

Aviation Trends and Developments in Air Traffic Management

7 March 2024



Aviation
Studies Institute





Resilient Airspace Design

Speaker: Assistant Professor Nuno Antunes Ribeiro

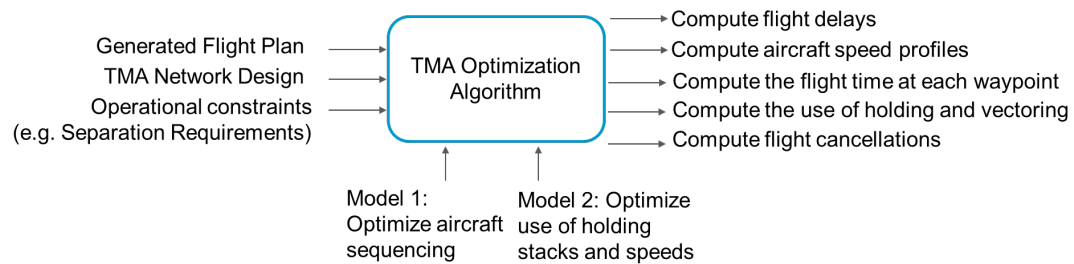
Principal Investigators



The Resilient Airspace Project



Nuno Ribeiro
Assistant Professor,
Engineering Systems and Design



Principal Investigators



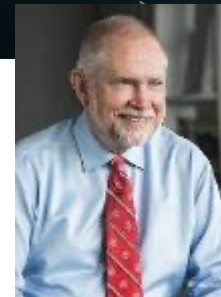
The Resilient Airspace Project



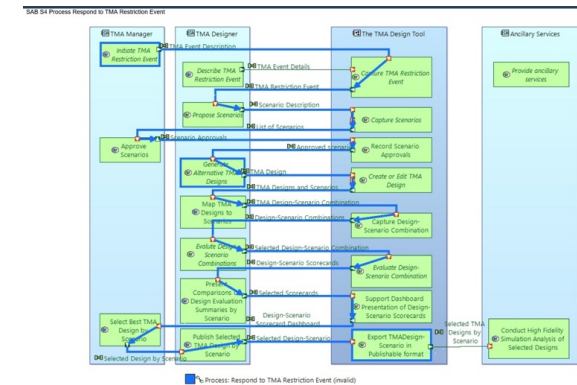
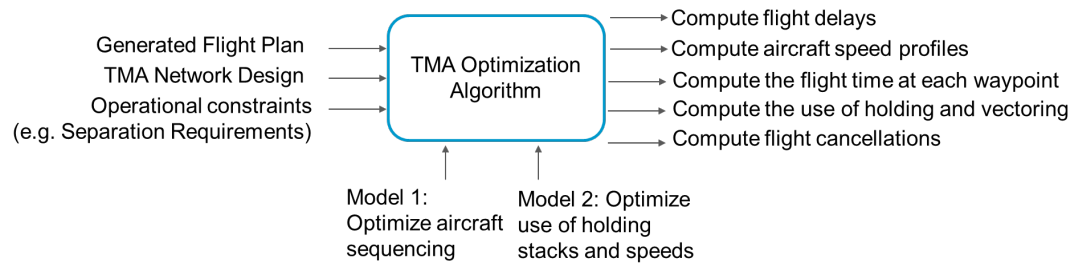
Nuno Ribeiro
Assistant Professor,
Engineering Systems and Design



The Rapid Evaluation Tools Project



Peter Jackson
Institute Director, Aviation Studies Institute
Professor, Engineering Systems and Design

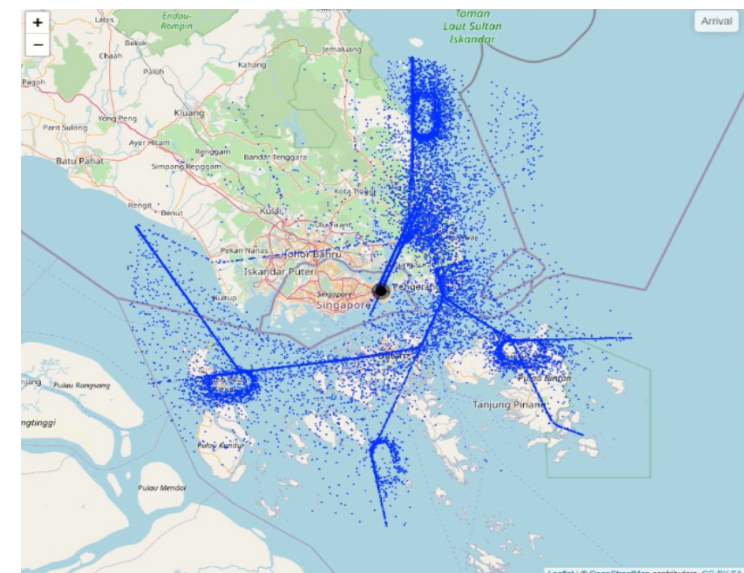
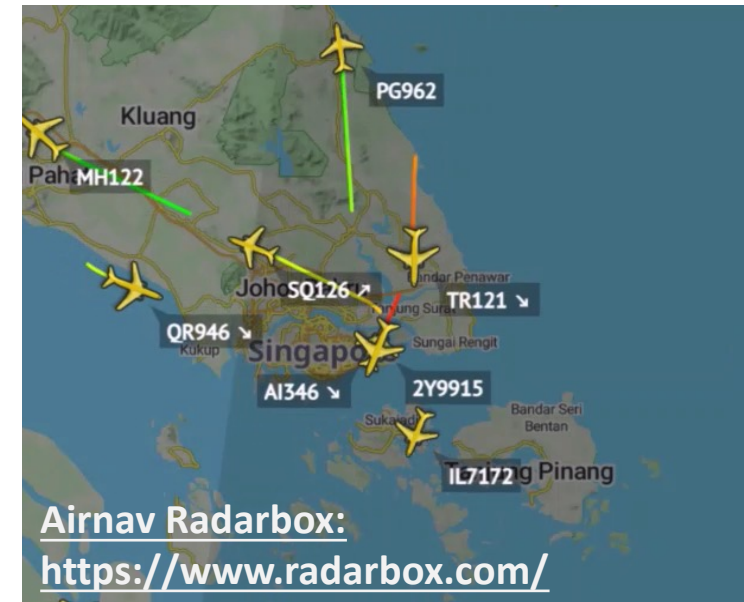


Problem Description



- **TMA (Terminal Manoeuvring Area):** The controlled airspace surrounding an airport where arriving and departing flights are merged and sequenced.
- **SIDs and STARs*:** a set of pre-defined flight paths for streamlined navigation.
- **TMA Management:** coordinates arriving and departing flights to prevent conflicts and maintain separation.
- **TMA interventions:** Air Traffic Control utilizes techniques such as speed adjustments, vectoring, and holding patterns to ensure real-time separation.

*Standard Instrument Departures (SIDs)
Standard Terminal Arrivals (STARs)



