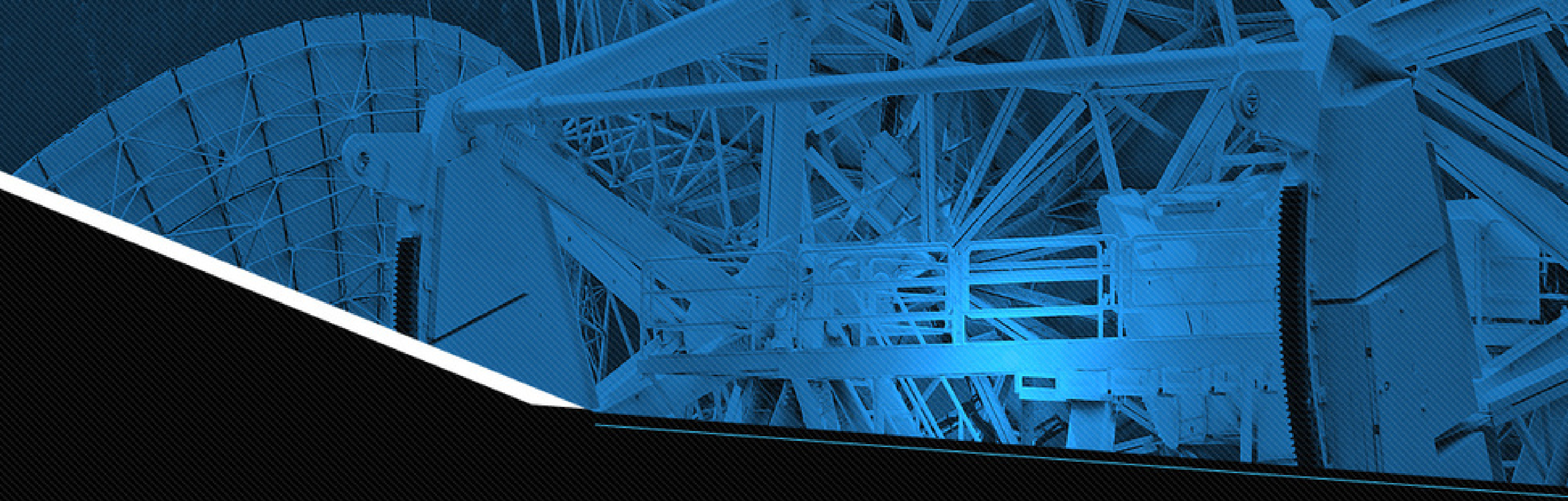
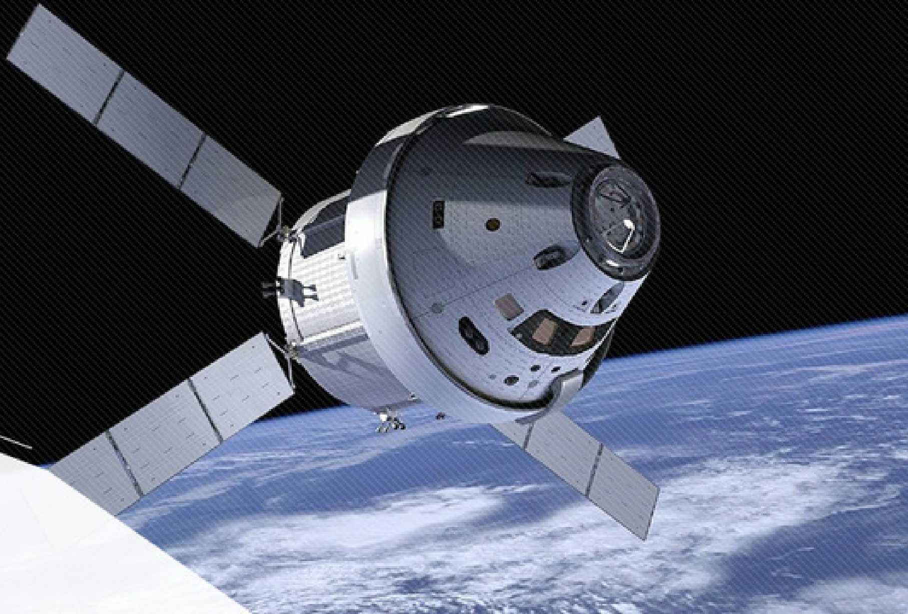


SURVIVAL ANALYSIS TO SUPPORT MAINTENANCE FOR AEROSPACE AGENCIES

Simone Ciardulli, Celeste De Bernardinis, Darvin Koka, Federica Rena



Problem statement

The satellite market is **growing** and **profitable**.

Having an accurate **prediction model** that estimates satellite lifetimes and establishes maintenance periods is necessary **to avoid the loss of a satellite**.

