AsaPy: A Python Library for Aerospace Simulation Analysis

Joao P. A. Dantas – Capt.

Decision Support Systems Subdivision

Institute for Advanced Studies

Brazilian Air Force

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Introduction

Simulation technologies in aerospace have expanded in commercial aviation, space exploration, and the military

The shift from live exercises to simulation is driven by cost reduction and increased safety

Simulation is used for designing, testing, and optimizing systems like aircraft, radars, and weapons

The vast amount of aerospace simulation data can be challenging, requiring well-designed algorithms and tools

AsaPy, a custom Python library, was created to simplify the analysis of aerospace simulation data, supporting decision-making

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Introduction

AsaPy integrates established techniques into a unified toolkit for aerospace data analysis

Offers a pipeline of routines, including pre-post-checks for specific analyses

Accessible to those not proficient in programming, enabling robust aerospace data analysis

Features include experimental design methods, statistical analysis, machine learning algorithms, and data visualization tools

Integrates scientific computing libraries like NumPy, SciPy, and Scikit-learn for high performance and scalability

Main Contributions

Review some of the available simulation software regarding data analysis

Present AsaPy's structure, effectiveness, and potential applications

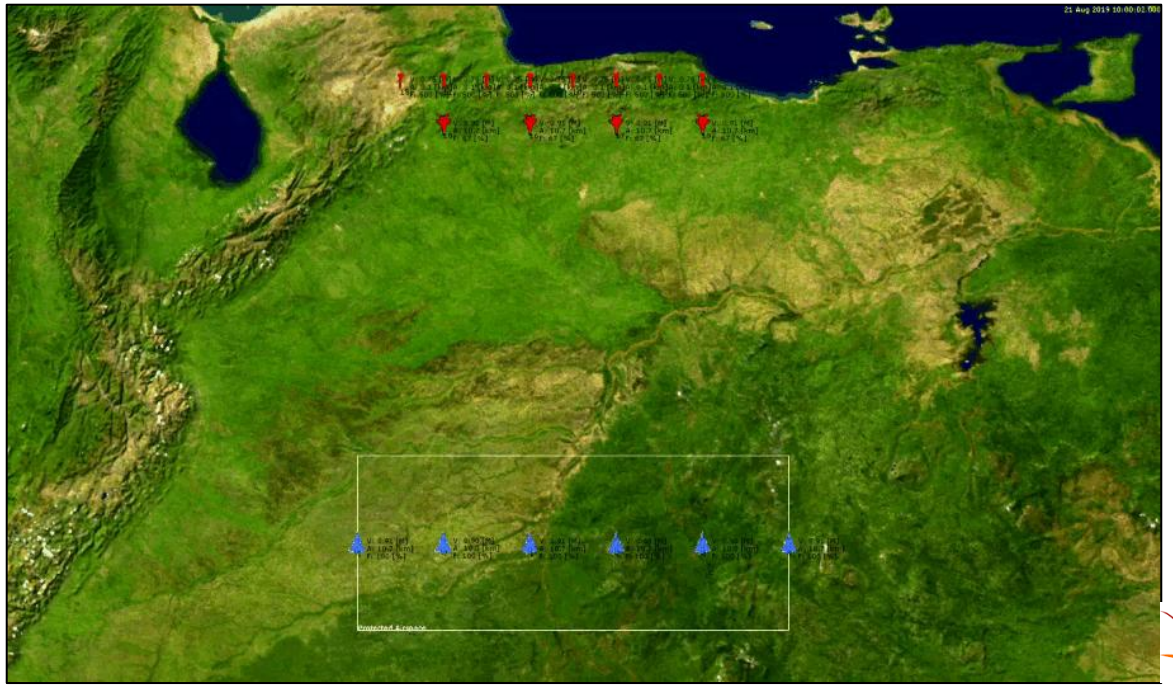
Introduce some use cases applied to the air combat domain

The authors did not find other library in the scientific community that serves the same purpose as AsaPy

Related Work

We focused on evaluating existing Computer-Generated Forces (CGF) tools with respect to their data science features

Computer-generated forces are autonomous, computer-controlled entities used to model human actors in many simulation-based training and decision support tools



FLAMES® Simulation Framework

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Related Work

Abdellaoui et al. (2009) analyzed and compared various modeling and simulation packages

- They analyzed architecture, autonomous operation, learning, organization, and realism, focusing on AI capabilities
- They briefly mentioned data science, only referencing entity databases without discussing data analysis of simulation results

Toubman et al. (2015) examined CGF learning capabilities

- They suggested using data for machine learning to extract behavior rules
- They did not address how Commercial Off-the-Shelf (COTS) and Goverment Off-the-Shelf (GOTS) products handle this approach
- Their study also did not discuss how to analyze simulation data for general conclusions

We surveyed publicly available information for COTS and GOTS products

Commercial Off-the-Shelf

Most simulation platforms go up to the stage of running the simulations and obtaining their raw data (providing a CSV file with the data)

Table 1: Mention of "Data Analysis" and "Design of Experiments" (DoE), on the websites of seven COTS CGF packages (in no particular order).

Product Name	Company Name	Mention of Data Analysis	Mention of DoE
STAGE	Presagis	No	No
VR-Forces	MAK Technologies	No	No
SWORD	MASA	No	No
VBS4	Bohemia Interactive	No	No
DirectCGF	Diginext	No	No
Steel Beasts Pro	eSim Games	No	No
FLAMES	Ternion	Yes	Yes

Goverment Off-the-Shelf

Besides these COTS products, a relevant GOTS package is the Advanced Framework for Simulation, Integration and Modeling (AFSIM)

AFSIM is an object-oriented C++ library for creating simulations in aerospace and defense contexts

It offers features for simulating and analyzing complex operational scenarios, including air-to-air combat, air-to-ground strikes, and reconnaissance missions

The Visual Environment for Scenario Preparation and Analysis (VESPA) supports creating scenario initial condition files compatible with AFSIM-based applications, enabling its use as a Design of Experiments tool

Aerospace Simulation Environment

AsaPy is developed for ASA, it is adaptable to other simulation frameworks.

Aerospace Simulation Environment – *Ambiente de Simulação Aeroespacial in Portuguese* (Dantas et al. 2022)

Custom-made in C++ for advanced programming flexibility

High-fidelity representation for accurate scenario reproduction

Supported by the Brazilian Air Force

Dedicated to modeling and simulation of military operational scenarios

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Related Work

In summary, all reviewed solutions lack an integrated approach with comprehensive data science tools

FLAMES and AFSIM are closest to what AsaPy aims to provide within the context of ASA

They still rely on third-party packages and focus on data recording and visualization rather than analysis

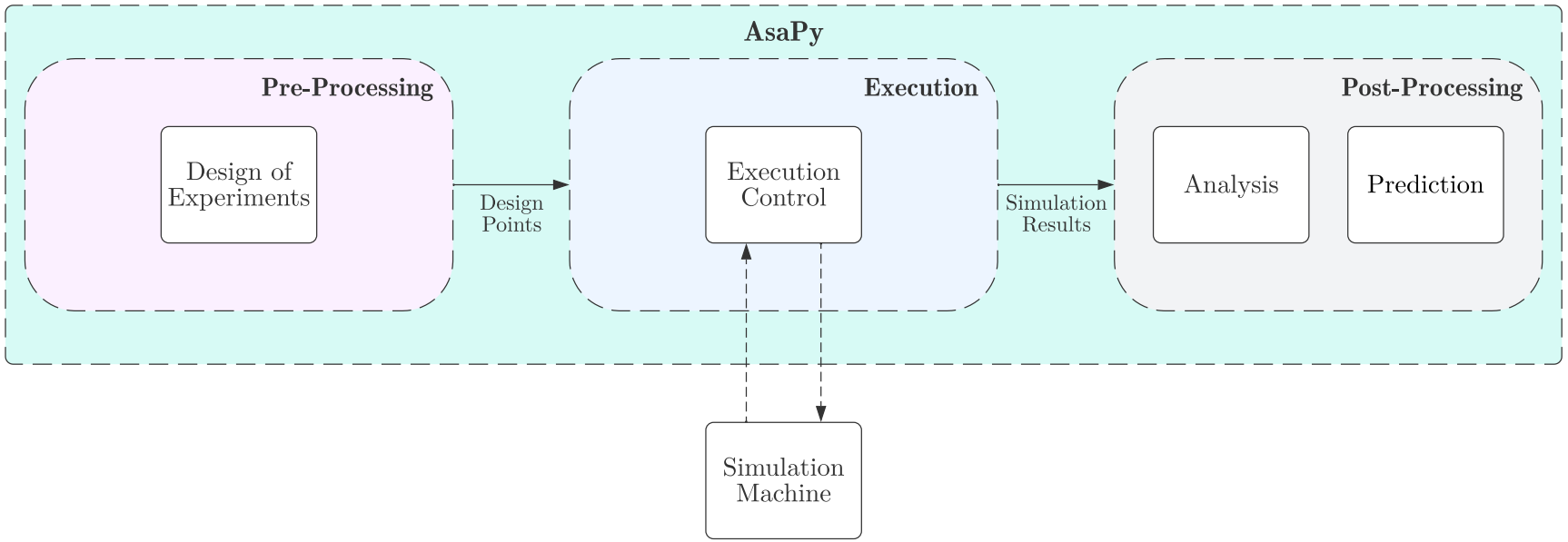
Structure

Design of Experiments: Define the input configuration for the executions

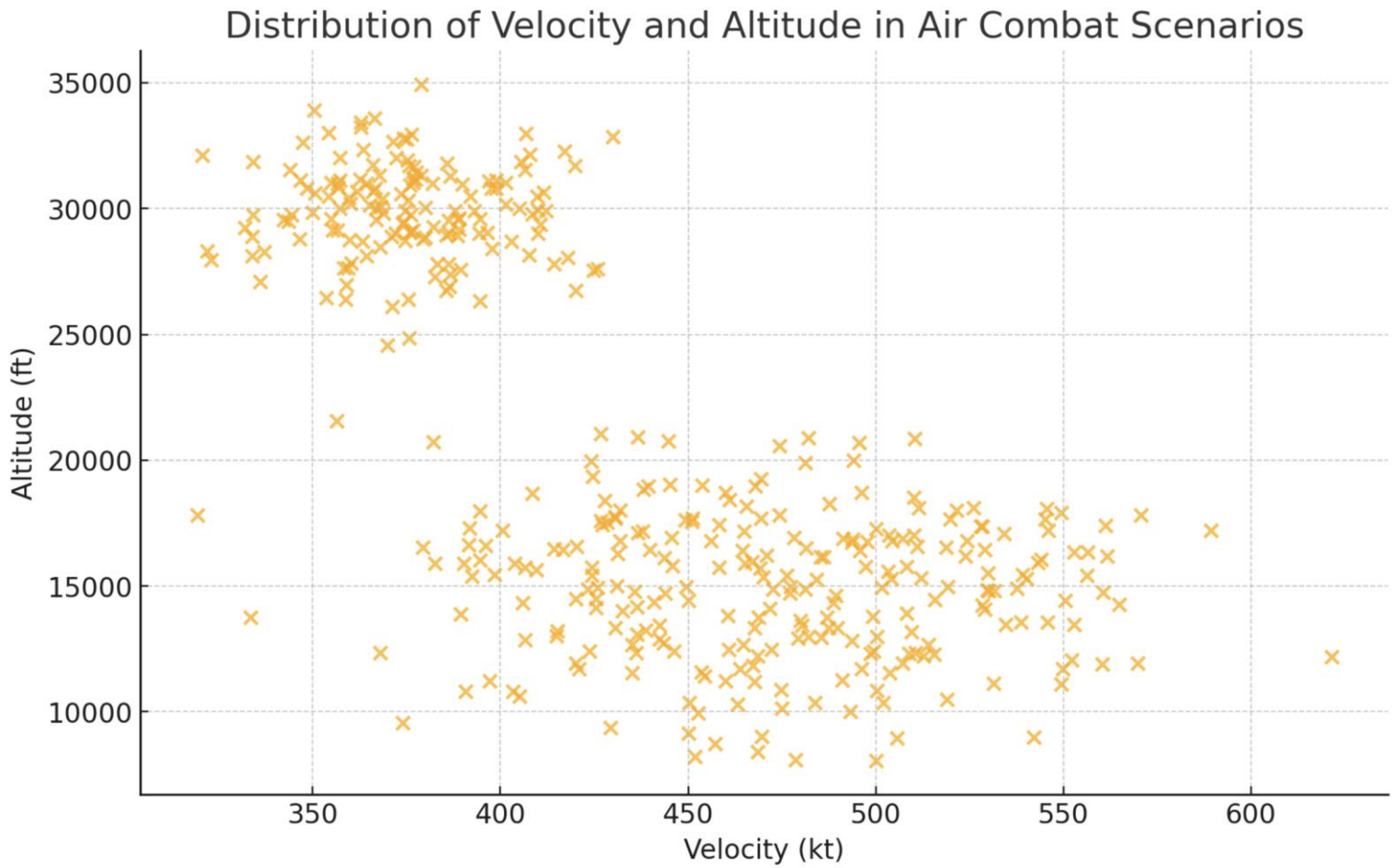
Execution Control: Monitor the progress of a batch of executions

Analysis: Conduct the actual data analysis

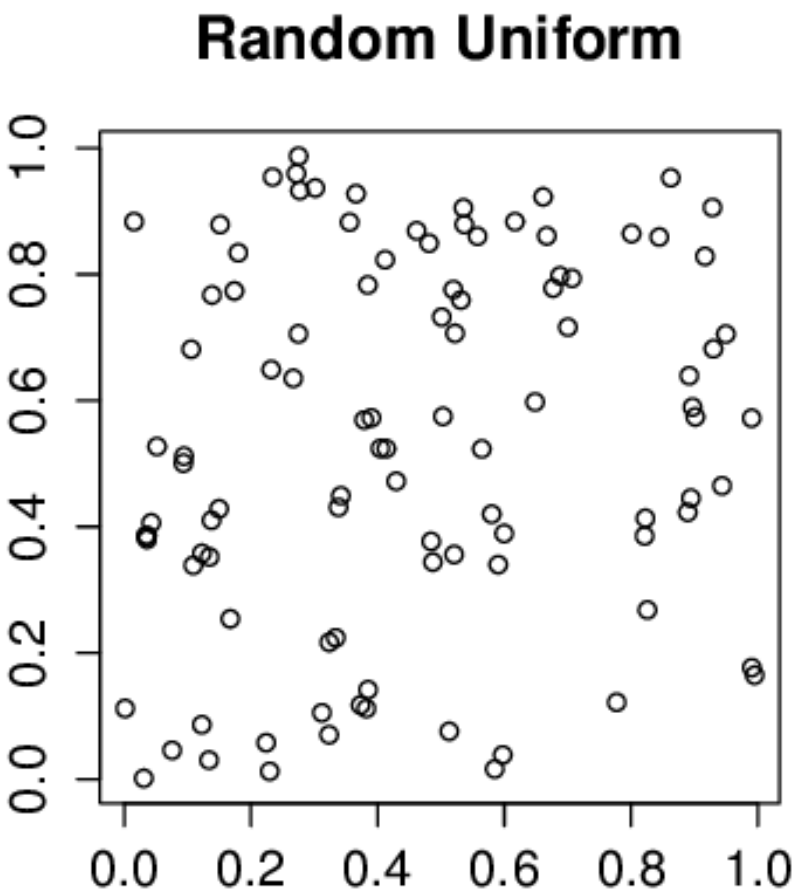
Prediction: Train a model to predict the outcome of new input configurations

