U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

The Design of Swarm Experiments: A Systems Engineering Approach to Swarm Research

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Melissa Jablonski, Jonathan Jablonski, Ross Arnold, Benjamin Abruzzo, Elizabeth Mezzacappa

US Army DEVCOM Armament Center, US Army Armament Graduate School

Presented by: Melissa Jablonski

OUTLINE

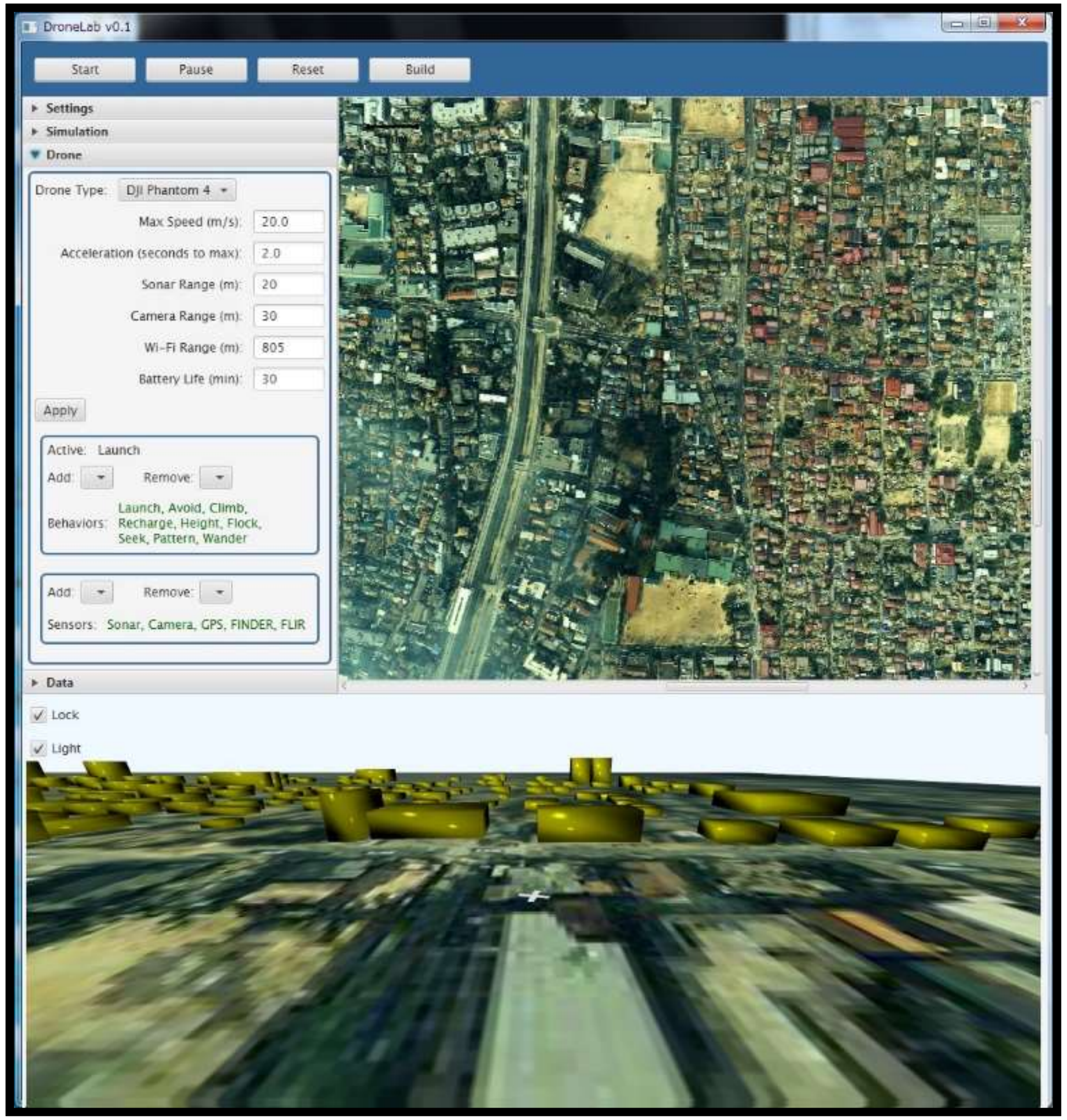
- Background
  - Swarm Intelligence
  - Computer Simulation Experimentation of Swarms
- The Design of Swarm Experiments Methodology
  - Plan
  - Design
  - Execute
  - Analyze
  - Assimilate
- Conclusions

BACKGROUND OF SWARM INTELLIGENCE

- Groups of entities of similar characteristics that tend to move together and work cooperatively toward an overarching goal
- Swarm intelligence is based on the concept of swarm theory: simple entities behaving in a collaborative manner can produce emergent effects
  - Think beehives and ant swarms
- Application of general systems theory