Despite the costs and risks associated with building, launching and operating satellites, some companies have managed to grow their space technology business. Boeing is one of those companies. Its Defense, Space and Security division managed to deliver 10 satellites in 2012 and acquire orders for seven more, contributing to the business unit's nearly $32 billion in revenue [source: The Boeing Company].

https://science.howstuffworks.com/satellite10.htm

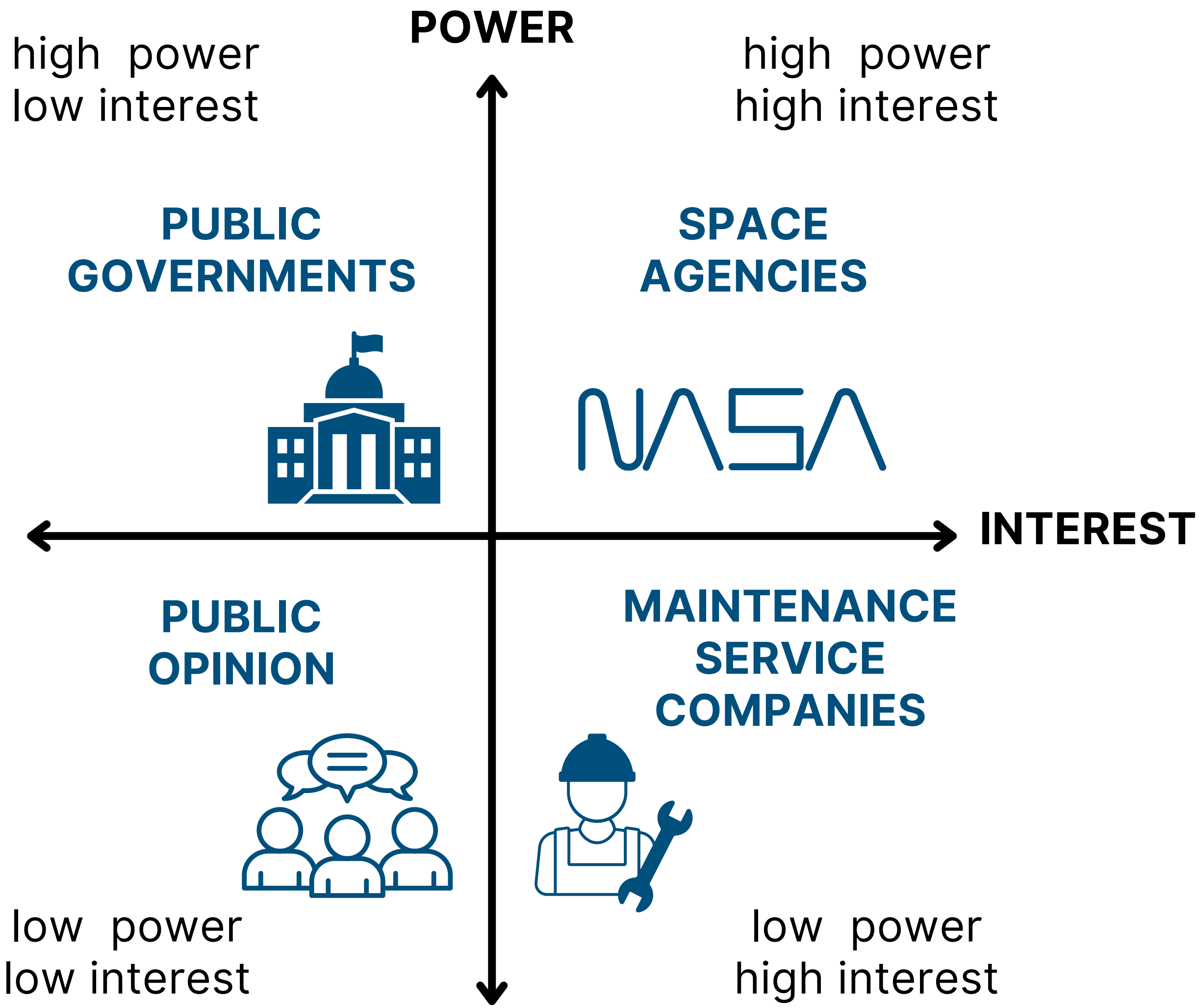
According to Eclipse Aviation, **the overall price of a satellite is about $1 million each.**[1] **Meanwhile, satellites launched in distant orbits cost around $150–$400 million each.**

This price tag is followed by the occasional expenses of maintaining and repairing the satellites. Keep reading for the detailed answer on how much a satellite costs and what other additional costs to anticipate.

https://opticsmag.com/how-much-does-a-satellite-cost/

Stakeholders

Our **main stakeholders** are space agencies, but they are not the only ones:



Goals of the project

Our aim was **providing space agencies** with an effective tool **to enhance predictive maintenance** for satellites.

- Is it feasible to formulate a **more accurate model** for predicting satellite lifetimes?

- **When** is it appropriate **to initiate maintenance** processes for the space agencies?