Problem Description

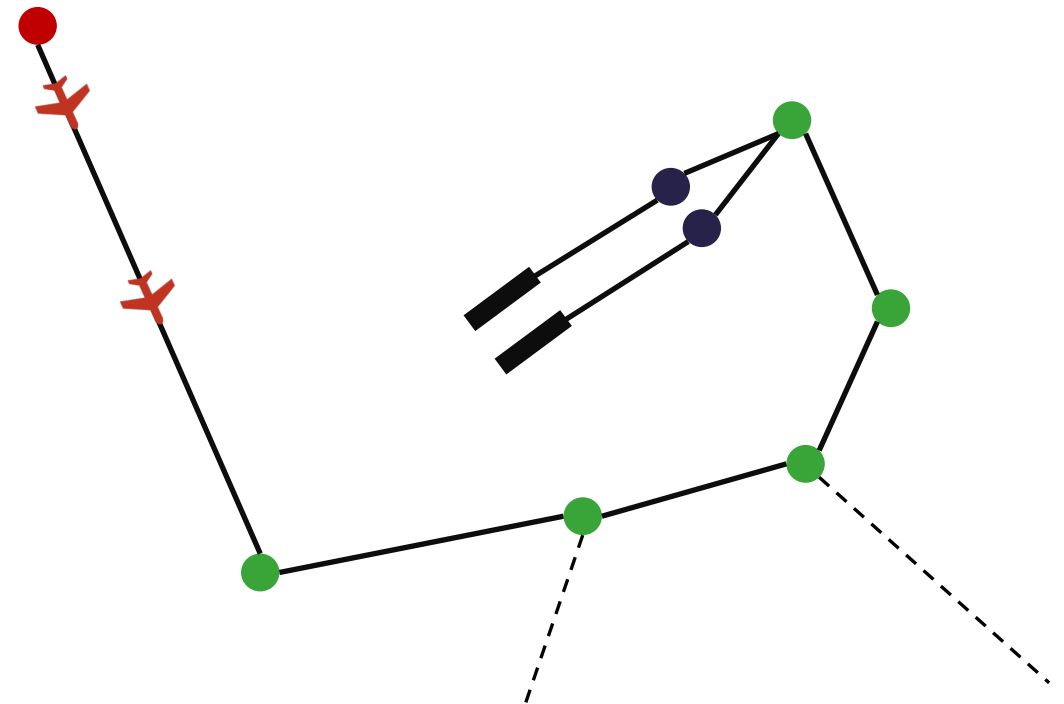


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Separation Requirements

1. Link Separations



Problem Description

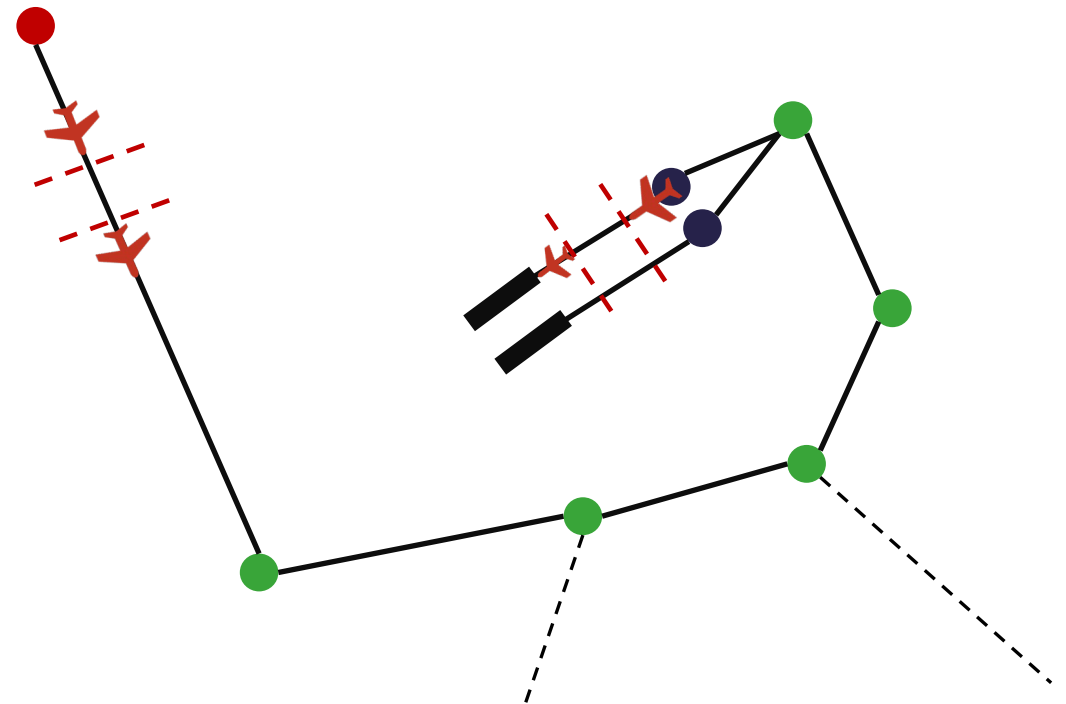


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Separation Requirements

1. Link Separations
2. **Runway Separations**



Problem Description



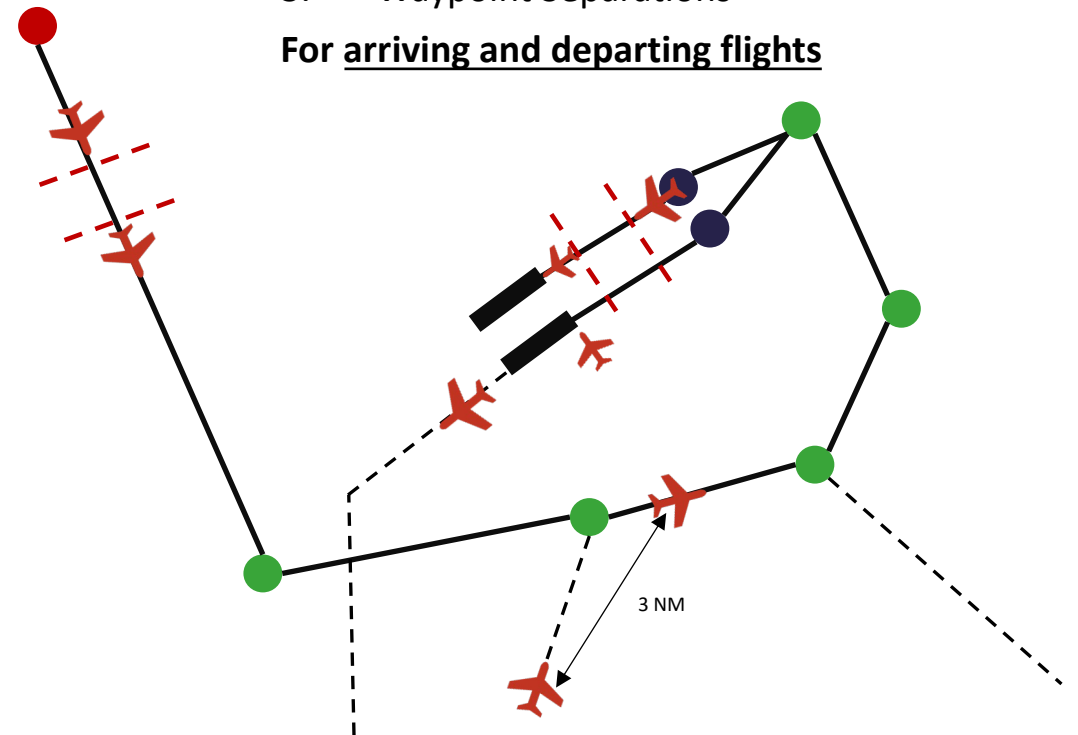
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Separation Requirements

1. Link Separations
2. Runway Separations
3. Waypoint Separations

For arriving and departing flights

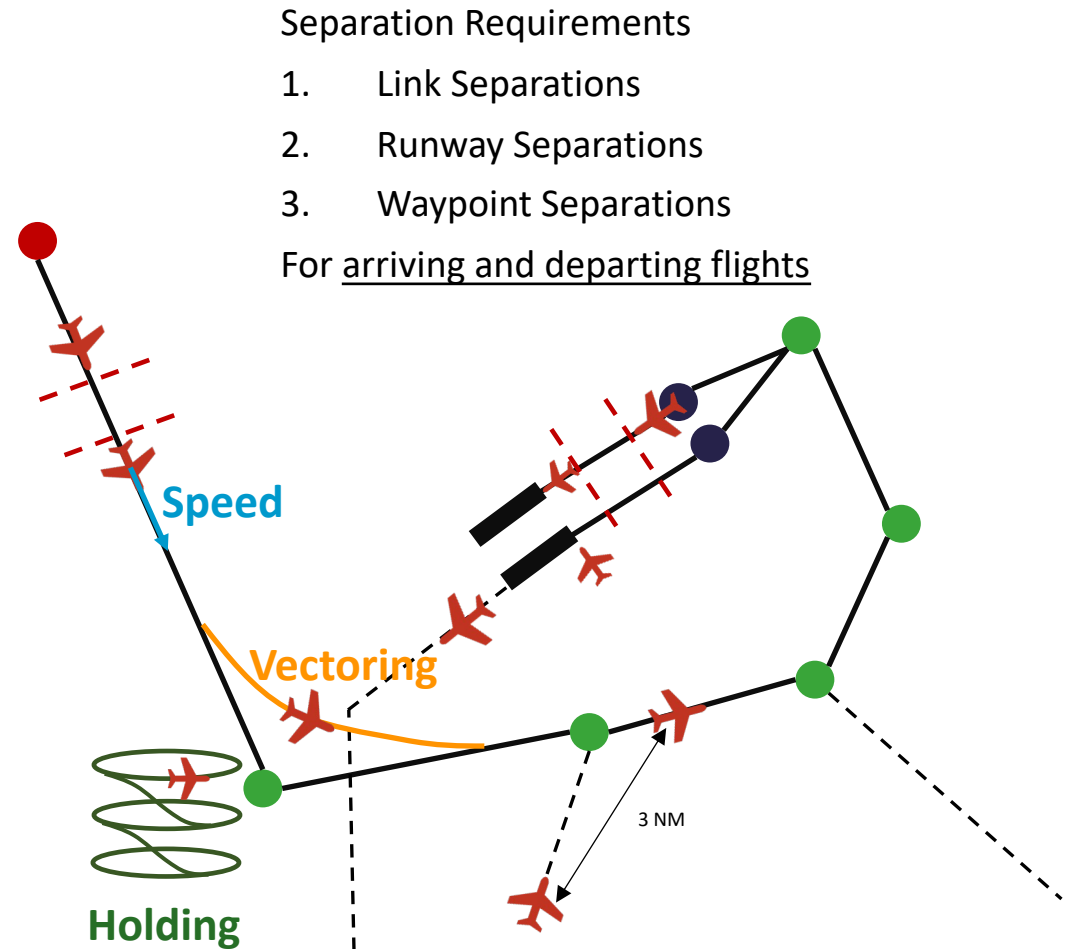


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*Standard Instrument Departures (SIDs)
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Problem Description



- **Airspace Restriction Events** require adjustments to default procedures, such as detours from the SIDs and STARs.



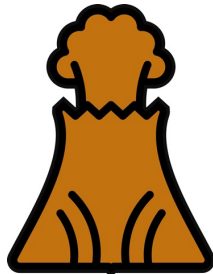
Storms



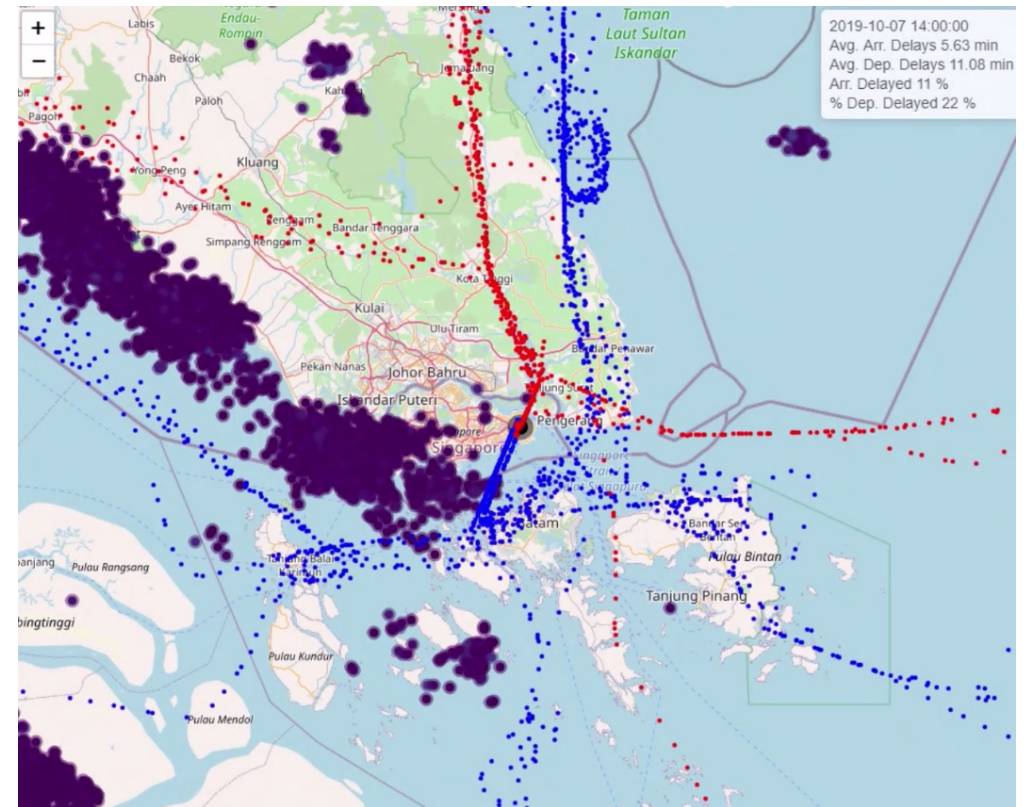
Wildfires



Military Exercises



Volcanic Activity

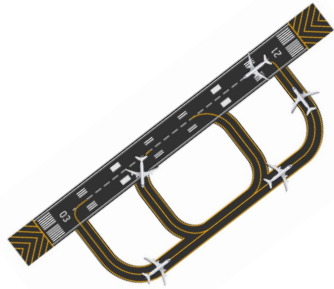


Storm Activity Causes Delays and Detours

Problem Description



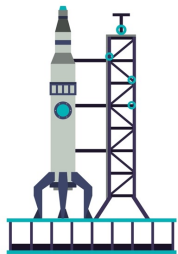
- **Future airspace developments** may require the re-design of existing procedures, such as modifying and adding new SIDs and STARs.



New Runway



Demand Forecasts



Spacecraft Launch and Recovery



Integration with Drones



Changi Airport new runway and passenger terminal.