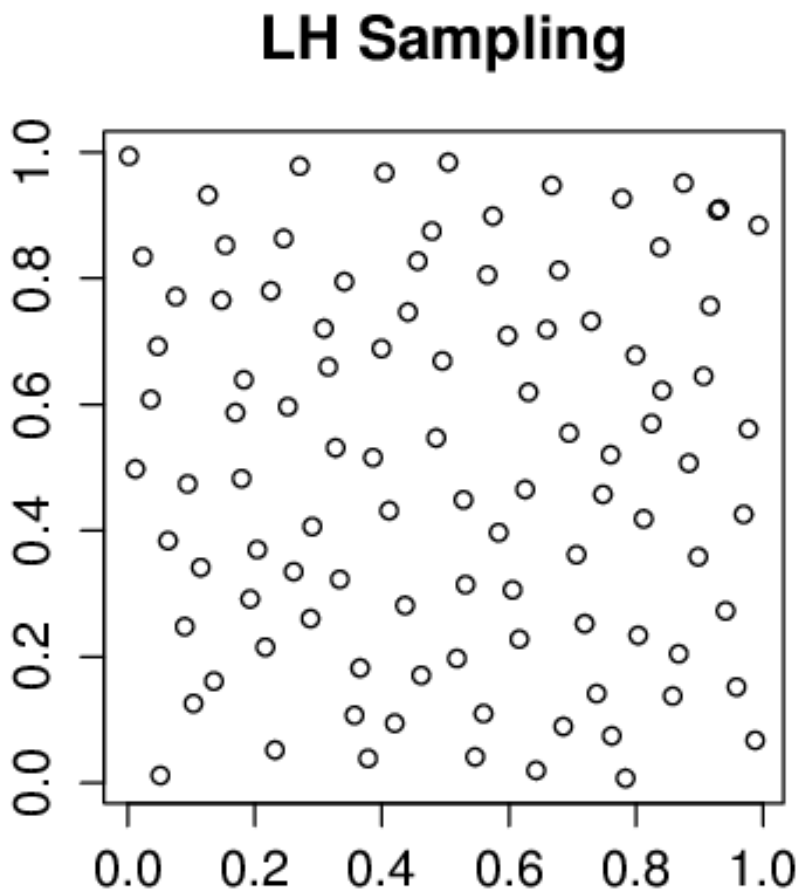


Design of Experiments



Design of Experiments





Design of Experiments

Currently, the module offers the Latin Hypercube Sampling (LHS) technique as its primary method

The module manages various data types, including numerical, categorical, and boolean

It generates input samples for diverse simulation executions, typically to run in batch mode with varying input parameters

Provides a pandas.DataFrame with parameters ready to be executed

	seed	agg_red	shot_phi_red	crank_trigger	break_trigger
0	990387867	0.52	long	0.72	1.22
1	433917215	0.30	medium	0.36	1.45
2	1676840561	0.73	long	0.90	1.50
3	80431878	0.33	medium	1.14	1.17
4	1418959451	0.10	medium	1.79	1.74
5	683630912	0.85	short	1.41	1.02
6	1242357077	0.93	short	1.91	1.92
7	1744194428	0.62	medium	1.55	1.33
8	2075010859	0.11	short	0.17	1.83
9	248247932	0.41	long	0.48	1.70

Execution Control

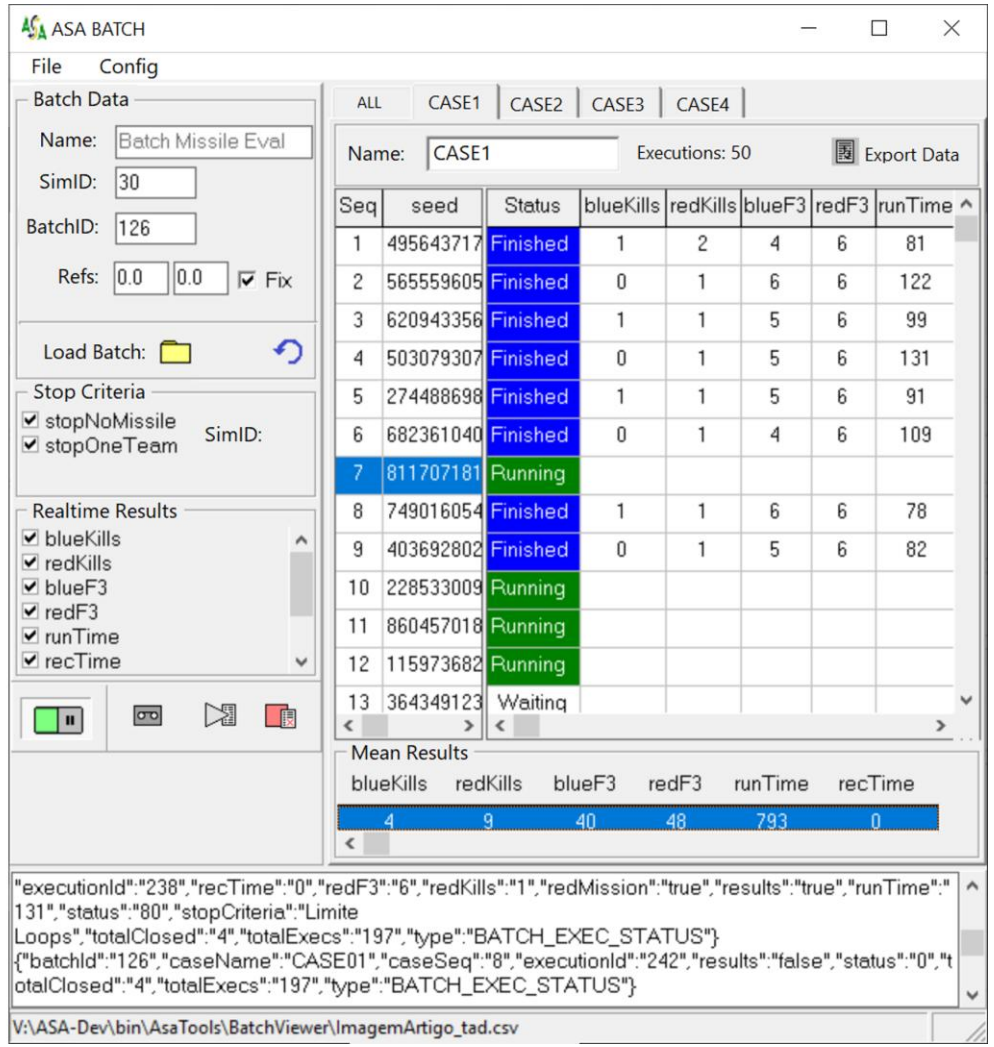
After creating scenarios and assigning input parameters, the next step is to run the experiments

This involves controlling executions by splitting runs into chunks and evaluating metrics to determine if early stopping is needed

Military analyses are often complex, requiring many runs to extract meaningful information

Runs are executed in batches to optimize computational resources

Not all planned executions may be necessary, which is only known during execution, so large batches are broken into chunks



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Execution Control

Each chunk is executed sequentially using all available computational resources

After each chunk, metrics are analyzed to decide whether to stop or continue

AsaPy implements a heuristic to observe the expected value variation of a key metric; if below a threshold, it assumes convergence

Evaluation metrics depend on simulation objectives; for defense, these might include remaining enemy aircraft and missiles expended

Early stop criteria are assessed across the batch; if many simulations meet criteria early, the whole batch can be terminated

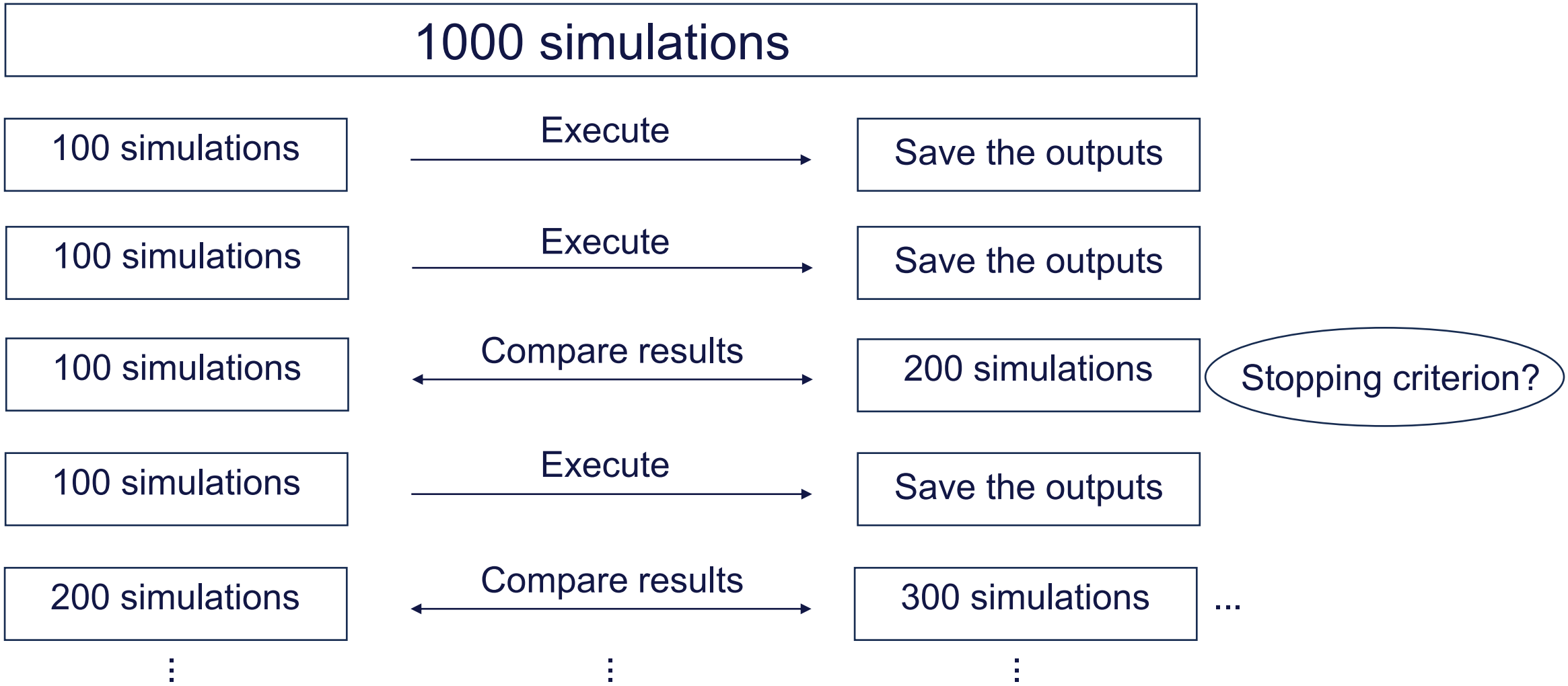
Listing 1: Usage example of the Execution Control module

```python
def simulate(doe: pandas.DataFrame) -> pandas.DataFrame:
    # 1. send execution requests using the Asa-client
    # 2. retrieve executions results
    return pandas.DataFrame.from_dict(asa_results)

def stop_check(result: pandas.DataFrame, last_result:
     pandas.DataFrame) -> bool:
    # compare results using Asapy or custom functions
    return compare_results(result, last_result)

ec = asapy.ExecutionController(simulate, stop_check, 100)
result = ec.run(doe)
```

Execution Control



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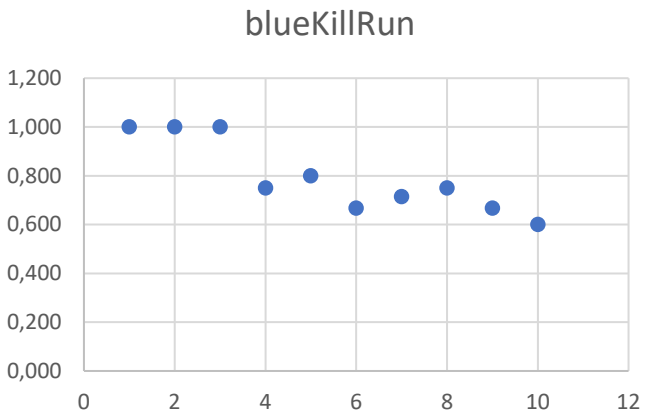

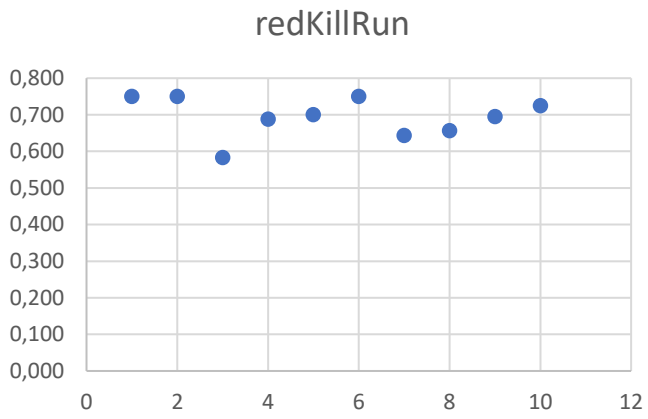

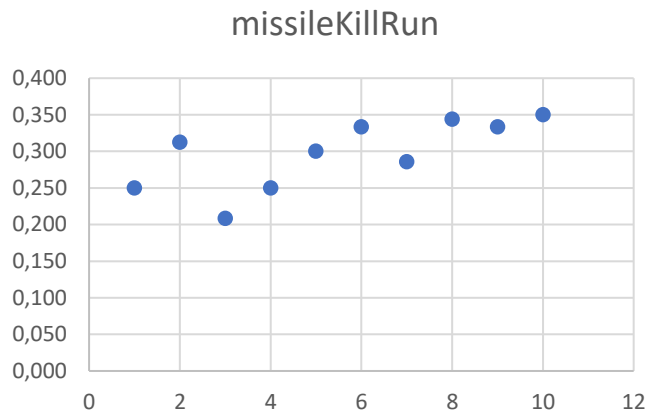

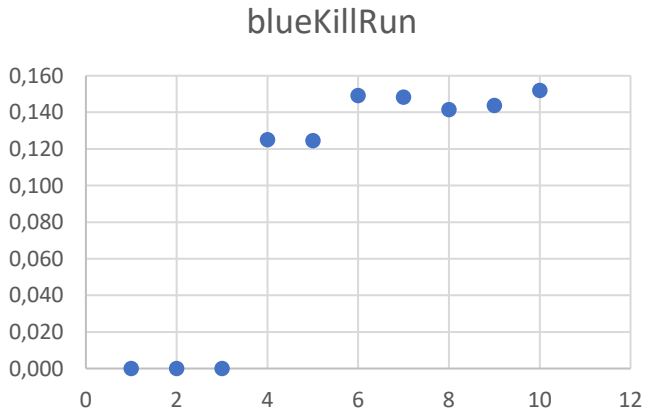

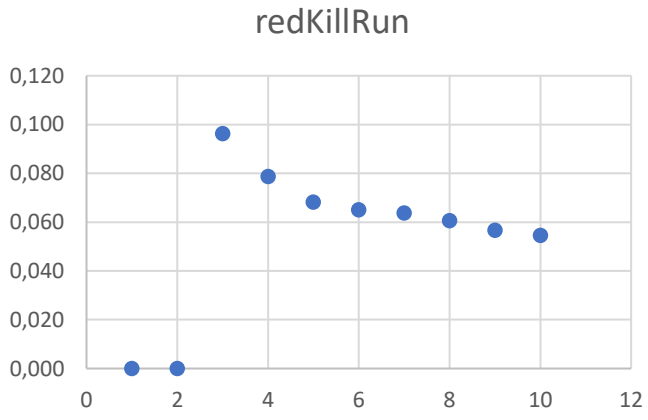

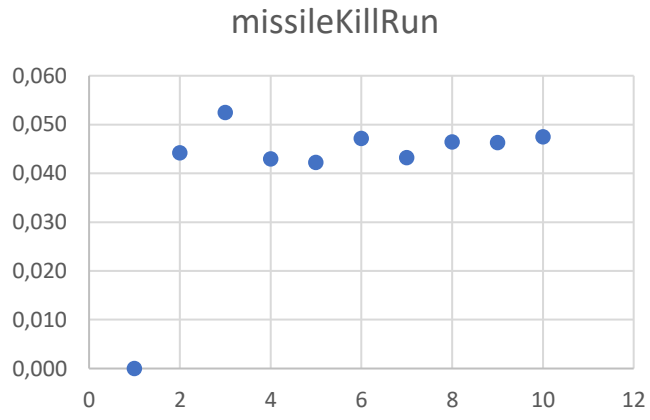

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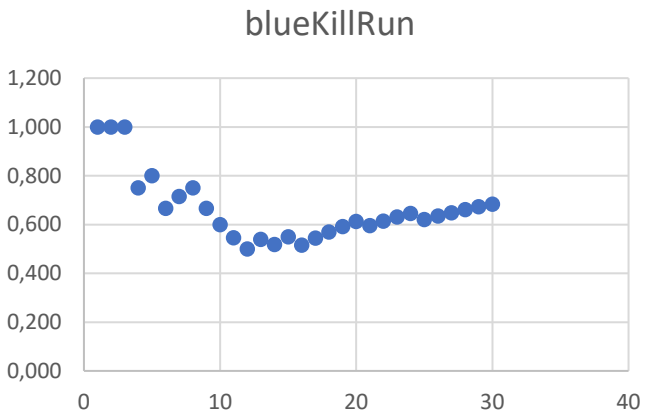

