation rise and underscore the urgency of establishing effective arms control mechanisms [2]. Existing treaties like the Outer Space Treaty establish important legal principles, such as the peaceful use of outer space and the responsibility of states for their space activities, but they were drafted in an era with far fewer actors, no large commercial constellations, limited dual-use technologies, and relatively simple space architectures. Article IV from the Outer Space Treaty stipulates, for example, that none of the signatory nations may place weapons of mass destruction in space. However, there are no regulations governing the placement of other types of weapons in space, which leaves considerable scope for the use of weapons [3]. These treaties therefore fail to address current technological realities.

This research work is part of the SACS (Supporting Arms Control in Space) research group. The goal of this group is to support the development of a future arms control treaty for outer space. This paper lays the foundation for the quantitative analysis of arms race stability (being one part of strategic stability) in space. Examining arms race stability makes it possible to identify those actions, technological developments, etc. that increase the risk of inadvertent escalation or an arms race. By focusing on the conditions under which stability is preserved or eroded, the analysis seeks to generate knowledge that is directly relevant to the design of preventive measures and future treaties.

In summary, this paper answers the research question: *In what ways can the distinctive dynamics of space armament and the principal drivers of space-based arms races be conceptualised and operationalised to assess the likelihood of an arms-race emerging under specific scenario conditions?*

Section 2 introduces the concept of space arms race dynamics and analyses its main drivers. Section 3 reviews existing arms race models, discusses their strengths and limitations, and explains why System Dynamics is particularly suitable for this research. Building on these findings, Section 4 develops a flow diagram of arming behaviour in space as a basis for future System Dynamics modelling. Finally, Section 5 presents conclusions and directions for future research.

# 2 Space Arms Race Dynamics

Before arms race stability in outer space can be analysed and modelled, it is necessary to establish a clear understanding of the underlying dynamics that drive competitive armament processes. Unlike traditional military domains, outer space is characterised by unique technological, strategic, and institutional features that shape how states perceive threats, pursue capabilities, and respond to the actions of others. This section therefore provides the conceptual foundation for the subsequent analysis.

## 2.1 Reasons for Analysing Space Arms Races

Empirical research on enduring rivalries suggests that war is most likely following repeated militarised disputes combined with capability asymmetries between rivals. Military build-ups are particularly destabilising when they take the form of unilateral expansions or asymmetric arms races that generate escalatory power distributions [4]. Although arms races do not directly cause war, the likelihood of conflict increases when one actor substantially expands its military capabilities relative to its rival, thereby creating conditions under which crises are more likely to escalate [4].

The importance of analysing arms race stability is further reflected in contemporary security dynamics. The twenty-first century has seen a renewed return of arms-racing, driven by technological innovation, disruptive weapon systems, and the erosion of arms control regimes [5]. While some scholars view arms-racing as a means of deterrence, others argue that it undermines military stability and increases the risk of conflict [5].

Assessing whether competitive dynamics remain bounded or develop into self-sustaining escalation processes is therefore essential for evaluating strategic stability, designing arms control and confidence-building measures, and identifying early-warning indicators of destabilising behaviour. Consequently, the analysis of arms race stability constitutes an important foundation for understanding strategic stability in outer space.

## 2.2 Space as a Conflict Domain

To analyse arms race dynamics in space, the special characteristics of the domain must be considered. First, space systems consist of ground, space, and communication segments that can be targeted by both kinetic and non-kinetic counterspace capabilities. Satellites are vulnerable, difficult to defend, and offensive and defensive capabilities are often hard to distinguish [6, 7, 2].

Second, the information environment is characterised by limited transparency and attribution challenges. Many counterspace capabilities, particularly cyber and electronic systems, are difficult to observe, while the purpose and capabilities of satellites often remain uncertain despite advances in space domain awareness [8, 9, 7, 2].

Third, the stakeholder landscape has become increasingly diverse. Commercial actors now play an important role alongside military and civil operators, linking economic and security interests more closely than before [10].

## 2.3 Definition of a Space Arms Race

Based on these specific dynamics of arms build-up in space, we define a situation as stable with regard to an arms race when incentives for states and other actors in space to pursue quantitative or qualitative build-ups of potentially offensive space capabilities remain limited. This applies not only to deliberate military weaponisation, but also to dual-use and commercial technologies that may unintentionally intensify competitive dynamics.