**Conduct rapid evaluation
of throughput and delay times
for alternative configurations and scenario adaptations
of SID and STAR routes
within a Terminal Manoeuvring Area (TMA).**

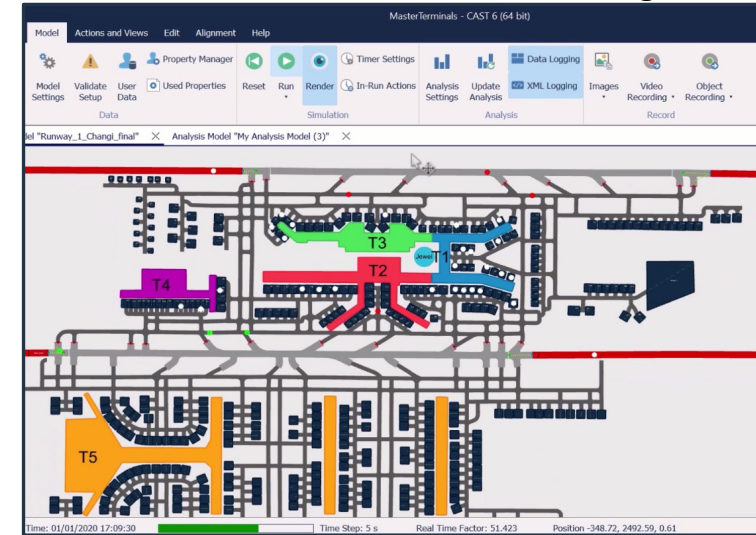
Simulation Tools

- **Micro-simulation Models:**
 - Model aircraft behavior and air traffic movement with high fidelity
 - Lengthy execution and development times.
- **Macro-simulation Models:**
 - Model air traffic flows at a low fidelity and high abstraction level.
 - Fast execution and development times

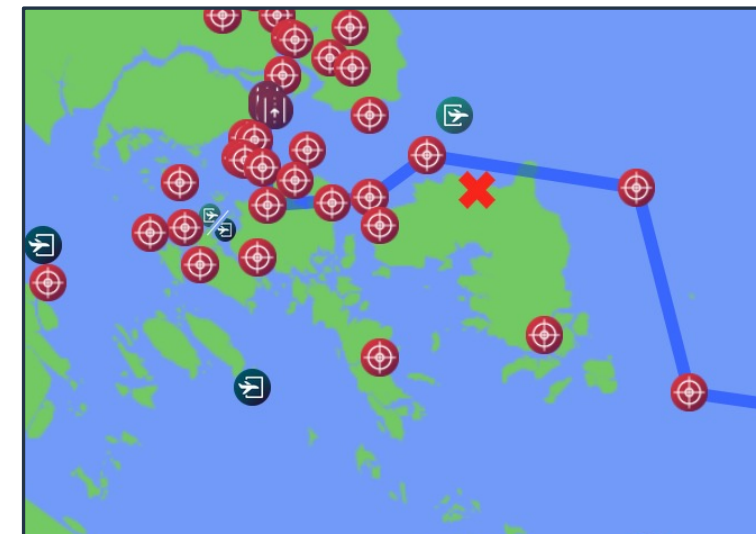
Macro-simulation facilitates the testing of numerous scenarios to gain preliminary insights

Selected scenarios can be further investigated using **Micro-simulation**

Micro-simulation model for Changi



Macro-simulation model for Changi



A Low Fidelity Modeling Tool for Rapid Assessment of Terminal Airspace Configurations and Planning Scenarios

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- Describe scenarios of airspace restriction events and future developments

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- **Simulate air traffic flows through each design** using optimization to ensure appropriate separations at waypoints and use of vectoring or holding

A Low Fidelity Modeling Tool for Rapid Assessment of Terminal Airspace Configurations and Planning Scenarios

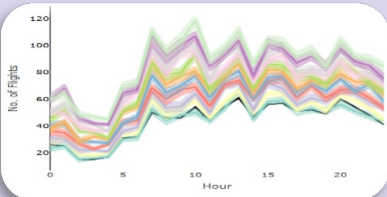
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- **Compare designs side by side for their impact** on simulated delays

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- Simulate air traffic flows through each design using optimization to ensure appropriate separations at waypoints and use of vectoring or holding
- Compare designs side by side for their impact on simulated delays
- **Rapidly identify best designs for further consideration**

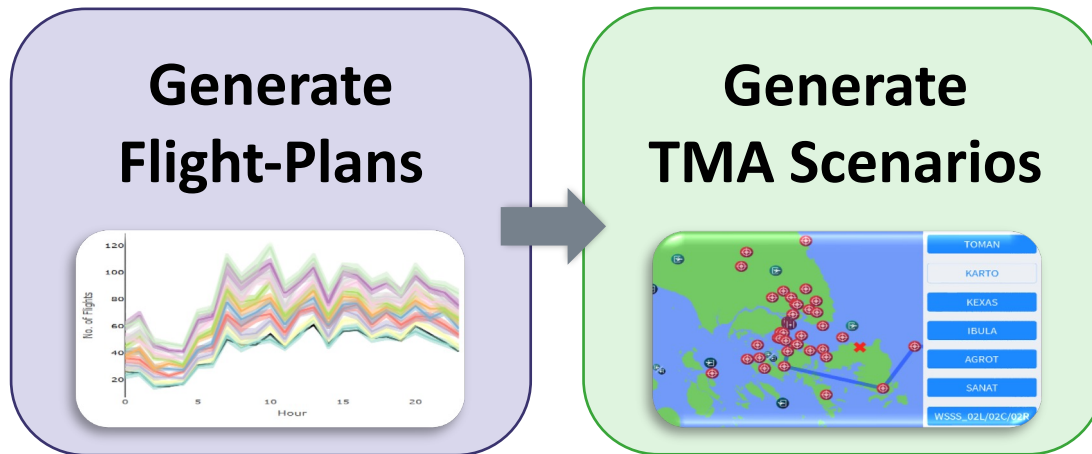
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Generate Flight-Plans



- Define the traffic volumes
- Define the mix of aircraft types
- Assign flights to different entry/exit fixes

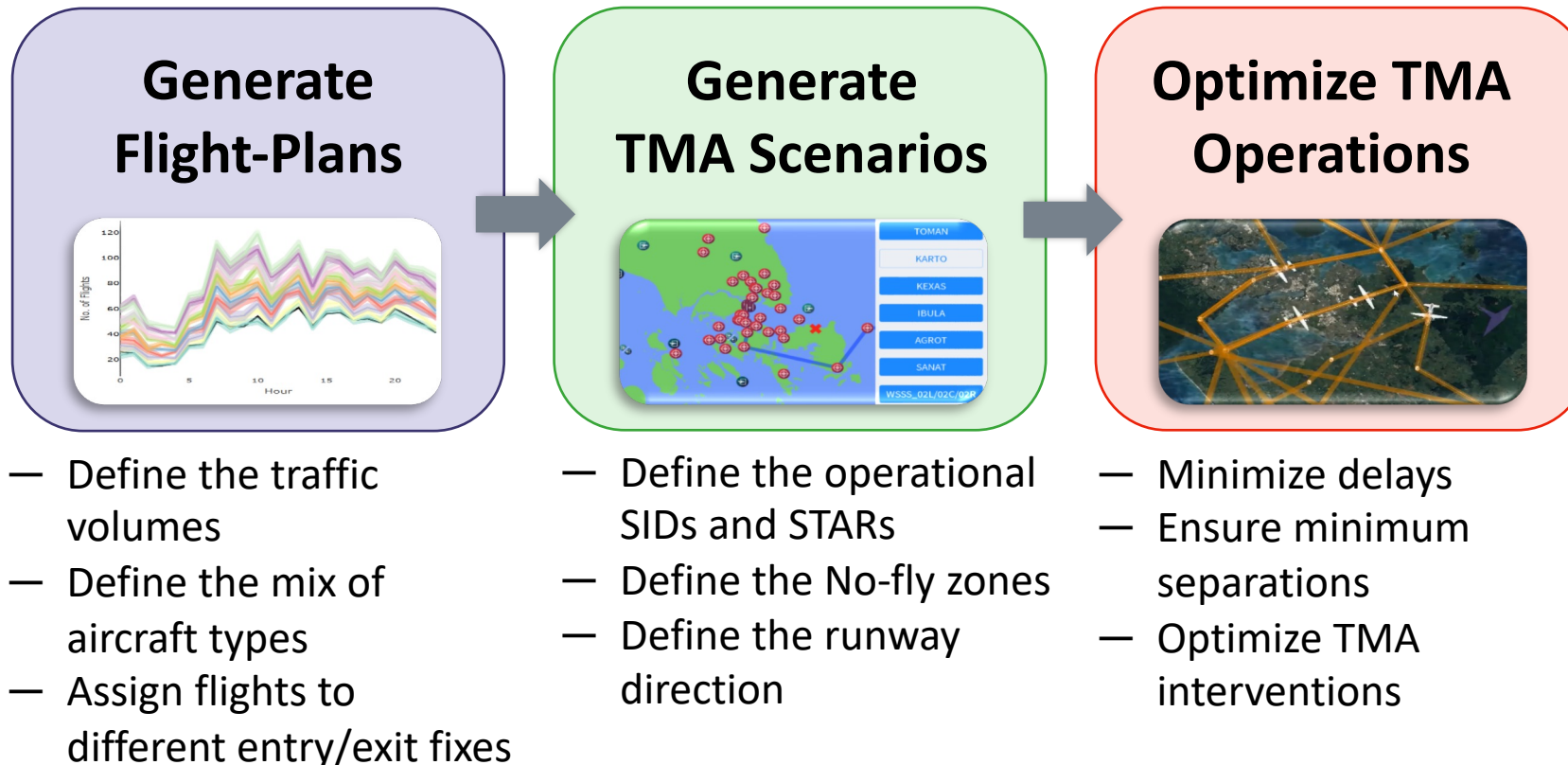
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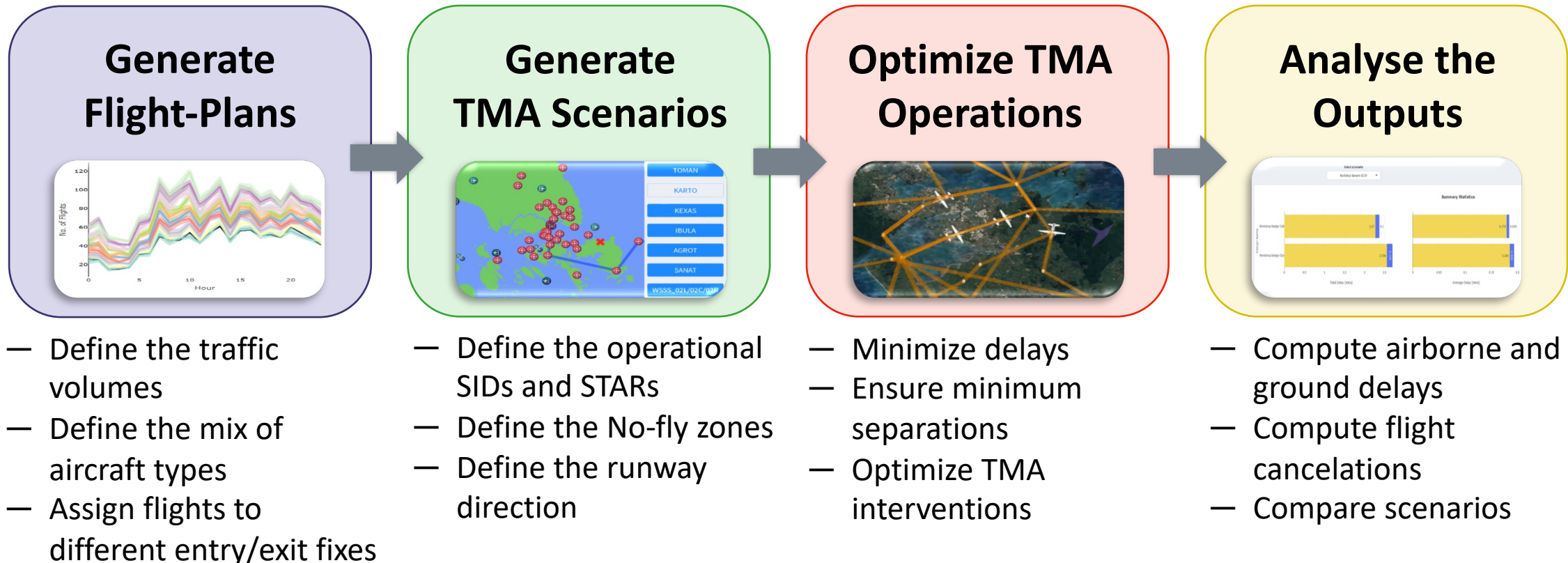
- Define the traffic volumes
- Define the mix of aircraft types
- Assign flights to different entry/exit fixes

- Define the operational SIDs and STARs
- Define the No-fly zones
- Define the runway direction

A Low Fidelity Modeling Tool for Rapid Assessment of Terminal Airspace Configurations and Planning Scenarios



A Low Fidelity Modeling Tool for Rapid Assessment of Terminal Airspace Configurations and Planning Scenarios



Generate Flight Plans

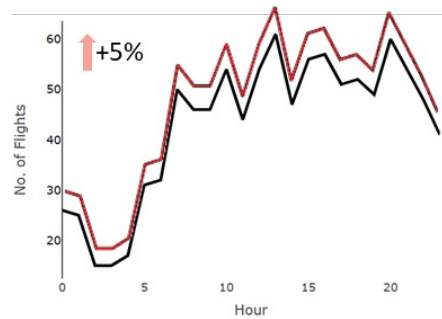
- Bootstrapping resampling methods are used to generate new flight plans.