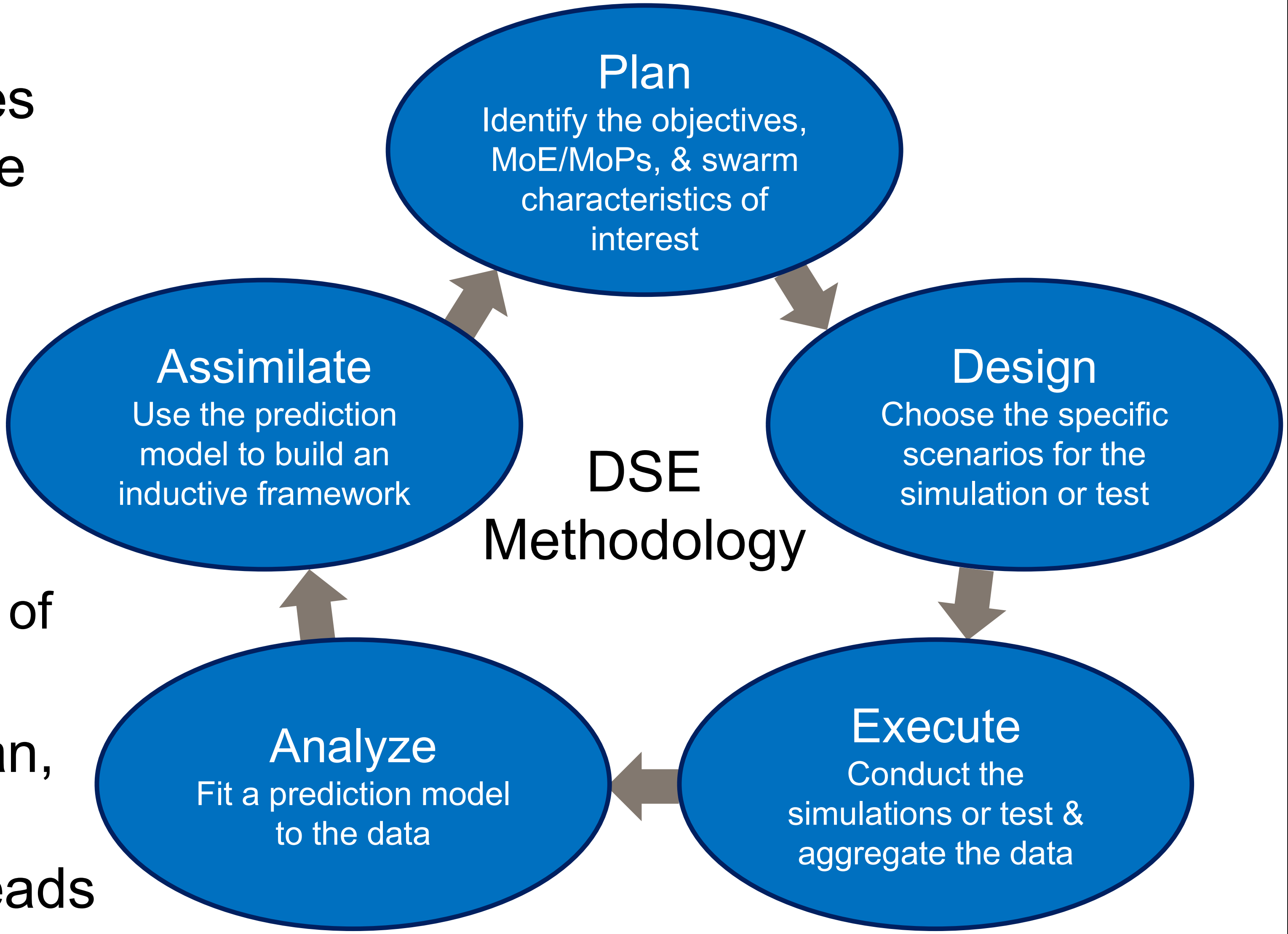
COMPUTER SIMULATION EXPERIMENTATION

- DroneLab is an example of a software application designed to facilitate simulation of large numbers of unmanned aircraft systems (UAS) operating cooperatively as a robot swarm
- Here, DroneLab is used to simulate swarms of UAVs after a natural disaster
- Certain parameters of the simulation (e.g. input variables) are varied to understand the effect each has on our output of interest: Time to find survivors



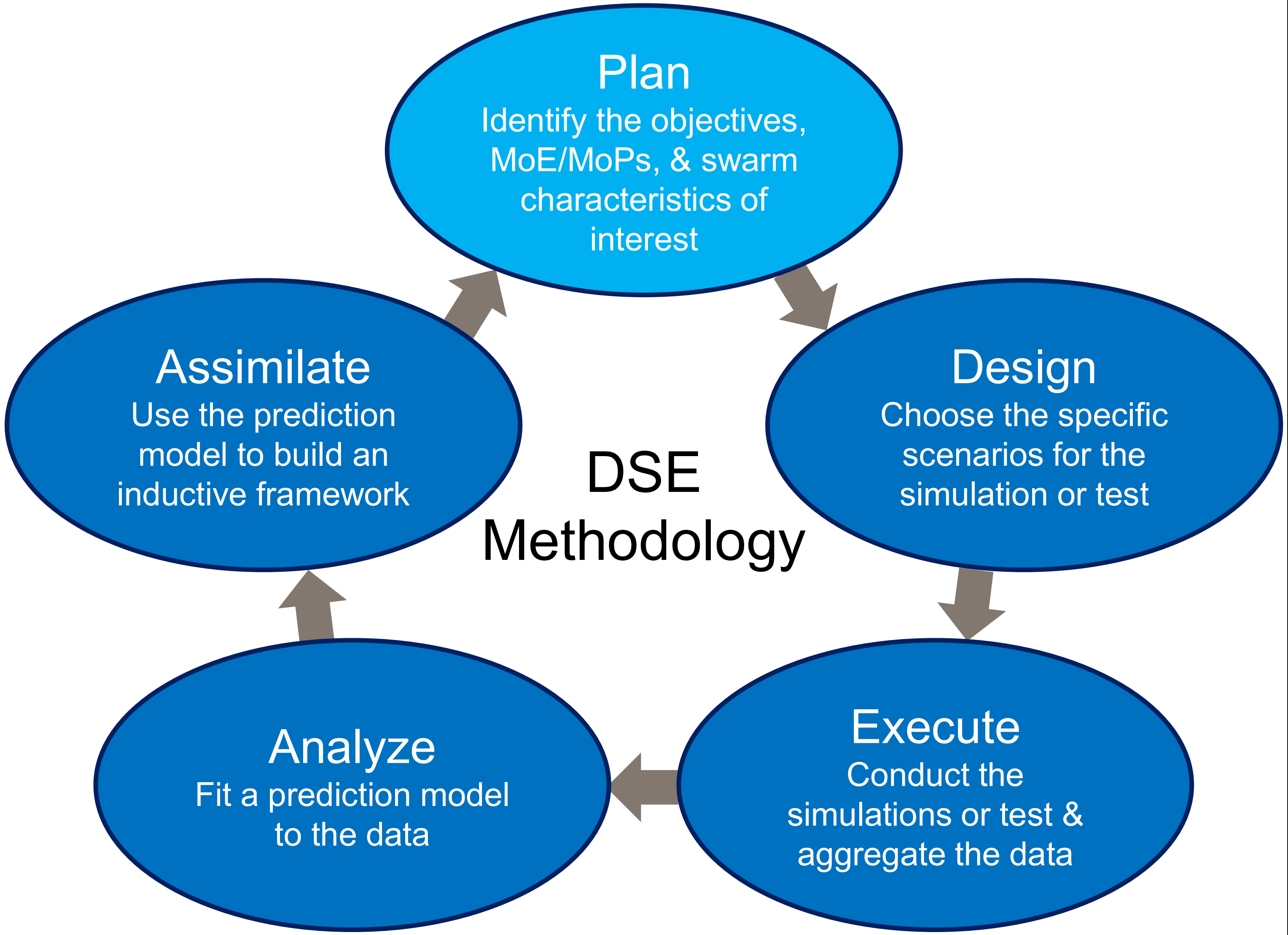
THE DESIGN OF SWARM EXPERIMENTS METHODOLOGY