Dataset description

The data come from UCS Satellite Database and SATCAT dataset, which contain more than **6000 satellites** currently orbiting Earth, and **28 covariates** for each satellite, including:

- **Launch Mass**, in kilograms
- **Power**: The amount of useable electric power produced by the satellite, given in watts
- **Date of Launch**
- **Expected Lifetime,** in years

Technical information

- **Apogee**, in kilometers
- **Perigee**, in kilometers
- **Period**, in minutes
- **Inclination**, in degrees
- **Class of Orbit**, with 4 levels: Elliptical, Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geosynchronous Orbit (GEO)

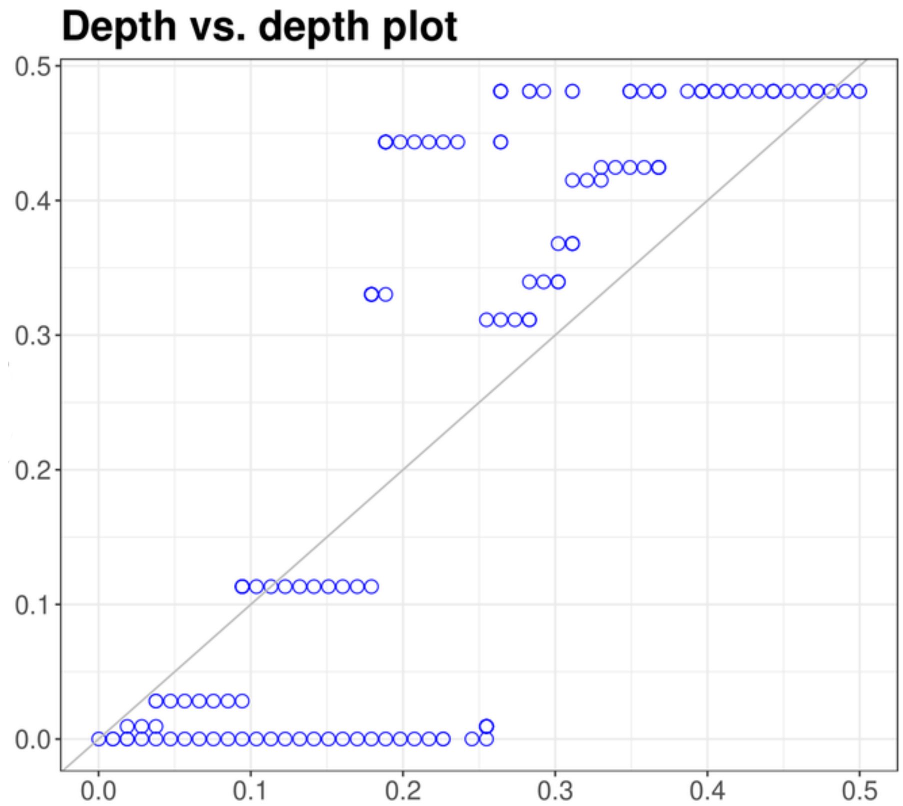
Orbit information

- **Purpose**, with 31 levels: Communications, Earth Observation, Space Observation,Technology Development, etc.
- **Users**, with 20 levels: Commercial, Civil, Military, Government, etc.
- **Country/Organization of UN Registry**

Mission information

The current models are not accurate

DDplot to assess the significant difference between the effective lifetimes Y_1 and the declared expected lifetimes Y_2



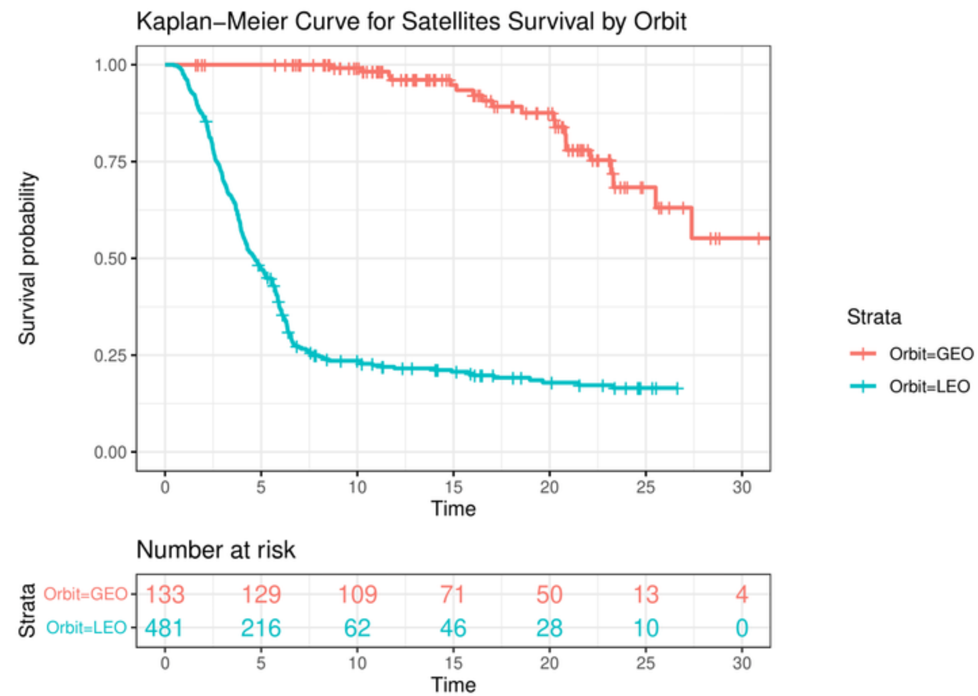
Result verified through **nonparametric paired test:**

