SURVIVAL ANALYSIS FOR SATELLITES LIFETIME PREDICTION TO SUPPORT SPACE TRAFFIC MANAGEMENT

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Dataset Description

Data come from UCS Satellite Database, which contains **6718 satellites** and **13** covariates:

Technical information

- **Satellite Name**
- **Launch Mass**, in kilograms
- **Date of Launch,** from 29/09/1988 to 21/10/2022
- **Expected Lifetime,** in years

Orbit information

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

Mission information

- **Purpose**, with 4 levels: Communications, Earth Observation, Space Science, Technology Development
- **Users**, with 4 levels: Civil, Commercial, Government, Military
- **Country**, the country of satellite's operator

Dataset Extensions

In order to proceed with our analysis we extended our dataset with the following covariates:

'Status': retired or censored.

'Final Date':
- the disposal date, if the satellite is retired.
- the censored date, set at November 17, 2023, if the satellite is still active.

'Effective lifetime': the difference between the final date and the launch date, in years.

'Continent': grouping the countries in continents.

Then, after an analysis of the missing values, we obtained a final dataset with **714 satellites and 13 covariates**.

Goals

To support **Space Traffic Management** (**STM**), we want to determine the factors that influence the lifespan of a satellite.

Survival analysis

We aim to investigate differences in expected lifespans among continents and within specific fields, deviating from our model's projections. This inquiry is intended to guide the creation of focused policies and regulations.

Nonparametric tests

- Looking for differences in the distributions of the expected lifetime and the predicted lifetime
- Quantifying it through CI