- Design of Experiments techniques are used to systematically sample the design space
- Best practice method
  - Generate valid, useful data
  - Support the development of an accurate model
  - Describe and predict the behavior of the system
- Supports continued research: plan, design, execute, analyze, and assimilate new knowledge that leads to planning the next research effort



PLAN

- First and perhaps most important step of the DSE process
  - Upfront time and effort to properly define the problem generally leads to a net reduction in overall project resources
  - Knowing the end goal allows for the planning of a path to get there
- Three primary tasks
  - Identification of the objective
  - Identification of measures of effectiveness/measures of performance
  - Identification of swarm/entity characteristics



PLAN

Identification of the objective

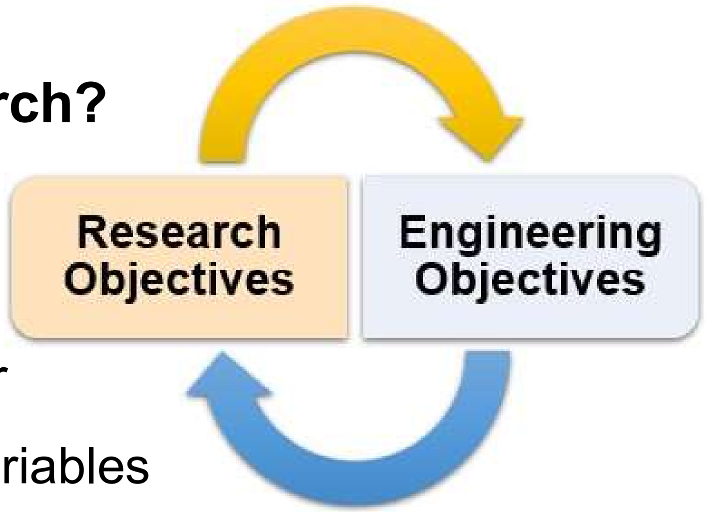
– Two primary questions to address

1. Why is your team conducting the research?

2. What does you team hope to accomplish as a result of the research?

– Consideration of Research and Engineering Objectives

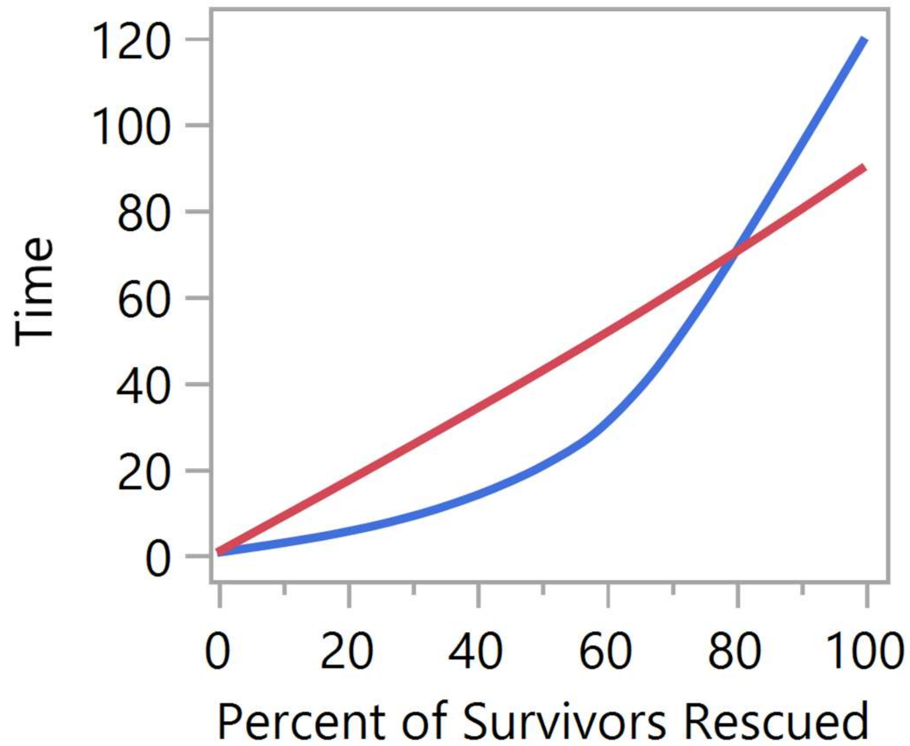
- Research Objectives
    - – Broad qualitative goals emphasizing general aspects of swarm behavior
    - – Understanding the interactions between independent and dependent variables
    - – Building of a theoretical framework explaining the interactions
- Engineering Objectives
    - – Based on quantitative measures considered in the context of specific applications
    - – Often mathematically expressed as a constrained optimization process
    - – Potentially a binary comparison between a proposed design relative to a baseline design



