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14. ABSTRACT
This talk presents an in-advance planning optimization model, developed in partnership between Kessel Run and MITRE, for assigning tankers to receivers for aerial refueling while also factoring in a large list of operational constraints and considerations. Also discussed will be the additional challenges and opportunities with developing an optimization-based decision support system for USAF tanker planning as well as “man vs. machine” results highlighting the substantial potential benefits of optimization-based planning.

15. SUBJECT TERMS
Modeling and Simulation; Air Force Operations; jigsaw; tankers; optimization capability; sliding window phase

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USAF Tanker Planning Optimization

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Joint work with:

MITRE

USAF Kessel Run

Image from defense.gov

Project Background

- Until 2018, tanker plans were created on a whiteboard

- Kessel Run—the AOC-WS System Program Office—changed this by rapidly fielding a tanker planning tool called **Jigsaw**

- **Jigsaw** = Application for manually creating tanker plans
  - Saves time by automatically aggregating data
  - Provides real-time feasibility and efficiency metrics, resulting in better plans

- Now MITRE and Kessel Run are prototyping an optimization engine for a tanker planning system

Project Scope

- Focus: in-advance tanker planning
  - Optimizing refueling sequences; not tactical flight paths
  - Optimizing for a single 24-hour window
- Scale: Hundreds of requests w/ tens of tankers
- Design for Human-Machine Teaming
  - User should be able to edit and override plans
  - User may want to specify feasibility thresholds and trade-offs for optimizer

Image from af.mil

Why Build an Optimization Capability?

- **<u>Save Time</u>** – Automatically draft operator-quality plans
  - Users can do other things while plans are being drafted
  - Users can review and edit plans when they are done
  - Create time for users to solve other problems

- **<u>Boost Efficiency</u> –** Consider overwhelming numbers of possible plans and identify how to do more with limited tankers
  - Fulfill more requests within the preferred parameters while burning less fuel

Optimizer Can Double as a What-If Tool

- **Investigate how various changes could impact day-to-day operations, e.g.:**
  - What if tankers are repositioned to different bases?
  - What if the volume of requests increases?
  - What are the benefits of changing track locations?
  - What if we have more or fewer tankers? Many small unmanned tankers?
  - What if we have tankers with different performance characteristics?
  - What if we could turn tankers faster, e.g., via hot refueling?
  - What if we gain/lose certain diplomatic clearances?
  - What if we change our policy for using coalition tankers?

Optimizer Can Double as a Mechanical Turk

- Automatically generate “good enough” tanker plans for the purposes of simulation exercises and wargaming

Image from afcent.af.mil

Modeling Approach

High Level Problem Statement

- **Decide:**
  - Which tankers should service which receivers

- **Objective:**
  - Primarily maximize service—number of requests that can be fulfilled within requirements
  - Secondarily minimize a weighted combination of sorties and fuel burn

Image from amc.af.mil

Basic Problem Elements

Image from amc.af.mil

- **Tankers:**
  - Several types with different capacities
  - Have an associated base at which it must depart and return
  - Burn and deliver fuel from the same reserve
  - Can be configured to service different receiver types
- **Requests:**
  - **Basic Type:** For a specific amount of fuel at a specific track at a specific time
  - **Drag Request:** Meet at track A at time $T_{1,}$ follow receiver to track B at time $T_{2,}$ deliver X lbs of fuel over course of journey
- **Tracks:**
  - Pre-defined locations at which tankers can (wait to) meet receivers
  - At most one tanker can be in a track at any time

Model Constraints

- Limited tanker fleet
- Tanker capacities
- Tanker-receiver compatibility
- Plan for track jump time
- Maximum sortie length
- Minimum on-ground turn time
- Track capacity constraints
- Must return to home station
- Plan around sorties fixed by user
- Drag requirements
- Performance-limited requests
- Repeat customer preferences

List has been refined from many rounds of feedback with operational experts

Photo from safie.hq.af.mil

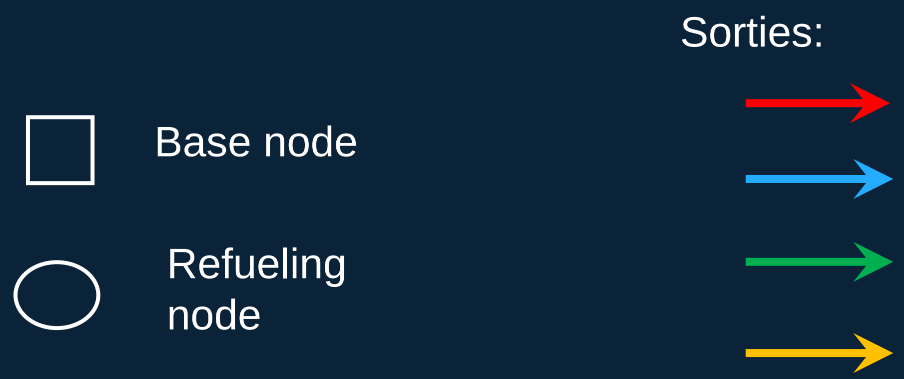
Optimization Process

- Three key steps:
  - **Step 1:** Construct a node-edge graph to define the refueling sequences the model will consider
  - **Step 2:** Use that graph to define an integer programming optimization model
  - **Step 3:** Construct a good solution according to the integer program using a two-pass decomposition heuristic