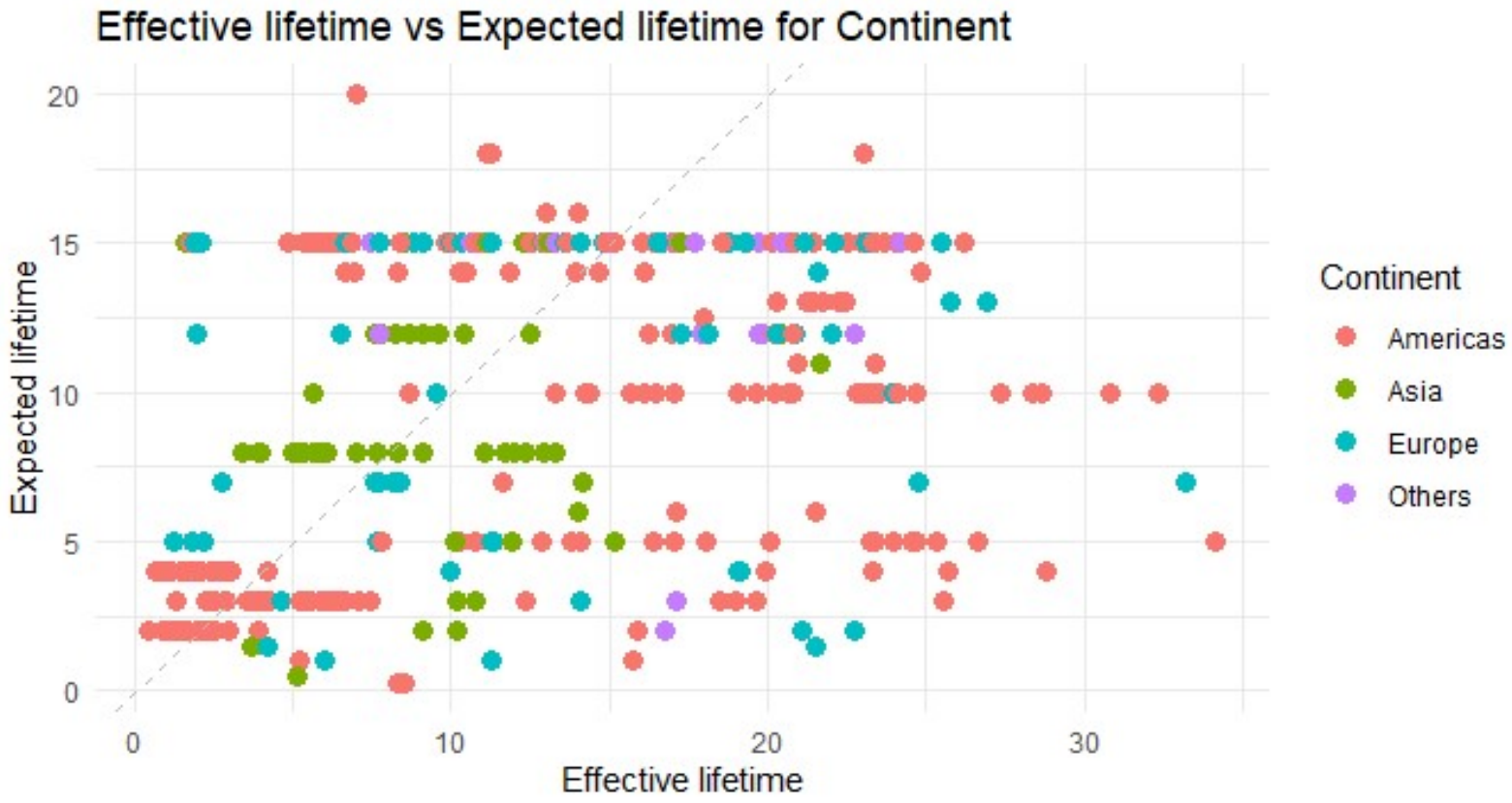
Anova

- Analysing the difference by continent, users and purpose

The reason why STM needs these analyses

Effective vs Expected lifetime (Continent)

Points above the dotted line are satellites that have exceeded their design life.