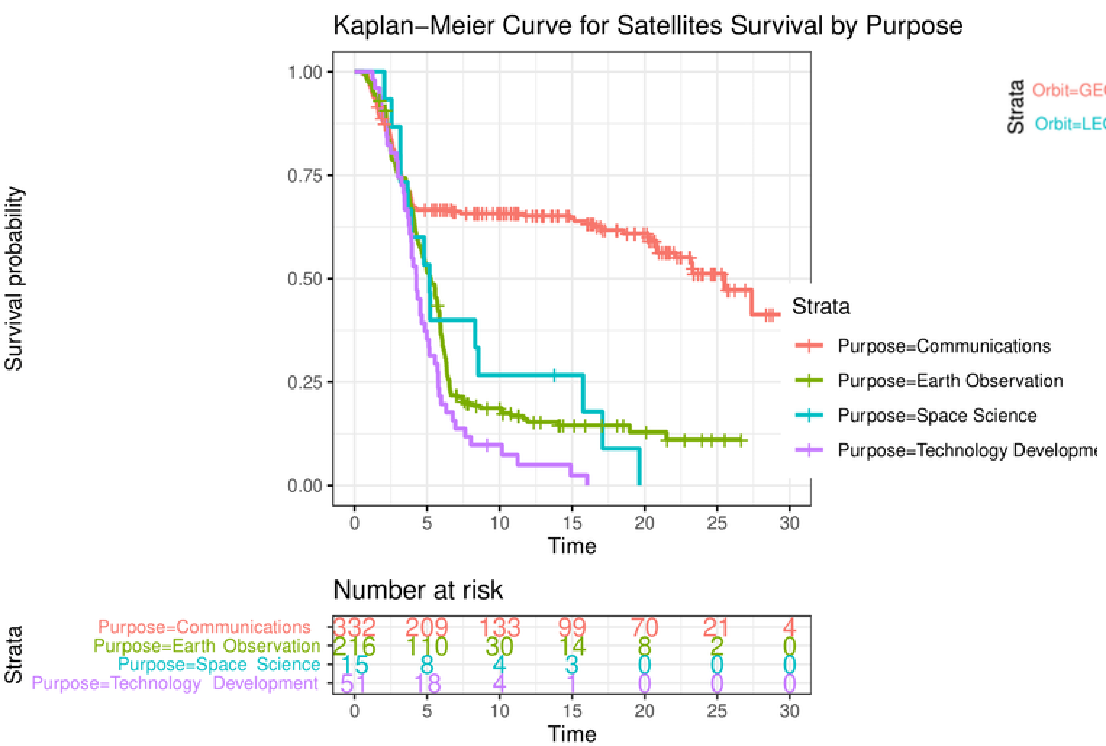
$$H_0 \ : \ Y_1 \stackrel{d}{=} Y_2 \ vs \ H_1 \ : \ Y_1 \stackrel{d}{\neq} Y_2$$

p-value: **0.037**

A step forward to the model

Survival curve estimates (**KM**) and **Log-Rank tests** highlight a significant difference in satellite lifetimes across the different groups.





The model

Stratified Cox model with respect to:

- Orbit
- Purpose

$$h_k(t|\mathbf{X}) = h_{0k}(t)\exp(\mathbf{X}^T\beta)$$

Variables considered in the model

Variable	**coef**
Apogee	-8.186e-03
log.Eccentricity	-1.727e-01
Mass	-1.385e-04
UsersCommercial	1.056e+00
UsersGovernment	-1.109e+00
UsersMilitary	8.191e-01
ContinentAsia	4.536e-01
ContinentEurope	6.647e-01

And the others? They are not significant.

	lwr	**pointwise**	**upr**
Perigee	-0.0018236728	0.0001098872	0.0016278746
Inclination	-0.004559258	0.001302818	0.009182801
Period	-0.015217030	0.001295519	0.030945062

