A choice-based framework for modeling the orbital environment

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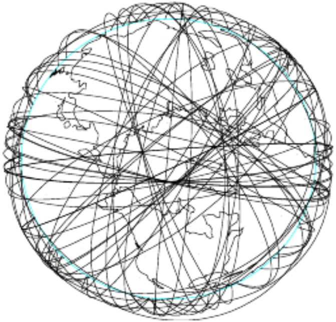


Launch patterns shape the orbital environment

Some launch-related questions all debris forecasting models must address:

- How many satellites will be launched in a given period?
- What kind of satellites will be launched?
- Where will the satellites be launched to?

Standard approach: Project historical launch trends forward, either as a function of time or on repeating cycles, e.g. [5, 11]

Standard approaches obscure the role of choice in orbit use
$\implies$ policy recommendations miss behavioral adjustments

Examples of behavioral adjustments:

- As a region becomes saturated with fragments, operators may shift launches to less-crowded regions $\implies$ observed debris formation may be lower than projected
- As new technologies make certain regions more valuable, operators may shift launches into it and create new congestion hotspots $\implies$ observed debris formation may be higher than projected

Integrating choice theory

We propose to integrate economic theory with debris environment models

This approach delivers

- debris environment projections accounting for behavioral adjustments
- estimates of willingness-to-pay for orbital environment changes
- projections of debris environment sensitivity to economic factors

Similar approaches have been used in other settings: travel mode choice [1], oil spill cleanup [2], nuclear plant operation [9], climate policy [13]

- [8] applies a related approach to orbit use

Framework overview

The framework involves three components:

1. A model of launch decisions
   - Input: current physical and economic state
   - Output: projected launch patterns
2. A model of the debris environment evolution
   - Input: current physical state and projected launch patterns
   - Output: updated physical state
3. Projections of relevant economic state variables
   - E.g. total government space budgets, distribution of revenues across space sector, average price per kg to different orbits, etc

Data requirements

Implementing the framework requires more data than typical approaches, but most data are already available or collected:

1. Physical state: distributions of objects in orbit
2. Economic state: budgets, sectoral revenues, and launch prices
3. Observed choices: launch events to specific orbits given current physical and economic states

Theory: Random-Utility Models

A popular approach for econometric choice modeling is the random-utility model (RUM) [6, 12]

Key assumptions:

- A decision-maker (DM) seeks to choose a product to maximize a scalar-valued function ("utility")
- Utility can depend on
  - Product and DM characteristics observed by the researcher
  - Product characteristics observed by the DM but unobserved by the researcher
- A DM chooses a product j over product k if & only if the utility of j exceeds the utility of k

Theory: Random-Utility Models

Formally, the utility to operator type i from launching to orbit j in period t is

$$U_{ijt} = X_{ijt}\beta + \nu_{ijt},$$

where

- X_{ijt} is a vector of observed orbit and operator characteristics in period t
- β is a vector of parameters to estimate
- ν_{ijt} is a random error term capturing features observed by the operator but not the researcher

The probability of observing i choose j in t is then

$$P_{ijt} = Pr(U_{ijt} > U_{ikt} \;\; \forall k \neq j).$$

Given data and distributional assumptions on ν_{ijt}, β can be estimated by maximizing the likelihood of the observed choices

The number of operators of type i launching in period t, N_{it}, is modeled as a count process:

$$N_{it} = f(M_{it}, \epsilon_{it}),$$

where

- M_{it} is a vector of observed aggregate state variables, e.g. sectoral revenues, government budgets, average collision rate, average utility
- $f(\cdot)$ is a finite-dimensional function to estimate
- ϵ_{it} is a random error term

Count models are often paired with RUMs to predict entry and sorting over environmental goods, e.g. [3]

Popular choices include:

- RUM: multinomial logit ($\nu_{ijt} \sim$ Type 1 Extreme Value), with fixed or random coefficients
  - Fixed coefficients are computationally simpler, random coefficients allow for richer substitution patterns [7]
- Count model: Poisson ($f(M_{it}, \epsilon_{it}) = e^{\theta' M_{it}} + \epsilon_{it}$) or (if many zeros) negative binomial or hurdle model

The debris environment model

We augment the Particle-in-a-Box (PIB) model in [10] with:

- 50km circular orbital shells
- Objects distinguished by type
  - Satellites: civil govt, military, commercial, other
  - Debris: rocket bodies, MROs, inactive payloads, collision fragments
- Analytical fragmentation formulas from [4]

Object characteristics (e.g. cross-sectional area, mass) are fixed and exogenous

- can make them vary exogenously or as choices

The debris environment model

Governing equations and notation:

- Operator type i, debris type k, orbital shell j
  - satellites S_{ij}, debris D_{kj}
  - active lifetime μ_i, decay rate δ_{kj}, "unavoidable" collision rate L_{ij} or L_{kj}, launch rate q_{ij}, new fragments γ_{kj}