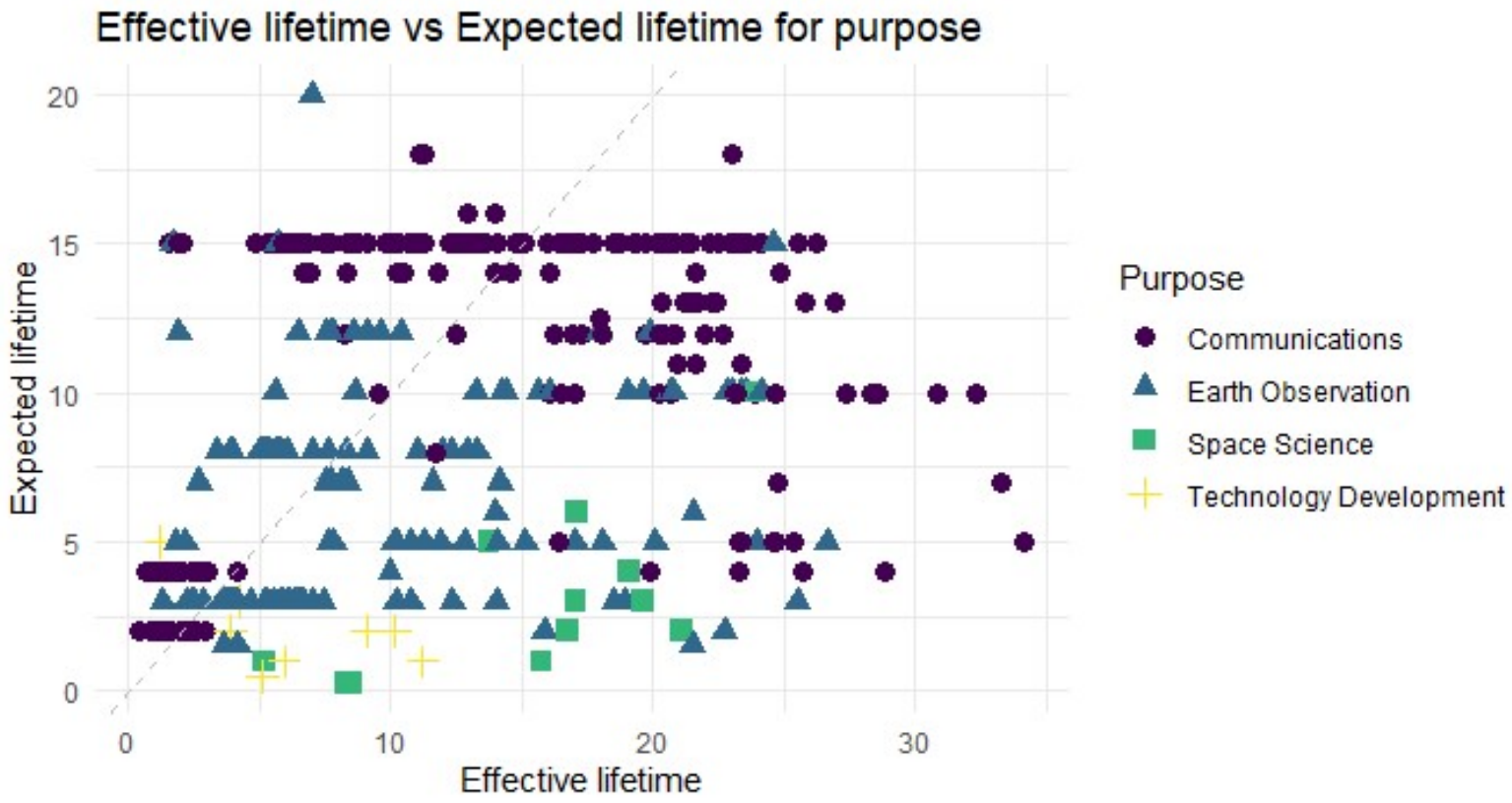


Asiatic satellites lifetime seems to be the closest one to the expected lifetime.

The reason why STM needs these analyses

Effective vs Expected lifetime (Purpose)

Points above the dotted line are satellites that have exceeded their design life.



Space Science and Technology Development satellites lifetime in general have much longer actual lives than planned.

Exploratory Analysis

PERMUTATIONAL TWO-WAYS ANOVA

Is there a significant difference between groups?