## 2.4 Drivers of Space Arms Race Development

According to realist theory, which forms the basis of this research, states are driven by fear, material interests, and prestige [11]. Under international anarchy, these motives generate insecurity, competition for power and relative gains, and efforts to preserve status [11].

Informational and observational conditions make the so-called security dilemma a central driver of arms race instability in space. Because most space systems are dual-use and the intentions of their users cannot be reliably verified, defensive measures may be interpreted as offensive preparations [2]. Combined with attribution difficulties and uncertainty about adversaries' capabilities and intentions, this encourages worst-case assumptions and competitive military responses regardless of the actual offence-defence balance [2, 12].

Physical and technical characteristics reinforce arms race dynamics by increasing both the strategic value and vulnerability of space systems. Because modern military operations depend heavily on space-based services, states have strong incentives to expand and harden their orbital infrastructures [2, 13]. The availability of diverse counterspace capabilities and the potentially severe consequences of disruptions further encourage investments in both defensive and offensive space capabilities [6, 5].

Stakeholder diversity contributes to arms race instability because states pursue different strategic objectives and deterrence postures, ranging from resilience-based approaches to offence-dominant strategies, while all sharing the same space [9, 14, 15, 16, 17]. At the same time, commercial actors have become strategically relevant, blurring the distinction between civilian and military capabilities [2]. The resulting uncertainty surrounding dual-use technologies and commercial infrastructure can encourage competitive capability expansion and create a commercial space security dilemma [18].

# 3 Arms Race Models in Literature

This Section describes the types of modelling of arms race dynamics that most frequently appear in academic literature and then discusses which type of model is best suited for the dynamics of space arms races described in this paper.

## 3.1 Richardson-like Models

Modelling arms races in a wide variety of conflict domains has long been and still is the subject of many scientific publications. Richardson presumably laid the foundation for modelling arms race dynamics with his linear differential equations describing two nations responding to each others arming behaviour [19].

Differential equation models provide a mathematically rigorous way to describe how systems evolve over time by expressing the rate of change of key variables. At their core, these models use ordinary or partial differential equations to formalise how one variable responds to another, allowing researchers to capture escalation patterns, thresholds, saturation effects, and time-dependent sensitivities. Differential equation models focus on explicit analytical structure, making causal assumptions transparent and enabling precise exploration of stability, equilibrium conditions, and long-run trajectories.

Richardson used this modelling method to simulate changes in the level of armament of two nations. The stronger the perceived threat from the opponent, the greater the incentive to catch up and invest in weapons themselves. Constant parameters such as costs and grievances against the opponent can slow down or fuel this race to catch up [19].

Building on this differential equation model, further research was conducted to improve the model and make it more realistic. Caspary [20] for example included carrying capacities and further economic constraints. Alternative approaches were the integration of "strategic considerations, institutional aspects and decision rules" [21] or using difference equations instead of differential equations to include more than just two nations into the arms race [22].

To this day there is still a lot of critique expressed against these kinds of models.

Theoretical and conceptual critique regards nations being described as structureless entities, neglecting internal politics, or that both actors have complete knowledge of each other's armament levels, which is unrealistic. The linear equations used within Richardson-like models also don't appear appropriate to model a often non-linear, disproportionate, and path-dependent world [21]. Further conceptual critique from Anderton [23] regards the lack of strategic interaction like bluffing, cooperation, or deliberate plotting, core aspects of real-world strategic behaviour and decision-making.

Empirical and methodological critique often regards measurement problems. Military expenditure and arms data are notoriously unreliable, rarely publicly available, and often based on state-reported or intelligence estimates that cannot be independently verified [23]. On top of that, Richardson-like arms race coefficients are extremely hard to measure with accuracy in practice and treated as constants. In reality they are time-dependent and shaped by political choices and external events [21].

One aspect that is particularly important and must be examined in every type of mathematical model is chaotic behaviour. Even simple non-linear arms race models may generate unpredictable long-term behaviour due to sensitivity to initial conditions. Multinational interactions, overshooting, delays in information processing, and discrete adjustments can all provoke chaotic outcomes [21].