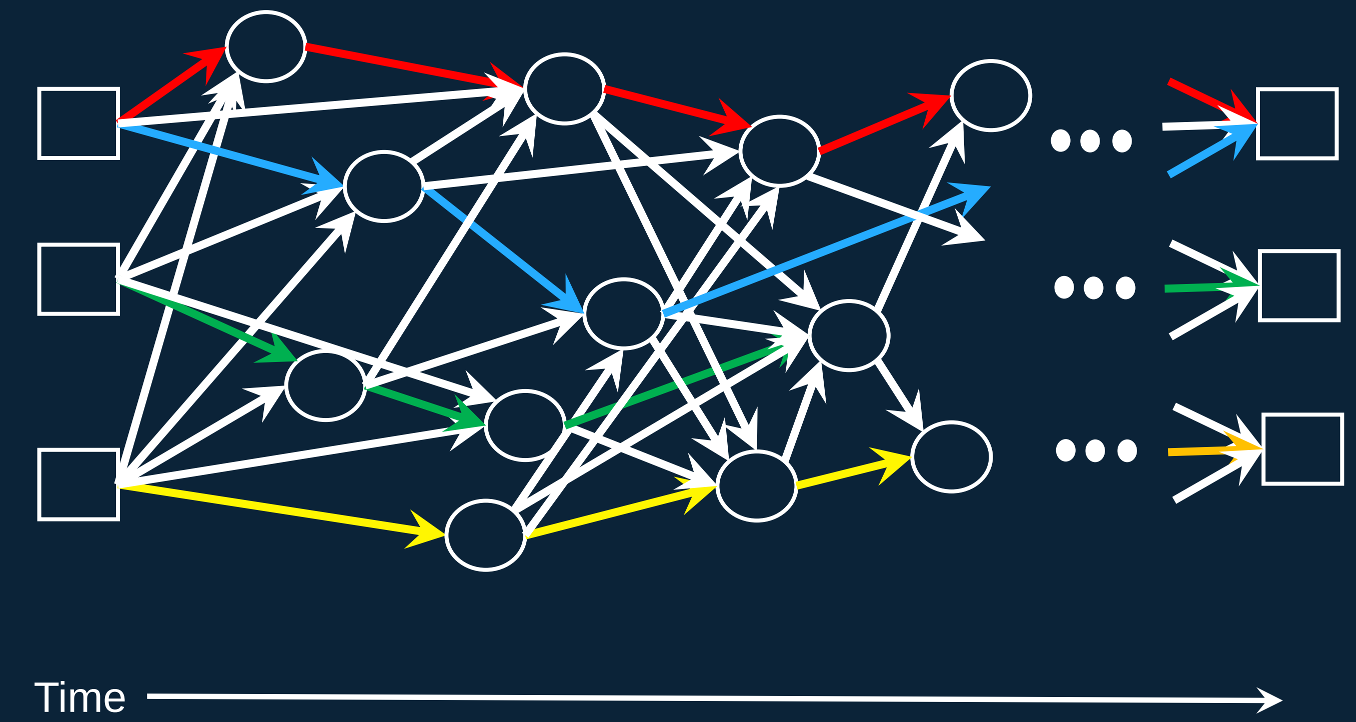
Graph Construction

- Graph defines the refueling sequences and track jumps to consider
  - **Nodes** are requests or bases
  - **Edges** specify back-to-back activities
  - **Edges** are not created if:
    - **Requests are too far apart in time**
    - **Tanker could not reposition in time for the next request**
    - **Requests would be needlessly bypassed**
  - **Paths** are potential sorties

- Graph implicitly enforces several constraints

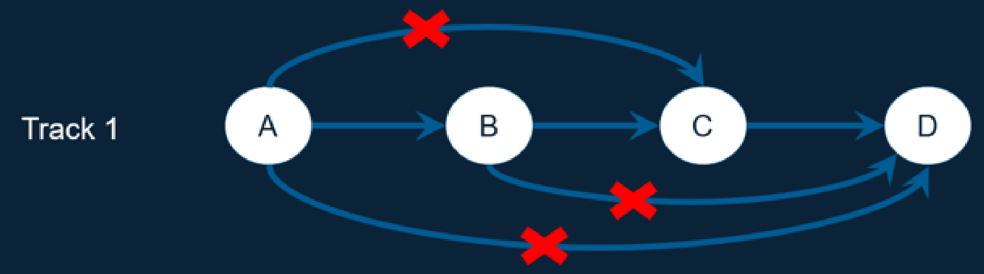


Notional time-space network with 3 bases

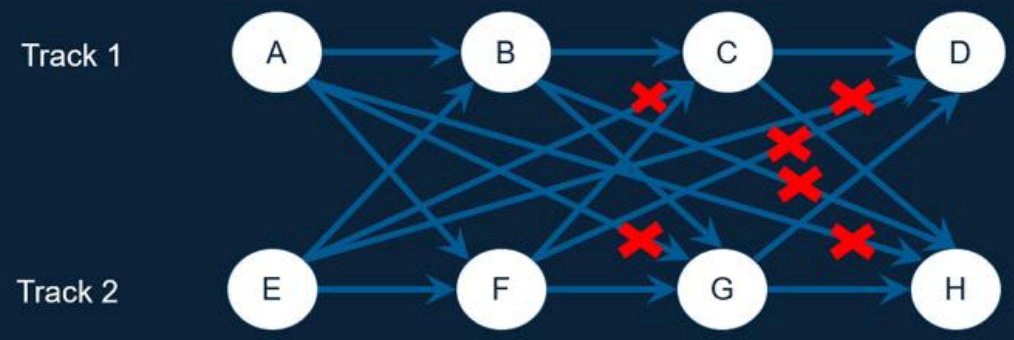


Graph explicitly enforces track capacity constraints

- Graph does not allow tankers to needlessly bypass requests
  - I.e., tanker would be in position to service a request but does not
- Prevents multiple tankers from existing in the same track at the same time
- Also a dimension reduction heuristic



Same-track notional example



Track jump notional example

Integer Programming Model

- Main Decision Variables:
  - 1 If tanker t should use edge **e** in the graph; 0 otherwise

- Minimizing weighted combination of:
  - Penalties for missing requests
  - Fuel burn estimates
  - Penalty for each additional sortie

- Basic constraints include:
  - One sortie and config per tanker
  - Tanker flow balance constraints
  - Request satisfaction constraints
  - Tanker capacity constraints
  - Maximum sortie length constraints

Minimize

$$\sum_{r \in R} pen_r \; skip_r + \sum_{\tau \in \mathcal{T}} burn_\tau \; e_\tau + \sum_{\tau \in \mathcal{T}(TO(.,.))} pen_{mx} \; e_\tau$$

$$\sum_{\tau \in \mathcal{T}(RS(r))} e_\tau + skip_r = 1 \qquad \forall\, r \in R$$

$$\sum_{\tau \in \mathcal{T}(TO(t))} e_\tau \leq 1 \qquad \forall\, t \in T$$

$$\sum_{\tau \in \mathcal{T}(RS(t,x,r))} e_\tau - \sum_{\tau \in \mathcal{T}(FS(t,x,r))} e_\tau = 0 \qquad \forall\, r \in R;\ \forall\, x \in CFG(t)$$

$$\forall\, t \in T$$

$$\sum_{\tau \in \mathcal{T}(TO(t))} (burn_\tau + deliv_\tau) e_\tau \leq cap(t) \qquad \forall\, t \in T$$

$$\sum_{\tau \in \mathcal{T}(TO(t))} time_\tau e_\tau \leq MaxTime \qquad \forall\, t \in T$$