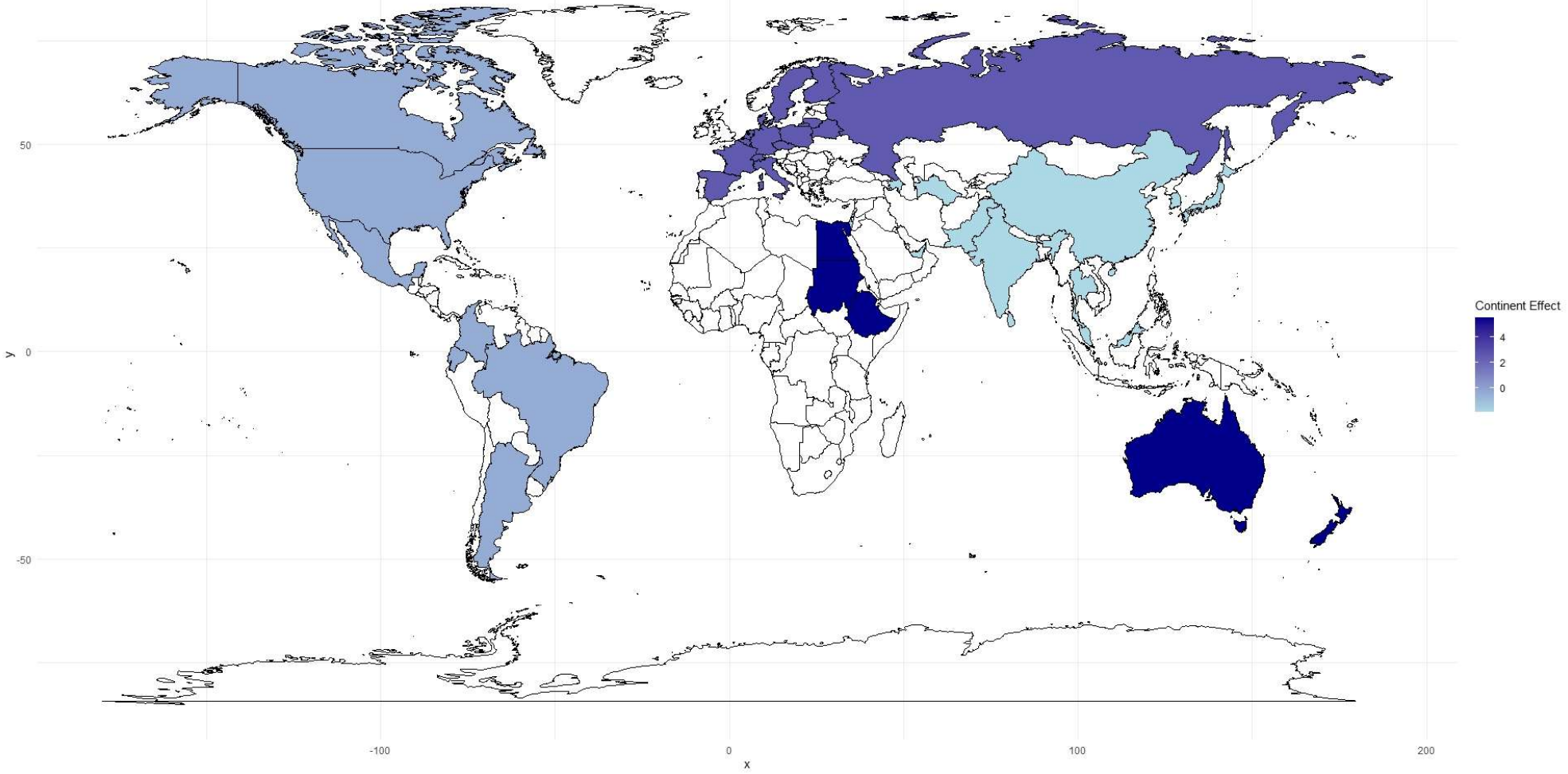
$$\text{Lifetime} = \mathbf{mean} + \mathbf{continent.effect}_i + \mathbf{purpose.effect}_j + \mathbf{interaction}_{ij} + \epsilon$$

Tests	p-value
$H_0: interaction_{ij} = 0 \ \ vs \ \ H_1: \exists \, interaction_{ij} \neq 0$	0.163
$H_0: purpose.effect_j = 0 \ \ vs \ \ H_1: \exists \, purpose.effect_j \neq 0$	0
$H_0: continent_i = 0 \ \ vs \ \ H_1: \exists \, continent_i \neq 0$	0