## 3.2 System Dynamics Models

System Dynamics (SD) is a method for understanding and modelling the behaviour of complex systems over time. It is especially suited for problems characterised by feedback loops, time delays, accumulations (stocks), and flows, all of which are central to arms race dynamics.

They incorporate differential (and sometimes difference) equations, but wrap them in a more accessible and interpretable modelling framework, making them well-suited for interdisciplinary security studies. Rather than solving equations analytically, SD focus on simulating plausible future scenarios, capturing non-linear interactions, and testing policy interventions in dynamic systems.

System dynamics models have also been used in the simulation and modelling of various arms races.

Wilmes [24] for example models the arms race between two fictitious nations using SD, incorporating sub-models for technology, military planning, and the race itself. The model includes delays from research and procurement, resource constraints, and feedback from perceived threats. These elements are modelled using stock-and-flow structures, which allow the simulation of both the quantitative aspects of arms races as well as their qualitative aspects over decades.

Fisunoğlu [25] provides another SD approach. In his work, he translates the Richardson differential equation model into a more realistic SD model. The model treats economic capacity and total armament as stock variables shaped by flows such as economic growth, desired strength ratios, investment, and depreciation, all of which interact within each country's internal system. The two national systems are further linked through their total and target armament levels, creating a coupled dynamic in which each state's armament decisions influence the other's trajectory.

Even though SD models resolve many of the criticisms levelled at linear differential and difference equation models, it should be noted that they are not a perfect solution either. SD models offer to include way more details compared to their linear model counterpart. The flexibility that makes these models so useful can also become a drawback when models are built on weak theoretical foundations, leading to "garbage in, garbage out" dynamics with limited scientific value. As the number of factors and variables increases, such models can grow unwieldy, and in some cases alternative simulation approaches, such as Agent-Based Models, may yield more meaningful insights, even though they share many of the same limitations [25].

### 3.3 Game-theoretic Approaches to Arms Races

Game-theoretic approaches, as mentioned above, are another alternative modelling approach to arms races and arming behaviour. These models offer an exploratory way to examine the behaviour of agents or players.

Triezenberg, Langeland, and Downing [26] presents a game-theoretic model for the study of conflicts in space. It is not purely an arms race model but, in addition to investment and armament actions, also includes actions such as attack or defence.

While game-theoretic and agent based models offer the opportunity to capture the richness and complexity of real-world situations, they can just like SD-models quickly become either too complex to validate or end up in chaotic behaviour [26].

### 3.4 Deciding on a Modelling Technique

The choice between deciding for a differential equation, SD or game-theoretic model for simulating arms races in space depends on modelling objectives, data availability, and the desired balance between analytical tractability and practical simulation.

In order to make a modelling choice, we will first outline the objectives of the model. The overall aim is to identify the technological, economic and organisational factors that most strongly influence arms race instability in space, and to understand the patterns of armament and disarmament that shape those dynamics. The focus is on how different types of weapons, qualitative capability differences, and asymmetric innovations change the behaviour of nations. The model also aims to examine how commercial support, information uncertainties and different governance approaches influence arms race stability. These mechanisms shall be mapped in a dynamic framework that takes into account quantitative developments as well as perceptions, delays and political feedback. On this basis, the model will ultimately contribute to the development of robust and realistically implementable arms control approaches for space.

From these considerations a clear rationale for choosing system dynamics over differential-equation or game-theoretic models emerges. System dynamics offers a middle ground between mathematical precision and conceptual accessibility, making it particularly suitable for a domain where technical complexity intersects with political decision-making.

System Dynamics models additionally offer:

1. Balance of rigour and interpretability: System dynamics retains a formal mathematical backbone (stocks, flows, feedback loops, non-linear functions), yet presents these structures in a way that remains intelligible to non-technical stakeholders. This is essential for the political applicability of this research. Policy-makers, military planners, and diplomats must be able to understand and evaluate model assumptions without advanced mathematical training.