Generate Flight Plans

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Inputs:

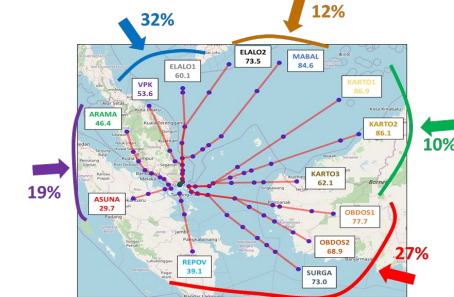
Set the Traffic Volumes



Set the Mix of Aircraft Types

Weight	13:00
L	0.1%
M	57.7%
H	42.1%
J	0.1%

Set the traffic flow mix at entry/exit fixes

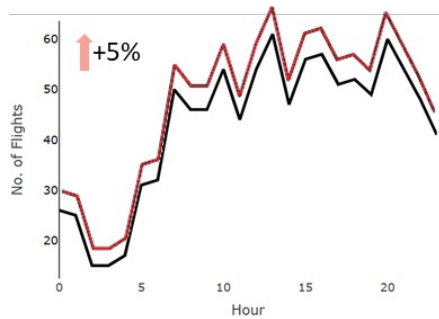


Generate Flight Plans

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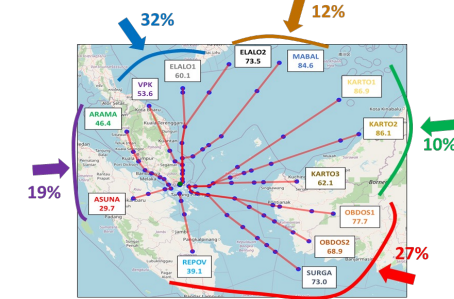
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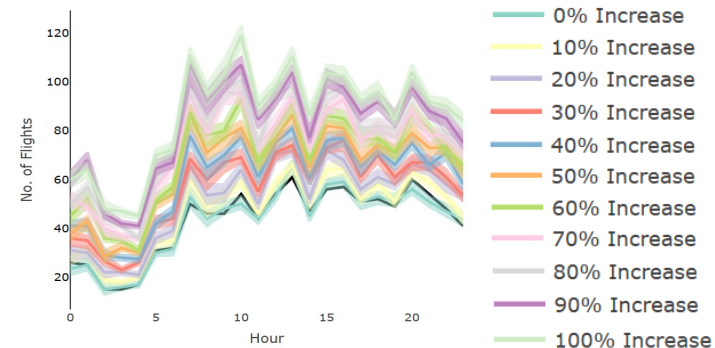
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Output:

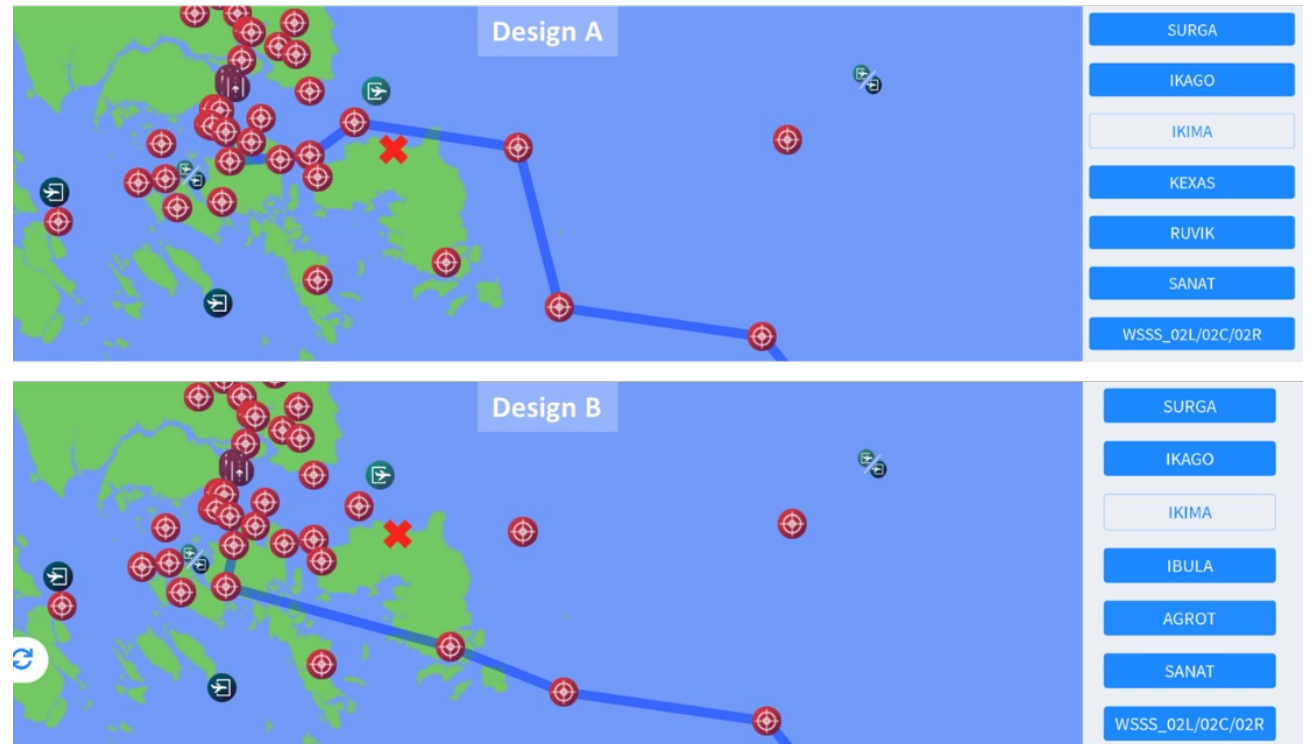
Detailed Flight Plan

ID	Arr Time	Dep. Time	Aircft. Type	Entry Fix	...
1	00:24	07:35	A340	KARTO	...
2	00:14	06:57	B747	OBDO1	...
3	00:54	06:45	B777	ELALO	...
4	00:45	08:14	A320	REPOV	...
5	00:33	06:33	A320	ARAMA	...
6	00:16	07:13	B737	KARTO	...
...

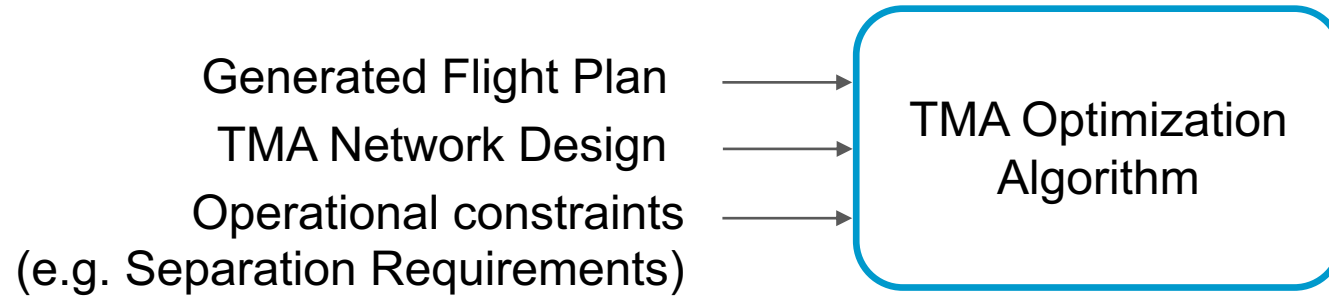


Generate TMA Scenarios

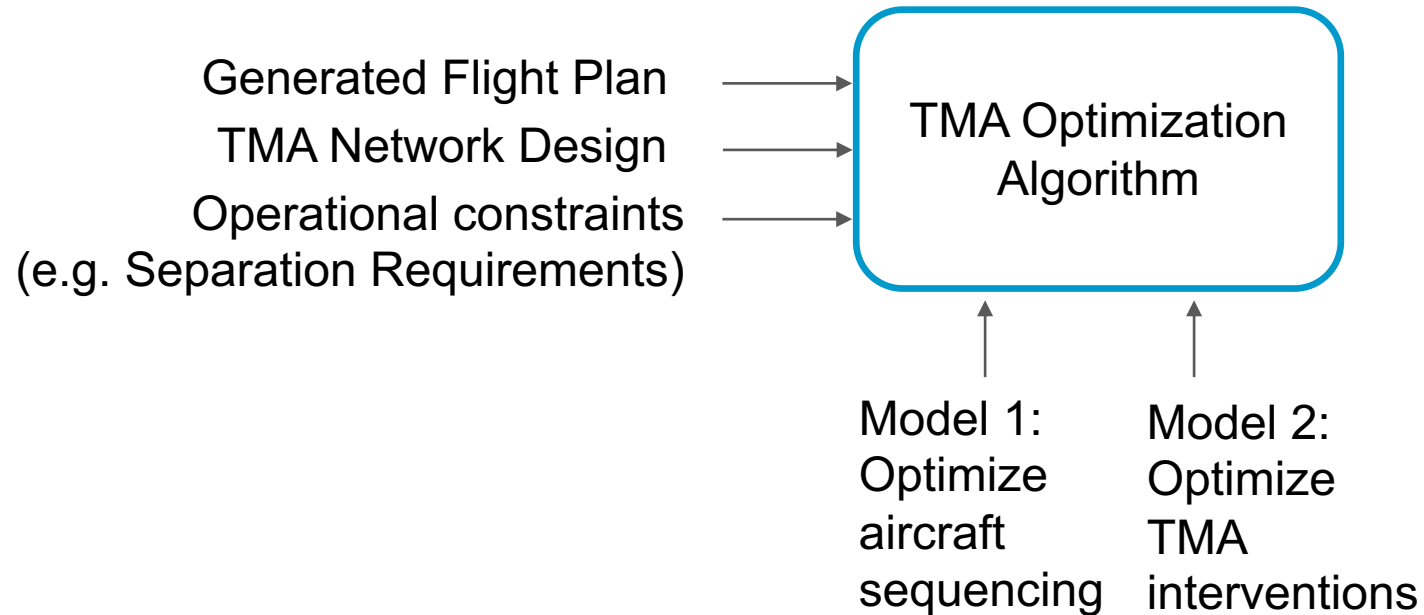
- The TMA Design Tool enables quick adjustment of TMA SIDs and STARs to accommodate:
 - Description of restriction events,
 - Insertions of no-fly zones,
 - Changes in runway operation directions
 - Modifications in operating rules;
 - Add new SIDs and STARs