Exploratory Analysis

CONTINENT EFFECT

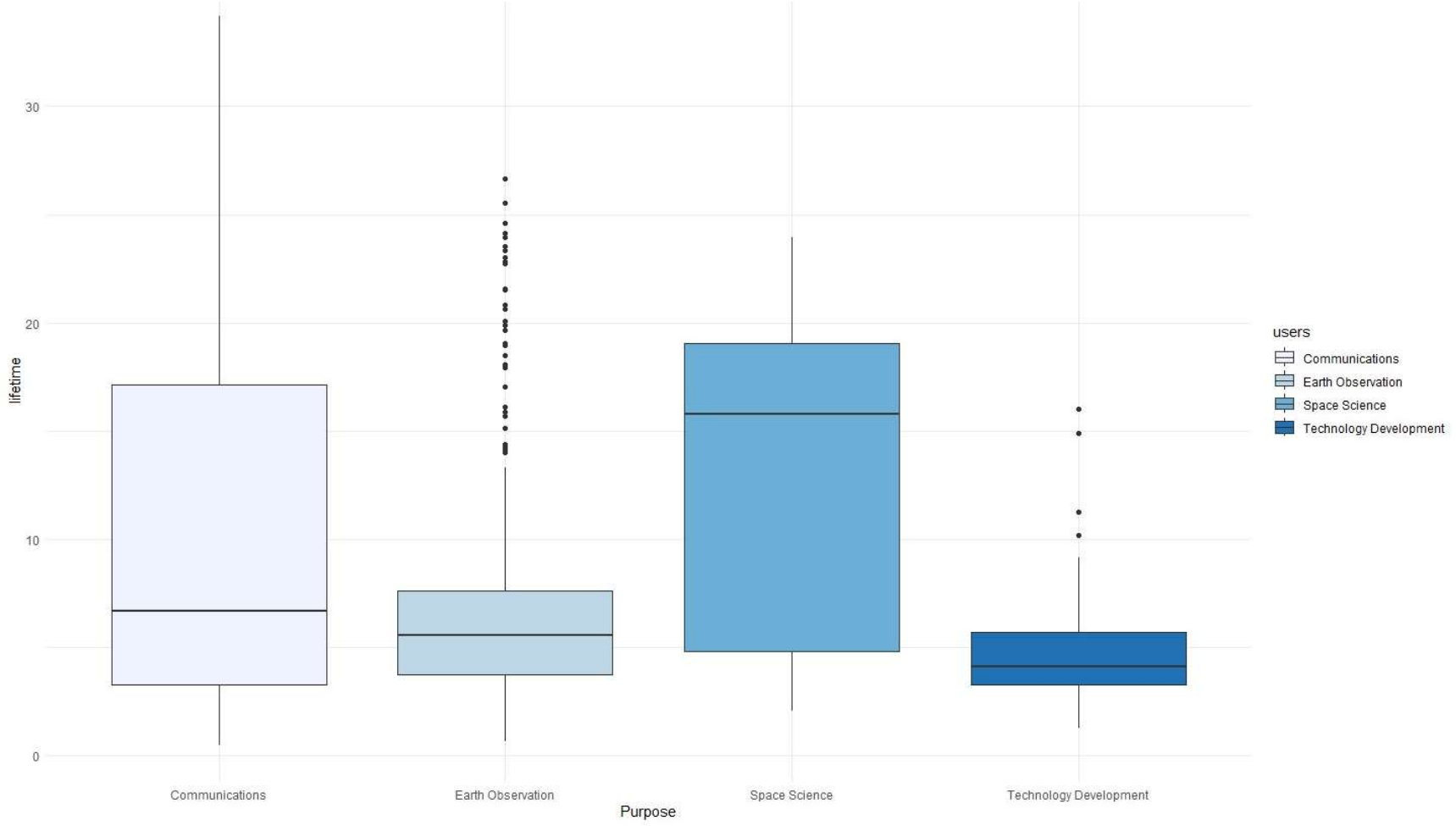
$$H_0: continent.effect_i = 0 \; vs \; \exists \; continent.effect_i \neq 0$$