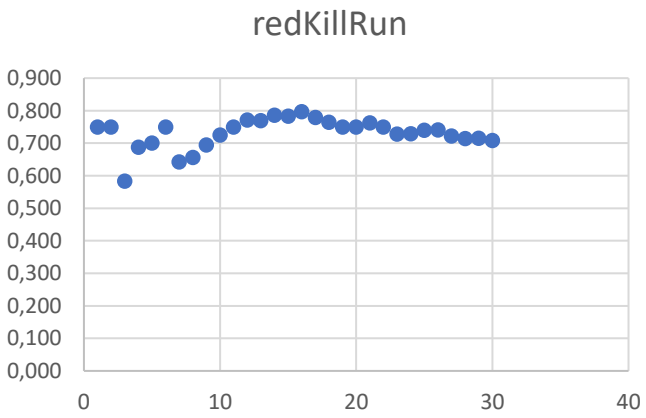

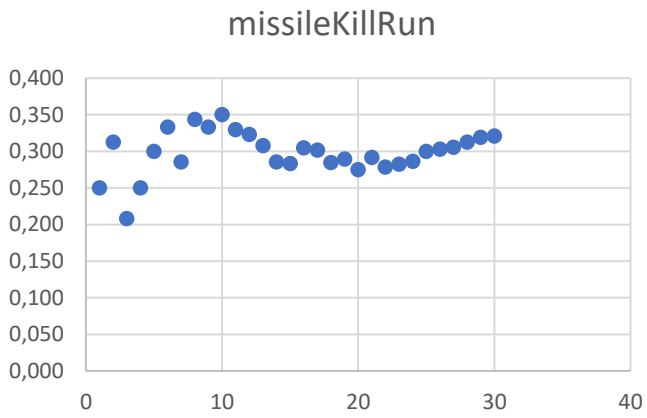

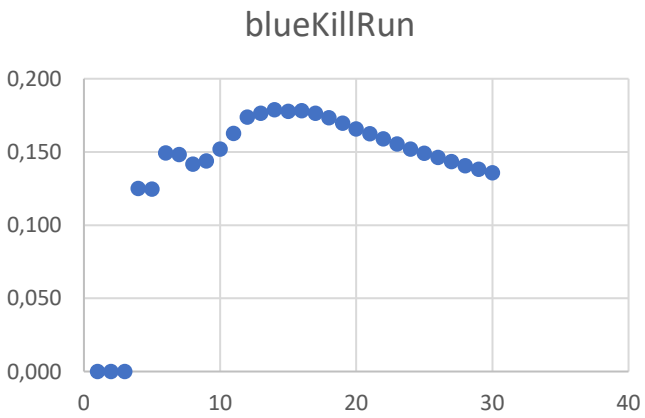

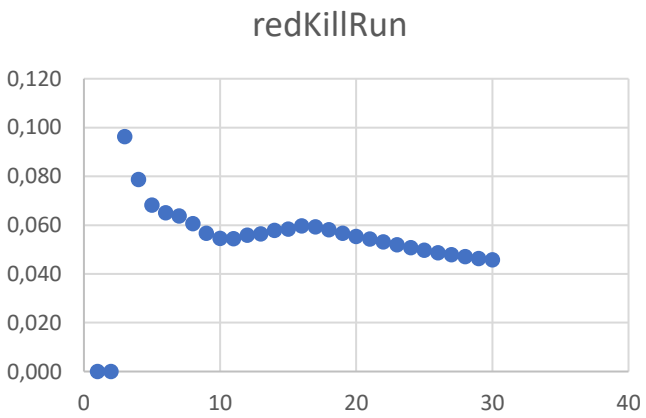

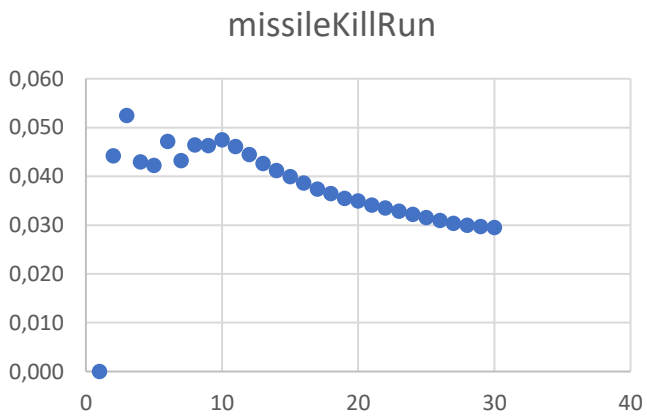

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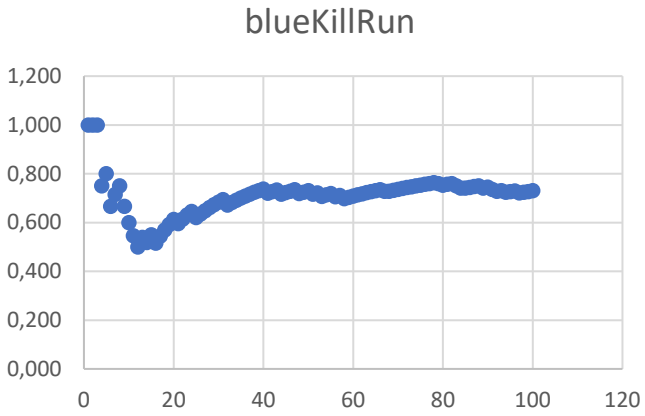

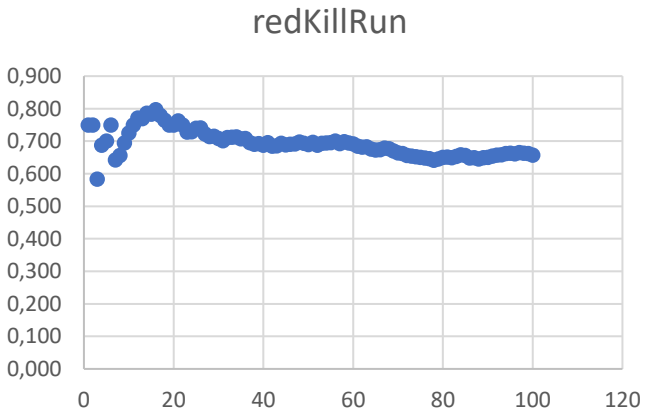

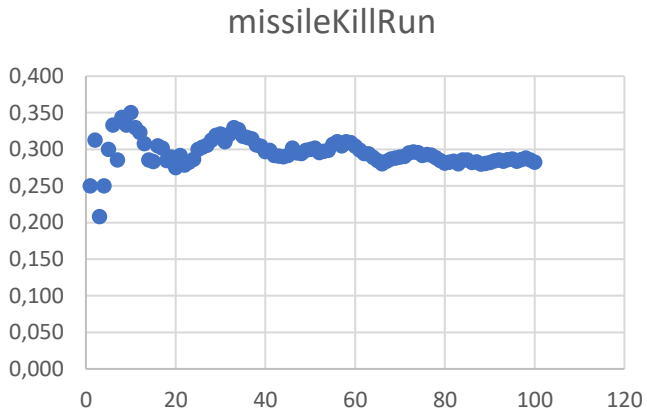

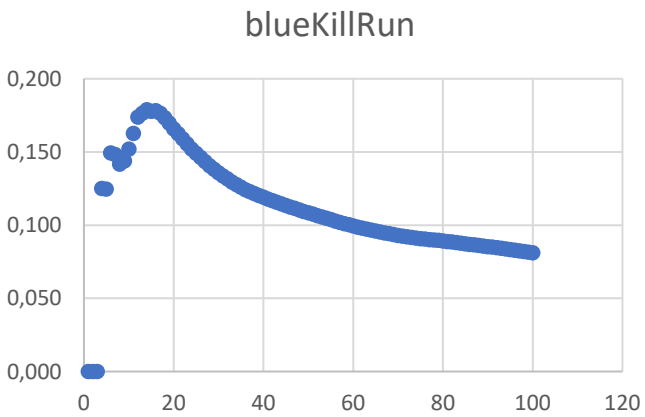

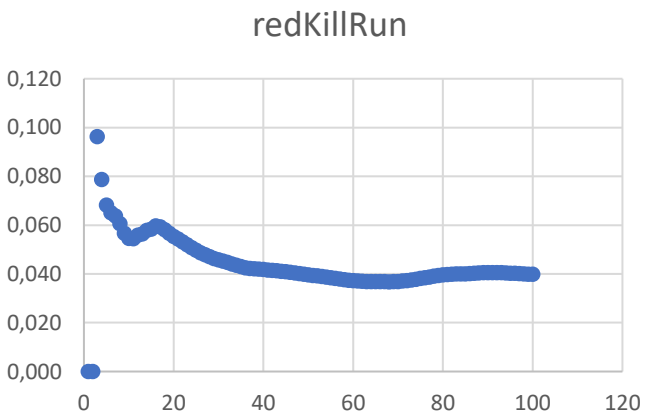

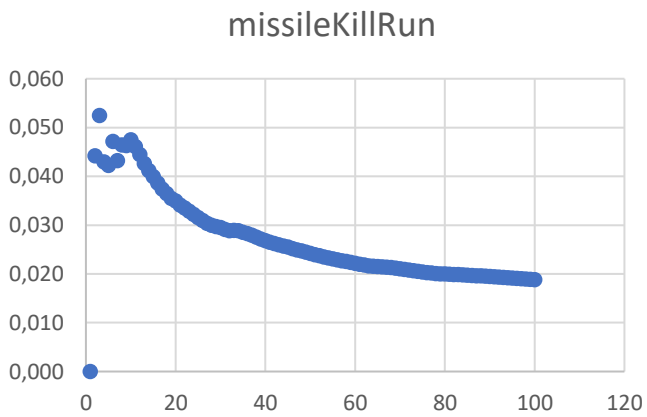

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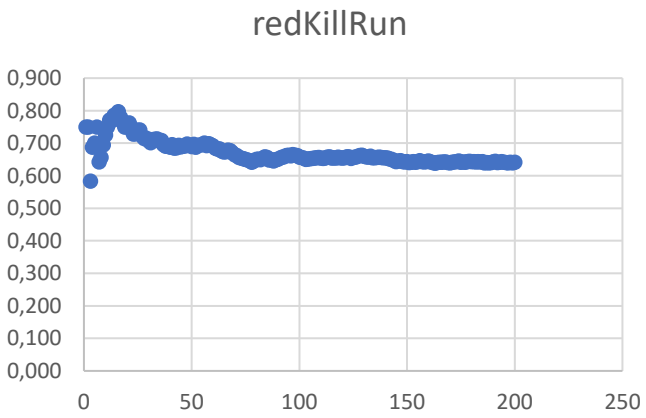

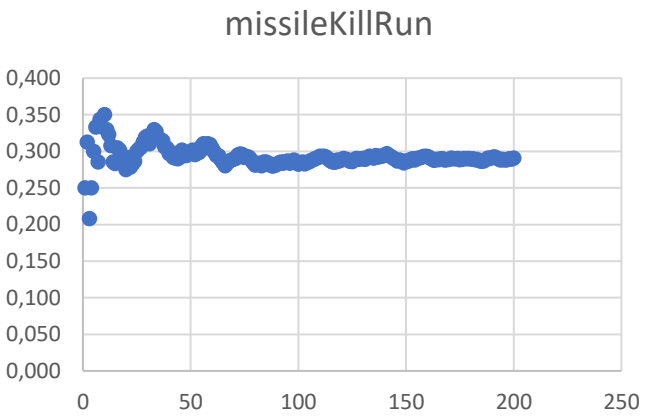

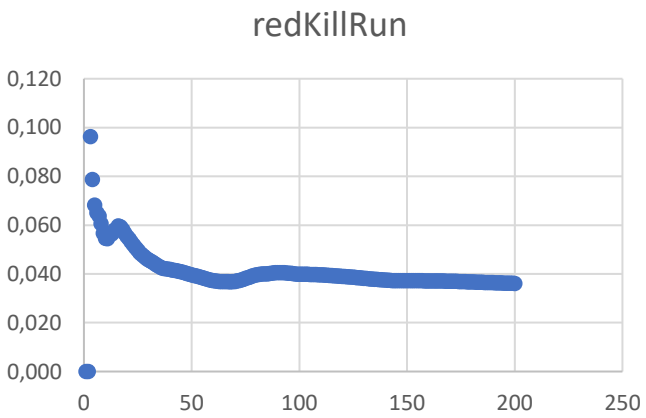

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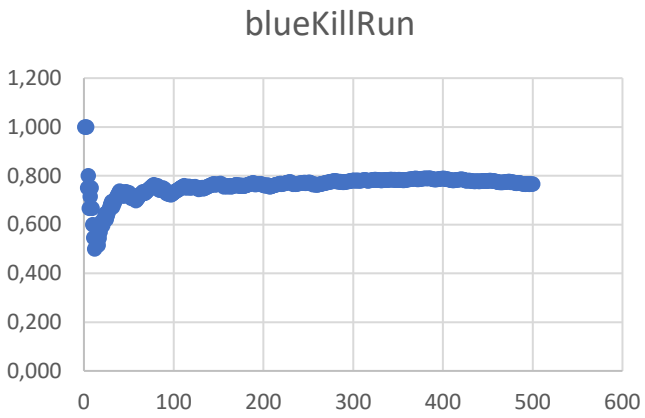