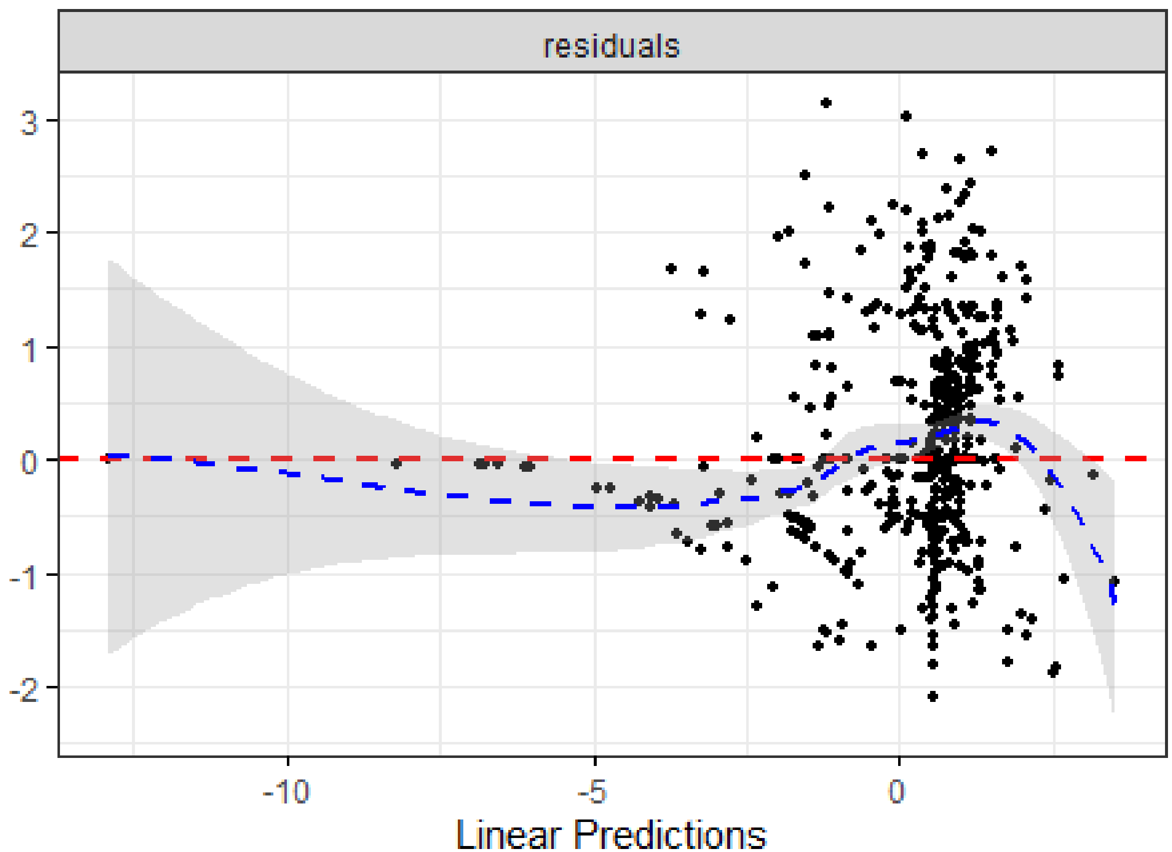
Reverse percentile intervals

Assumptions and goodness of fit

H0: Hazards are proportional vs H1: Hazards not proportional

Variabile	p
Apogee	0.075
log.Eccentricity	0.675
Mass	0.887
Users	0.330
Continent	0.386
GLOBAL	0.230

Deviance Residuals



Model selection

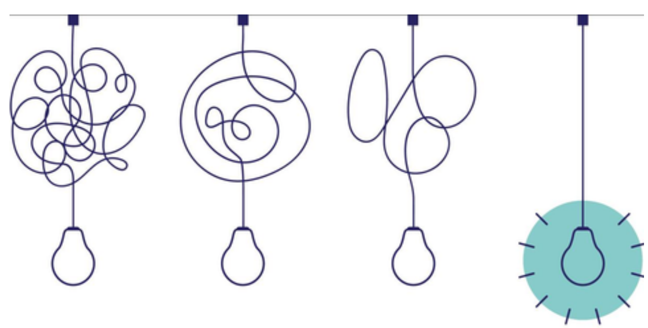
Our data are characterized by high collinearity. We tried to solve this problem by using:

- PCA and MCA
- Penalized Survival Analysis

Neither of the two methods has led to better results than those already achieved:

Model	AIC
Stratifed Cox model	2391.17
PCA + Cox model	3397.345
Penalized Cox model	2464.633

Following the Keep It Simple philosophy, we have opted for the final model previously presented.



The prediction

We found the predicted lifespan of the satellites using an R package called ***coxed*.**

The method chosen employs a **generalized additive model (GAM)** to map the model's estimated linear predictor values to duration times:

1. It computes expected values of risk for each observation through the estimated coefficients from the Cox model, creating the **exponentiated linear predictor (ELP).**

2. The observations are ranked from smallest to largest according to their values of the ELP

3. It uses a **cubic regression spline** to model the observed durations as a function of the linear predictor ranks generated.

Satellite Name	Predicted lifetime	Effective Lifetime	Expected lifetime
Starlink-2216	3.338002	2.48	4
SpaceBEE-NZ1	3.061470	2.57	2
Iridium Next 123	7.837608	6.40	15

Is our model better than the existing one? (1)

We wanted to ensure that **our model markedly deviates from the existing ones** utilized by space agencies, by a **Paired Permutation Test**