Exploratory Analysis

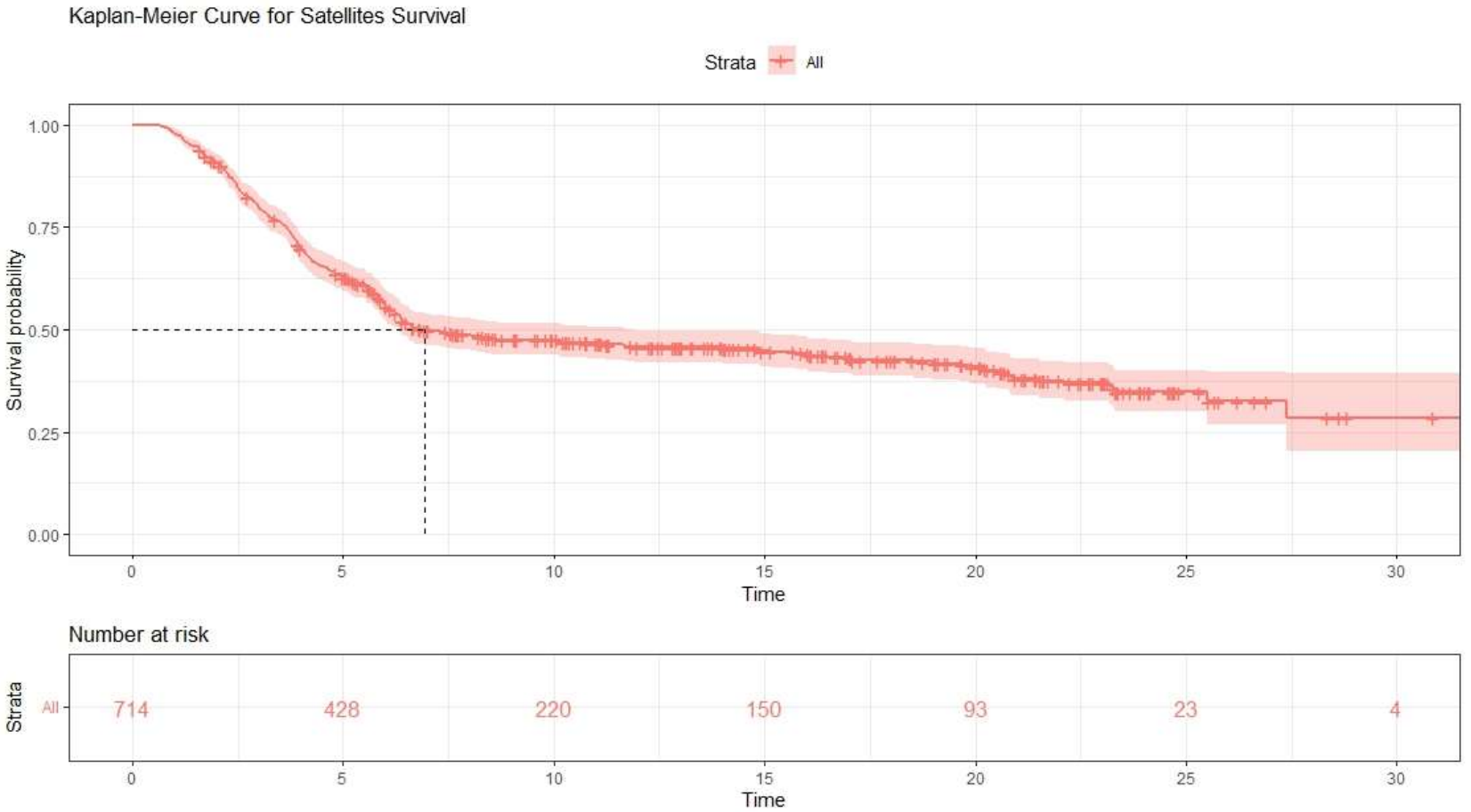
PURPOSE EFFECT

$$H_0: purpose.effect_j = 0 \; vs \; H_1: \exists \, purpose.effect_j \neq 0$$



Survival Analysis (Kaplan-Meier Estimator)

$$\hat{S}(t) = \prod_{j:t_j^* \leq t} p_j = \prod_{j:t_j^* \leq t} \left(1 - \frac{d_j}{n_j}\right)$$