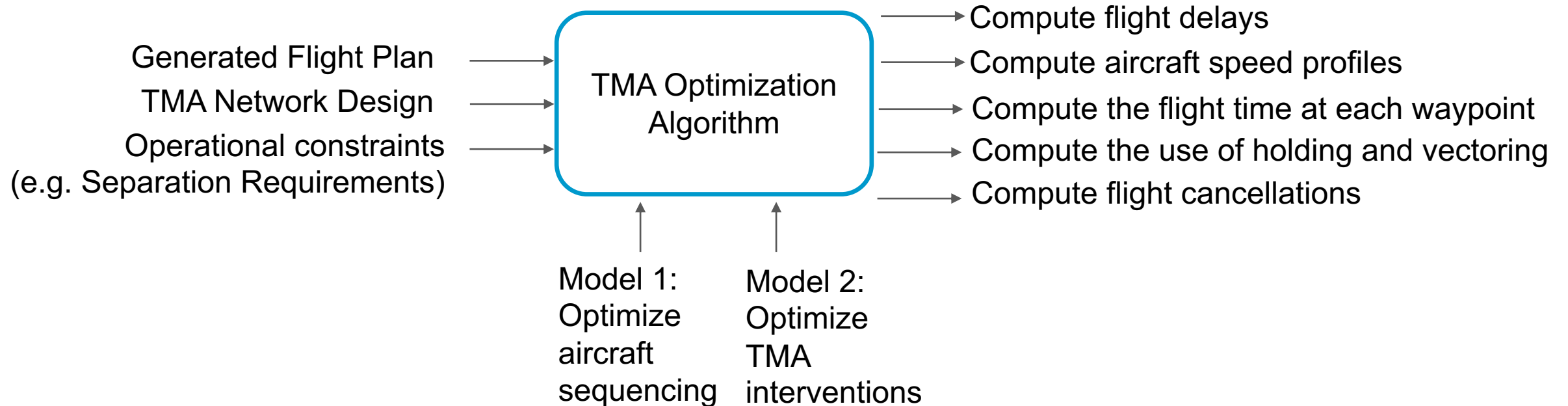
Optimize TMA Interventions



Optimize TMA Interventions



Optimize TMA Interventions



Optimize TMA Interventions

Simulation Approaches

Optimization-Based

Rule-Based

- We have developed an optimization algorithm to sequence and schedule flights in the TMA waypoints and runways
- The algorithm strives to minimize airborne and ground delays while maintaining adherence to separation requirements.
- This is achieved by adjusting the variables associated with aircraft speed, utilization of holding patterns, and vectoring.
- The algorithm aims to **mimic air traffic controllers' decisions through optimization** rather than rules-based algorithms

Mathematical formulation

Objectives:

$$O_1 = \min M \left(\sum_{i,j,k \in \mathcal{P}_{ijk}} Z_{ijk} + \sum_{i,j,k \in \mathcal{P}_{ij}^n} Z_{ij}^n \right) \quad (1)$$

$$O_2 = \min \sum_{i \in \mathcal{F}} \sum_{k \in \mathcal{N}} (T_{ik} + H_{ik}) + D_i - u_i \quad (2)$$

Constraints:

$$\text{s.t. } Y_{ik} = Y_{ig} + T_{ik} + H_{ik} \quad \forall i, k, g \in \mathcal{L}_{ikg} \quad (3)$$

$$Y_{jk} - Y_{ik} \geq s_{ijk} - Z_{ijk} \quad \forall i, j, k \in \mathcal{P}_{i,j,k} \quad (4)$$

$$Y_{ik} \leq e_i + e_i^{max} \quad \forall i, k \in \mathcal{N}_{ik}^e \quad (5)$$

$$Y_{ik} \geq e_i \quad \forall i, k \in \mathcal{N}_{ik}^e \quad (6)$$

$$D_i \geq Y_{ik} - e_i \quad \forall i \in \mathcal{F} \quad (7)$$

$$T_{ik} \geq t_{ikg}^{min} \quad \forall i, k, g \in \mathcal{P}_{i,j,k} \quad (8)$$

$$T_{ik} \leq t_{ikg}^{max} \quad \forall i, k, g \in \mathcal{P}_{i,j,k} \quad (9)$$

$$H_{ik} \leq h_{ik} \quad \forall i, k \in \mathcal{N}_{ik}^h \quad (10)$$

$$Y_{ik} \leq Y_{ig} + T_{ik} \quad \forall i, k, g \in \mathcal{P}_{ijk}^0 \quad (11)$$

$$Y_{j,k'} - Y_{i,k'} \geq s_{ij,k'} - Z_{ij,k'}^n \quad \forall i, j \in \mathcal{P}_{i,j}^n \quad (12)$$

$$T_{ik}, D_i, H_{ik}, Y_{ik}, Z_{ijk}, Z_{ij}^n, Z_{ij}^{ad} \in \mathbb{R} \quad (13)$$

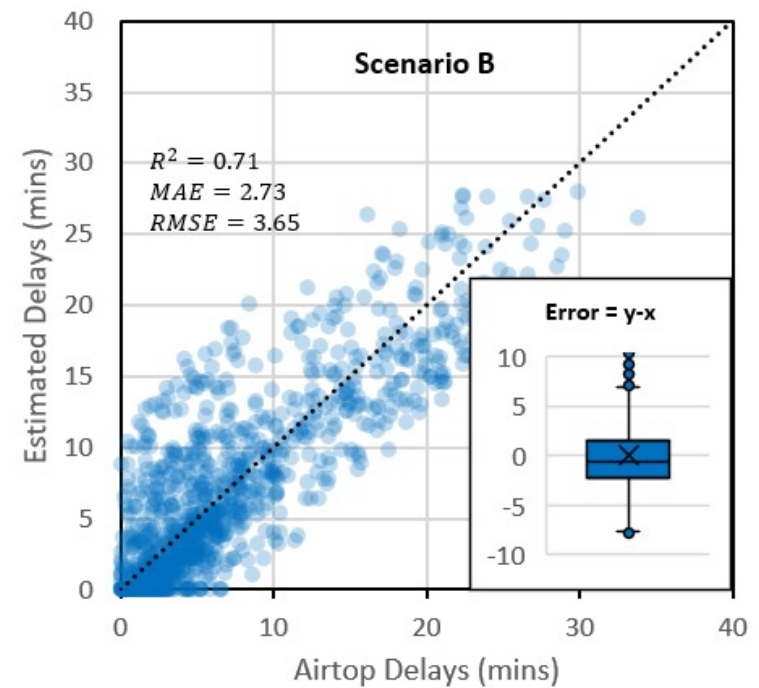
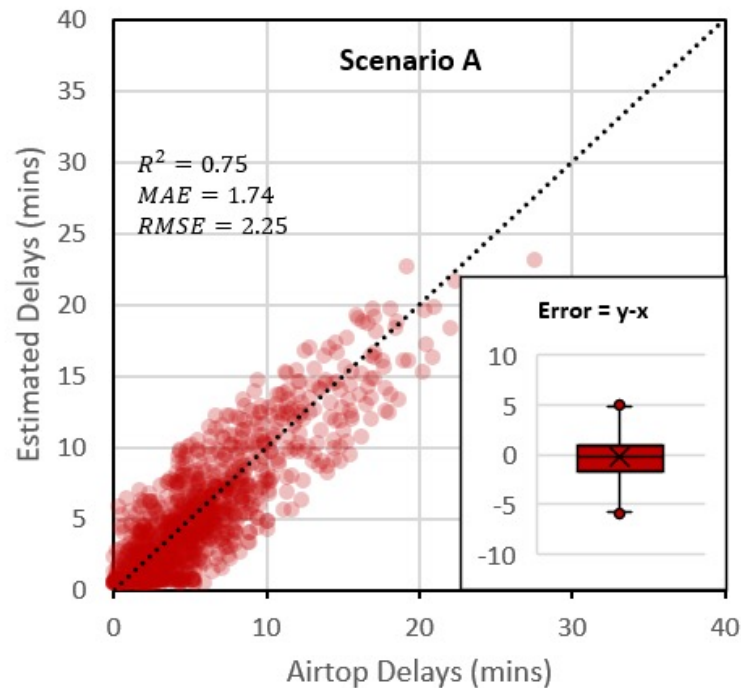
(Alternative to rule-based) optimization-based models generate solutions in one-single step and do not require extensive setting of rules

Optimize TMA Interventions

- The optimization model has been **validated and compared** with the results from a micro-simulation (rule-based) model (Airtop – Transoft Solutions)

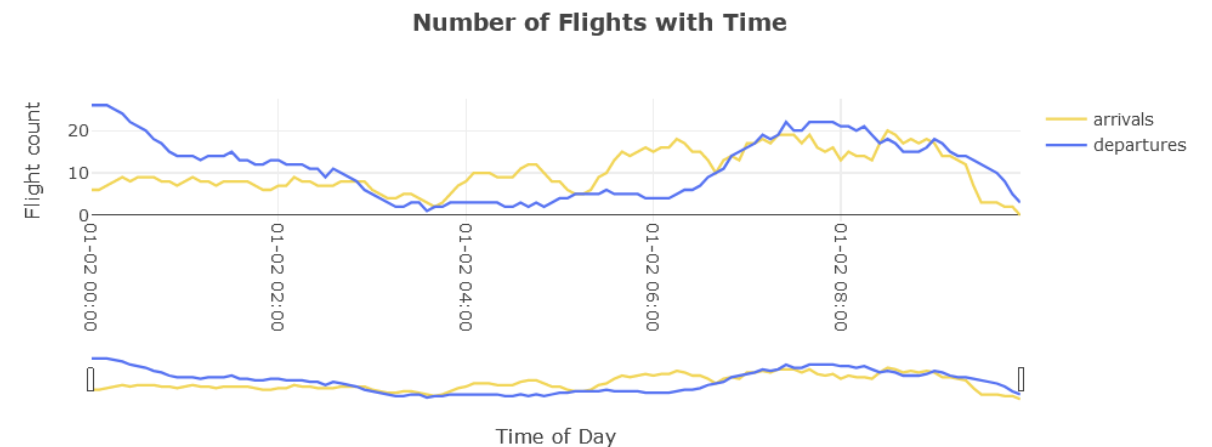
Scenario A - typical day of operations with no disruptive events, adhering to typical demand patterns;

Scenario B - day with a disruptive event occurring in a specified region of the airspace, necessitating an increase in separation requirements.