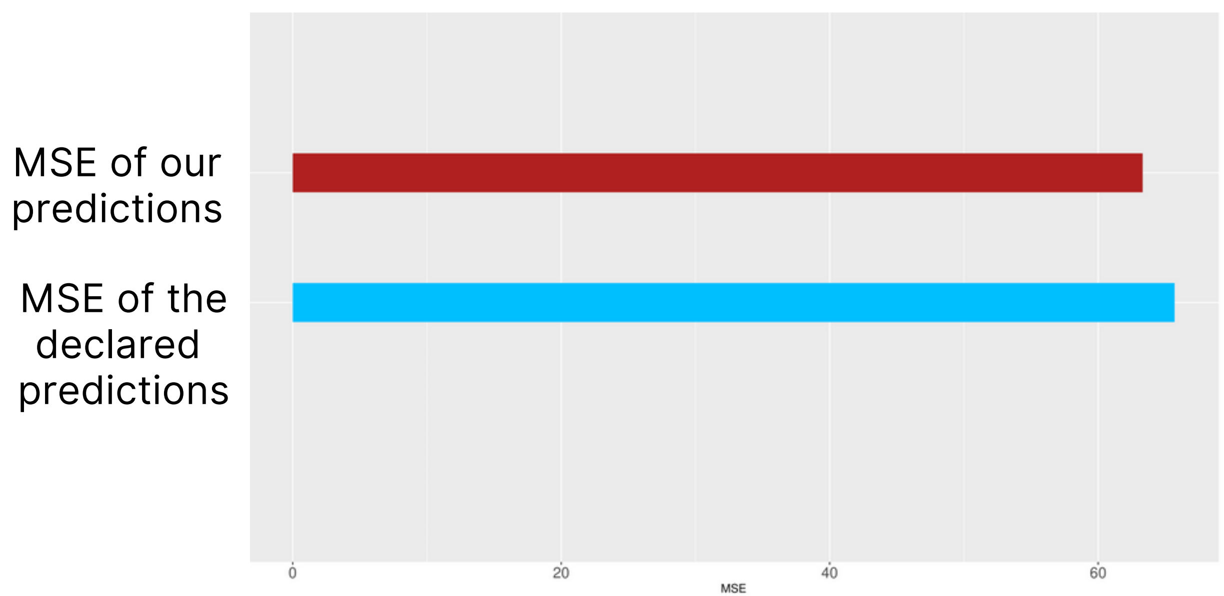
$$(Y_{i1}, Y_{i2}) \overset{iid}{\sim} (Y_1, Y_2),\ i = 1, \dots, n_{ret} \qquad H_0 : Y_1 \overset{d}{=} Y_2 \text{ vs. } H_1 : Y_1 \overset{d}{\neq} Y_2.$$

$\mathbf{Y}_1$ is the random variable that denotes the predicted lifetime's observation

$\mathbf{Y}_2$ is the random variable that denotes the expected lifetime's observation

The **p-value** of the test is **zero** → The two models are **significantly different**, but **is our model better?**

Mean Square Error with respect to the effective lifetime of retired satellites



Is our model better than the existing one? (2)

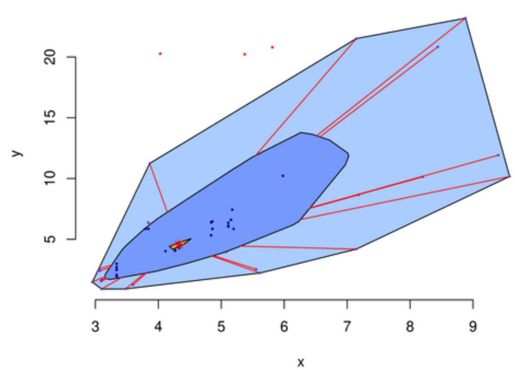
How many outliers does our model produce? And their?

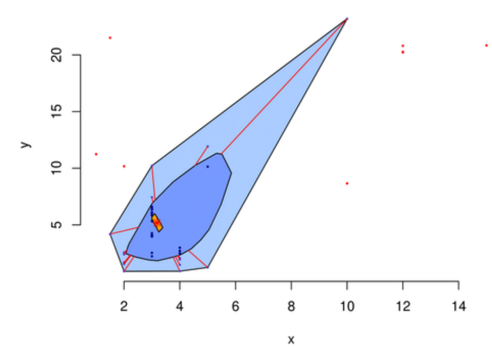
Considering these two different datasets with retired satellites:

Dataset 1		Dataset 2	
Lifetime **predicted** by **our model**	**Actual lifetime**	**Expected** lifetime	**Actual lifetime**

3 outliers (Dataset 1)

8 outliers (Dataset 2)





Americas: where our business starts

MOTIVATION

It’s crucial for us to promote ourselves effectively and focus our resources to the most promising markets for our business.