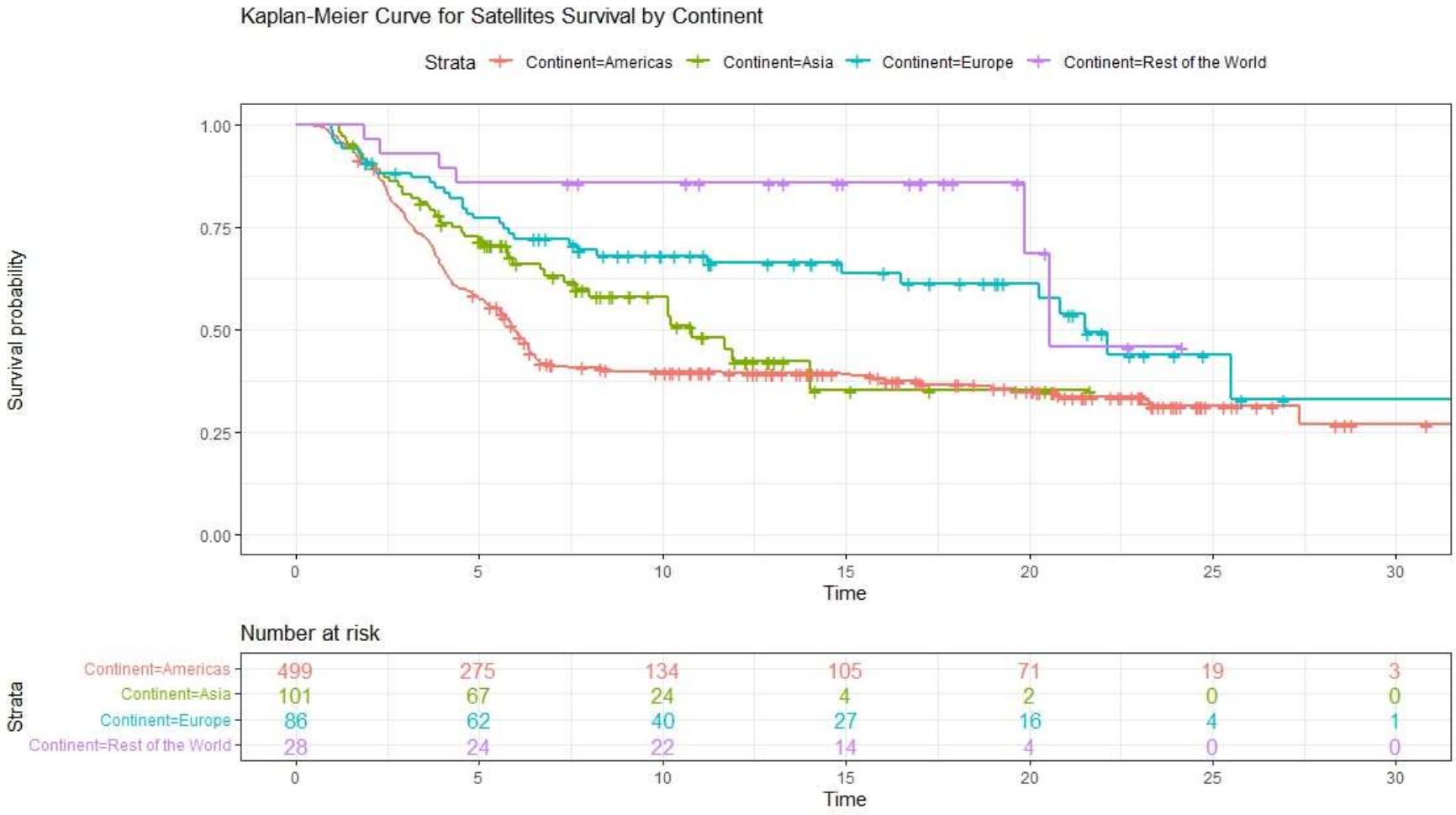


The median survival is equal to 6.32 years

Survival Analysis (Log-Rank Tests)

Examining differences in survival curves across distinct groups.
All the tests are characterized by a p-value lower than 2e-16.

$$H_0 : S_1(t) = S_2(t) = S_3(t) = S_4(t) \text{ vs. } H_1 : H_0^c$$



Survival Analysis (Cox Model)