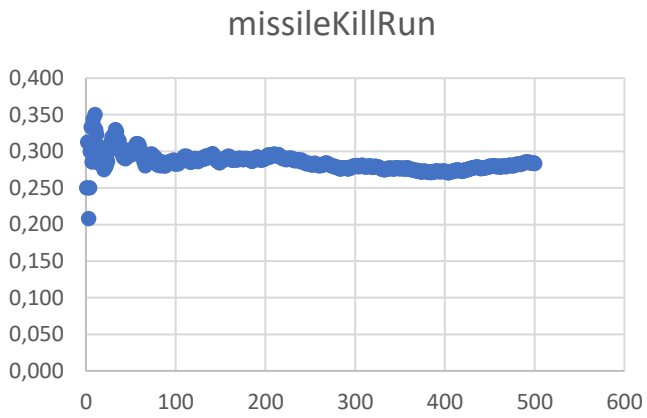

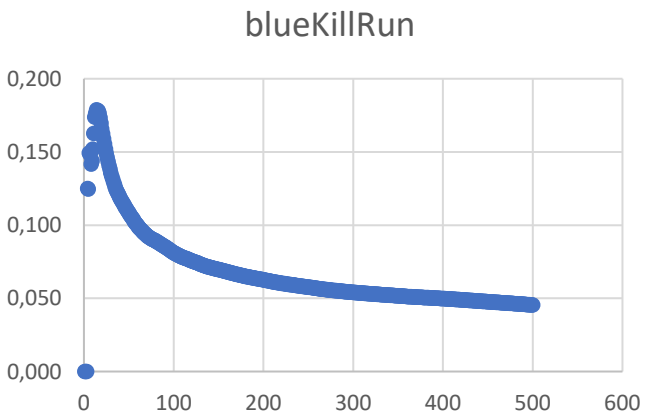

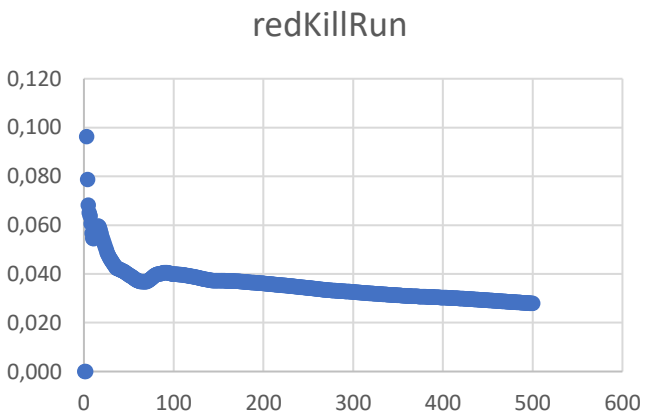

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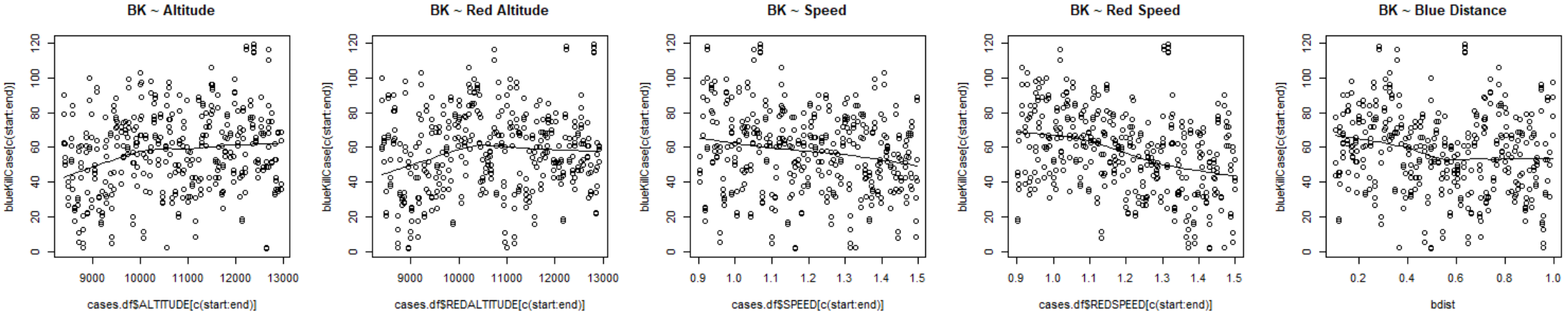
Analysis

The most important part is to truly transform raw simulation data into good insights for decision-maker

Using data helps reduce uncertainty in decisions, providing a quantitative analysis, making them more reliable

Identifying patterns and trends allows for anticipating problems and bring some opportunities

Continuous data-based feedback promotes constant improvement in processes and results



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Analysis

Part of the analyst's role is to translate the information contained in simulations into easy-to-understand analyses

Dashboards, graphs, and diagrams help with these tasks

Analyses are valid for certain limitations and simplifications – make it clear in which sample space those conclusions are valid (DO NOT GENERALIZE)

Continuous process: if the data does not reflect certain information or conclusions cannot be drawn, run new simulations in other scenarios

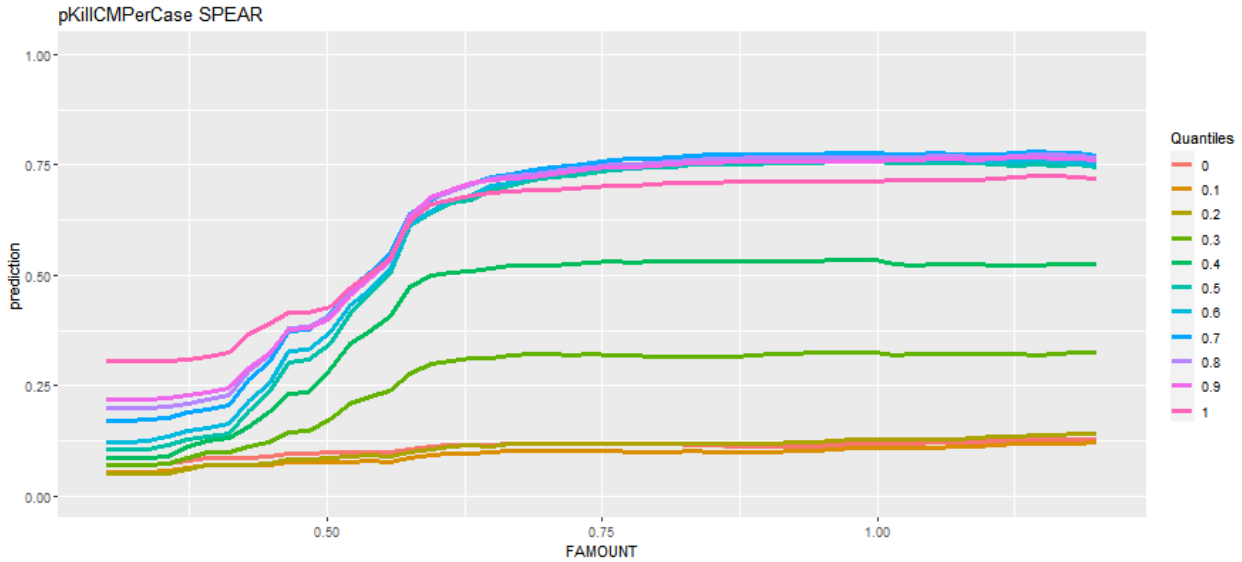
Analysis

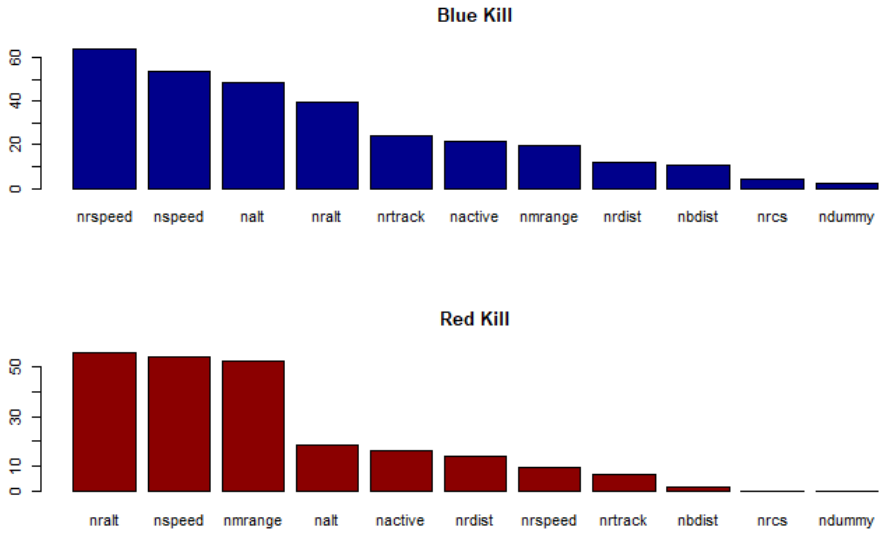
AsaPy package contains some preliminary analysis methods

Open-source: the idea is for this package to be updated as new analyses are performed

Prototype: methods may contain errors or be outdated

Agnostic: methods are independent of data type; they only need to respect the input structures of the methods (generally pandas.DataFrame)





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Method for analyzing relationships between variables

- Descriptive statistics
- Correlation
  - Coefficients: Pearson, Spearman, Kendall
  - Measure of the strength and direction of the linear relationship between variables
- Linear Regression
  - Model to predict the value of one variable based on another
- Scatter Plots
  - Graphical representation of the relationships between two variables
- Residual Plot
  - Graphical representation of the errors between observed and predicted values

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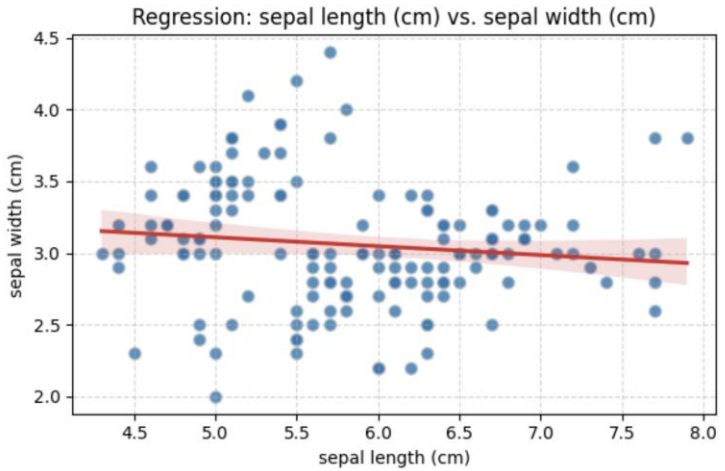
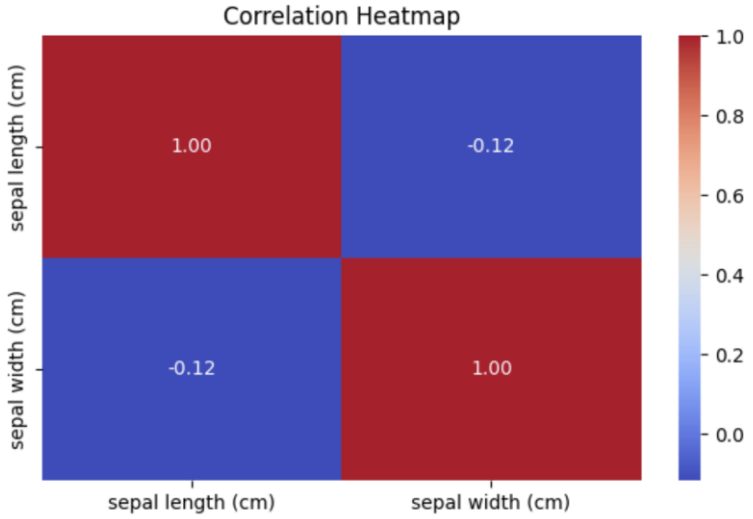
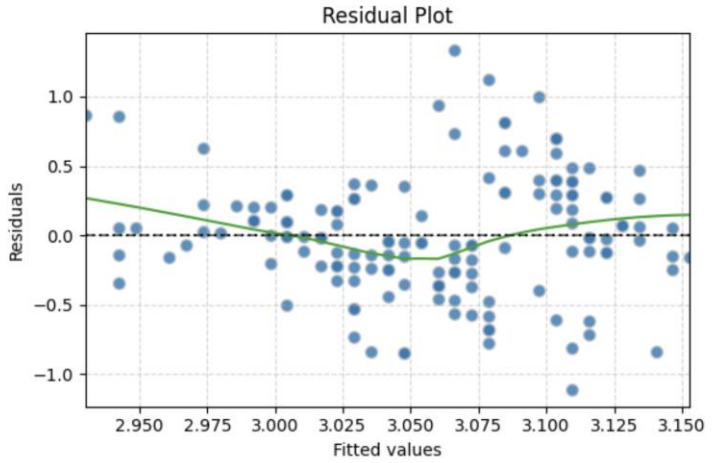
Test 3: Little or No Relationship (using Iris dataset)
Descriptive Statistics

	sepal length (cm)	sepal width (cm)
count	150.000000	150.000000
mean	5.843333	3.057333
std	0.828066	0.435866
min	4.300000	2.000000
25%	5.100000	2.800000
50%	5.800000	3.000000
75%	6.400000	3.300000
max	7.900000	4.400000







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ANOVA is a statistical technique used to compare the means of three or more groups to see if at least one mean is significantly different from the others.

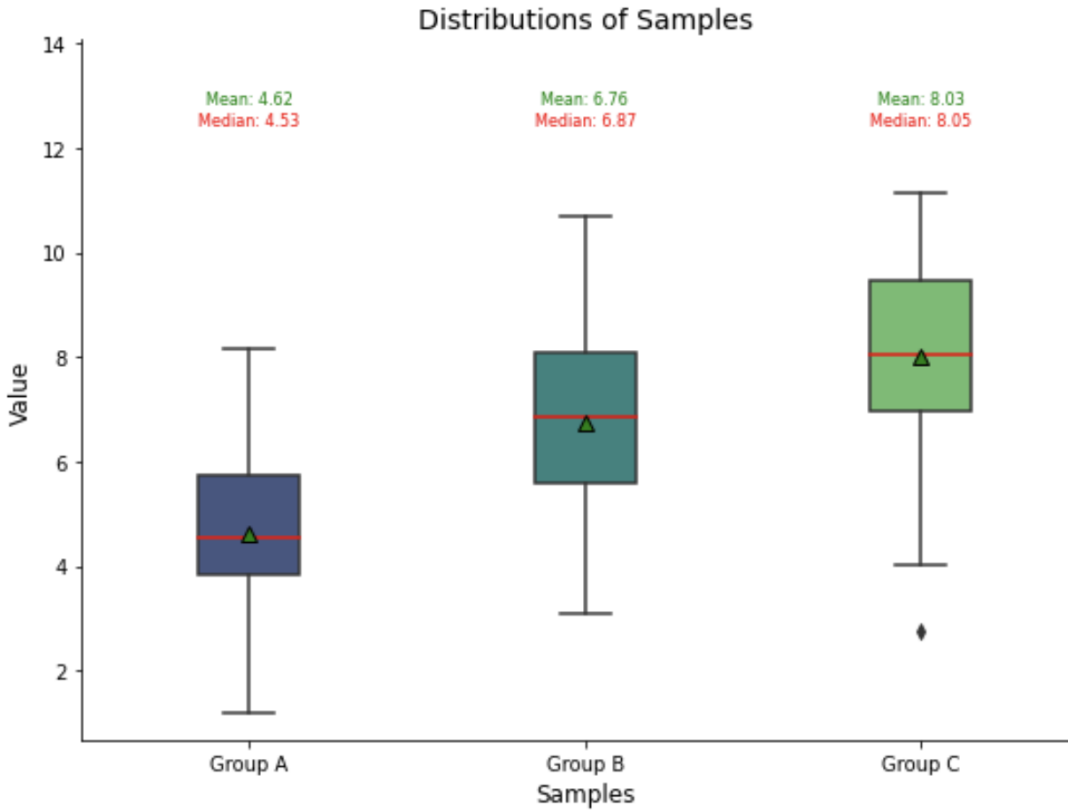
Assumptions of ANOVA:

Independence: Observations must be independent of each other

Normality: Data in each group should be approximately normally distributed

Homogeneity: Group variances should be approximately equal

asapy.anova




```
ANOVA Summary:

                sum_sq     df          F        PR(>F)
C(samples)  177.359216    2.0  24.994316  2.650394e-09
Residual    308.675214   87.0        NaN           NaN
The ANOVA test result is significant. There is a statistical difference among the samples.


Post-hoc (Tukey HSD) Test Results:

Multiple Comparison of Means - Tukey HSD, FWER=0.05
=====================================================
 group1  group2 meandiff p-adj  lower  upper  reject
-----------------------------------------------------
Group A Group B    2.134 0.0001 0.9743 3.2937   True
Group A Group C   3.4021    0.0 2.2424 4.5617   True
Group B Group C   1.2681 0.0287 0.1084 2.4278   True
-----------------------------------------------------
```

```
Running ANOVA test

Residuals DO follow a normal distribution.

Variances ARE homogeneous across the groups.
```

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asapy.bootstrap

Resampling method that involves repeatedly collecting samples (with replacement) from the original data

Estimate the precision of sample statistics (such as means, variances) through resampling