PLAN

Identification of measures of effectiveness & measures of performance

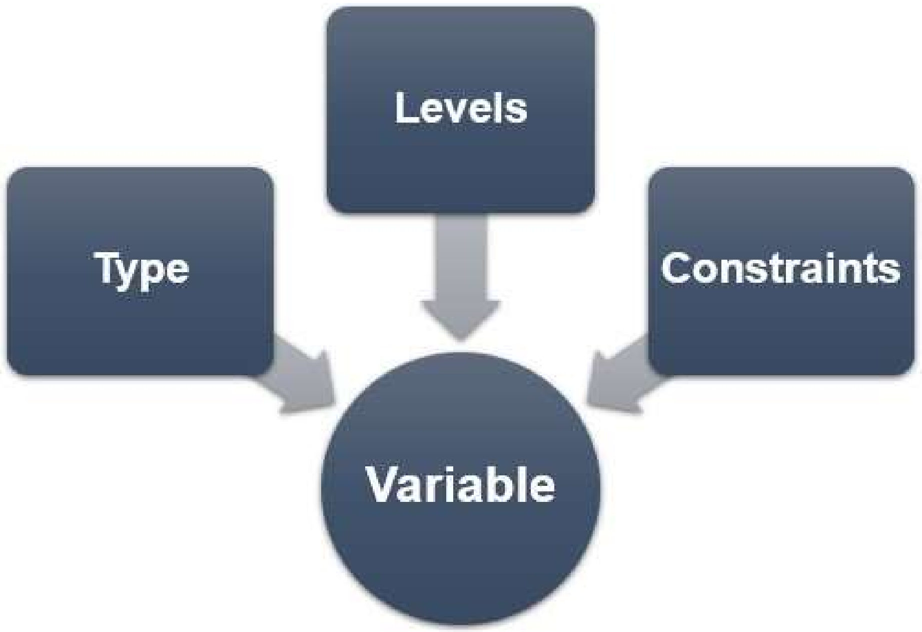
- These are the dependent or predicted variables, the output of the simulation or result of the test
- The metrics that matter and can be measured
- Consider both the engineering and research objectives, may be multiple ways of looking at the same data
  - Engineering MoP/MoE: Time to rescue 80% of survivors
  - Research objective may have you delve further into the performance over the entire mission time and differences in curve shape



PLAN

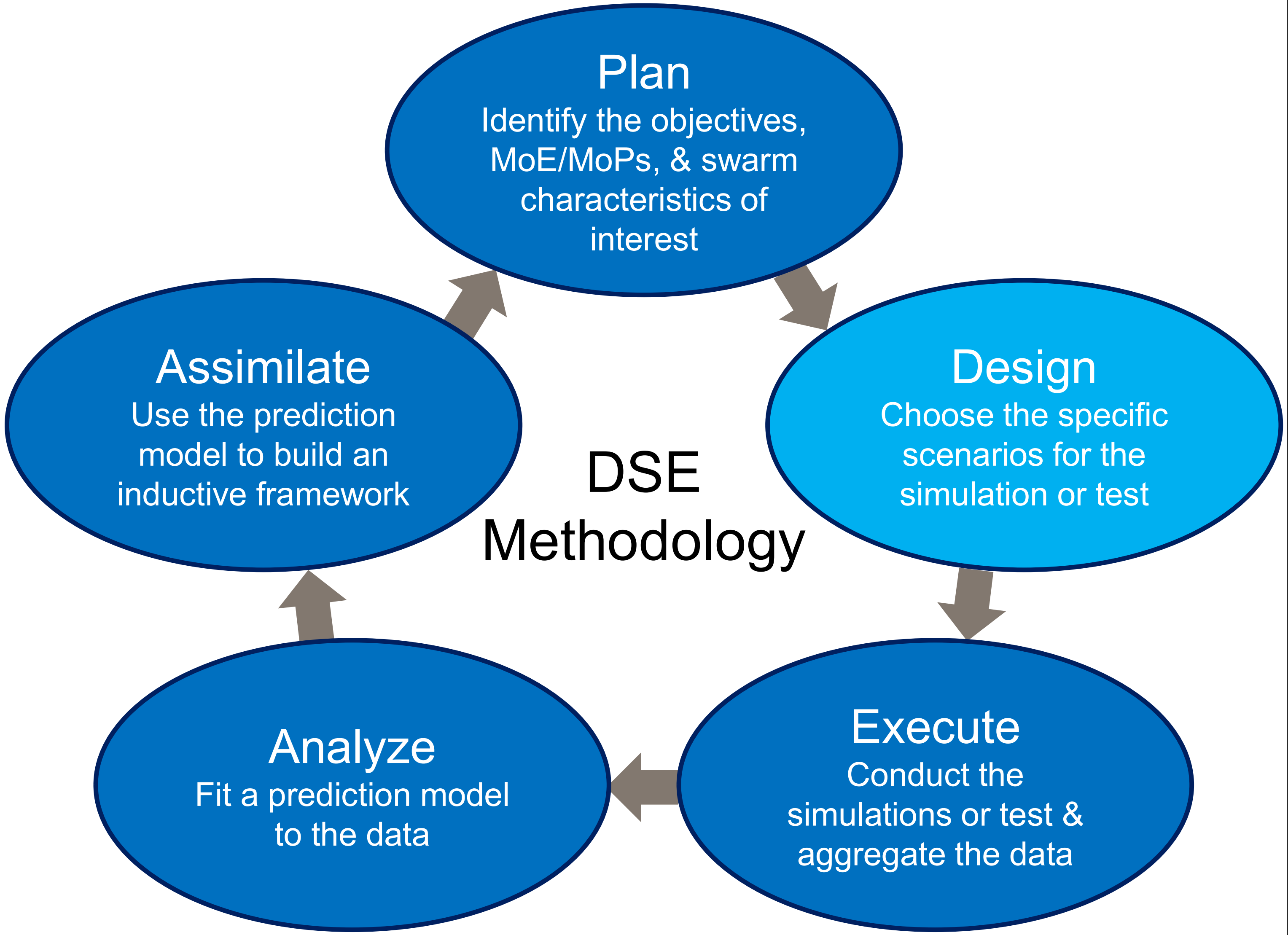
Identification of swarm/entity characteristics