We came up with the following Stratified Cox-PH model:

$$h_k(t|\mathbf{X}) = h_{0k}(t)\exp\left\{\beta_0 \cdot \text{Period}_{\text{Long}} + \beta_1 \cdot \text{Continent}_j\right\},$$

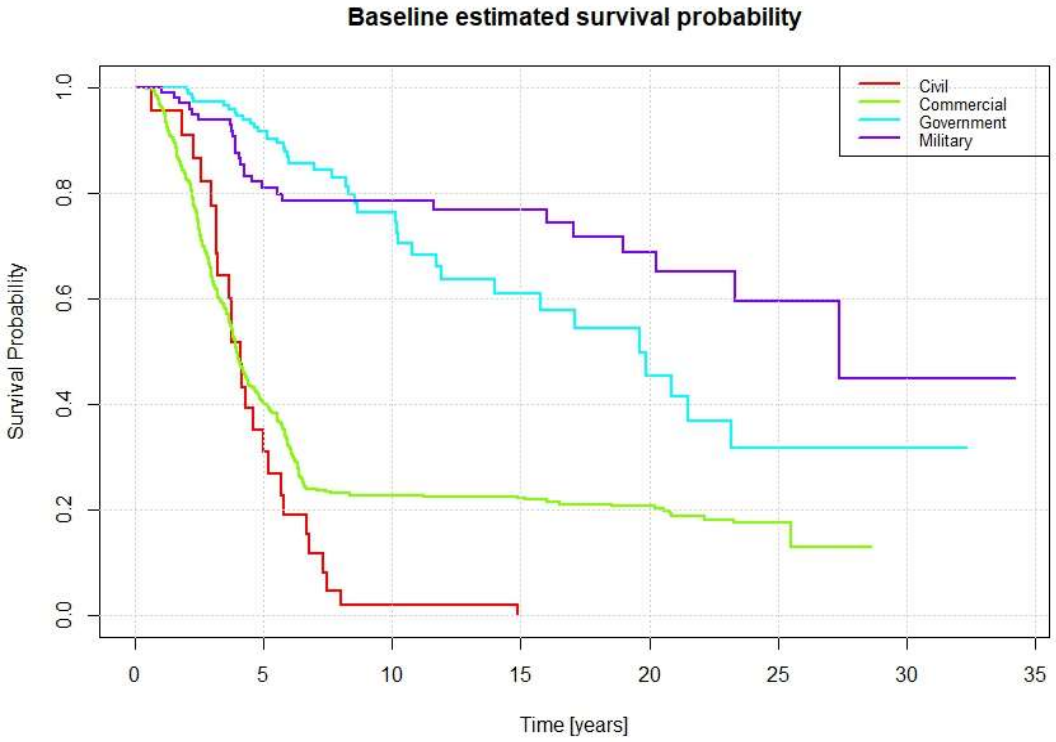
$$j = \text{Europe, Others,}$$

$$k = \text{Civil, Commercial, Government, Military}$$

$$\beta_0 = -0.1993$$

$$\beta_{1_{\text{Europe}}} = -0.6859$$

$$\beta_{1_{\text{Others}}} = -1.4622$$



H_0 :Hazards are proportional

vs.

H_1 :Hazards are not proportional

	chisq	df	p
Per.disc	0.33611	1	0.56
Continent_Europe	0.20466	1	0.65
Continent_Others	0.00507	1	0.94
GLOBAL	0.55974	3	0.91

What's next

1. Improving the model through a **penalised** approach or **Accelerated Failure Time** models

2. A **paired univariate permutation test and confidence intervals** to compare the expected lifetime and the predicted lifetime distributions

3. Performing a **permutational anova** on the difference between the expected and the predicted lifetimes

References

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  From https://www.ucsusa.org/resources/satellite-database

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- Tay K., Simon N., Friedman J., Hastie T., Tibshirani R., Narasimhan B. **Regularized Cox Regression** (2023).
  From https://glmnet.stanford.edu/articles/Coxnet.html