Minimum Turn Time Constraints

- **Requirement:** Need a minimum amount of time before a tanker can fly a second sortie
- **Step 1:** Model a potential second sortie as a separate tanker and couple it with a "frontline" tanker
- **Step 2:** Add the following if-then constraints:
  - If turn tanker t_2 is going to use take-off edge e_j then corresponding frontline tanker t_1 must have used a landing edge that would afford at least X hours to turn the tanker
  - At least Y hours if the tanker is to be re-configured

$$\sum_{\tau \in \mathcal{T}(LE(\pi(t)),x,x,v) \bigcup \mathcal{T}(LE(\pi(t)),!x,x,v)} e_\tau \geq e_{t,x,h(t),v} \qquad \forall \ (t,x,h(t),v) \in \mathcal{T}(TTO(t))$$

Performance-Limited Request Constraints

- **Requirement:** Performance-limited requests require the tanker to be sufficiently empty so it can descend to a low altitude
- Add the following if-then constraints:
  - If tanker **t** is going to be assigned performance-limited-request **r** then tanker **t** must have burned and delivered a minimum amount of fuel prior to serving **r**

$$\sum_{\tau \in \mathcal{T}(RS(r,t))} burn_\tau \, e_\tau + \sum_{\tau \in \mathcal{T}(Bef(r,t))} (burn_\tau + deliv_\tau) \, e_\tau \geq MinOff(r,t) \sum_{\tau \in \mathcal{T}(RS(r,t))} e_\tau \qquad \forall \, t \in T; \forall \, r \in PLR$$

Heuristically Solving the Integer Program

- **Challenge:** Cannot feed the entire integer program to the solver at once
  - The solver may take too long to produce a decent looking solution

- **Solution:** Iteratively improve a solution by only working with a subset of the variables at any time

- Frequently called a **matheuristic approach**
  - **Matheuristic = Mathematical-programming-based heuristics**

Solving the Integer Program with Heuristics

Basic Idea:

- Define the complete integer program
- **For** each of two phases:
  - **While** not done:
    - Fix a subset of the variables
    - Solve the remaining sub-model as an integer program, starting from the current best known solution
    - Update the best known solution

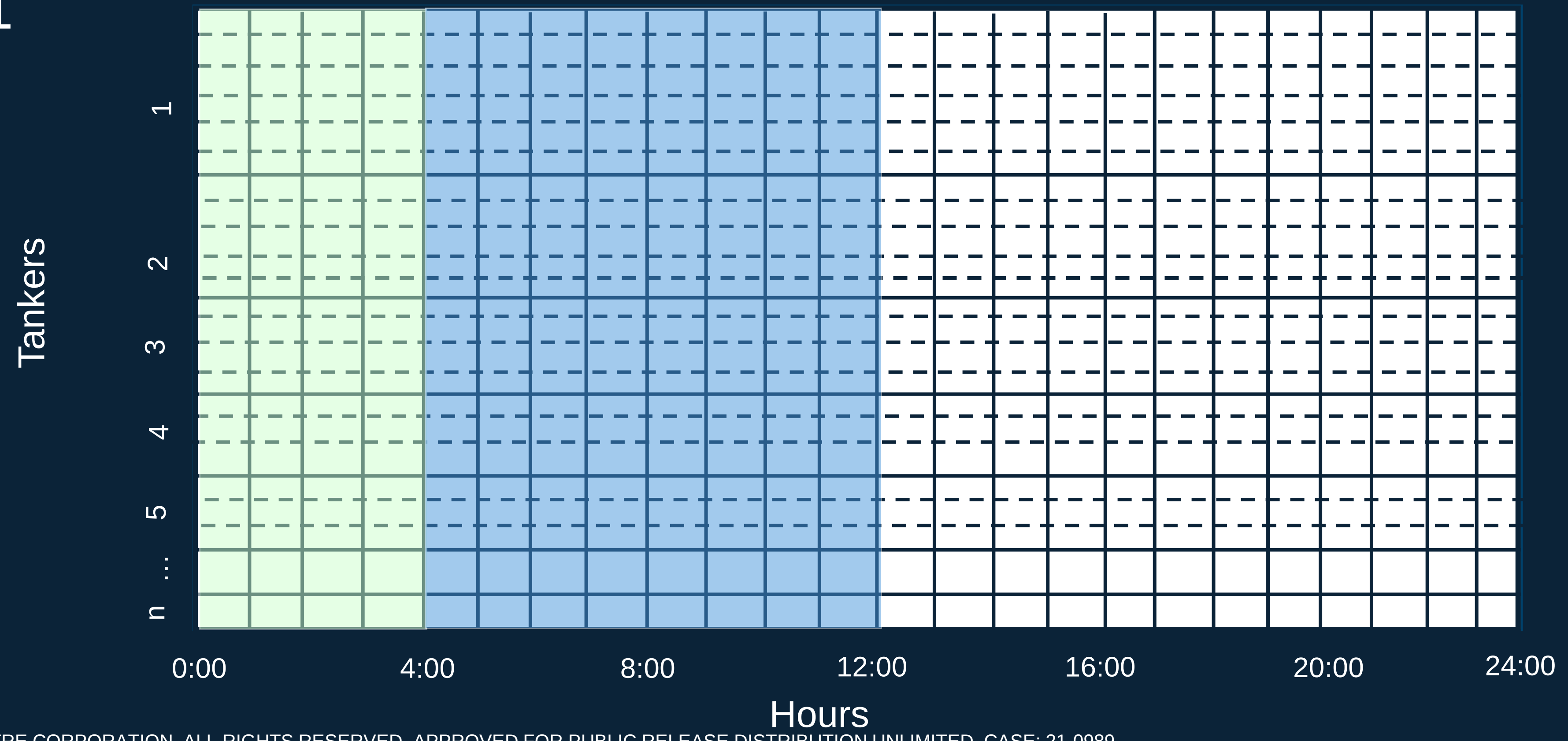
- Two phases:
  - **Sliding window phase** makes earlier day decisions before later ones
  - **Regional swap phase** looks at the entire planning window for subsets of tankers

Notional Example: The Sliding Window Phase

Key:

- (green) Decisions being optimized that will be locked by the end of this step
- (blue) Additional decisions being optimized