Applications

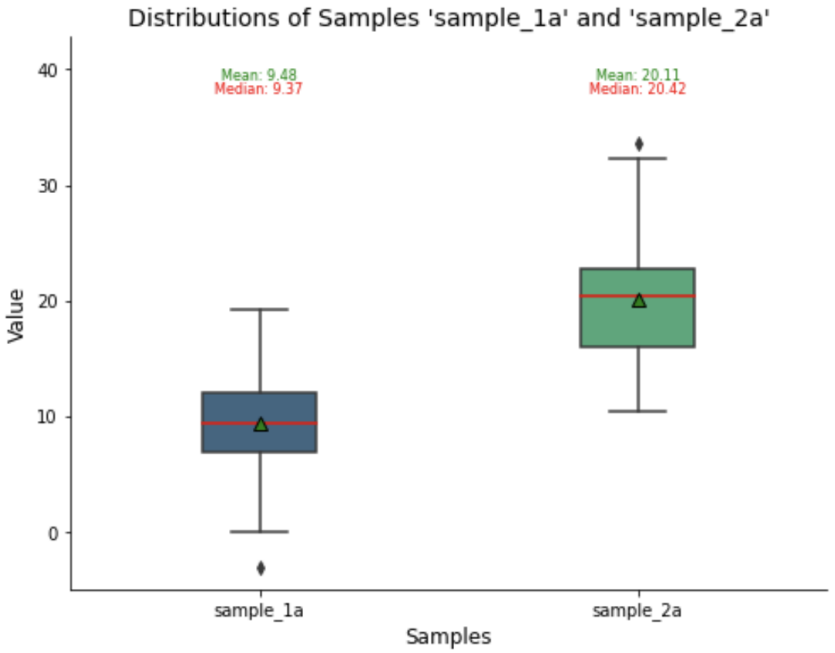
- Validation of statistical models
- Statistical inference without assuming a specific distribution for the data

Advantages

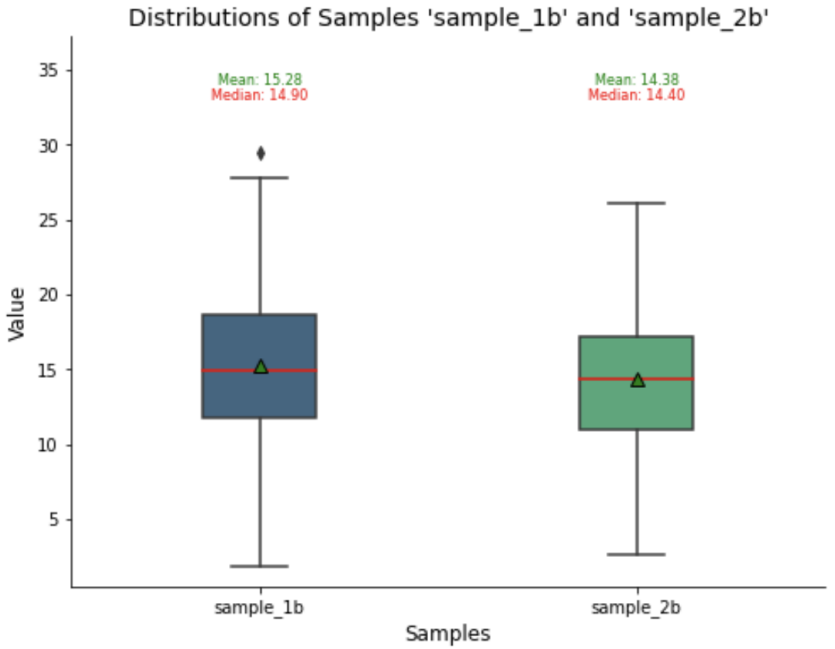
- Does not require assumptions about the data distribution
- Can be applied to small samples

asapy.bootstrap

```
Scenario 1: Obvious Difference
------------------------------------------------------------
Bootstrap Hypothesis Test Results (sample_1a vs sample_2a)
------------------------------------------------------------
Observed difference in means: -10.6308
Adjusted Bootstrap p-value: 0.0000
Sample 'sample_1a' is statistically lesser than sample 'sample_2a' (p = 0.0000).
------------------------------------------------------------
```




```
Scenario 2: No Obvious Difference
------------------------------------------------------------
Bootstrap Hypothesis Test Results (sample_1b vs sample_2b)
------------------------------------------------------------
Observed difference in means: 0.8992
Adjusted Bootstrap p-value: 0.2010
There's no sufficient evidence to claim one sample is statistically greater or lesser than the other.
------------------------------------------------------------
```



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asapy.feature_score

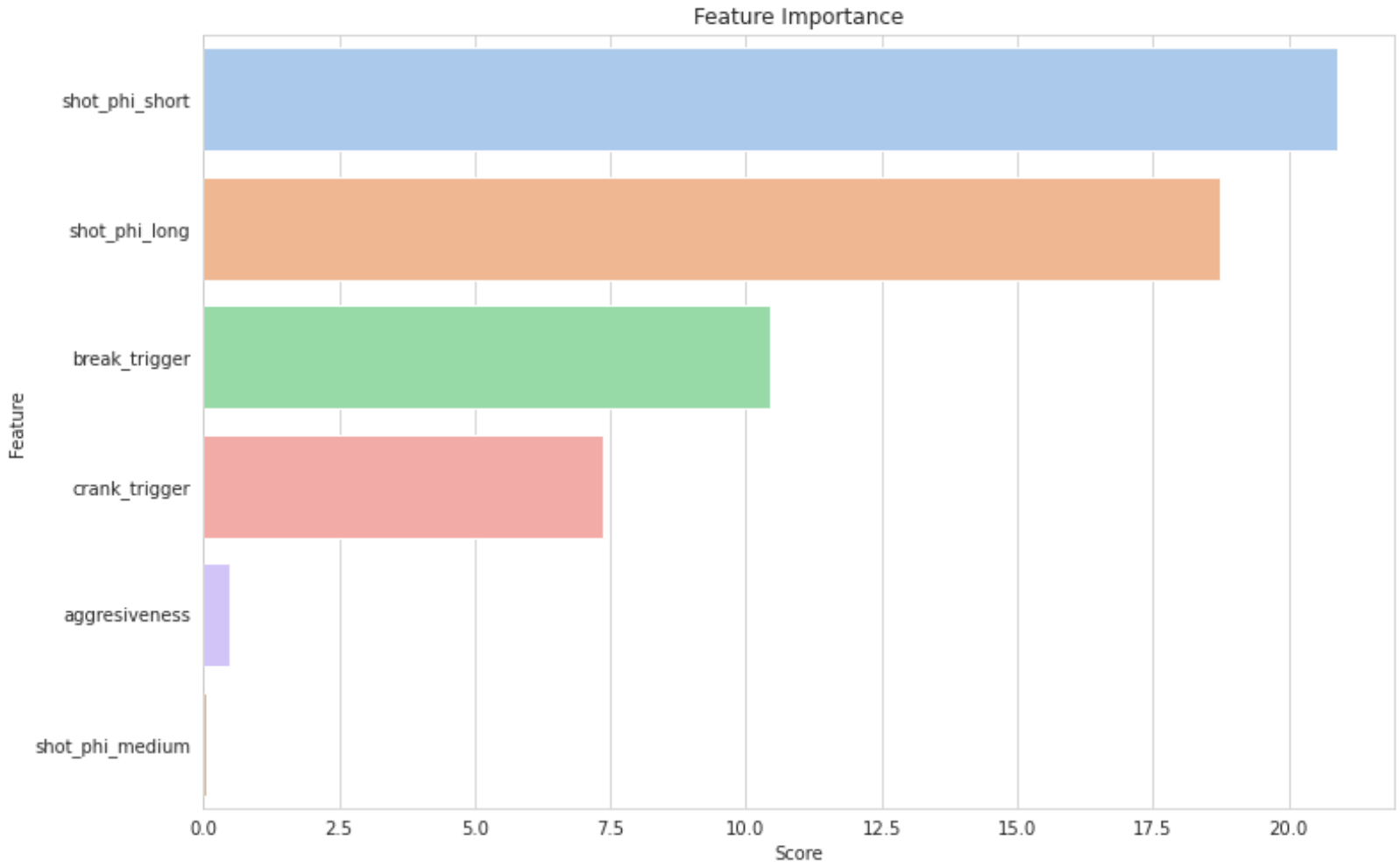
Variable importance evaluation

Calculates the relative importance of each variable (feature) in a predictive model using a specified scoring function

Why it is Important:

- Identifies the most relevant variables for prediction
- Reduces model complexity, increasing interpretability and potentially performance
- Minimizes the risk of overfitting by eliminating irrelevant features

asapy.feature_score



asapy.fit_distribution

Statistical Distribution Fitting

The process of finding the statistical distribution that best describes the observed data

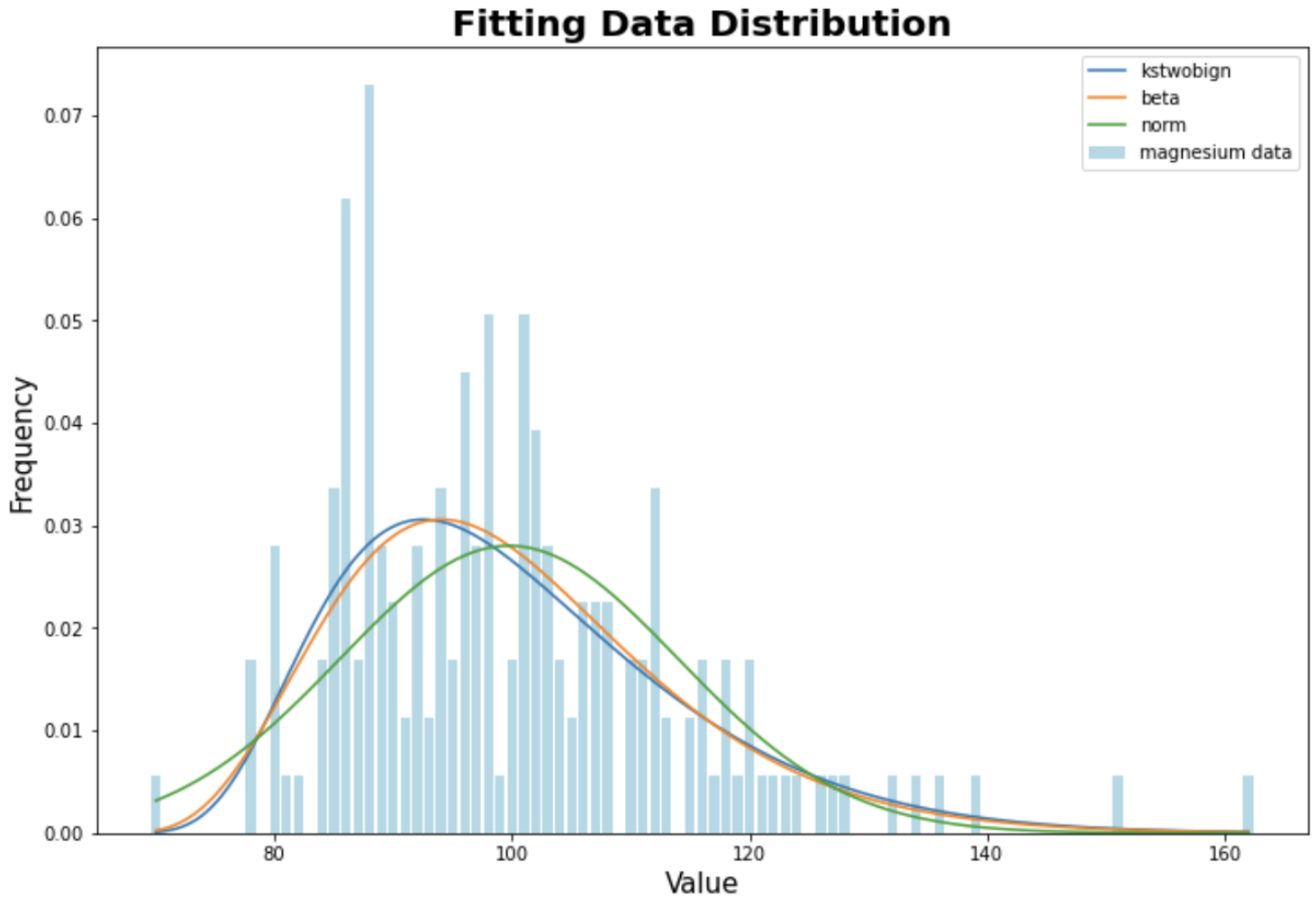
AsaPy checks 93 different distribution objects

Why it is Important

- Allows for precise modeling of data, aiding in inferences and predictions
- Facilitates the understanding of data characteristics, such as central tendency, variability, and shape

asapy.fit_distribution

Distribution_Type	P_Value	Statistics	Parameters
kstwobign	0.619613	0.0556452	(51.96, 55.16)
beta	0.585262	0.0571824	(6.06, 5334914.75, 65.16, 30436461.8)
norm	0.110071	0.0892933	(99.74, 14.24)
expon	0	0.317447	(70.0, 29.74)
uniform	0	0.386541	(70.0, 92.0)
chi2	0	0.915856	(0.64, 70.0, 3.93)



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asapy.detect_outliers/remove_outliers

Observations that significantly deviate from the rest of the data

May indicate natural variability, measurement errors, or rare events

Why it is important to detect and remove outliers

- Outliers can distort statistical analyses and predictive models
- Identifying and treating outliers can improve the accuracy and robustness of models
- Helps understand data variability and identify possible errors

asapy.detect_outliers/remove_outliers

```
data_update, drop_lines = Analysis.remove_outliers(X)
data_update
```

	age	sex	bmi	bp	s1	s2	s3	s4	s5	s6
0	0.038076	0.050680	0.061696	0.021872	-0.044223	-0.034821	-0.043401	-0.002592	0.019908	-0.017646
1	-0.001882	-0.044642	-0.051474	-0.026328	-0.008449	-0.019163	0.074412	-0.039493	-0.068330	-0.092204
2	0.085299	0.050680	0.044451	-0.005671	-0.045599	-0.034194	-0.032356	-0.002592	0.002864	-0.025930
3	-0.089063	-0.044642	-0.011595	-0.036656	0.012191	0.024991	-0.036038	0.034309	0.022692	-0.009362
4	0.005383	-0.044642	-0.036385	0.021872	0.003935	0.015596	0.008142	-0.002592	-0.031991	-0.046641
...	...	...	...	...	...	...	...	...	...	...
404	-0.056370	-0.044642	-0.074108	-0.050428	-0.024960	-0.047034	0.092820	-0.076395	-0.061177	-0.046641
405	0.041708	0.050680	0.019662	0.059744	-0.005697	-0.002566	-0.028674	-0.002592	0.031193	0.007207
406	-0.005515	0.050680	-0.015906	-0.067642	0.049341	0.079165	-0.028674	0.034309	-0.018118	0.044485
407	0.041708	0.050680	-0.015906	0.017282	-0.037344	-0.013840	-0.024993	-0.011080	-0.046879	0.015491
408	-0.045472	-0.044642	0.039062	0.001215	0.016318	0.015283	-0.028674	0.026560	0.044528	-0.025930

asapy.pareto_front

A statistical technique for identifying the most significant factors in a dataset