2. Capacity to represent delays, perceptions, and feedback: Space arms races are shaped by long development cycles, delayed responses, misperceptions of intent, and reinforcing or balancing feedback loops. System dynamics is designed precisely for such temporal and behavioural complexities, whereas classical differential-equation models struggle to incorporate perception-driven or policy-driven delays without becoming analytically intractable.

3. Flexibility to include multiple actors and heterogeneous processes: SD models can scale to include several interacting actors, each with their own internal dynamics, resource constraints, and strategic postures. Differential-equation models become unwieldy once more than two actors or more than a handful of variables are introduced, and game-theoretic models rapidly explode in complexity when extended beyond stylised two-player interactions.

4. Integration of stochastic elements and scenario exploration: Space security involves uncertainty e.g. in the form of technological breakthroughs, budget shocks, and geopolitical shifts. SD models can incorporate stochastic components and run large numbers of simulations to explore plausible futures.

5. Practicality and computational efficiency: Game-theoretic models capable of capturing long-term arms-race dynamics, incomplete information, and multi-actor interactions are often computationally demanding and time-consuming to specify. SD models, by contrast, allow rapid prototyping, iterative refinement, and efficient simulation across long time horizons.

Choosing system dynamics now does not preclude later integration into a broader game-theoretic framework. In fact, SD can serve as a conceptual and empirical foundation for identifying key variables, feedback structures, and behavioural patterns that will later inform a more complex crisis-behaviour model. This staged approach avoids premature over-complexification while ensuring that future game-theoretic extensions rest on a well-tested dynamic core.

# 4 Modelling Arming Behaviour in Space

This Section now deals with how the specific dynamics of space arms races and the drivers of space arms races described in Section 2 can be represented using SD models. The basis for a nation's arming behaviour is provided by Kreutzer [27]. In his work, he provides a flow-diagram for the arms planning of a nation. It includes the nation's desired margin of superiority, evaluation of it's own capabilities and authorisation of spending on new weapons [27]. This diagram shall be expanded with the results from Section 2.

The building blocks that can be integrated into the model in any number are a governmental production model, a commercial production model and a technological innovation model, which are represented in Figures 1, 2, and 3. They are connected to each other via interfaces and can thus be combined for a large number of scenarios, similar to a modular system.

## 4.1 Governmental Production Model

Kreutzer [27]'s diagram of a nation's arms accumulation that builds the basis of the governmental arms race model incorporates:

- The nation's current armament level, weapons under development and estimated domestic armament level
- The estimated opposing armament level including a bias in estimating it
- The nation's desired armament level depending on the own desire of superiority and the own and opposing level of armament

The drivers of arms races in space resulting from Section 2 that shall be incorporated into Kreutzer [27]'s model can be summarised as followed:

- Motives of the nations/their deterrence archetype
- Rivalry with one another
- Perception of the Offence-Defence-Balance (ODB)
- Dependency on space systems
- Opportunity due to a good commercial space industry

In addition, the influence of treaties is to be factored in to test which measures within an arms control treaty have the greatest impact on the nations armament behaviour.

The impact of a nation's motives on its armament behaviour were displayed in Section 2. As described there, the motives predominantly affect the own desire of superiority over other nations. In order to translate a nation's motivations into a quantitative model, they can be assigned to one of the space actor archetypes described in [9] (denial-dominant, mixed deterrence or offence-dominant). From this, the desired margin of superiority can then be derived. Flanagan et al. [9]'s deterrence archetypes also describe how nations behave in terms of communication and signalling. For this reason, an auxiliary variable for communication and transparency measures is introduced into the model, which receives the deterrence archetype as input. The way in which communication between two nations is structured then has an impact on how the ODB is perceived and also how the other nations capabilities are estimated.

Being in a rivalry or conflict with another nation, similar to the pursued motives of a nation, can create insecurity and increase the desire of superiority. This parameter will therefore go alongside the nations motives into the desire for superiority.

Perceiving space as offence-dominant reinforces incentives for a security competition. Therefore this should be connected to the nations desired margin of superiority. Quantifying this factor could prove challenging, as perception is a highly subjective matter. Whether a nation perceives space as offence-dominant can generally be observed through its arming behaviour and public declarations regarding weapons.

A high dependency on space services creates incentives to develop a large and robust space architecture, therefore influencing the desire for space capabilities.