Sliding window phase step 1



Notional Example: The Sliding Window Phase

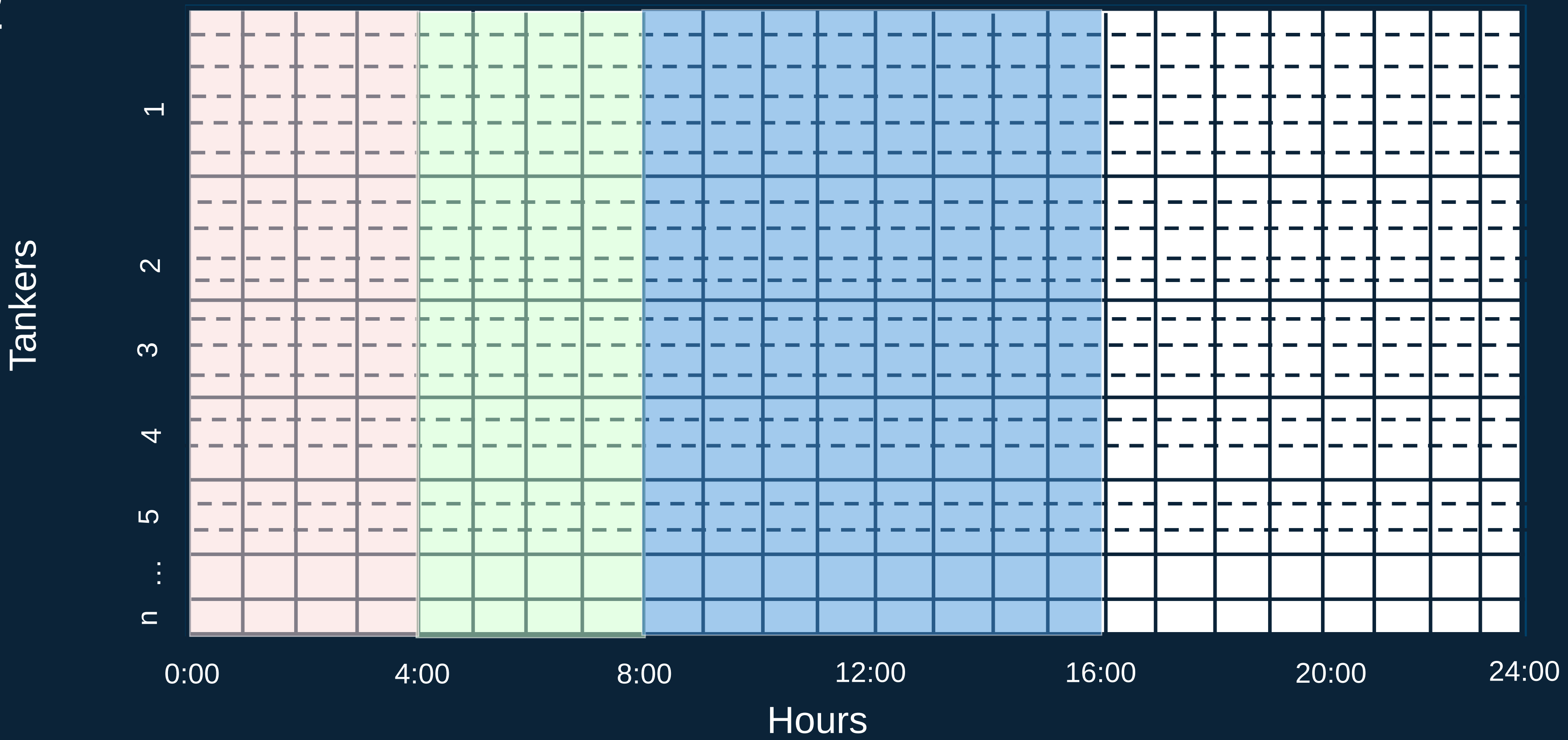
Key:

Decisions being optimized that will be locked by the end of this step

Additional decisions being optimized

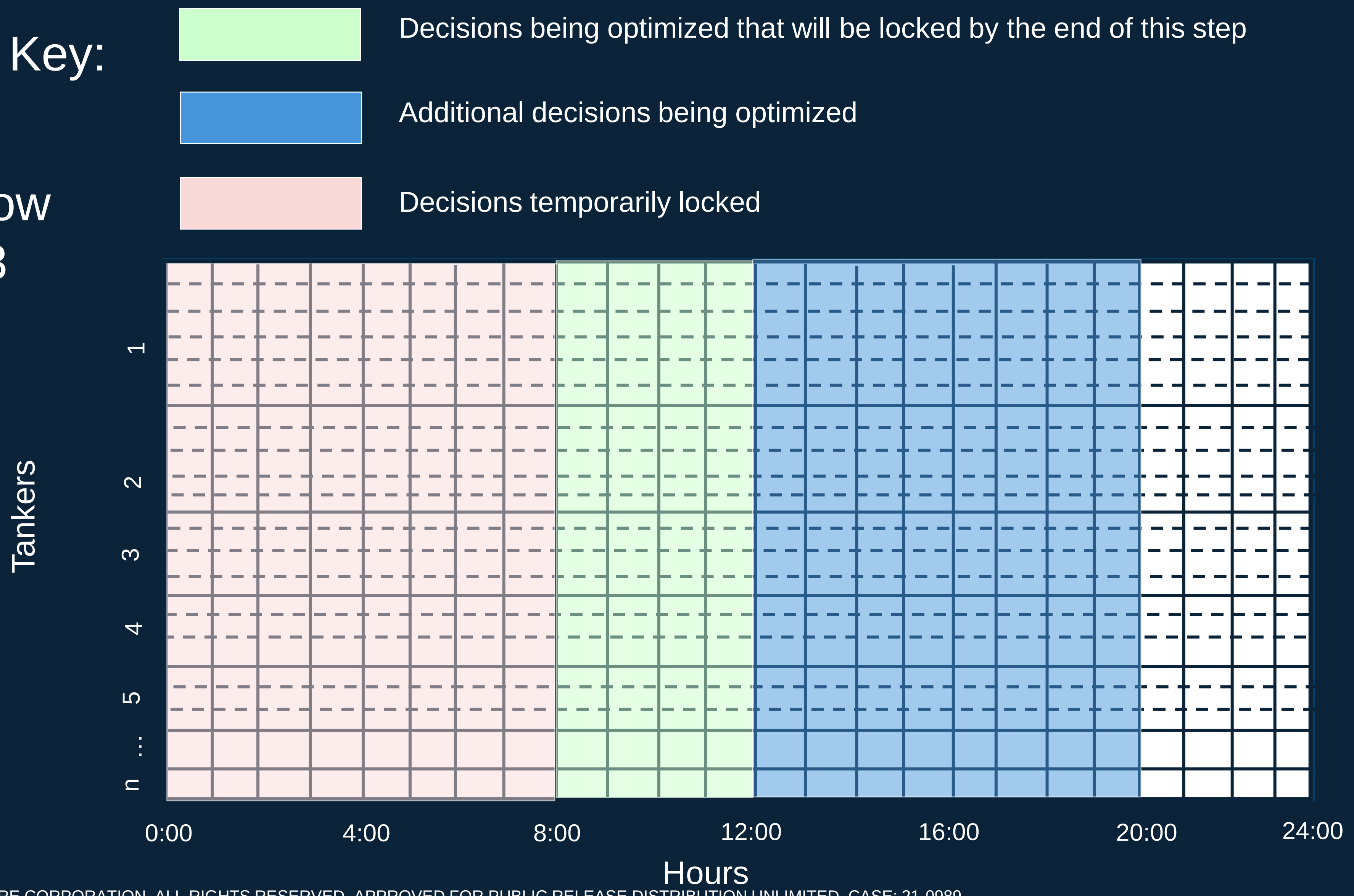
Decisions temporarily locked

Sliding window phase step 2



Notional Example: The Sliding Window Phase

Sliding window phase step 3

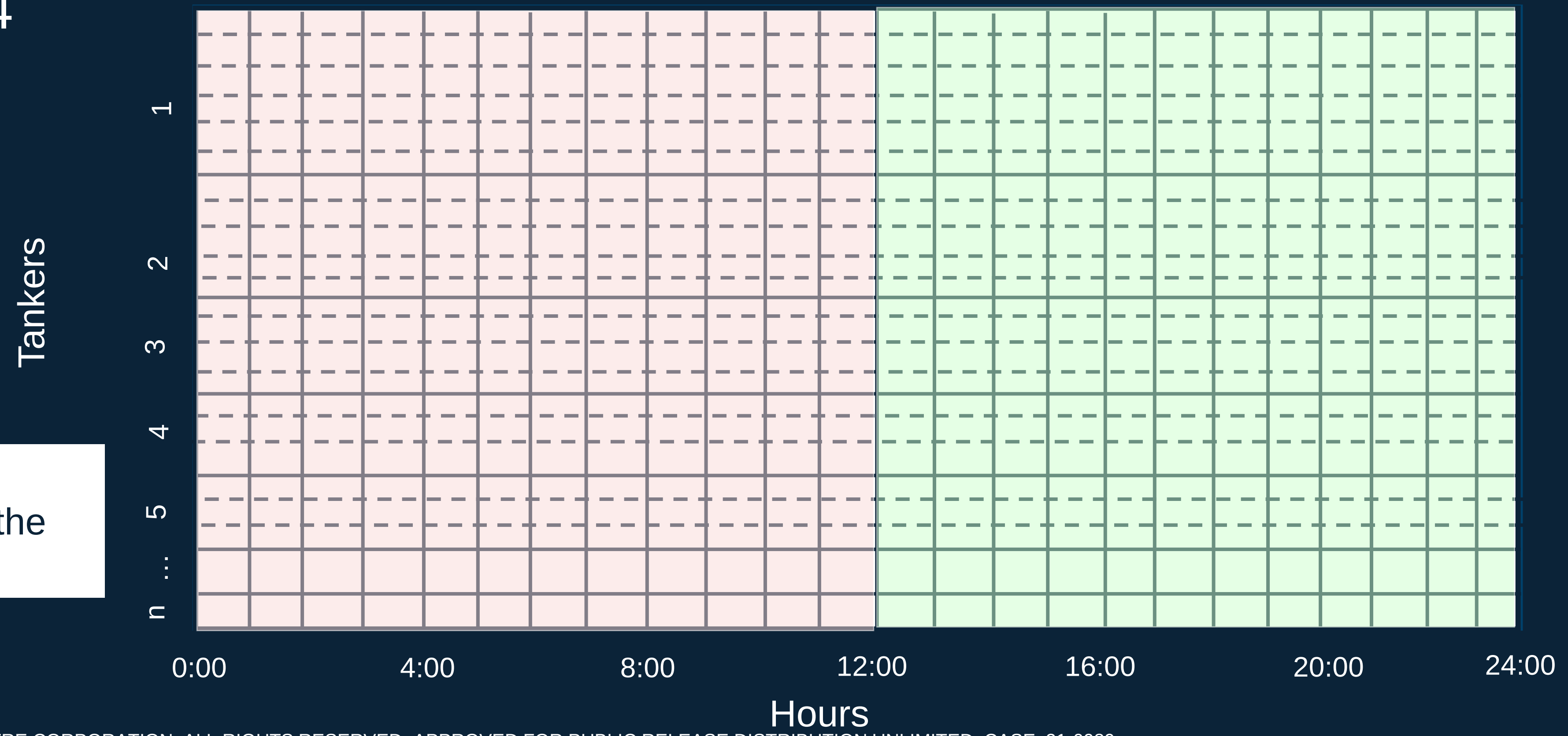


Notional Example: The Sliding Window Phase

Key:

- Decisions being optimized that will be locked by the end of this step
- Additional decisions being optimized
- Decisions temporarily locked