QUESTION

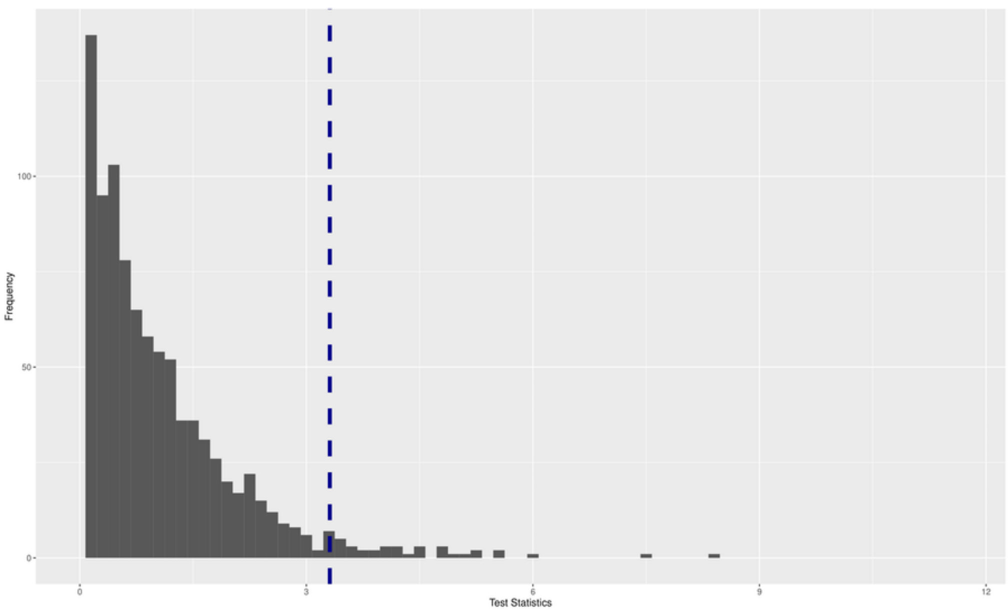
Is the continent a suitable criterion for choosing the market where to start our business?

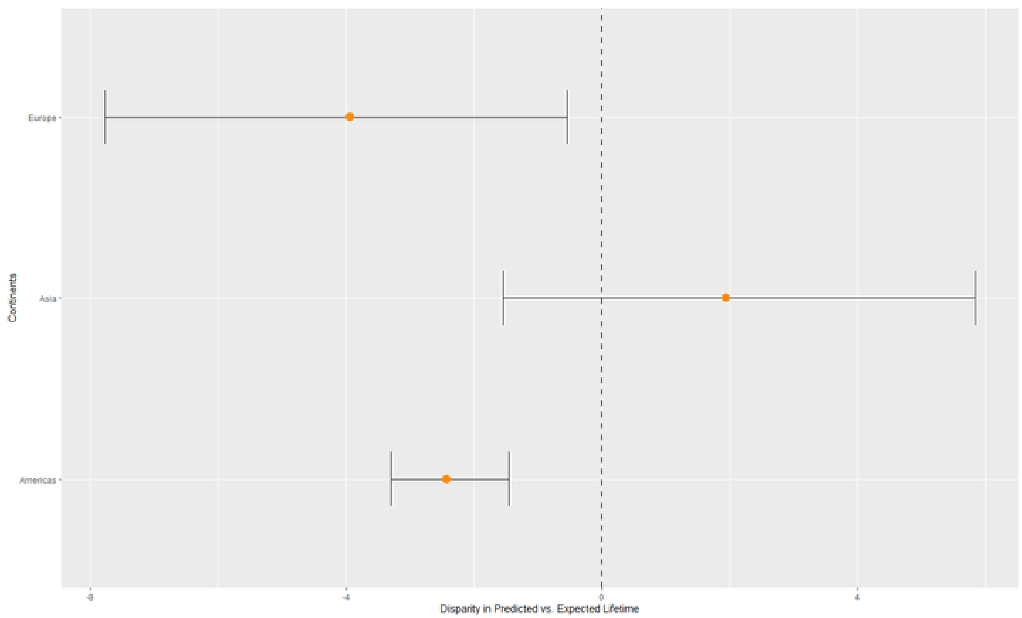
PERMUTATIONAL ONE-WAY ANOVA

$$Predicted_{ij} - Expected_{ij} = \mu + continent.effect_i + \epsilon_{ij}; \quad i = 1, \ldots, g; \; j = 1, \ldots, n_i$$

$$H_0: \; continent.effect_i = 0 \; \forall i \quad vs \quad \exists i \; s.t. \; continent.effect_i \neq 0$$