And lastly, being able to finance a commercial space industry offers technological innovations as well as cheaper production and launching costs. Therefore intersections to commercial actors will be included into the model with connections to a nation's current arms and arms under development as well as the technological innovation level of the nation.

## 4.2 Technological Development Model

The definition of arms race stability introduced in Section 2 refers not only to the quantity of space capabilities but also to their quality. An arms race can also take the form of technical development. The work of Wilmes [24] is used as the basis for this sub-model. Technological innovation is only possible if the nation has the budget for it and access to critical components and skilled personnel and will therefore be an essential part of it. Technological advances can then have various effects, such as lower production costs, shorter production times and improved, or even entirely new, products [24].

## 4.3 Commercial Production Model

A special feature of space is that commercial actors now have a major influence. It is therefore essential to incorporate them into an arms race model. Assumptions about commercial involvement into space conflicts and armament dynamics will be taken from Whitman Cobb [18]. According to them, nations can decide to maintain a cost-intensive commercial space industry through government subsidies, regulations and even laws. The advantages they derive from this include lower production and launching costs, state-of-the-art technology and the possibility of using commercial capabilities in space for military purposes. As governments

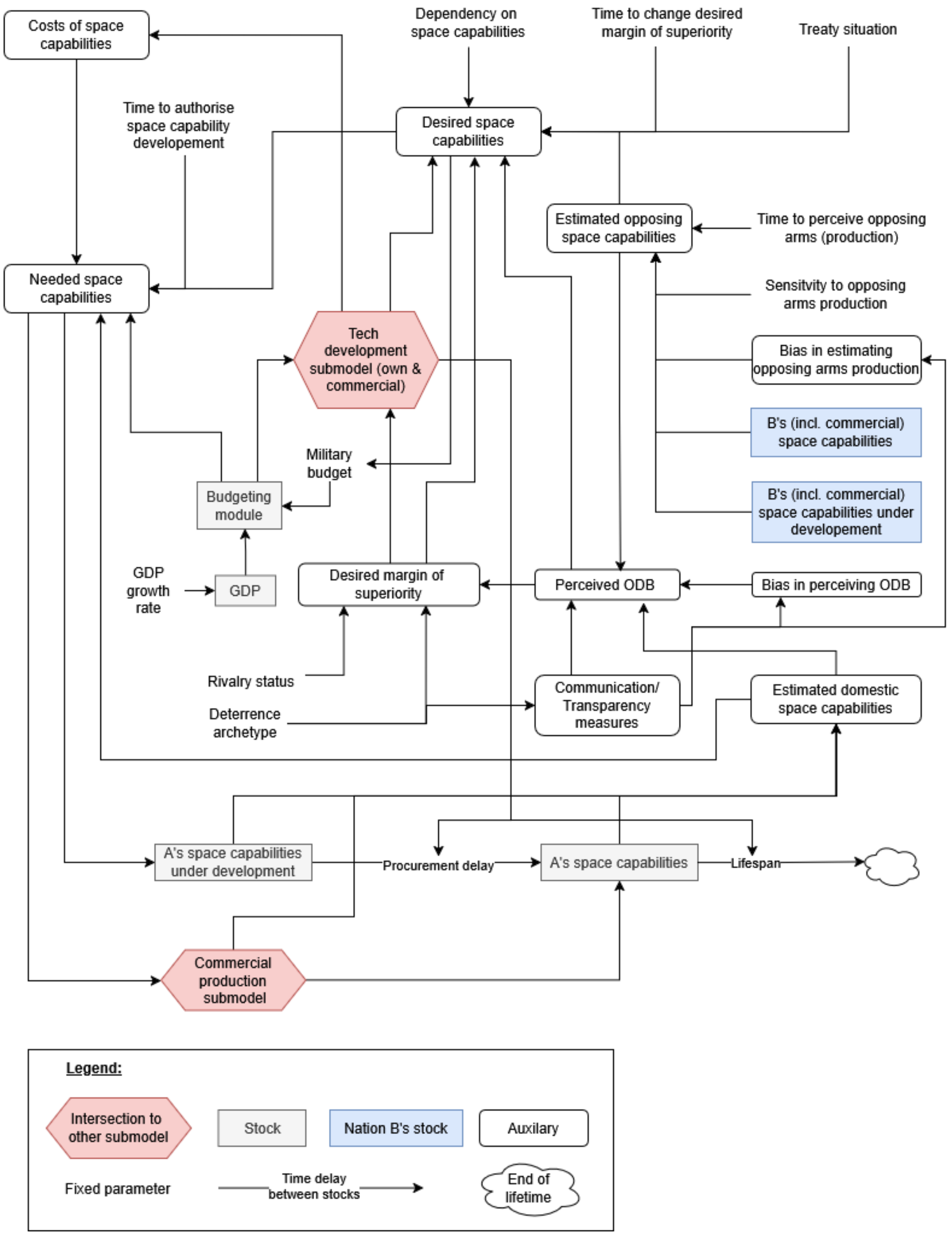


Figure 1: Flow-diagram of a nations governmental production of space assets