Sliding window phase step 4



Steps taken is configurable, as is the time spent per step

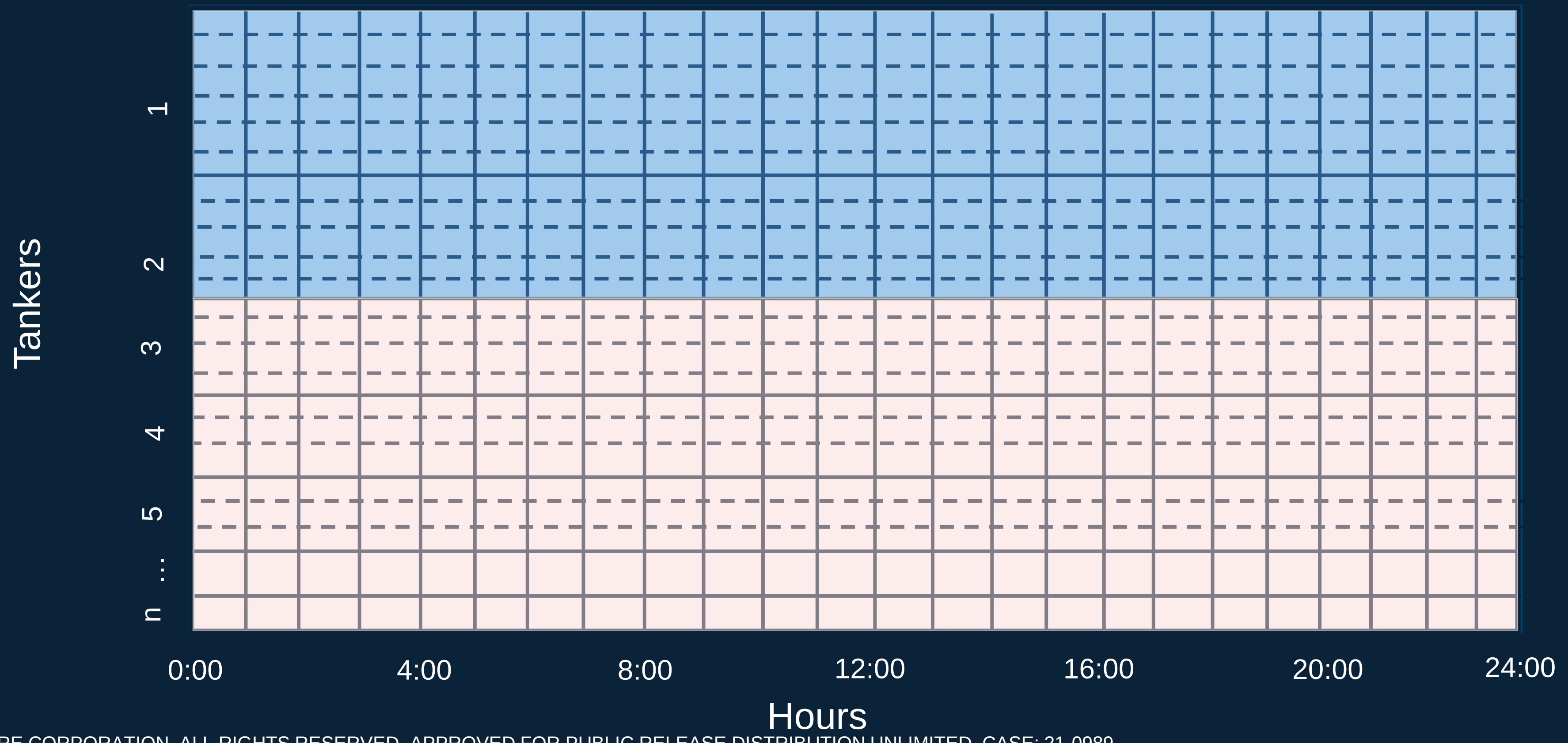
Notional Example: The Regional Swap Phase

Key:

Decisions being further optimized

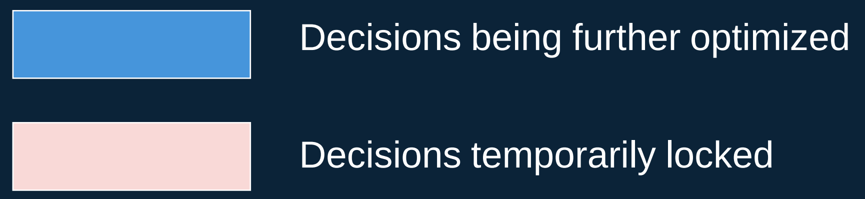
Decisions temporarily locked

Regional swap
step 1

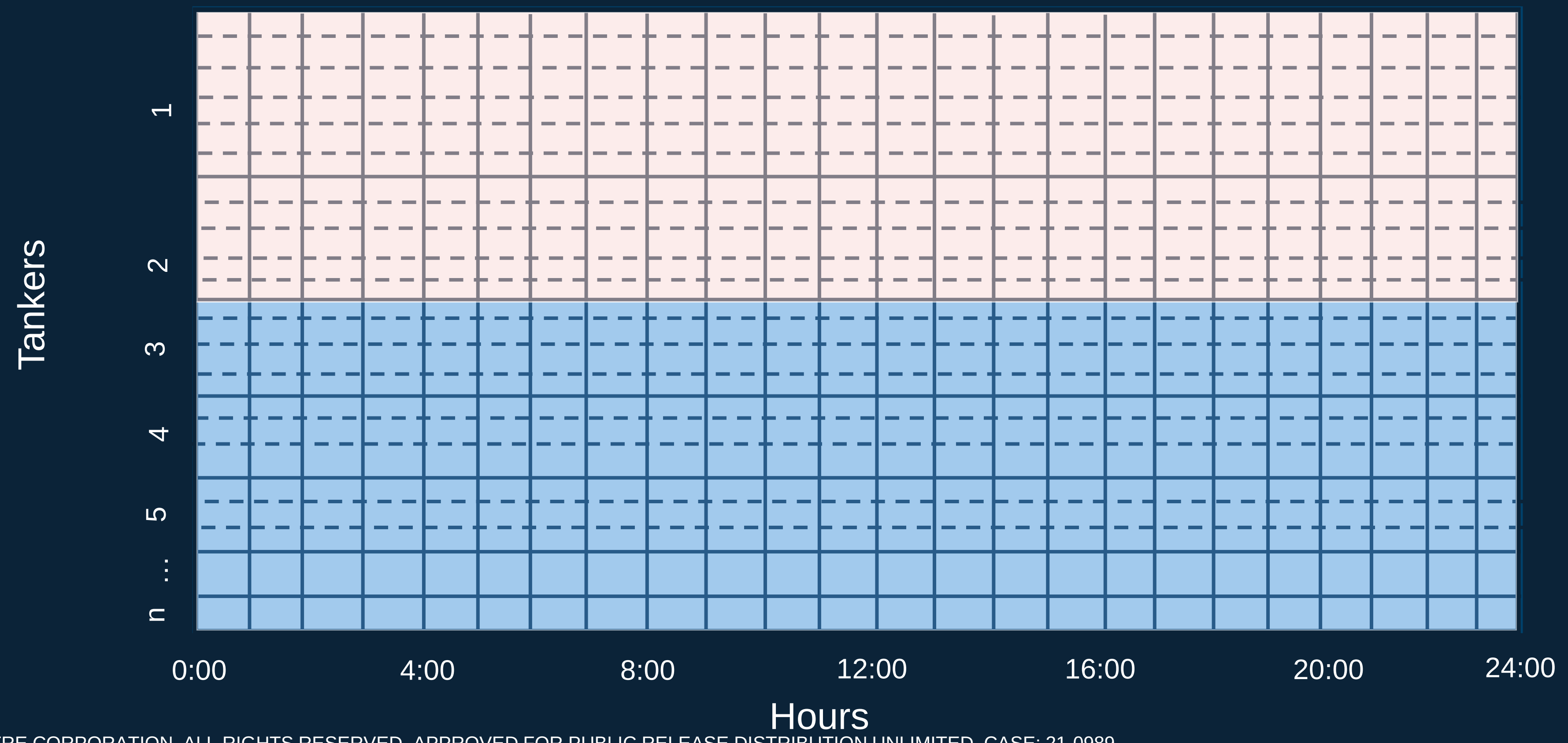


Notional Example: The Regional Swap Phase

Key:



Regional swap step 2



MITRE

Experimental Results

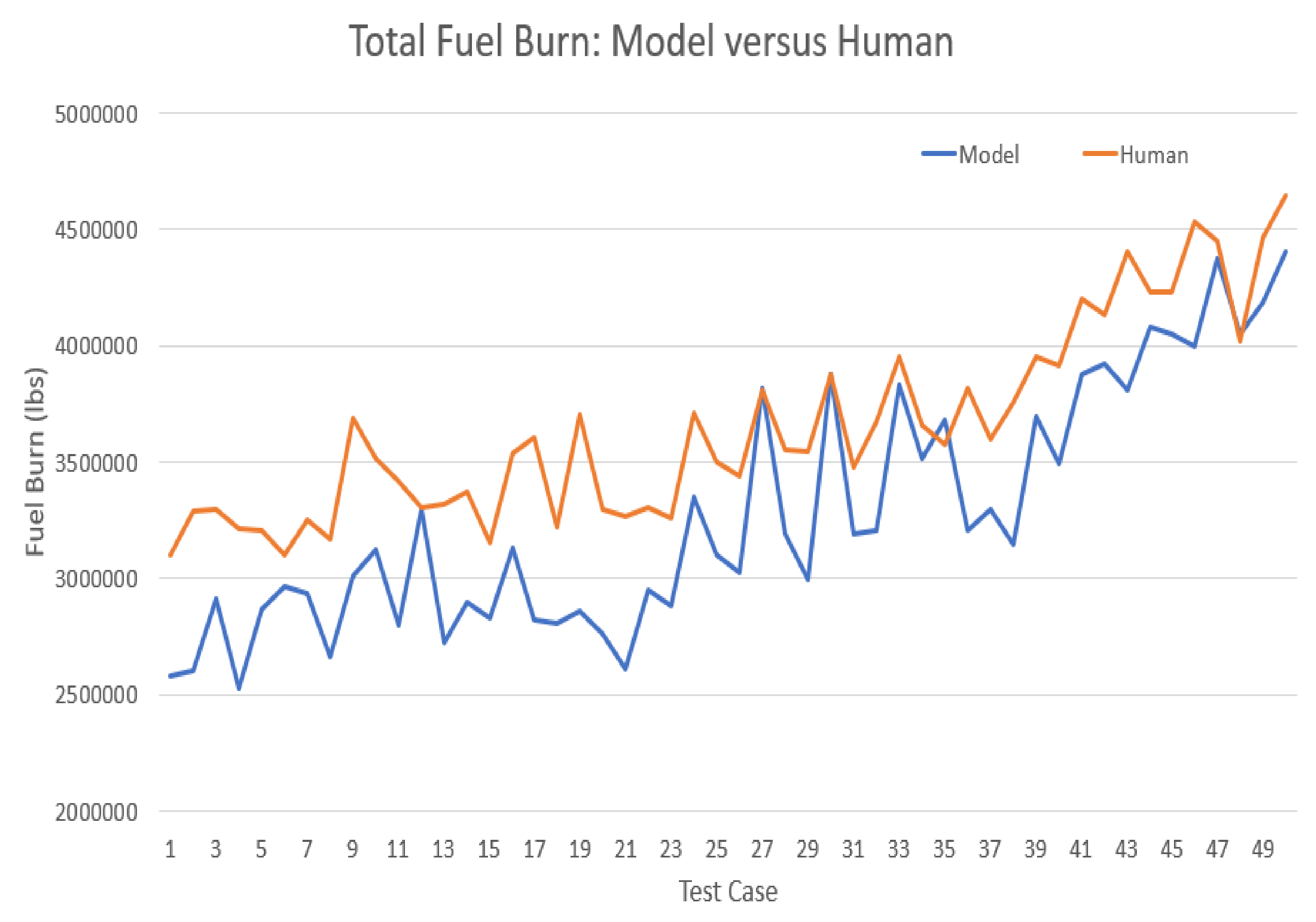
Man vs. Machine Testing

- Experiment Design:
  - Take (obfuscated) historical data on human plans
  - See how optimizer would have planned the same requests with the same resources with an expert-informed guess on the planning constraints
- Helps estimate potential efficiency gains

- Future Testing:
  - Man vs. Human-Machine Team testing (preferred to Man vs. Machine)
  - Test if optimizer allows operators to plan more requests with limited resources