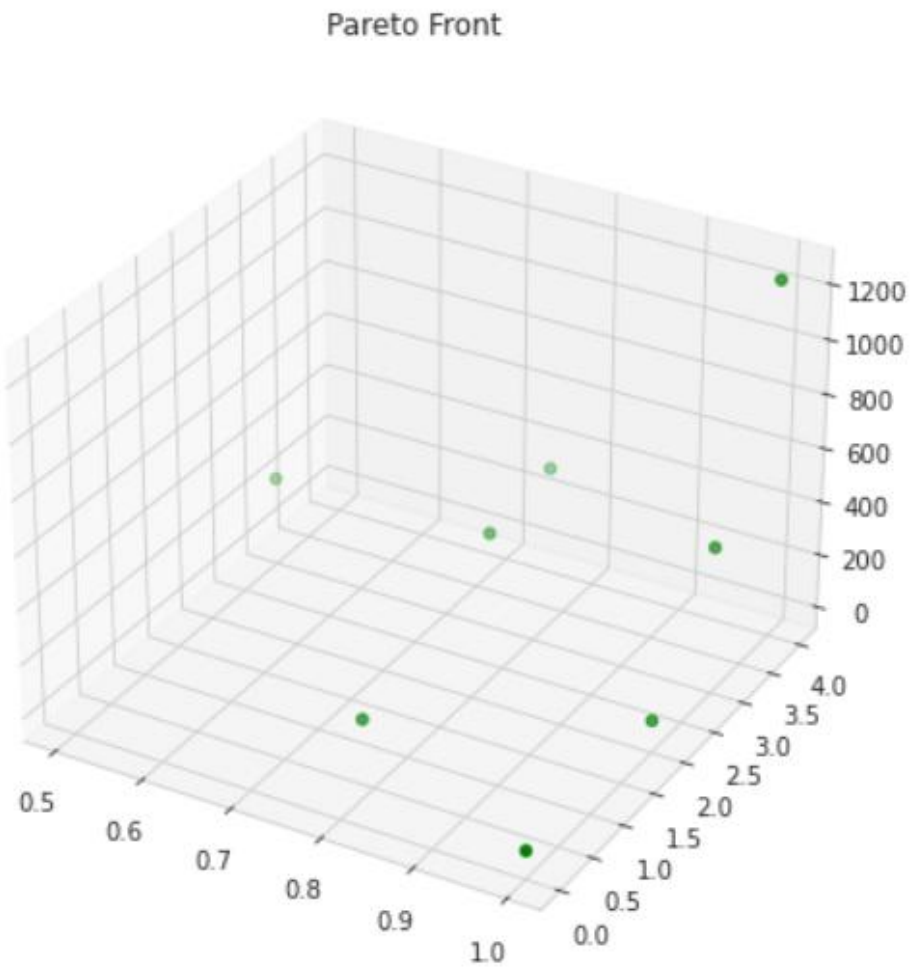
Based on the Pareto Principle, also known as the 80/20 rule, which states that approximately 80% of the effects come from 20% of the causes

Why It's Important

- Helps focus on the most important factors that impact a process or system
- Facilitates the prioritization of problems and efficient allocation of resources

asapy.pareto_front

aggressiveness	shot_phi	crank_trigger	break_trigger	m_0_blue	m_1_blue	m_2_blue
0,1	Short	1,0	1,2	1,0	2,0	36,9
0,8	Short	0,7	1,1	1,0	4,0	1239,0
0,6	Short	0,6	1,2	1,0	3,0	464,4
0,2	Short	0,8	1,0	0,8	3,0	274,7
0,5	Short	1,0	1,2	0,8	1,0	6,7
0,2	Short	0,9	1,1	0,5	3,0	246,1
0,2	Short	0,7	1,0	0,8	4,0	316,6
0,4	Short	0,7	1,1	1,0	0,0	23,0



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Prediction

Create and train machine learning models for prediction

- Supervised machine learning models
- Includes neural networks, random forests, and other algorithms
- Covers the entire model creation process: data preprocessing, hyperparameter tuning, cross-validation, evaluation, and prediction

Advantages

- Allows obtaining estimated results without the need for new simulations, saving time and computational resources
- Built on popular libraries like TensorFlow and Scikit-learn, facilitating integration with other machine learning tools and workflows
- Well-defined pipeline for preprocessing, training, and evaluating results

Prediction

The prediction module offers preprocessing methods like scaling, normalization, and feature engineering, and handles missing values and categorical features

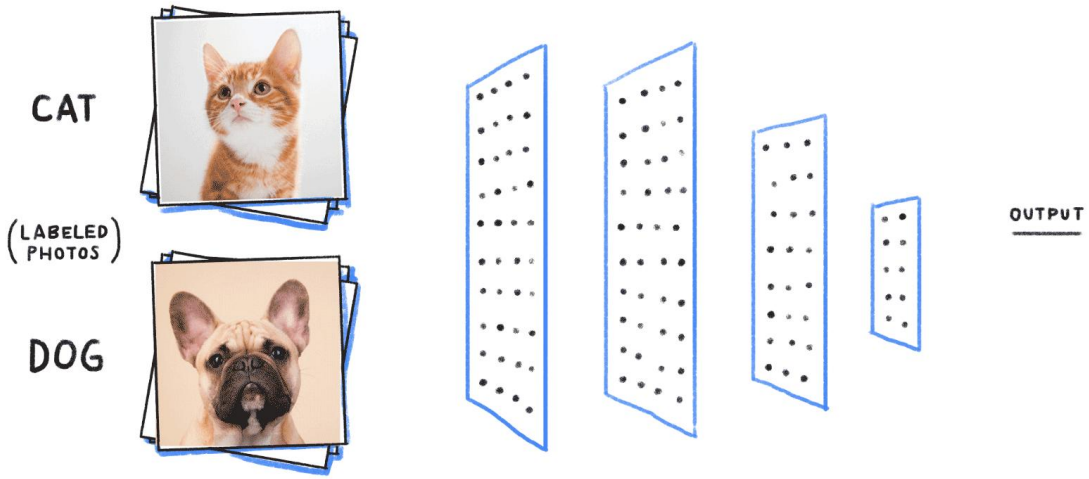
Tutorials are available to guide users in creating and evaluating models

Hyperparameter tuning methods, such as random search, optimize model performance

Cross-validation methods, including k-fold cross-validation, are included

Various evaluation metrics are provided, such as accuracy, precision, recall, F1 score, mean squared error, and more

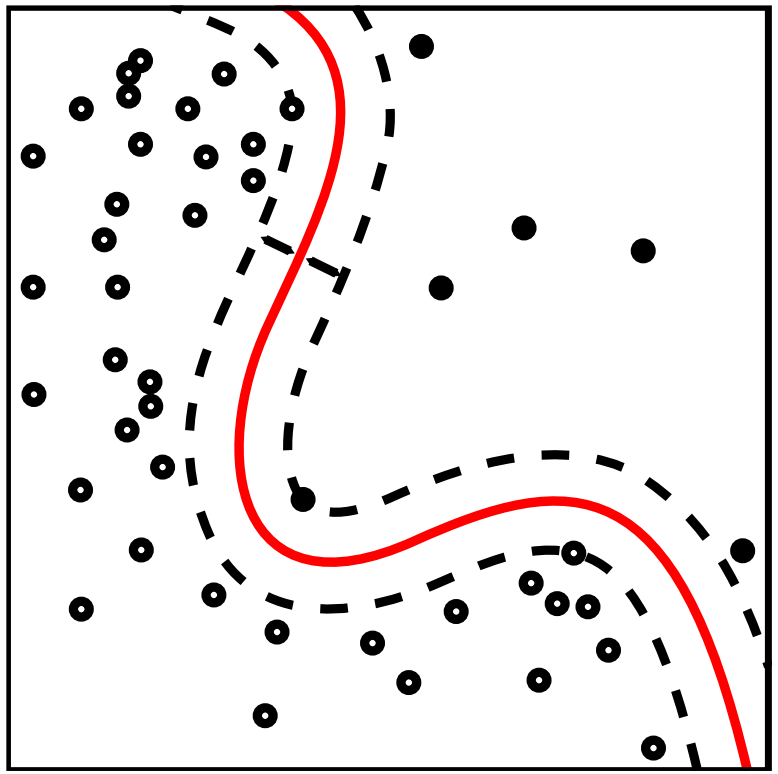
Options for visualizing model performance with plots are also available.



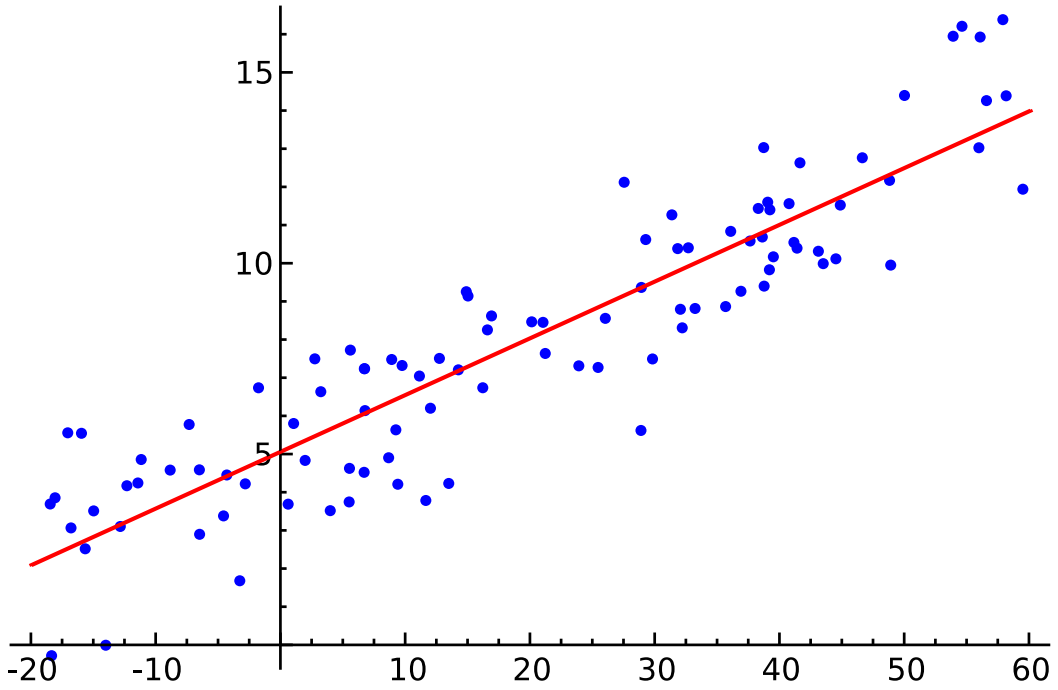
Source: https://becominghuman.ai/building-an-image-classifier-using-deep-learning-in-python-totally-from-a-beginners-perspective-be8dbaf22dd8