- These are the independent predictor variables, the inputs of the simulation or what is being controlling in the test
- Type of variable
    - Continuous, discrete, mixture, categorical
- Range or levels of the variable
    - Minimum and maximum or discrete levels
- Constraints or combinations of variables that can’t physically be tested or would not be useful to test/simulate
    - Example: higher flight speeds will result in lower battery life



DESIGN

- What combinations of inputs to simulate or test?
- Design of experiments (DOE) approach
- Systematically vary the independent variables to identify the effect each has on the dependent variables
- 3 broad classes:
  - Factorial/Optimal Designs
  - Space Filling Designs
  - Hybrid Designs



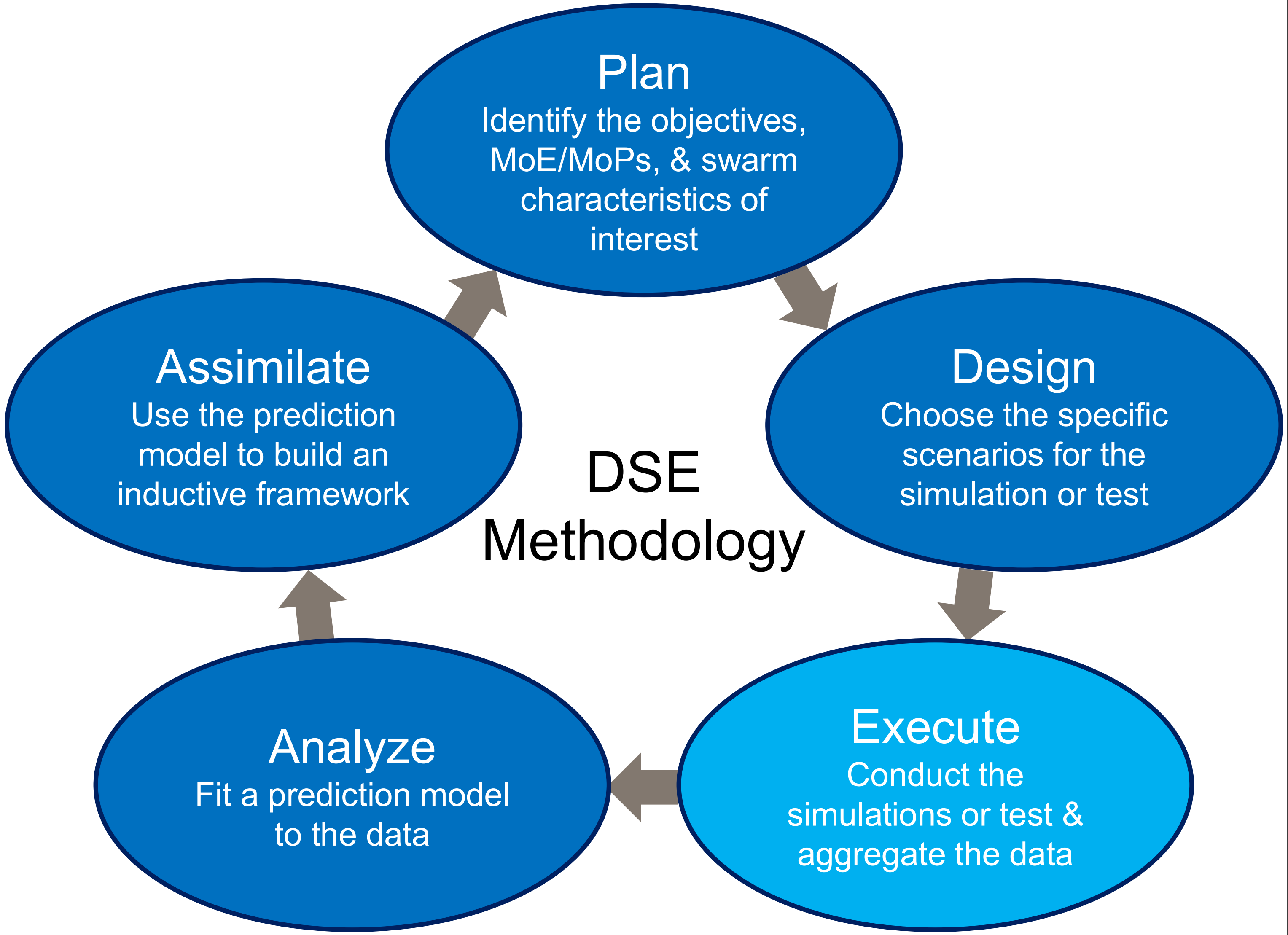
DESIGN

Recommended Designs for Drone Experiments

	Factorial and Optimal Designs	Space filling designs	Hybrid designs
Description	Place points in extremal corners to maximize leverage and achieve repetition in lower dimension projections	Distribute points throughout the design space, avoid repetition even in lower dimension projections	Combination of factorial/optimal and space filling designs
Expected Experimental Noise	**High** live testing, very noisy simulations	**Low** deterministic or low-noise simulations, high noise data that can be replicated	**Low to Mid**
Available Resources	**Low** typically 10-50 unique runs	**High** typically at least enough runs for 10x the number of factors	**Low to Mid**
Expected Response Behavior	**Simple** can be described by a multiple linear regression model	**Complex** high order, non-linear behavior	**In between**
Examples	Full factorial designs, Fractional factorial designs, D-optimal designs, I-optimal designs	Latin Hypercube, Maximum Projection, D-optimal Latin Hypercube	Space filling augmented with I-optimal points, Fractional factorial augmented with space filling points

EXECUTE

- Run the simulations or conduct the test
- Recommend putting some upfront effort into automation
  - Simulation setup, submission of runs, extraction of results, and data aggregation
- Track and report any errors and outlier runs
  - Analysis of this data can aid in identifying implementation issues
  - Can lead to improved verification of the model/simulation