become powerful customers, space companies start to compete over contracts to secure their economic success. On the other hand commercial actors can also hesitate with offering their services to the government if the risk of being drawn into a conflict and therefore potentially losing some of their assets comes up.

The model for commercial production of space assets is structured similarly to Kreutzer [27]'s model for nations, but without the threat posed by the production of other nations. Instead, the main drivers for commercial production will be profit and competitiveness. To bridge the commercial and governmental model, two interfaces for communication between the two sub-models will be built in. Governments can provide financial support and order space assets from their commercial space industry. However, commercial actors can also refuse or restrict services based on the current political situation. On top of that, commercially received space assets as well as the military use of commercial space assets will be perceived by other nations (with a bias in perception). This way, the outgoing threat from a commercial space industry that is heavily integrated with or used by the military can be incorporated into the arms race model.

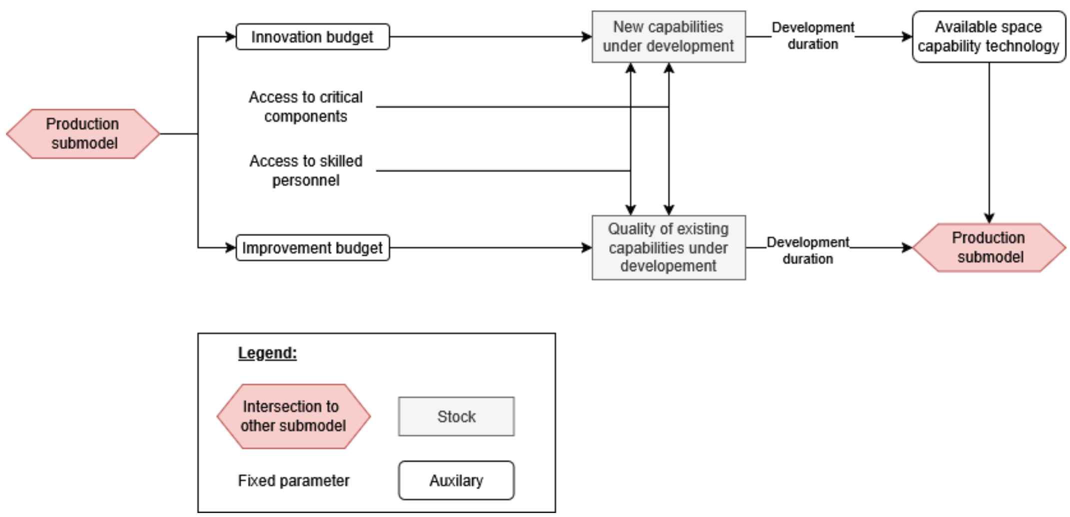


Figure 2: Flow-diagram of the technological innovation sub-model

## 4.4 Flow-Diagrams of Arms Race Dynamics in Space

Taking Kreutzer [27]'s model of a nations arming behaviour as a base, including space specific characteristics as described above, a technological sub-model as described by Wilmes [24] as well as a sub-model for commercial actors result in the following three flow-diagrams that describe arming behaviour in space.

In all three Figures (1,2, and 3) interfaces are highlighted in red. Stock variables are displayed in light gray rectangles, auxiliary variables in white rounded rectangles and parameters as simple text.