Prediction

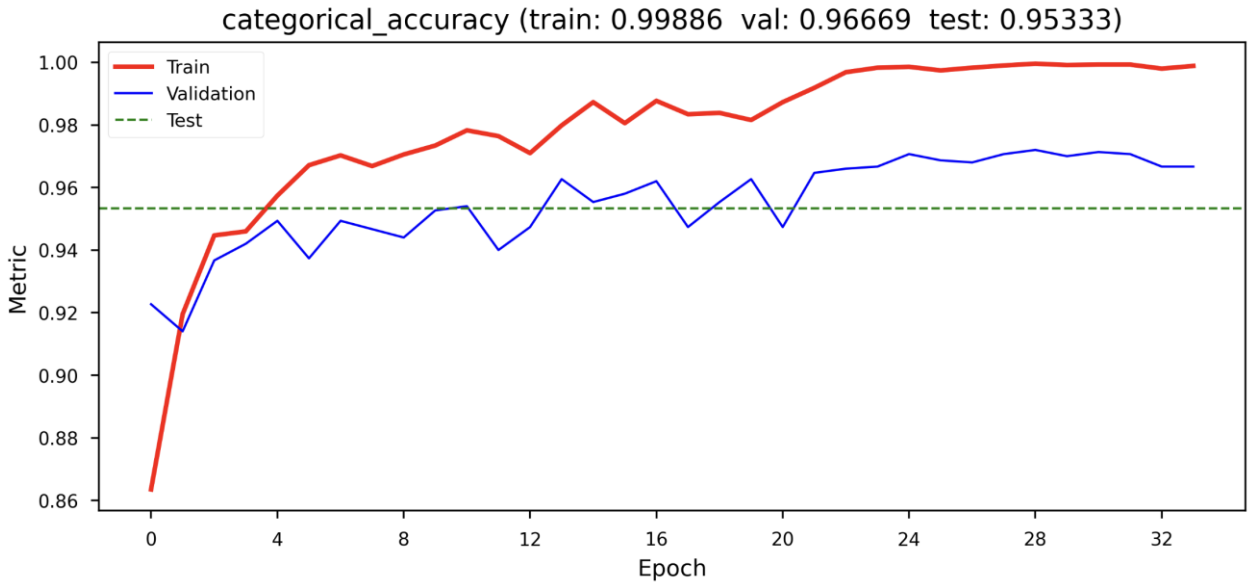
Classification

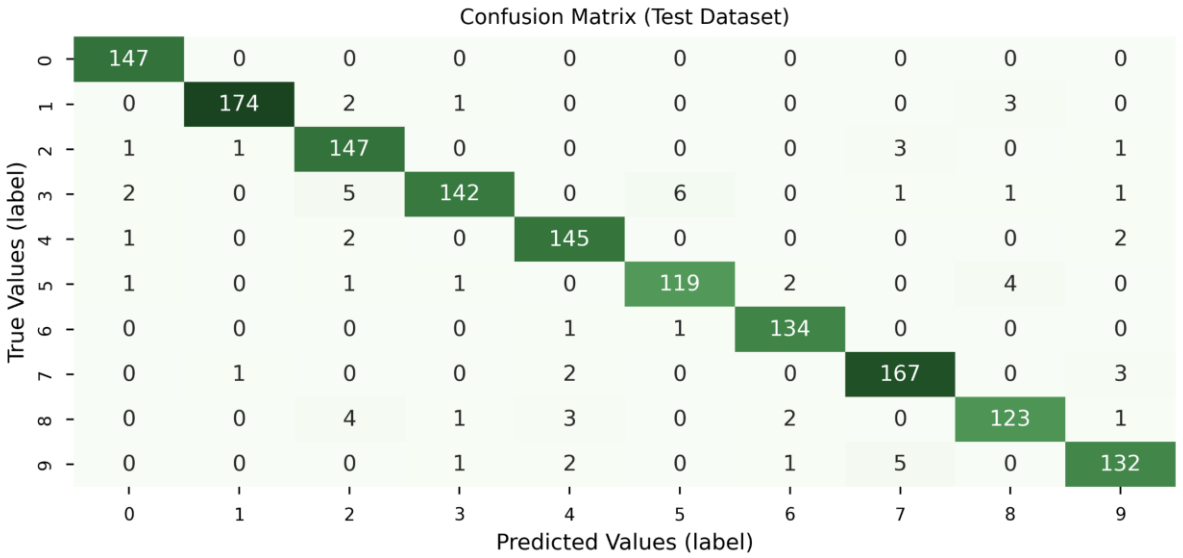


Regression



Prediction





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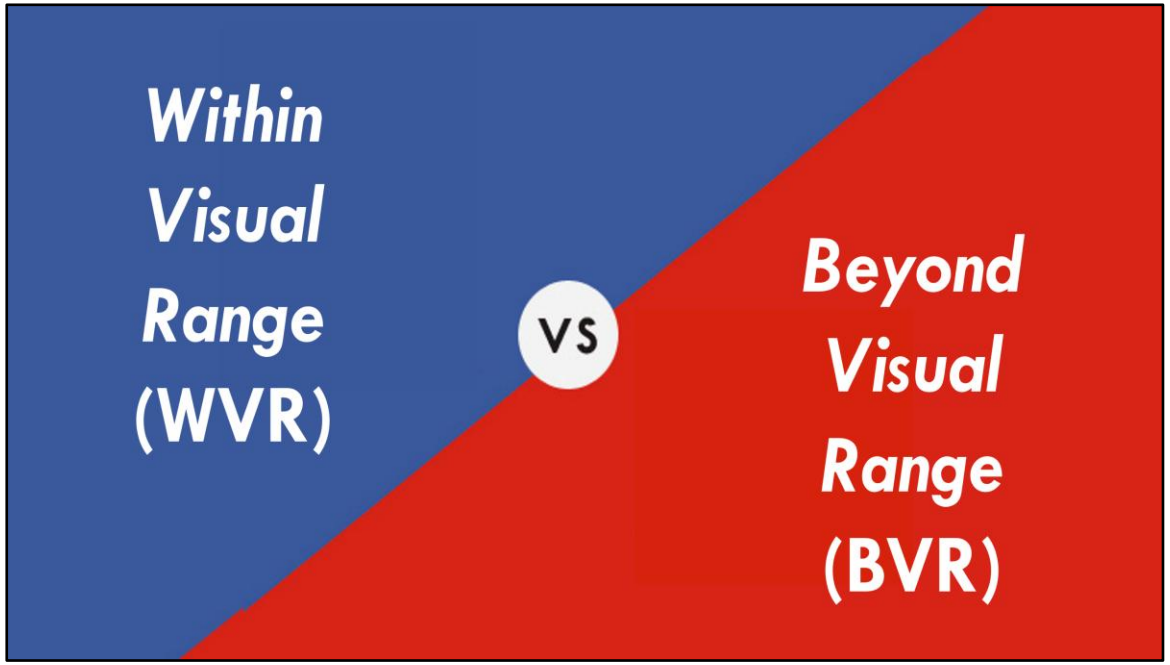
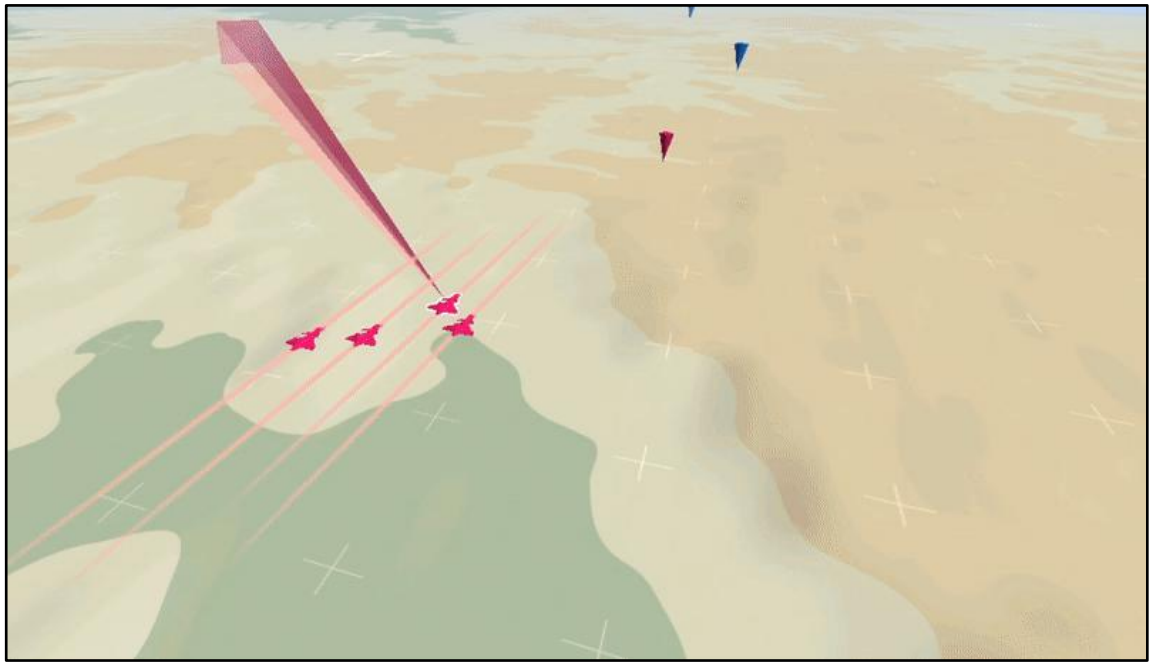
Case Study: Air Combat

Within Visual Range (WVR) vs Beyond Visual Range (BVR)

BVR air combat: Pilots engage without direct visual contact (~ 40 nautical miles)

Technological innovation in modern warfare: Emergence of advanced sensors and weapons





Engagement Decision Support

Dantas et al. (2021) developed an engagement decision support tool for BVR air combat in Defensive Counter Air (DCA) missions

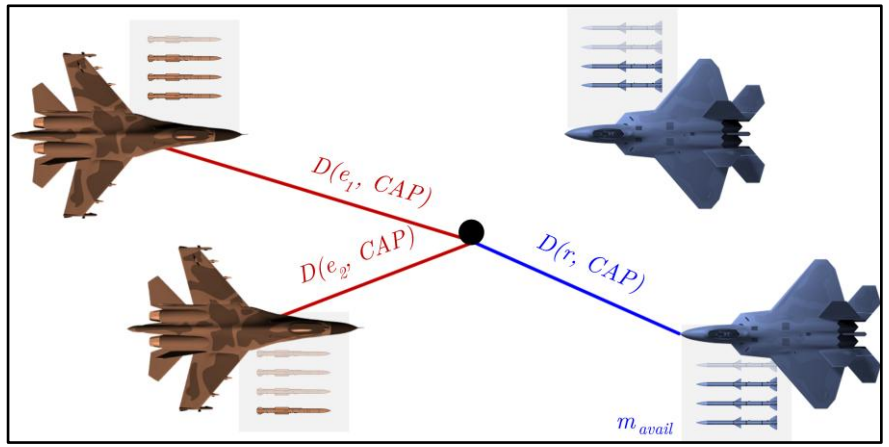
Refers to the pilot's decision to engage a target by executing offensive maneuvers in BVR air combat

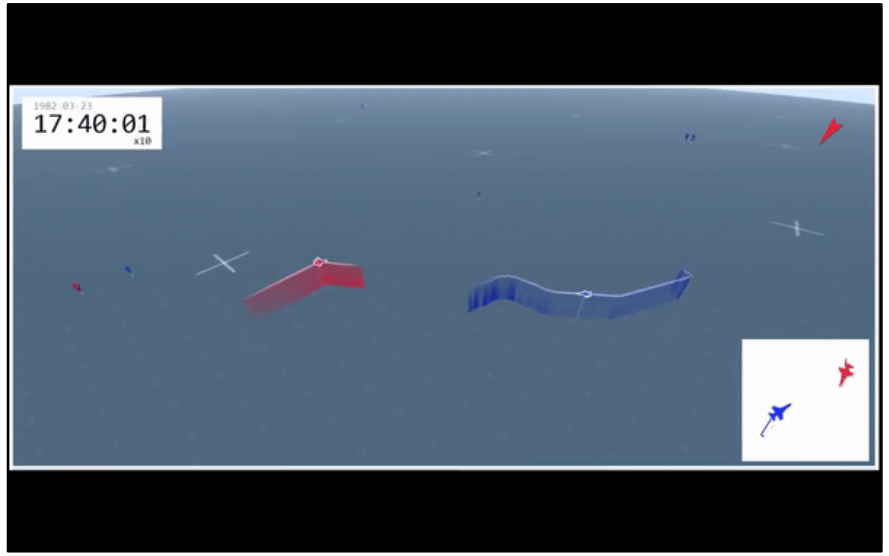
Conducted 3,729 simulations, each lasting 12 minutes, resulting in 10,316 engagements

Variables: Included distance, angle between the longitudinal axis, and altitude difference between the reference and the target

Metric: DCA index, based on distances between aircraft from both teams and the number of missiles deployed

Created a supervised machine learning model using XGBoost, determining engagement quality





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Weapon Engagement Zone Evaluation

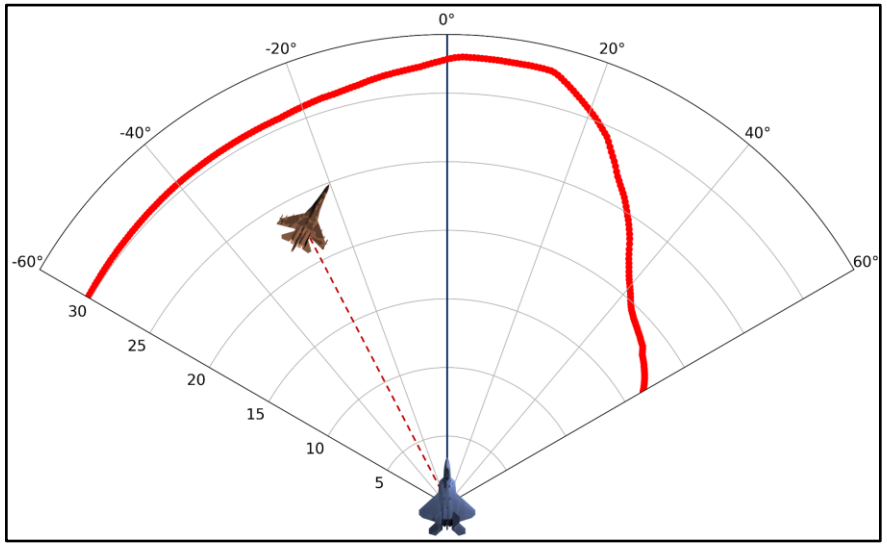
Dantas et al. (2021) calculated air-to-air missile's Weapon Engagement Zone (WEZ) in BVR air combat

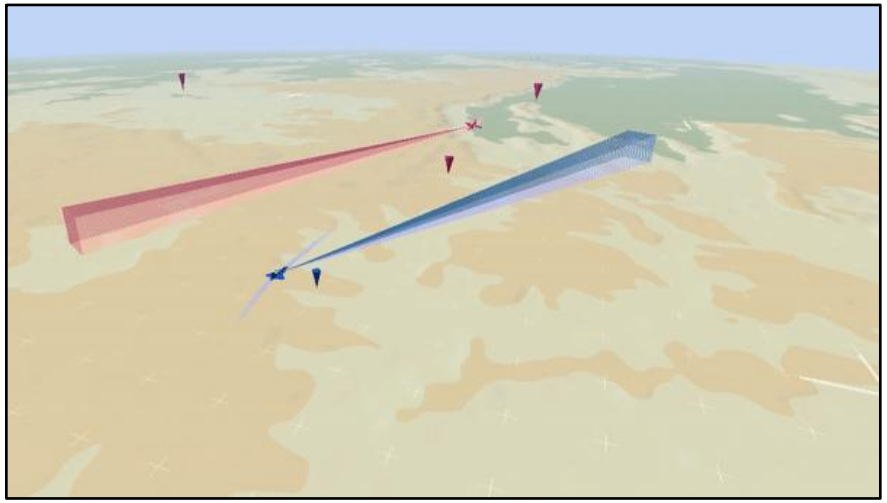
LHS method to design experiments considering seven input variables: shooter altitude, shooter speed, target altitude, target speed, target heading, relative position of the target, and shooter pitch

Created a supervised machine learning model using a Deep Neural Network (DNN) to predict WEZ maximum launch range

Used metrics like mean absolute error and coefficient of determination to ensure model accuracy

Enhanced strategic planning in air defense, providing real-time insights





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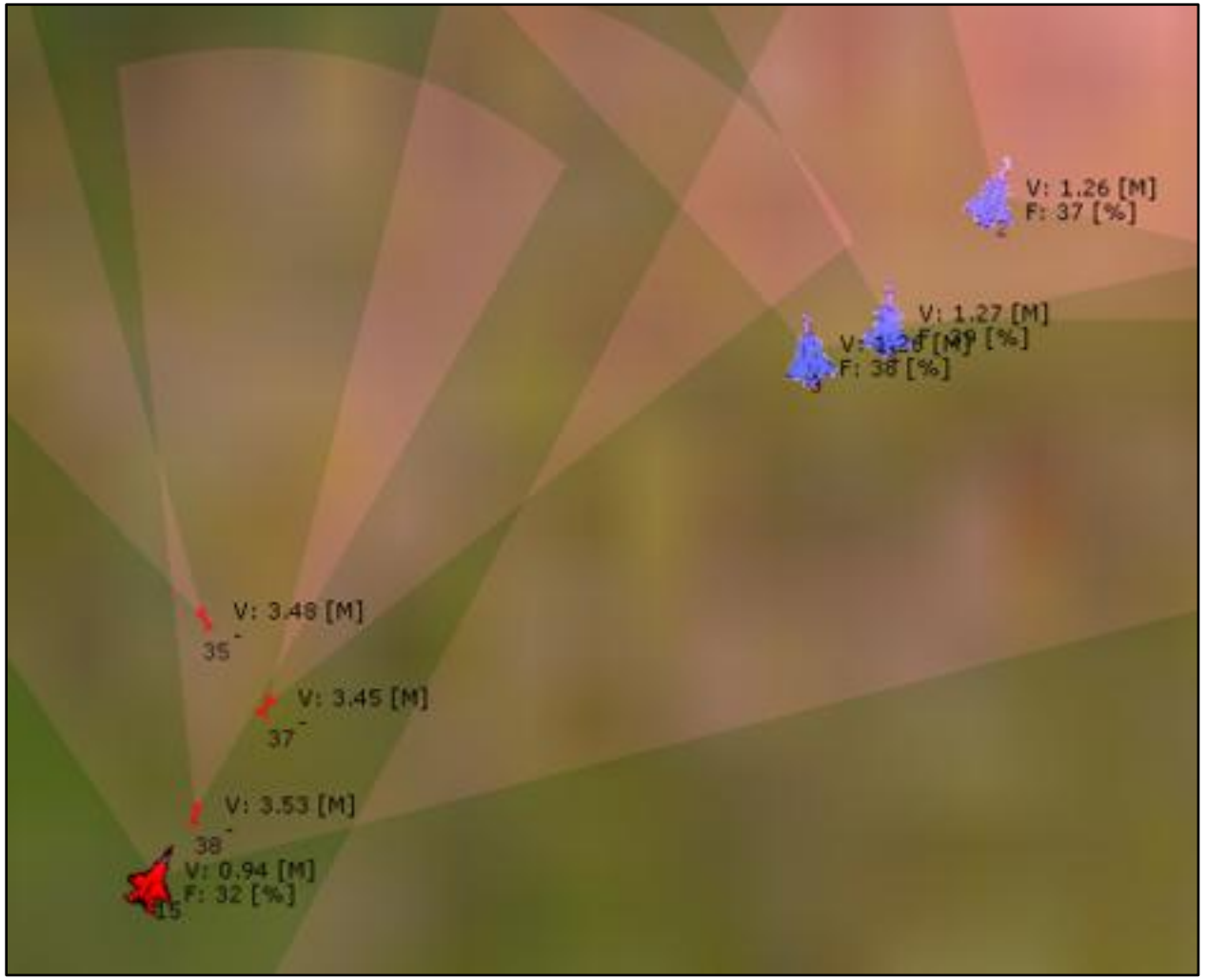
Missile Hit-Prediction

AsaPy works with different simulation softwares, including commercial and open-source platforms

Dantas et al. (2022) used FLAMES simulation platform to generate data for predicting missile launch effectiveness, employing AsaPy for data organization and analysis

Built seven supervised models to predict missile effectiveness, using resampling techniques like SMOTE to address class imbalance

Calculated the training and inference time of the models and compare them.