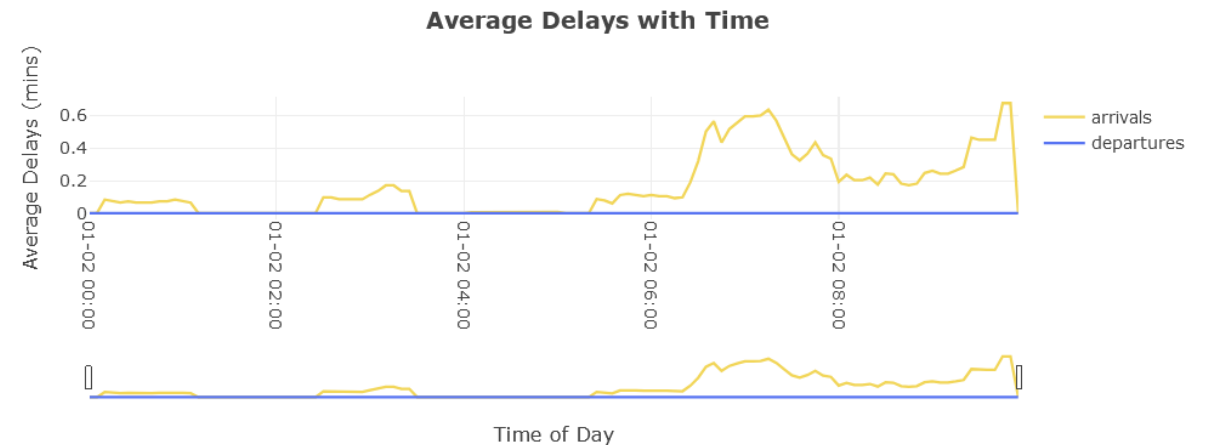
Analyse the Outputs

- Various analyses can be conducted using the TMA Design Tool, resulting in **different types of charts and tables**, including:
 - Runway Throughput
 - Airborne Delays and Ground Delays
 - Use of Holding Stacks
 - Time-Space Diagrams
 - Flight Cancelations
 - Comparative Analysis



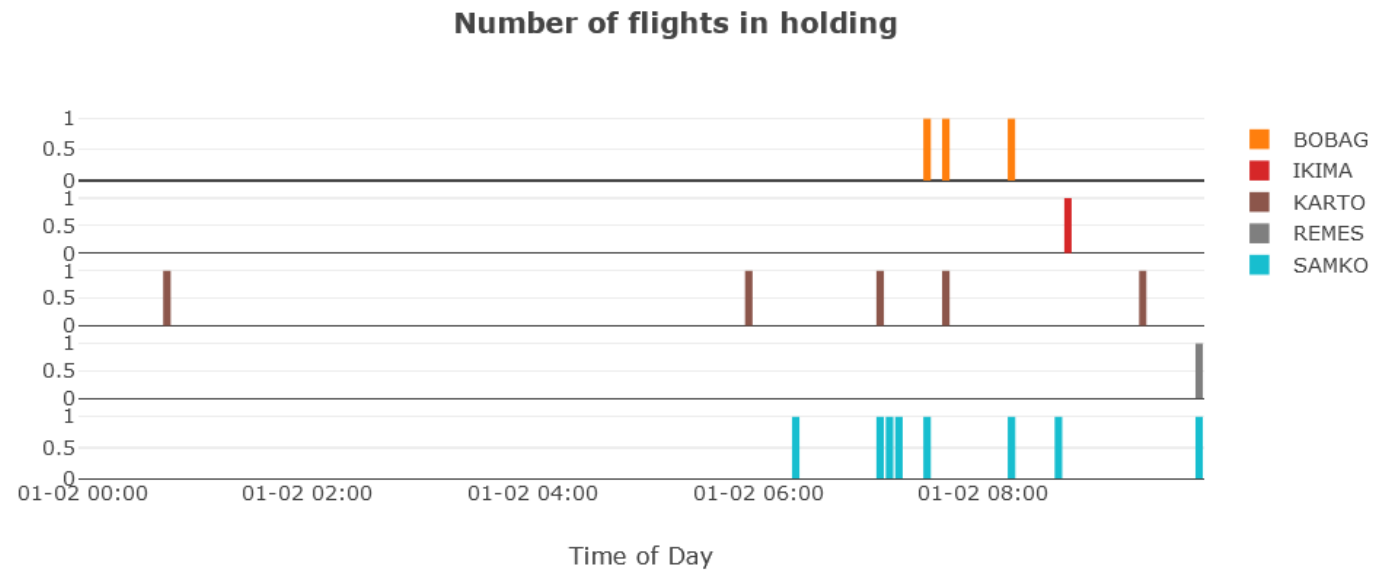
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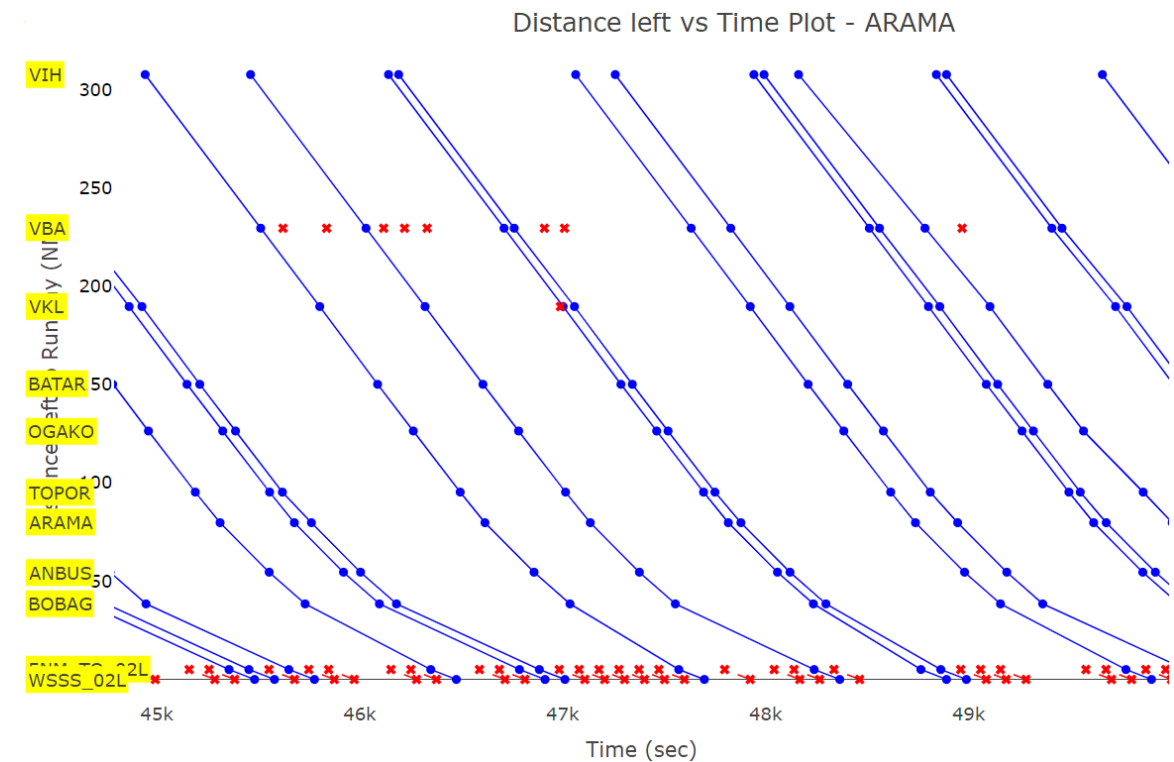
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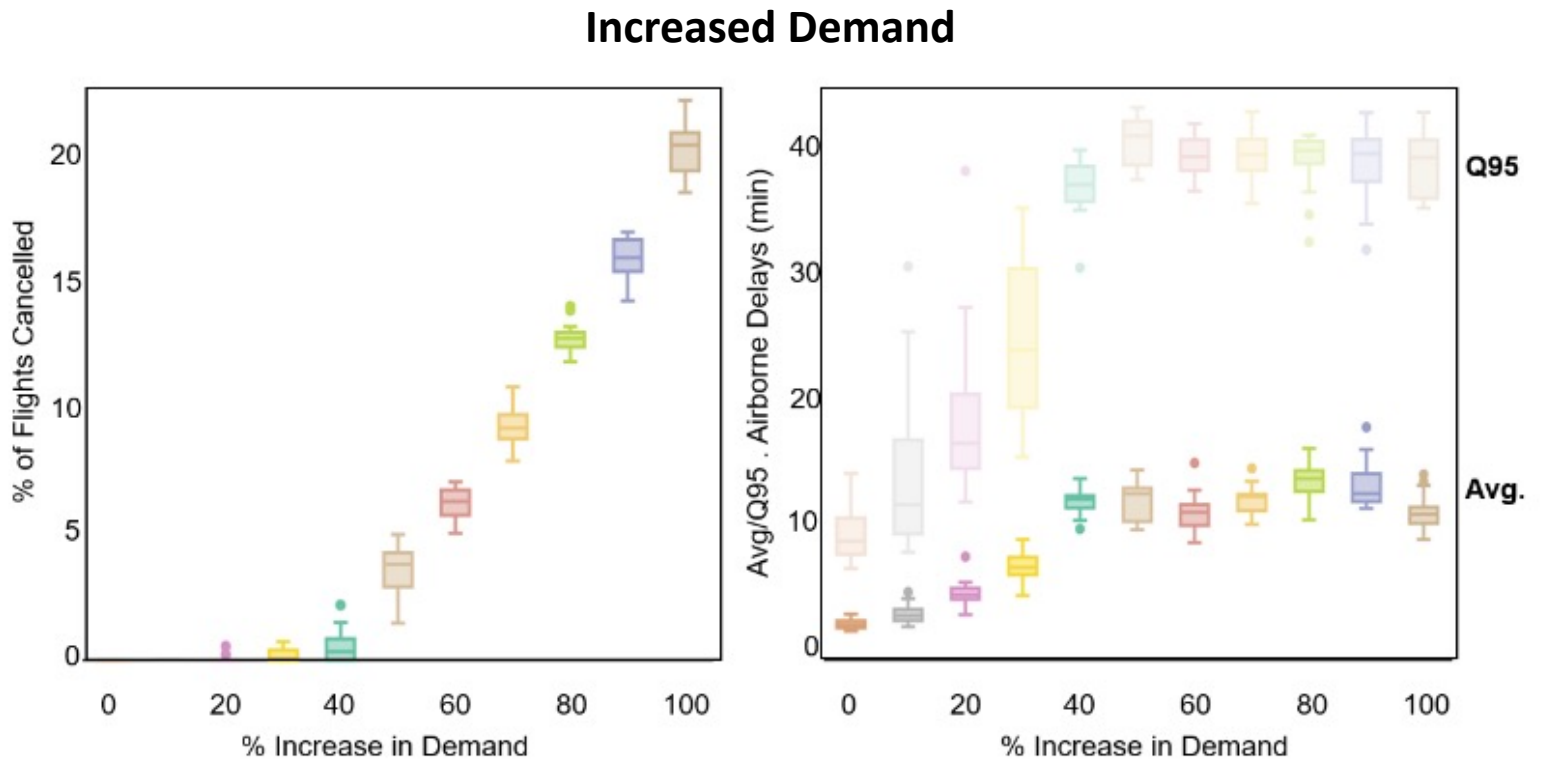
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TMA Design Tool Demo

Speaker: Assistant Professor Nuno Antunes Ribeiro & Peter Jackson

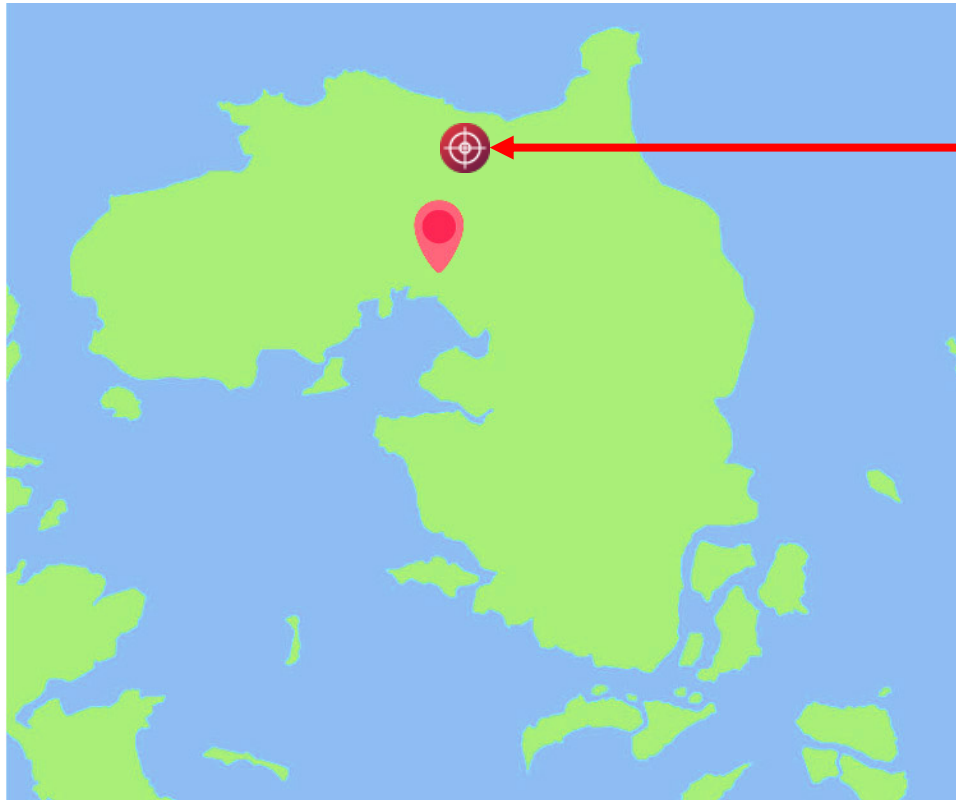
Airspace Restriction Event

- Suppose an old volcano were to threaten to become active again



Airspace Restriction Event

- Suppose an old volcano were to threaten to become active again
- A lot of air traffic flows across waypoint LAVAX nearby