Figure 1 illustrates the arming behaviour of Nation A in response to the actions of Nation B. Nation B's space capabilities are depicted as blue rectangles. The diagram is intentionally simplified so that Nation B may, if required, be able to also represent a composite of several nations while remaining consistent with the modular building-block logic of the model. The state represented in the flow-chart may possess its own commercial space sector, although this component can equally be omitted. The same flexibility applies to the technological development sub-model.

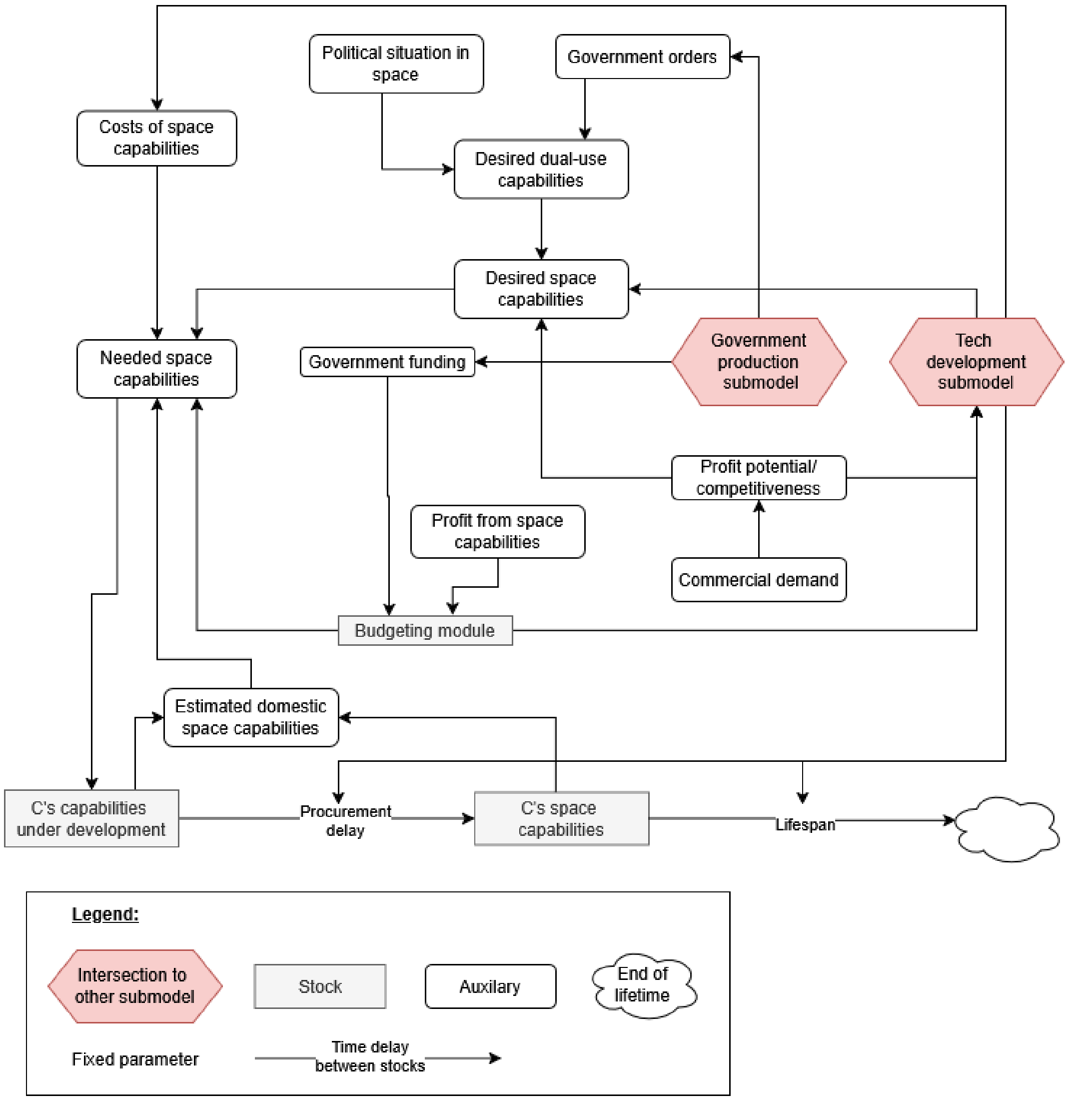


Figure 3: Flow-diagram of commercial production of space assets

The technological sub-model depicted in Figure 2 again was kept simple enough to be used either from a governmental or a commercial actor. With this model, it is also possible to decide whether only one of the two development strands will be implemented. Certain nations or commercial players, for example, place more value on improvement than on innovation.