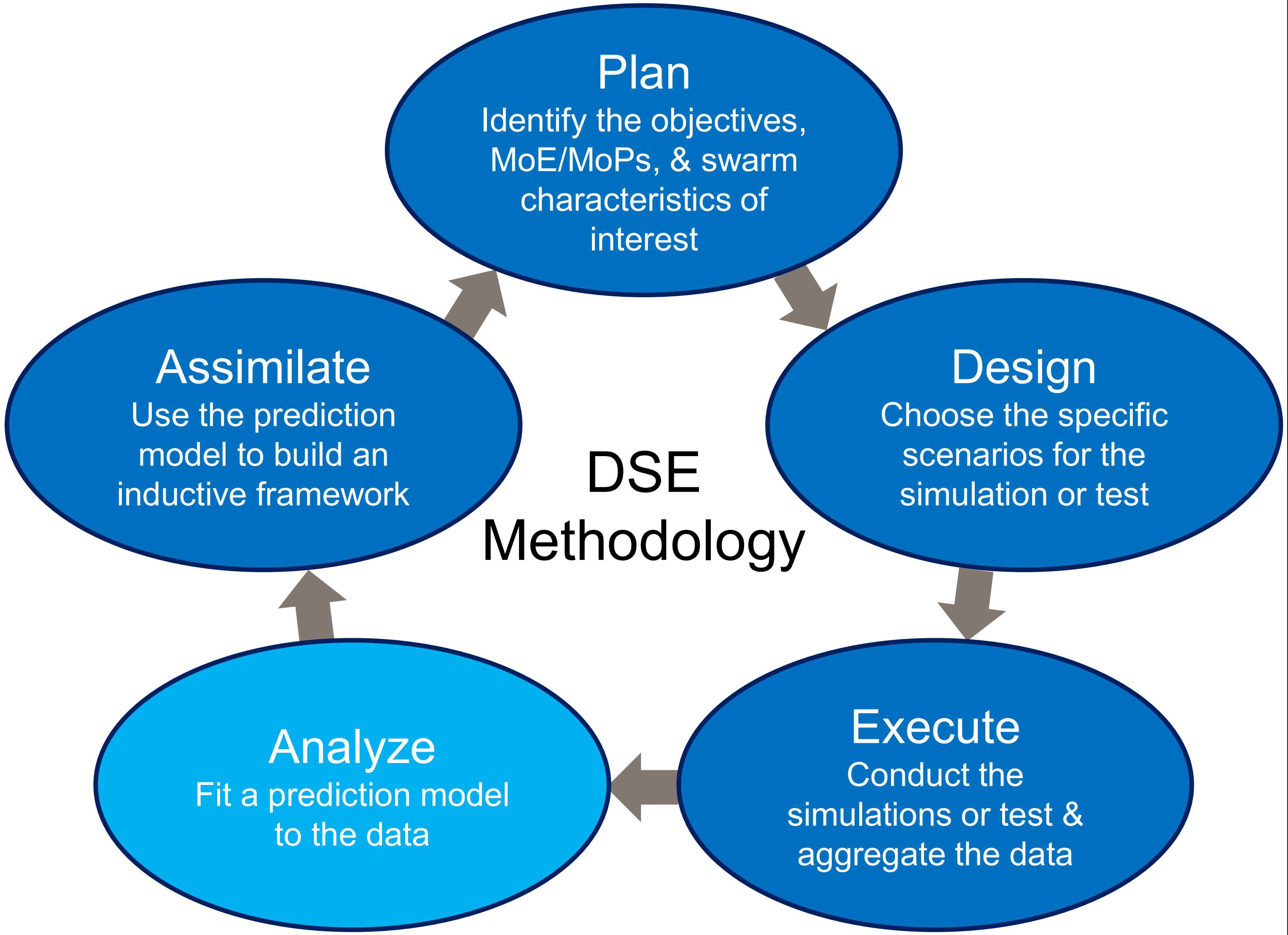
EXECUTE

Sample Simulation Matrix

Simulation Number	Total Drones	Portion Relay	Portion Spiral	Portion Anti-Social	WiFi Range	Scenario	Terrain	Time to find 80% of survivors	Error Flag	Outlier Flag
1	17	0.29	0.65	0.06	63	B	urban	•	•	•
2	35	0.29	0.51	0.20	585	B	rural	•	•	•
3	11	0.55	0.18	0.27	61	A	rural	•	•	•
4	47	0.19	0.60	0.21	796	B	urban	•	•	•
5	46	0.13	0.15	0.72	735	A	urban	•	•	•
6	20	0.40	0.05	0.55	650	B	urban	•	•	•
7	25	0.00	0.28	0.72	197	A	urban	•	•	•
8	17	0.12	0.29	0.59	102	B	urban	•	•	•
9	37	0.78	0.14	0.08	548	B	urban	•	•	•
10	22	0.18	0.64	0.18	416	B	rural	•	•	•
11	31	0.77	0.19	0.03	84	A	rural	•	•	•
12	32	0.59	0.22	0.19	672	B	urban	•	•	•
13	13	0.54	0.23	0.23	577	B	urban	•	•	•
14	19	0.11	0.26	0.63	799	A	rural	•	•	•
15	13	0.23	0.54	0.23	57	A	urban	•	•	•
16	37	0.30	0.27	0.43	54	B	rural	•	•	•
17	45	0.47	0.02	0.51	794	A	rural	•	•	•
18	9	0.11	0.89	0.00	599	A	rural	•	•	•
19	37	0.30	0.19	0.51	789	A	rural	•	•	•
20	32	0.47	0.53	0.00	770	A	rural	•	•	•

ANALYZE

- The process of fitting a prediction model to data is commonly called statistical learning or machine learning
- Fit a mathematical equation to predict the output as a function of all the inputs
- Large number of model fitting methods exist; several are recommended for designed experiments and continuous response data
  - Linear Regression
  - Gaussian Process/Kriging
  - Neural Networks