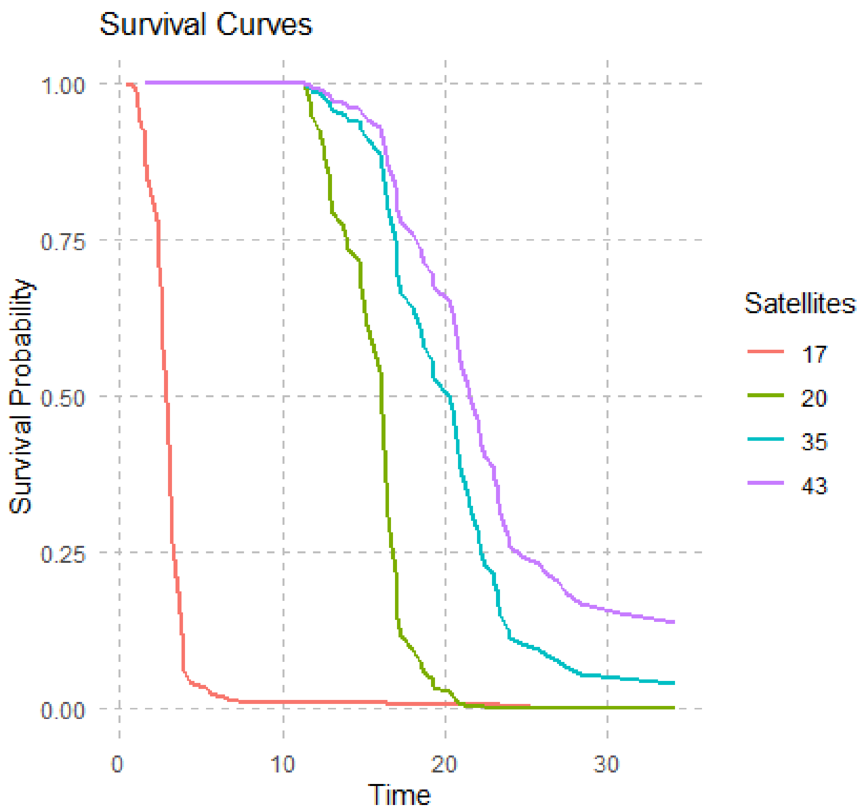
p-value =0. 039

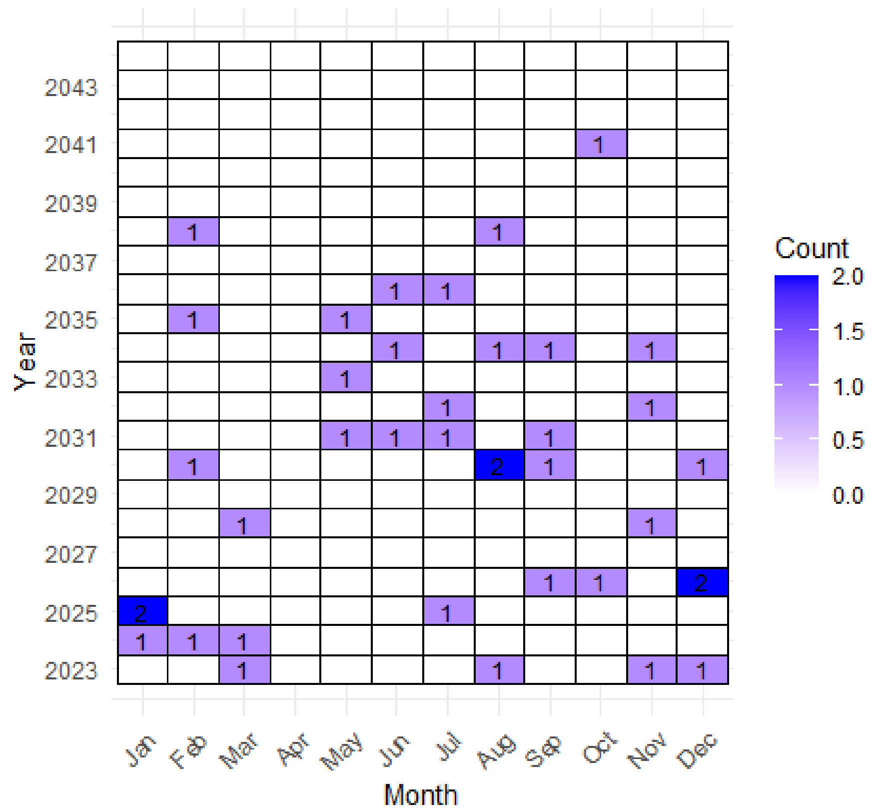




When to perform maintenance

We computed the **0.1 quantile** of each survival curve and the **expected date for maintenance**, obtained by adding the quantile to the launch date.



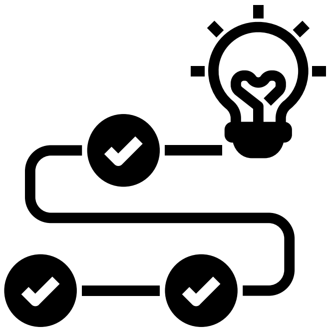


Conclusions

- Our model provides a **more accurate estimation** of satellite lifespan, ensuring fewer losses

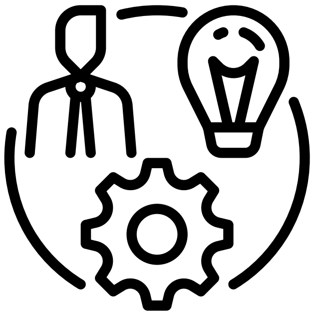
- Our strategic focus on the **American market**, which holds the most promise for our business, has allowed us to maximize the impact of our solution

- We set a conservative critical survival threshold for satellites, providing a **robust strategy for maintenance** scheduling



Further developments

- Analyzing in detail the reason of decommissioned to propose a more precise schedule based on the type of failure
- Deeper investigation of the **most profitable sector** for our buisness
- Incorporating a **‘Maintenance’ variable**, allowing for a second maintenance date and further refinement of the model



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