Satellites :

$$\dot{S}_{ij} = q_{ij} - (\mu_i + L_{ij})S$$

Debris:

$$\dot{D}_{kj} = -L_{kj} - \delta_{kj} D_{kj} + \delta_{kj+1} D_{kj+1}$$

- For IP: $+\sum_i \mu_{ij} S_{ij}$
- For CO: $+\sum_k \gamma_{kj} L_{kj}$
- Assume no new RBs, MROs; 100% successful active collision avoidance

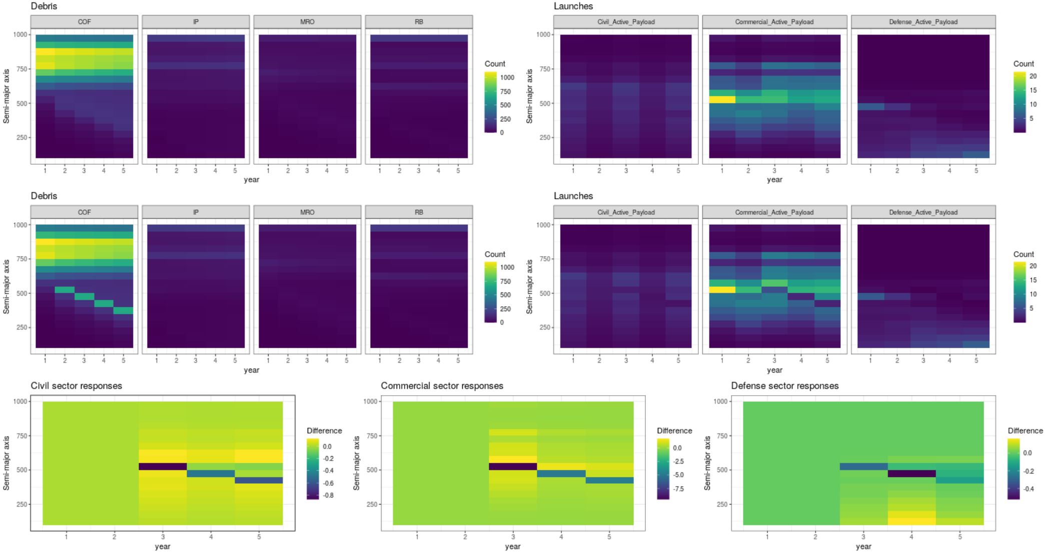
We illustrate the effect of substitution in this framework using:

- a multinomial logit RUM with fixed coefficients
- a PIB model of the 100-1000km LEO environment

Scenario: An unexpected fragmentation occurs in shell j at the start of year t. How would operators have responded in following years?

We illustrate the behavioral response using a choice model estimated on 2006-2019 data with repeating total launches from 2014-2015

An illustrative example



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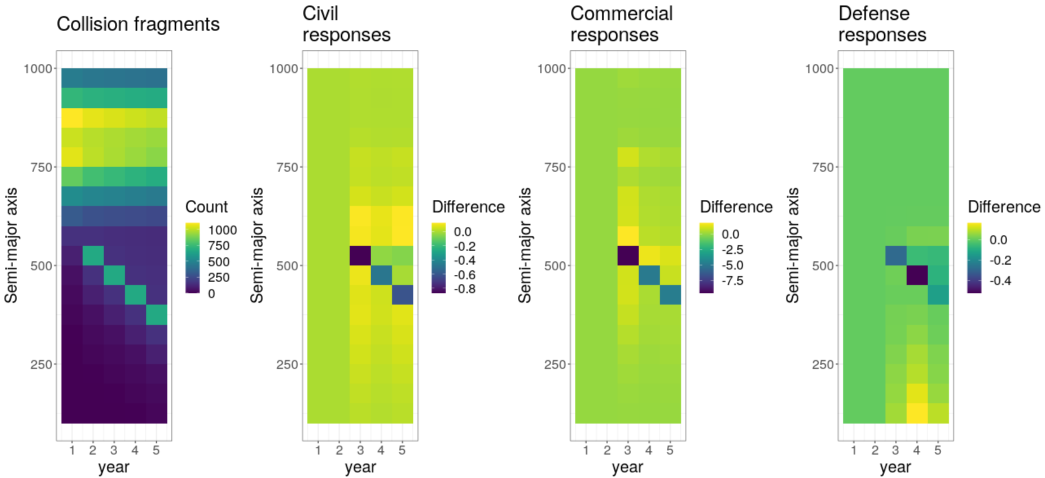

Next steps

Current limitations:

- MNL projects constant substitution elasticities
- PIB model needs more calibration
- Only choice dimension is launch

Some next steps:

- Calibration to long-term simulations
- Incorporating more flexible choice models
- Exploring alternate values for other choice variables (e.g. PMD, avoidance)
- Incorporating announced launch plans

Integrating choice dimensions can enrich orbital environment projections

- Orbit users will respond to the state of the orbital environment
  - The orbital environment will evolve based on orbit users' choices

- Policy success depends on behavioral responses
  - How should ADR be prioritized?
  - How effective will standards and guidelines be?
  - Will keep-out zones backfire?

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