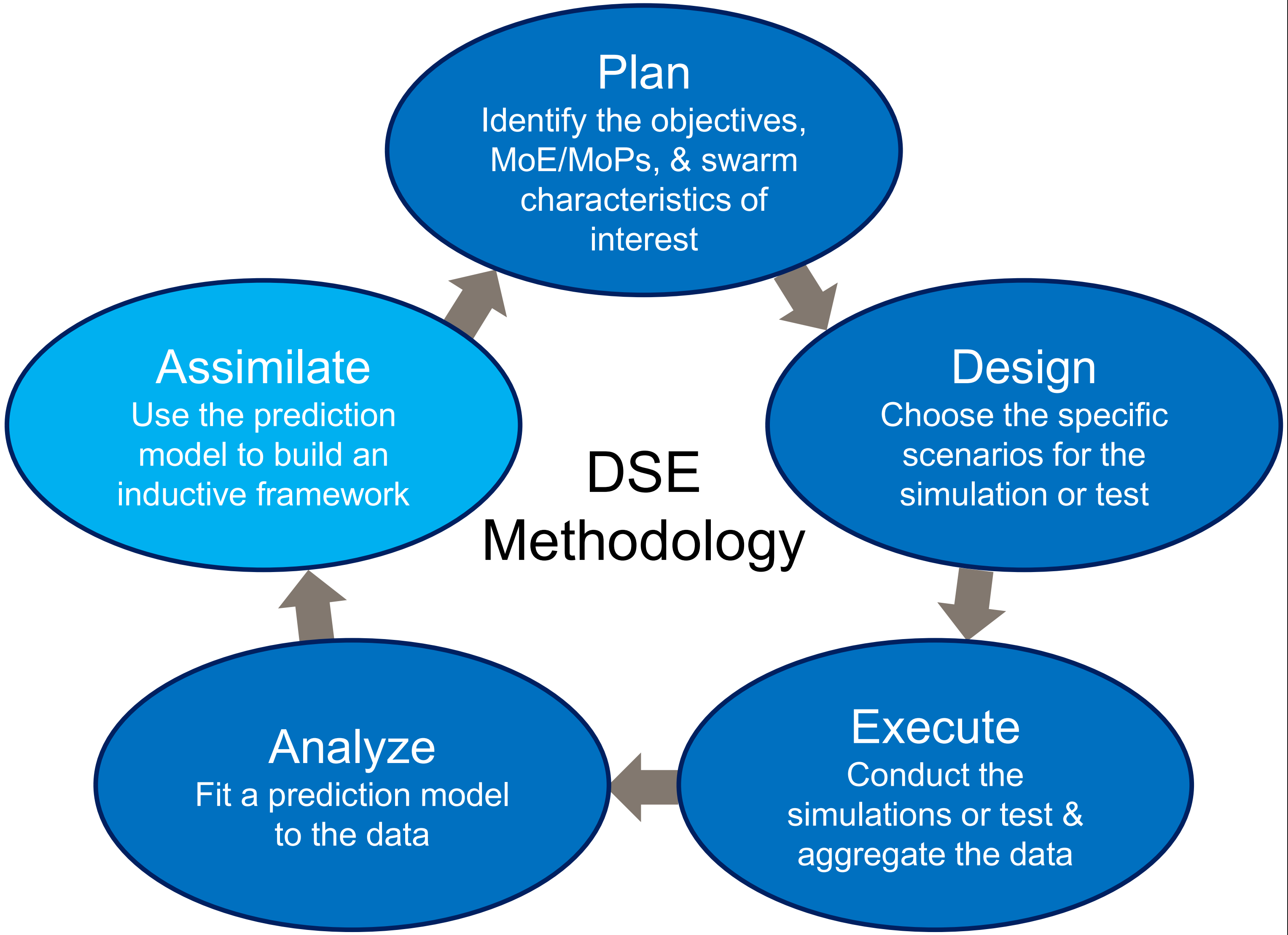
ANALYZE

Recommended Model-Fitting Methods for Drone Experiments

	Linear Regression	Gaussian Process	Neural Networks
Description	Linear approximation of response based on one or more predictor variables	Multidimensional interpolation using spatial correlation to make predictions	A set of inter-connected feedforward activation functions loosely inspired by the architecture of a biological brain
Advantages	Simple and highly interpretable, Estimate of expected model error, Estimate of expected error of predictions	Excels at fitting highly complex response surfaces, Estimate of expected model error	Excels at fitting highly complex response surfaces
Typical Uses	Simple response behavior	Complex response behavior	Complex response behavior with large amounts of data

ASSIMILATE

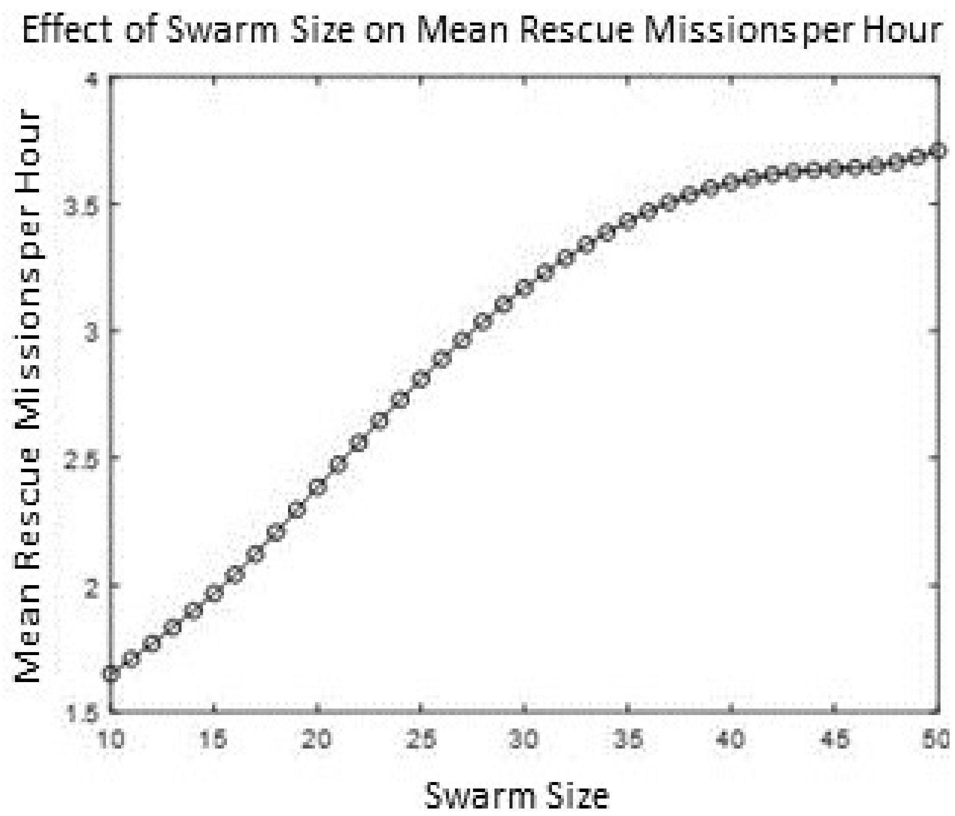
- What can be learned from the prediction model?
- Model is a closed form equation that can near instantaneously emulate the simulator or test
  - Make predictions anywhere within the original variable bounds
  - Easily see relationships between inputs and outputs
  - Numerically optimize for specific scenarios or goals
  - Rank the importance of independent variable on the outputs of interest