Lab Results: Significant Potential Savings

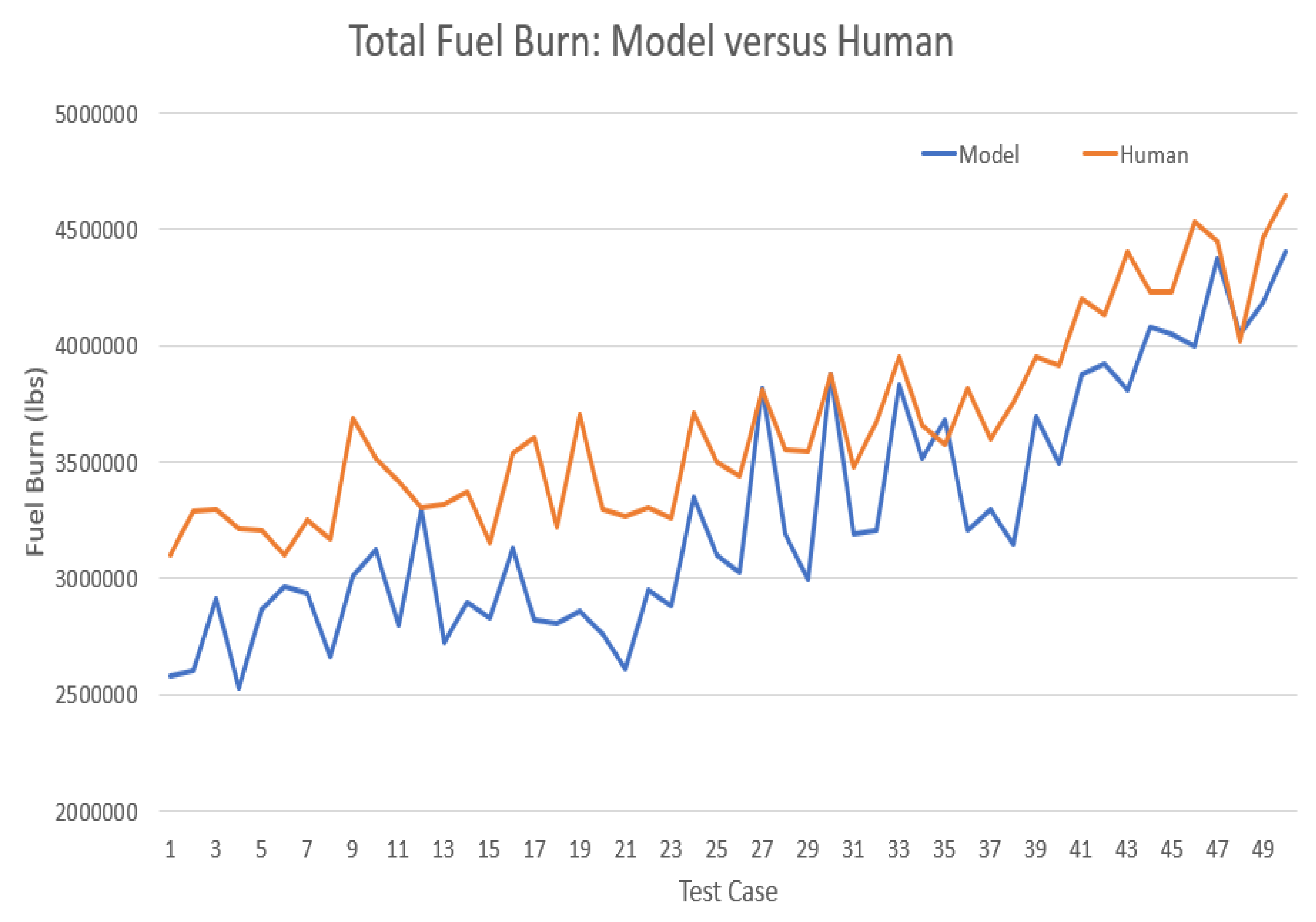
Current working results



- According to latest test results:
  - Model **burned 10% less fuel on average**
  - Model saved **over 350,000 lbs of fuel per day on average**
  - This could translate to saving an AOC **tens of millions in fuel per year** if these results are typical

Lab Results: Significant Potential Savings

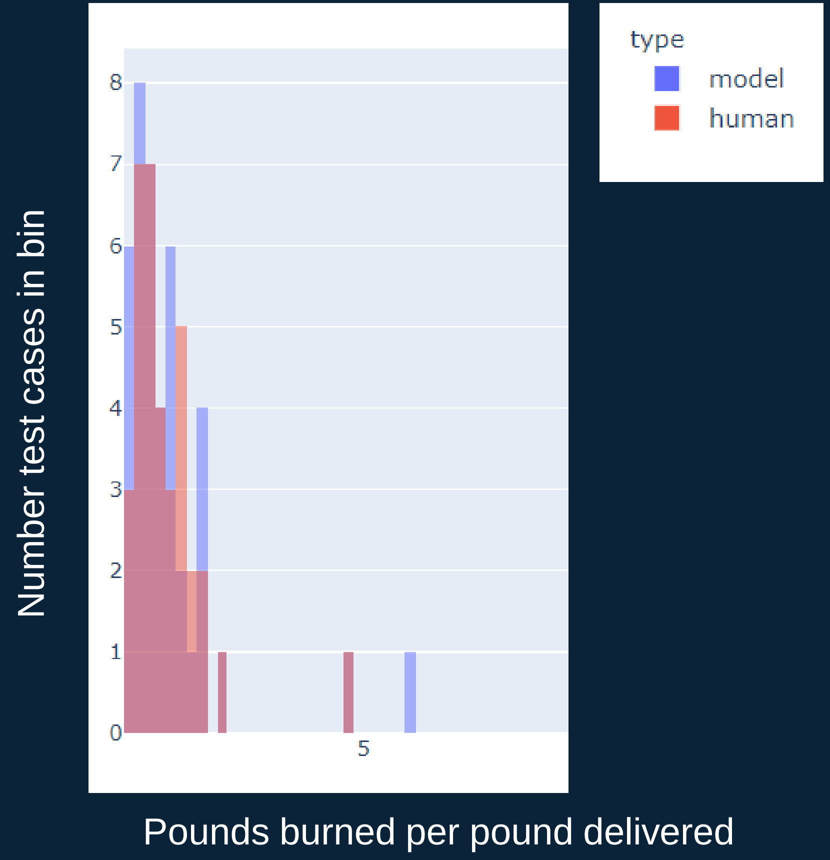
Current working results



- **Model does not always beat humans yet:**
- **Missing data**—sometimes humans made moves the model could not
- **Limited variables**—model currently cannot (even though humans can):
  - Change time of request
  - Change altitude or location of request
  - Have tankers temporarily wait in an empty track
  - Have tankers refuel other tankers

Lab Results: Man vs. Machine

Current working results



- In general, model was more fuel efficient but humans may have placed more value on having tankers available for short-notice requests
- Can be corrected by tuning the objective function (if needed)

Model Validation Strategy

- First-level validation: Valid if operational SMEs think output is useful
  - Must meet all scheduling requirements and provide a useful starting point for users
- Validating for human-machine teaming
  - Imperfections are okay if the user can easily fix them
  - Human-machine results should be measurably better than human-without-model results
- Must anticipate full-range of representative cases, including edge cases
  - Operators and researchers must collaborate on this

Opportunities for Further Improvement

- More degrees of freedom
  - Adjust request service times
  - Switch to nearby tracks or altitude blocks
  - Allow tankers to be temporarily moved to empty tracks
- Pre-caching information
  - So the model can “hot start” search once user is ready, providing responses in minutes
- Crew rest limitations
- Automated sensitivity analyses
  - Warn user about plan fragilities
- Refueling track re-positioning
  - When may it be operationally advantageous to move a track?
- Making algorithm more parallelizable
- Idle orbiting requests
  - Let users tell us when they want to pre-position a tanker in the air w/ spare fuel

Summary

- We are getting very promising lab results with our tanker planning optimizer:
  - Could potentially save **a major AOC tens of millions per year** in fuel (but it could instead be tuned to save sorties)
  - Automatically generates plans that meet complex requirements faster than humans
  - Can help operators fulfill more requests on days when tankers are limited

- An optimization capability won't just optimize; it can double as a what-if tool