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Fighter Aircraft Navigation

Use case to deep our understanding of efficient aircraft operation

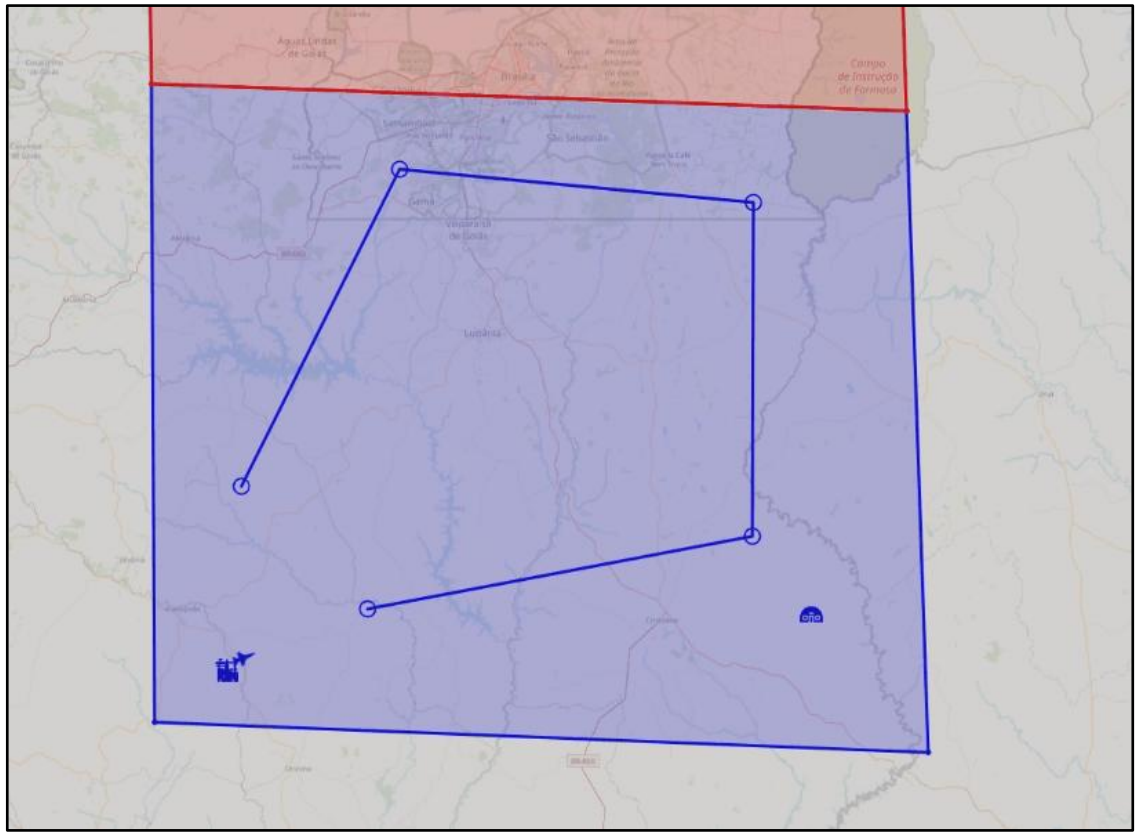
The aircraft navigates altitudes between 10,000 and 35,000 feet, adjusting speeds from 350 to 550 knots

Includes a 10-minute holding maneuver at the third route point, where the aircraft follows a circular path in the air

Experiments

Experiment 1 – Analysis of the Relationship between Time of Flight and Fuel Consumption

Experiment 2 – Analysis of the Relationship between Speed, Altitude, and Fuel Consumption

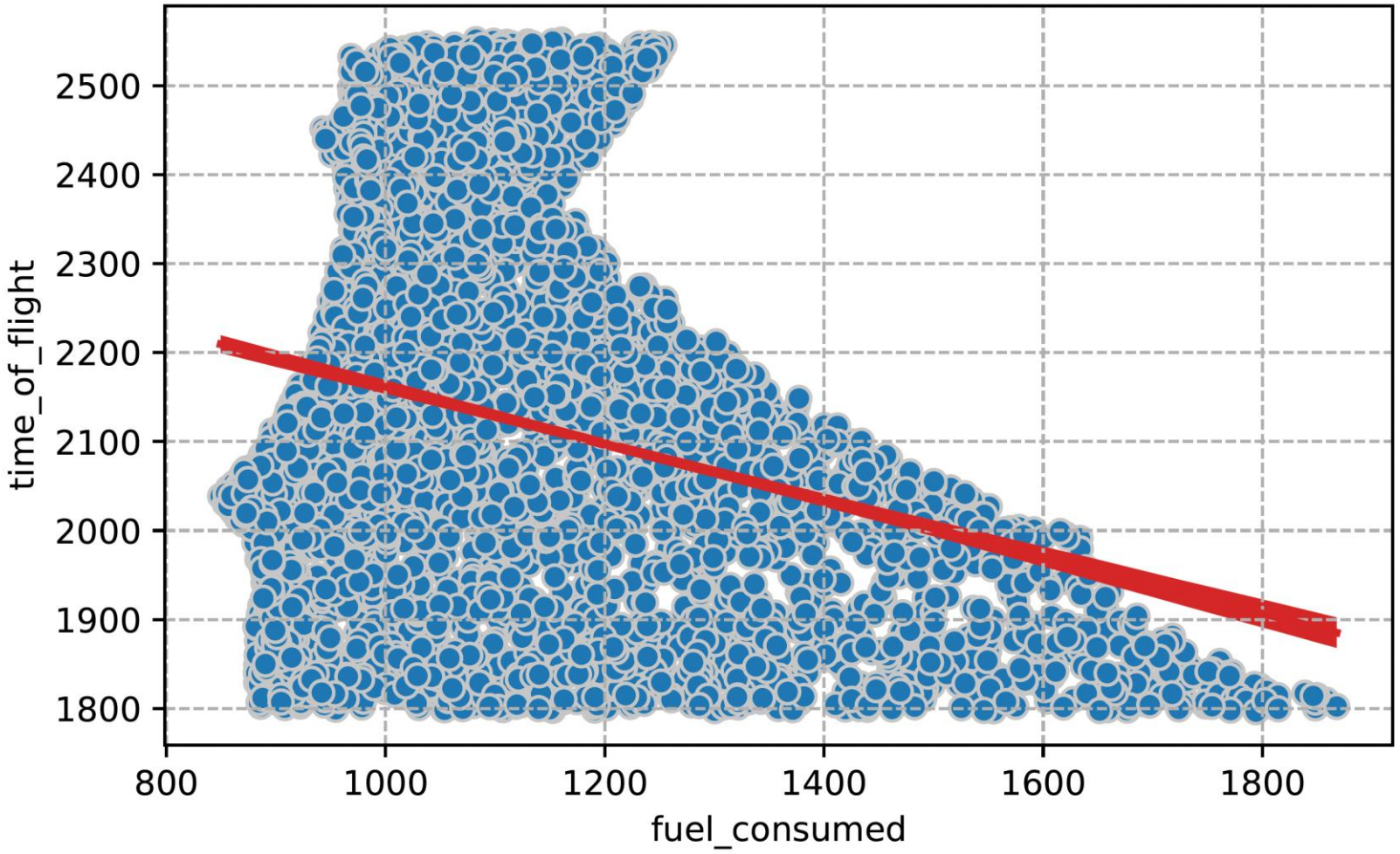


Experiment 1

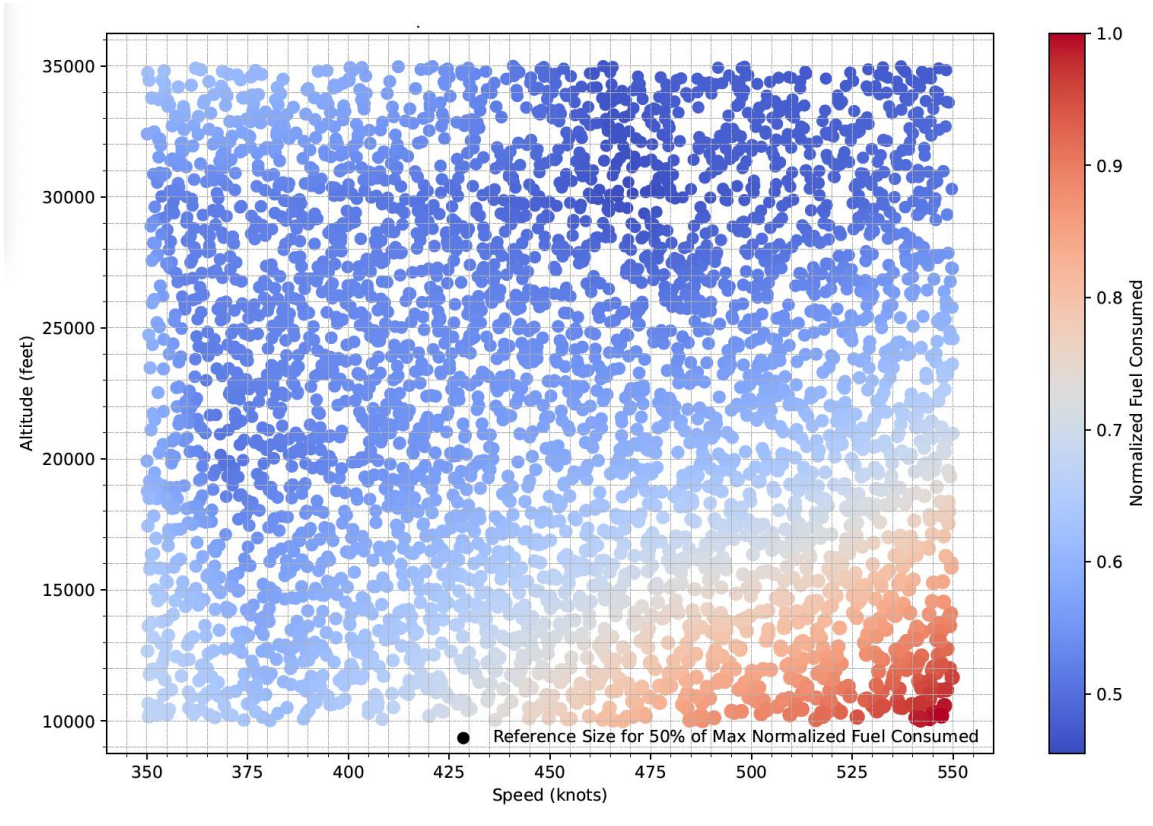
Relationship between Time of Flight and Fuel Consumption

4,000 flight simulations changing altitude and speed

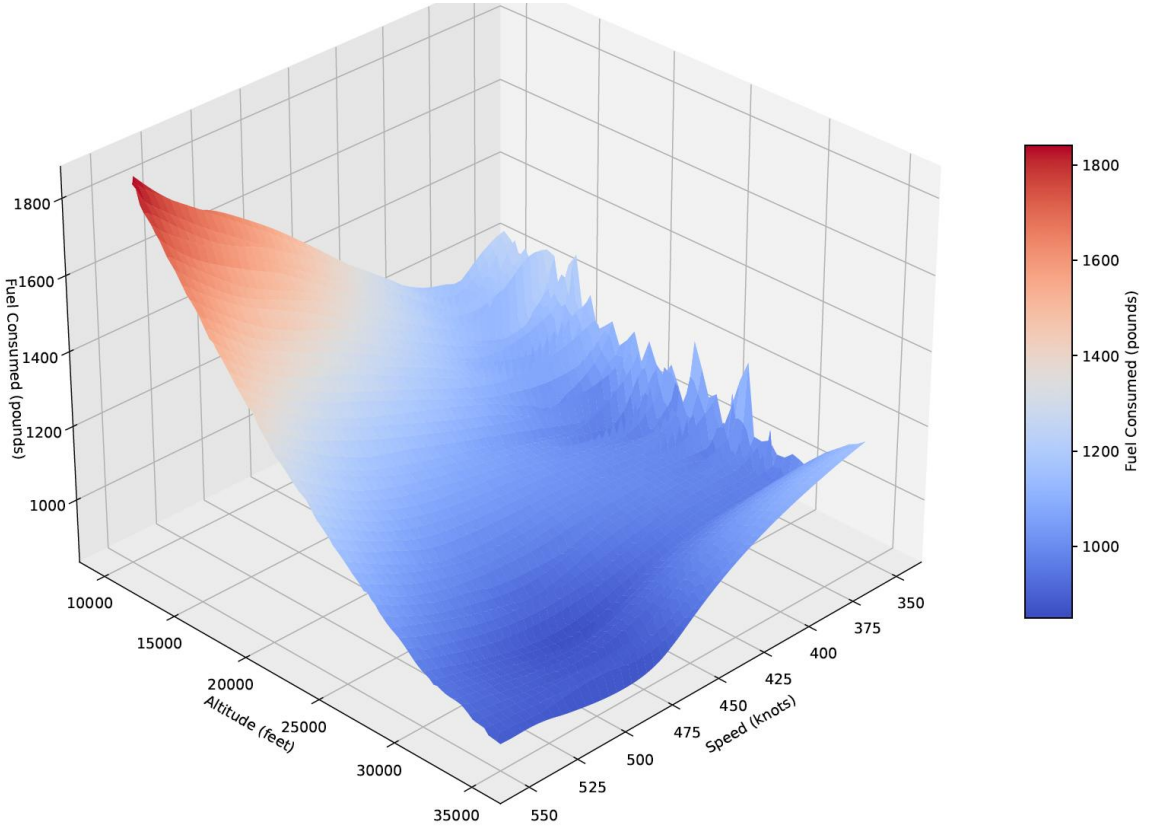
Expected to find a non-linear relationship, as the performance of aircraft changes with altitude and speed



Experiment 2



(a) 2D normalized surface plot showing the relationship between speed, altitude, and fuel consumption.



(b) 3D surface plot illustrating the dynamic interaction between speed, altitude, and fuel consumption.

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Fighter Aircraft Navigation

asapy / case_study / nav_demo / **nav_demo.ipynb**

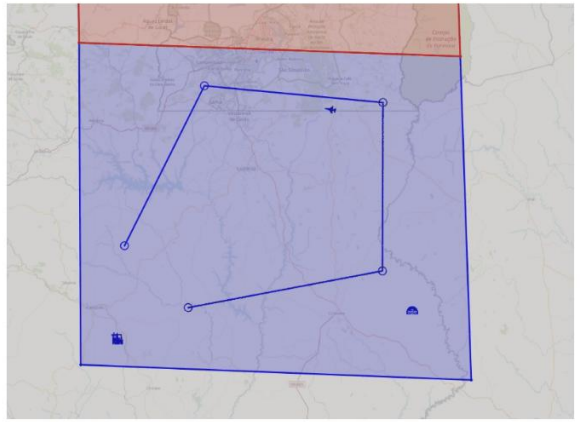
jpadantas case study update

Preview | Code | Blame 448 lines (448 loc) · 20.4 KB

Scenario: Fighter Aircraft Navigation Demonstration

General Description:

This scenario describes a navigation flight carried out by a fighter aircraft, focusing on the execution of maneuvers at different altitudes and speeds. The navigation encompasses an altitude range between Flight Level (FL) 100 and FL 350, as well as a speed variation from 350 knots to 550 knots. During this flight, at the third point of the route, the aircraft will perform a holding maneuver around a specific point (**Hold**) for 10 minutes, integrating it into the flight pattern.



This cell imports all the necessary modules for the execution and analysis of the simulations.

```
# Libraries for data analysis and plotting
import pandas as pd           # Library for data analysis and manipulation, nicknamed 'pd'.
import matplotlib.pyplot as plt # Library to create static, animated, and interactive data visualizations, nickna
import seaborn as sns         # Matplotlib-based library for drawing attractive and informative statistical graph

# Specific Library
import asapy                  # Provides Python bindings for the AsaPy API.

# Display Settings
import warnings               # Library for handling warnings.
warnings.filterwarnings('ignore') # Suppresses warnings to make the output cleaner.
```

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Conclusion

Streamlines and accelerates the analysis of simulation data

Not creating new analysis methods but contributing with a well-structured pipeline

Features experiment design, statistical analysis, machine learning algorithms, and data visualization tools

Future Work

- Introduce new DoE methods, such as Nearly Orthogonal Latin Hypercube
- Expand unsupervised machine learning algorithms – version 0.1.6 already includes some techniques
- Improve documentation with new examples, tutorials and use cases
- Conduct efficiency analysis: compare the performance of managing simulation output data from different systems (ASA and FLAMES). Focus on how AsaPy streamlines tasks like data reading, loading, cleaning, and preliminary analyses

Source Code

AsaPy is available as an open-source library

https://github.com/ASA-Simulation/asapy

Interested users can check the tutorials available in the repository

asapy / tutorials /

jpadantas update version 0.1.6

Name	Last commit message
..	
datasets	0.1.3
figures	0.1.3
models	0.1.3
simulations	case study, methods and tutorials update
analyze_relationship.ipynb	update version 0.1.6
anova.ipynb	case study, methods and tutorials update
bootstrap_test.ipynb	case study, methods and tutorials update
eda.ipynb	case study, methods and tutorials update
feature_score.ipynb	case study, methods and tutorials update
fit_distribution.ipynb	case study, methods and tutorials update
histograms.ipynb	update version 0.1.6
hypothesis.ipynb	update version 0.1.6
mixrpy.ipynb	update version 0.1.6
outliers.ipynb	update version 0.1.6
pareto.ipynb	update version 0.1.6
prediction.ipynb	update version 0.1.6
simulation_setup.ipynb	update version 0.1.6

Acknowledgments

Finep: Grant nº 2824/20

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Contact

Joao P. A. Dantas – Capt.

Decision Support Systems Subdivision

Institute for Advanced Studies

Brazilian Air Force

dantasjpad@fab.mil.br

www.joaopadantas.com

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