Figure 3 represents the production of commercial actor C. The incorporated intersection to a governmental production sub-model can also be used for multiple state actors, if multiple nations finance and/or order from this company. As the model as a whole focuses heavily on the armament behaviour of the nations under consideration, the economic aspect of the commercial model has been kept to a minimum. External stimuli, as well as competitive behaviour between different companies, are modelled solely via the auxiliary variable ‘commercial demand’ and via the interface to the governmental sub-model.

### 4.5 Planned Results

To analyse arms race stability, the model will track the accumulation and interaction of capabilities over time, capturing feedback loops, time lags, multipolar dynamics, and the effects of uncertainty, misperception and hypothetical treaty designs. The resulting outputs will provide indicators of arms race and escalation potential as well as system resilience.

A measure of arms race stability could therefore consider how high the chances of an arms race forming are in certain scenarios. It could also determine, based on the rate of change of certain key parameters, whether an arms race is looming, or whether the situation is stable. For an arms race to exist, expenditure on the capabilities in question must increase at an above-average rate over several years.

## 5 Discussion and Future Work

This study has proposed a domain-specific conceptualisation of arms race stability in outer space through the analysis of space-specific conflict dynamics. The analysis demonstrates that arms race stability in space is not solely a function of material capabilities, but is fundamentally shaped by perception. High levels of uncertainty, weak communication channels, and limited attribution mechanisms repeatedly transform defensive measures into perceived offensive threats. These dynamics create powerful reinforcing feedbacks that intensify competitive pressures and reduce the scope for restraint.

Situating these insights within the broader literature reveals a significant gap in existing modelling approaches. While arms race dynamics have been extensively studied in nuclear and conventional domains, only a small number of studies have attempted to model competitive behaviour in space, and even fewer have done so using formal dynamic methods. The decision to employ a System Dynamics approach is therefore both methodologically and substantively justified: the space domain is characterised by delays, feedback loops, non-linear escalation mechanisms, and complex interactions between governmental, commercial, and technological subsystems, features that are well captured by System Dynamics modelling. The flow diagrams developed in this paper provide an initial structural representation of these interactions and offer a foundation for more rigorous quantitative analysis.

This work also contributes to addressing a notable gap in current research. Despite the rapid transformation of outer space into a contested military domain, research on the systemic drivers of instability remains limited. The absence of robust normative frameworks and the accelerating pace of technological innovation create significant potential for miscalculation and conflict. By offering a structured conceptual foundation and a pathway towards quantitative modelling, this paper provides an initial step towards a more systematic understanding of arms race dynamics in space and supports ongoing efforts to craft more stable and cooperative futures in this increasingly critical domain.

The implications of these findings are twofold. First, they underscore the need for analytical tools capable of navigating the uncertainty and instability inherent in the space domain. A quantitative System Dynamics model would enable systematic exploration of how different policy interventions, transparency measures, or technological developments influence arms race stability over time. Second, the results highlight that arms race stability represents only one dimension of strategic stability. Crisis stability and first-strike stability remain equally critical, particularly given the increasing integration of space systems into nuclear command-and-control architectures. Future modelling efforts should therefore incorporate these dimensions to provide a more comprehensive assessment of strategic risk in space.

The next phase of this research will focus on formalising the qualitative structures presented here. A stepwise modelling strategy will be adopted to ensure behavioural validity and to minimise chaotic behaviour. Baseline functions for governmental production will be implemented and validated first, followed by the gradual integration of commercial and technological subsystems. Once operational, the model will allow for the development of a metric for arms race stability in space, enabling scenario-based comparisons and the evaluation of potential confidence-building measures or governance mechanisms.

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