ASSIMILATE

Research Goals

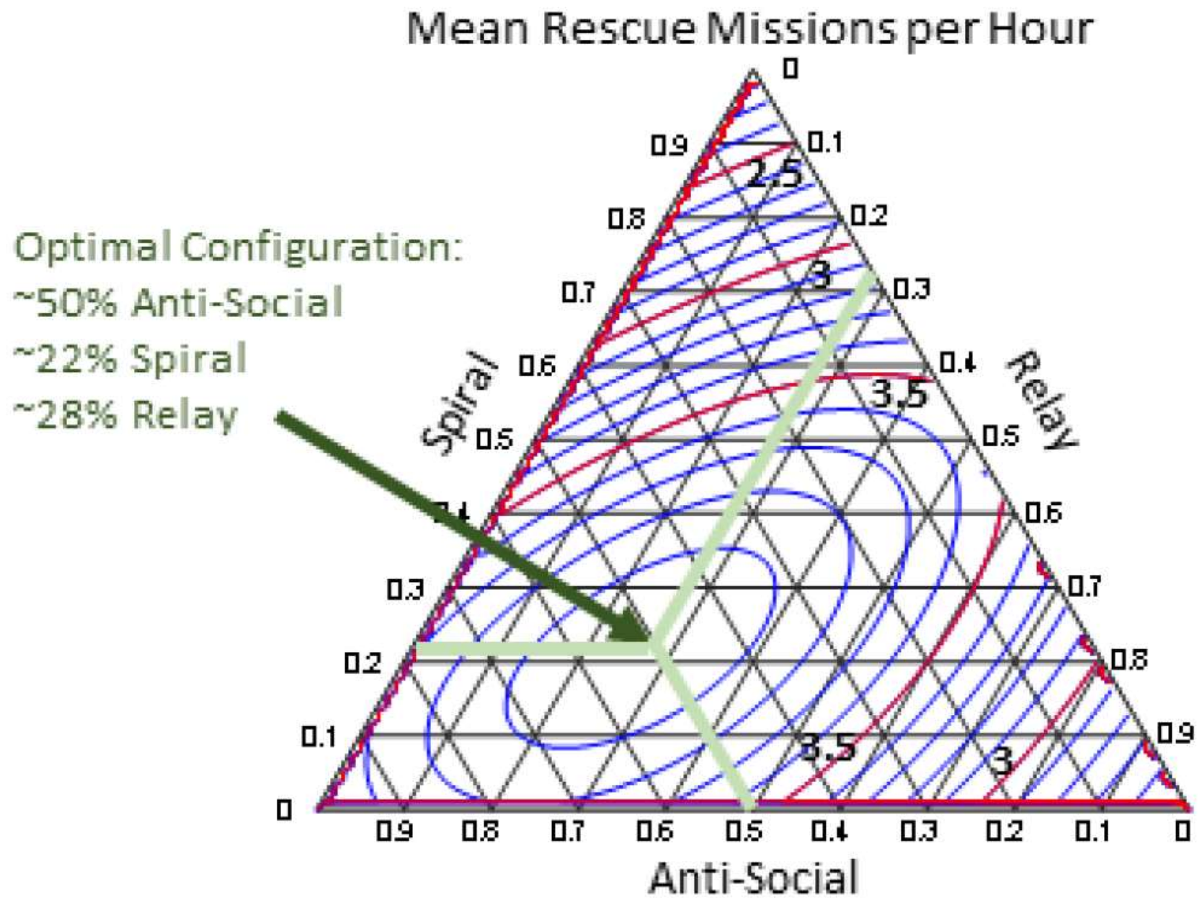
– Assessing old or formulating new hypotheses
– Understanding general interactions between independent and dependent variables
– Identifying regions in the design space which demarcate fundamentally different regimes of swarm behavior



ASSIMILATE

Engineering Goals

- Optimizing a swarm design relative to MoPs or MoEs
- Conducting trade studies in which physical specifications or behavioral roles are studied
- Assessing a swarm performance in “edge-cases” or mission critical scenarios



CONCLUSIONS

- Design of swarm experiments is a novel, rigorous method to systematically explore swarm and multi-agent systems in the face of uncertainty
- Generally applicable across the research community
- Explore both deterministic and non-deterministic problems
- Applicable to live swarm robotic testing and simulation environments
- Results in the ability to thoroughly explore and understand the behavior of multiple inputs and design parameters on the outputs of interest

QUESTIONS

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Melissa Jablonski
Systems Analysis Division
DEVCOM Armaments Center
melissa.n.jablonski.civ@army.mil
973-724-9912