Shortname: LAVAX

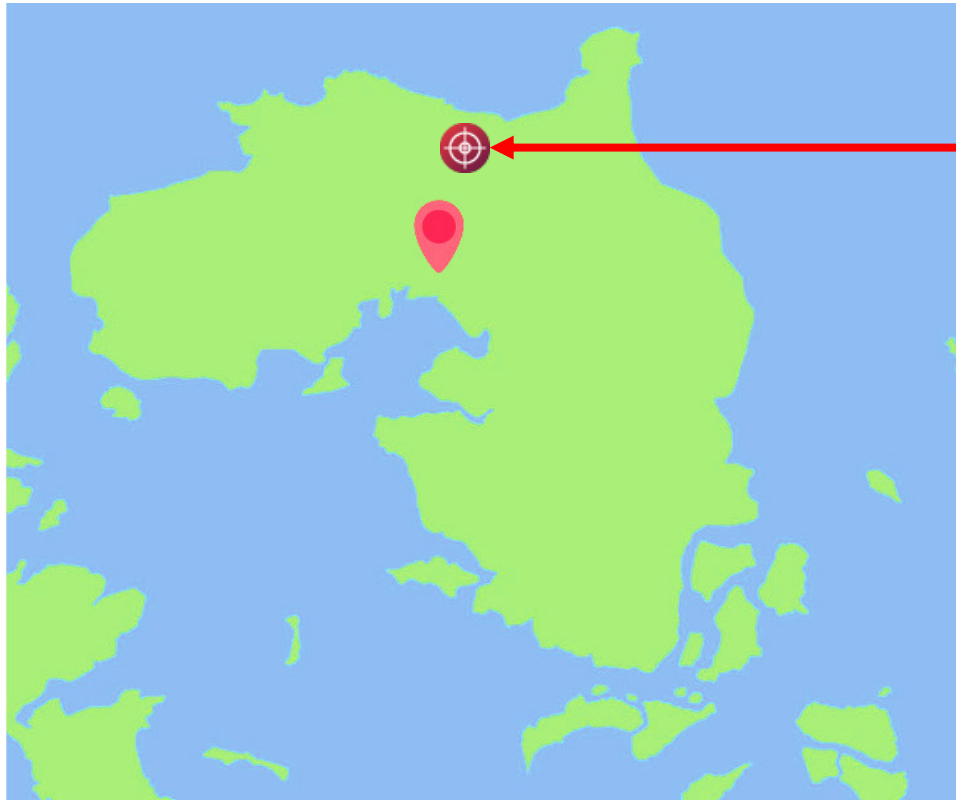
Location Type: waypoint

Latitude: 1.1639

Longitude: 104.4539

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Shortname: LAVAX

Location Type: waypoint

Latitude: 1.1639

Longitude: 104.4539

**Restriction Event:
LAVAX is unavailable**

Scenario To Consider

Scenario :

- LAVAX is unavailable
- Two runways
- Runway orientation is 02L/20R
- Name: “Scenario 02 Dir”

Choose runway to enable/disable

02L 02C 02R

Choose runway direction

02 20

Departures to the North

Exit and Entry Points for WSSS

Departures (SID)

ANITO	ADMIM	TOMAN
BAVUS	AROSO	MASBO
MERSING	VENIX	KADAR

Arrivals (STAR)

ARAMA	ASUNA	TOMAN
OBDOS	MABAL	LEBAR
REPOV	SURGA	ELALO

TOMAN, OBDOS, and SURGA

STAR TOMAN

AIP Singapore

AD-2-WSSS-STAR-5

25 JAN 2024

SINGAPORE/Singapore Changi

RWY 02L/C/R

KARTO ONE ALPHA ARRIVAL

KARTO 1A

STANDARD ARRIVAL CHART
RNAV (GNSS) -
INSTRUMENT (STAR)

ACC 134.2
 APP 124.05
 119.3
 TWR 118.6 / 118.25

TRANSITION ALTITUDE
 11 000ft

D-ATIS AP ID-WSSS
 128.025

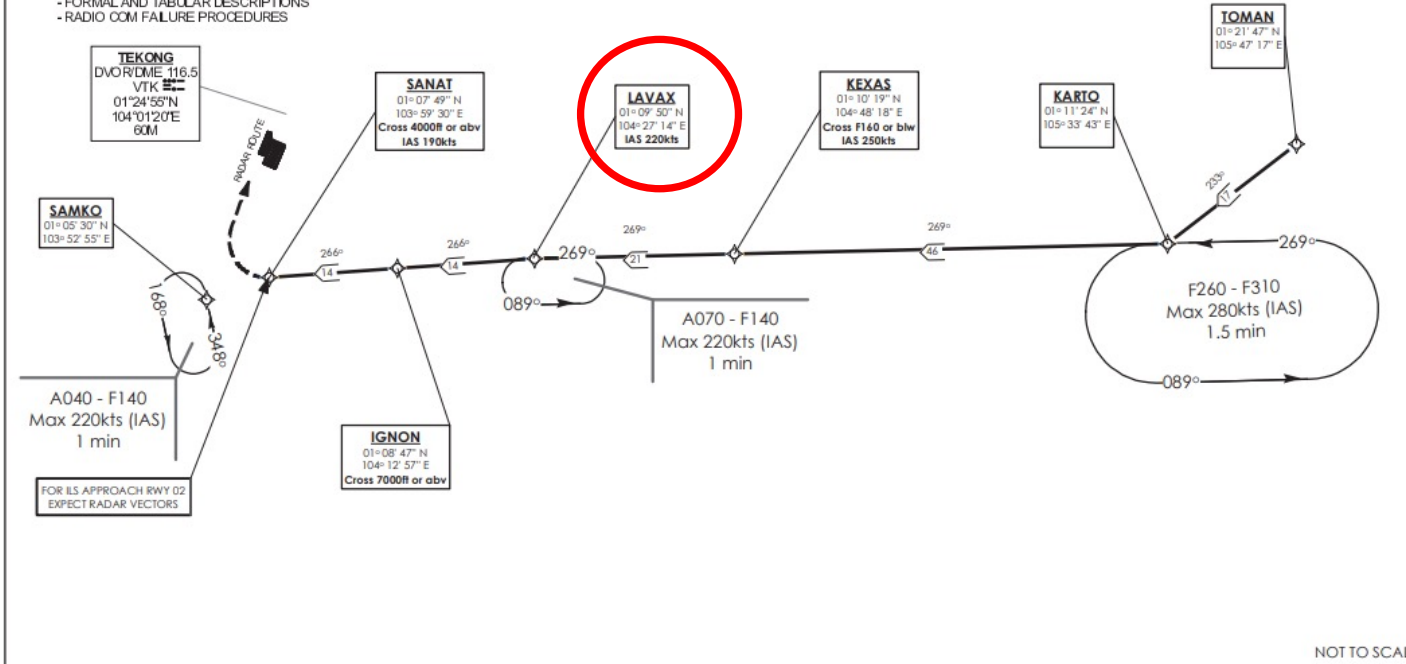
ELEV. ALT IN FEET
 BEARINGS, TRACKS AND
 RADIALS ARE MAGNETIC
 VAR 0°23'E (2020)

DISTANCES IN NM

NOTE: RADAR REQUIRED

NOTE: RNAV-1 NAVIGATION SPECIFICATION GNSS REQUIRED

NOTE: REFER TO BACK PAGE FOR
 - FORMAL AND TABULAR DESCRIPTIONS
 - RADIO COM FAILURE PROCEDURES



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CHANGES : Removal of Runway 2 closure crosses "X"

AIP AMDT 01/2024

STAR OBDOS

AIP Singapore

AD-2-WSSS-STAR-6

12 AUG 2021

SINGAPORE/Singapore Changi

RWY 02L/C/R

OBDOS ONE ALPHA ARRIVAL

OBDOS 1A

STANDARD ARRIVAL CHART RNAV (GNSS) - INSTRUMENT (STAR)

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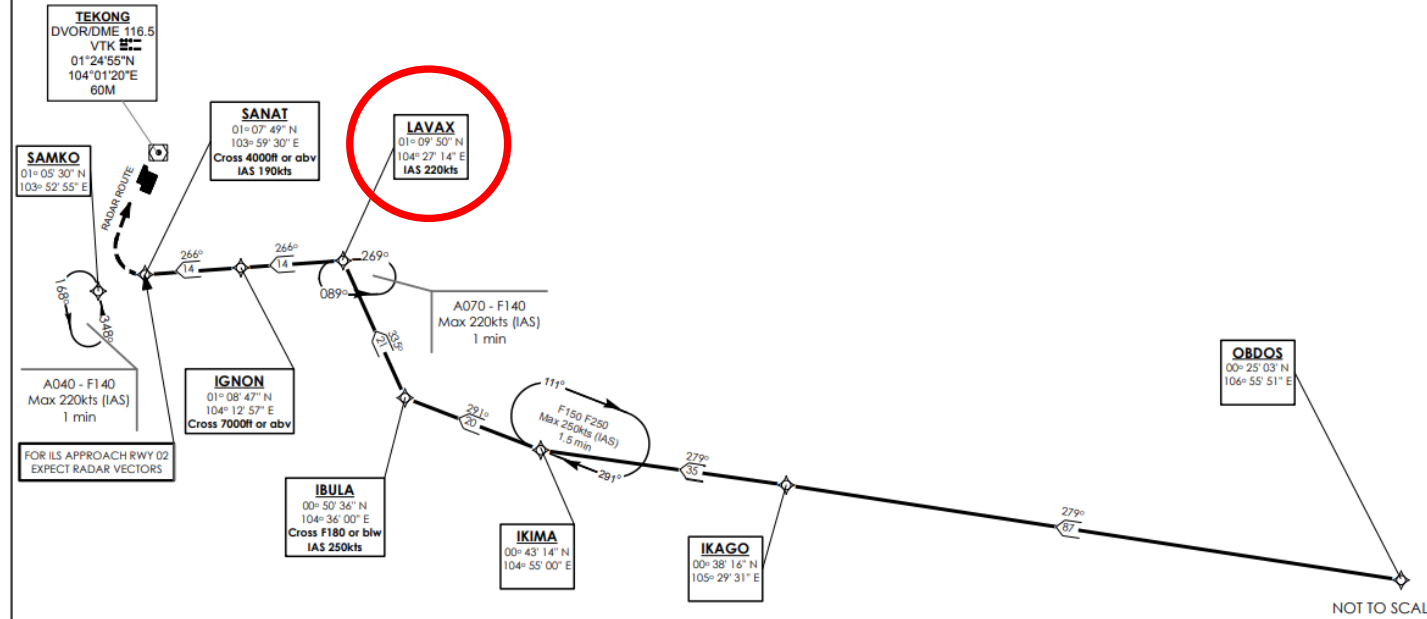
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CHANGES: MSA Revised

AIP AMDT 04/2021

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AD-Z-WSSS-S1AR-1/
12 AUG 2021

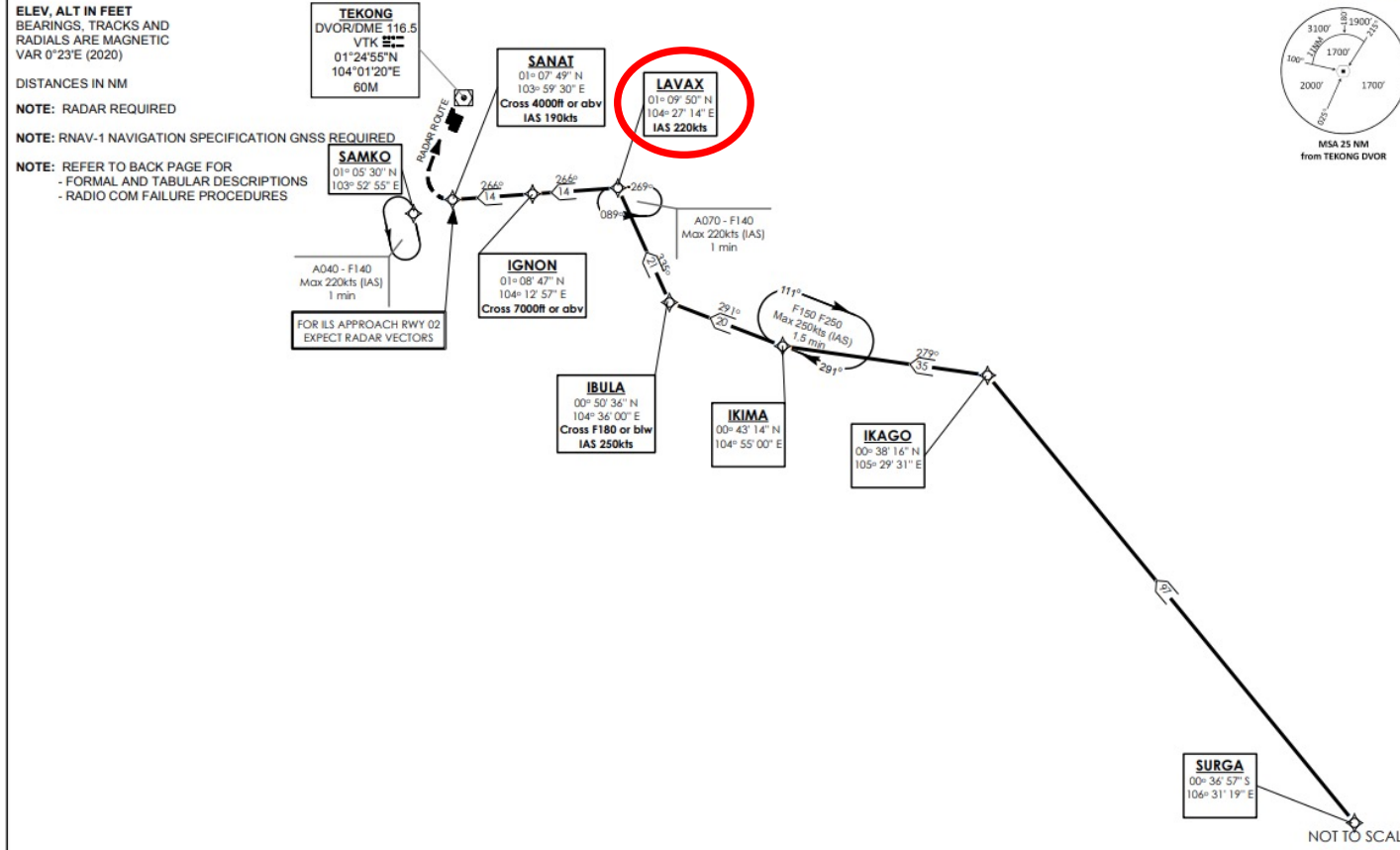
**STANDARD ARRIVAL CHART
RNAV (GNSS) -
INSTRUMENT (STAR)**

ACC 134.4
APP 124.05
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TWR 118.6 / 118.25

TRANSITION ALTITUDE
11 000ft

D-ATIS AP ID-WSSS
128.025

**SINGAPORE/Singapore Changi
RWY 02L/C/R
SURGA ONE ALPHA ARRIVAL
SURGA 1A**



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CHANGES : MSA Revised

AIP AMDT 04/2021

STAR Affected TOMAN

TOPOM to KADAR

ARAMA to SAMKO

ASUNA to SAMKO

TOMAN to SANAT Waypoints affected : 1

OBDOS to SANAT Waypoints affected : 1

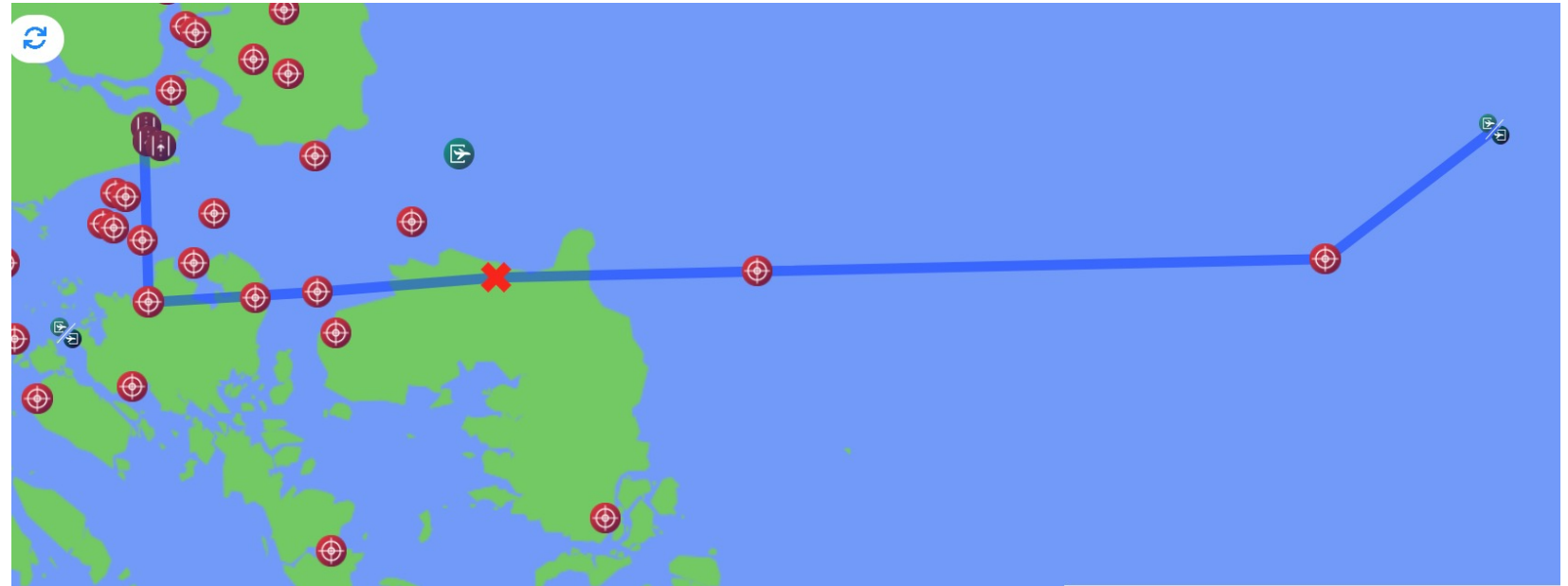
MABAL to SANAT

PASPU to SAMKO

REPOV to SAMKO

SURGA to SANAT Waypoints affected : 1

ELALO to SANAT



STARs Affected: OBDOS

TOPOM to KADAR

ARAMA to SAMKO

ASUNA to SAMKO

TOMAN to SANAT Waypoints affected : 1

OBDOS to SANAT Waypoints affected : 1

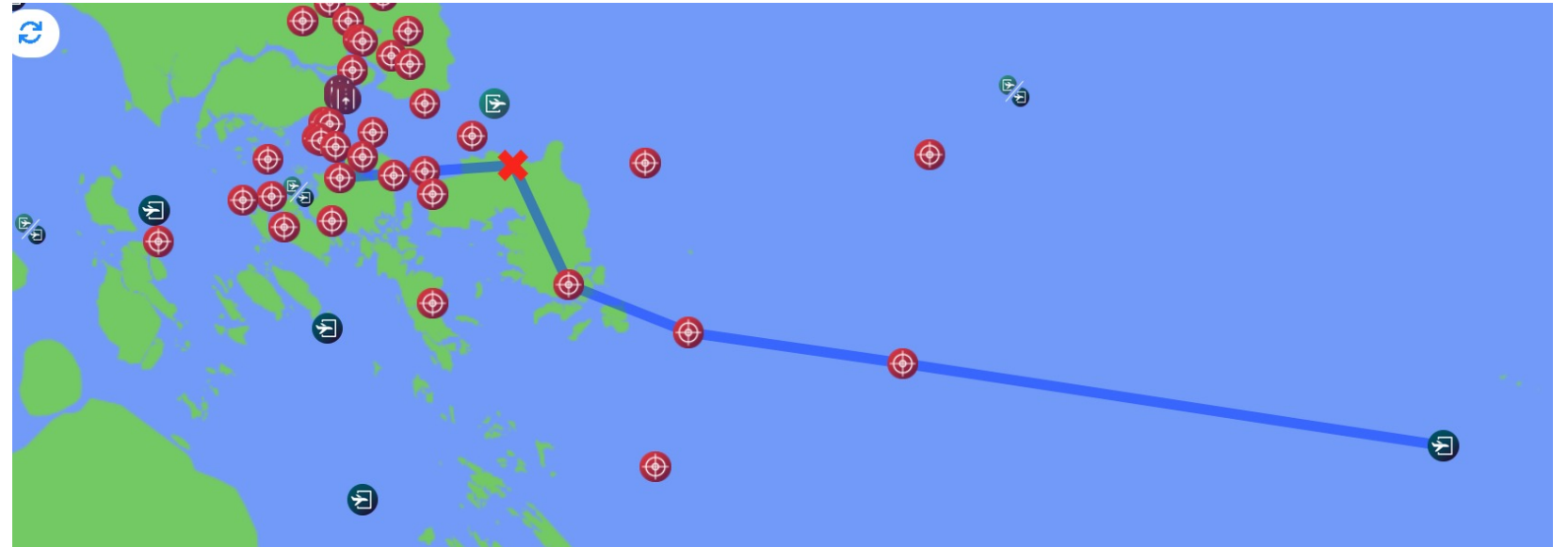
MABAL to SANAT

PASPU to SAMKO

REPOV to SAMKO

SURGA to SANAT Waypoints affected : 1

ELALO to SANAT



STARs Affected: SURGA

TOPOM to KADAR

ARAMA to SAMKO

ASUNA to SAMKO

TOMAN to SANAT Waypoints affected : 1

OBDOS to SANAT Waypoints affected : 1

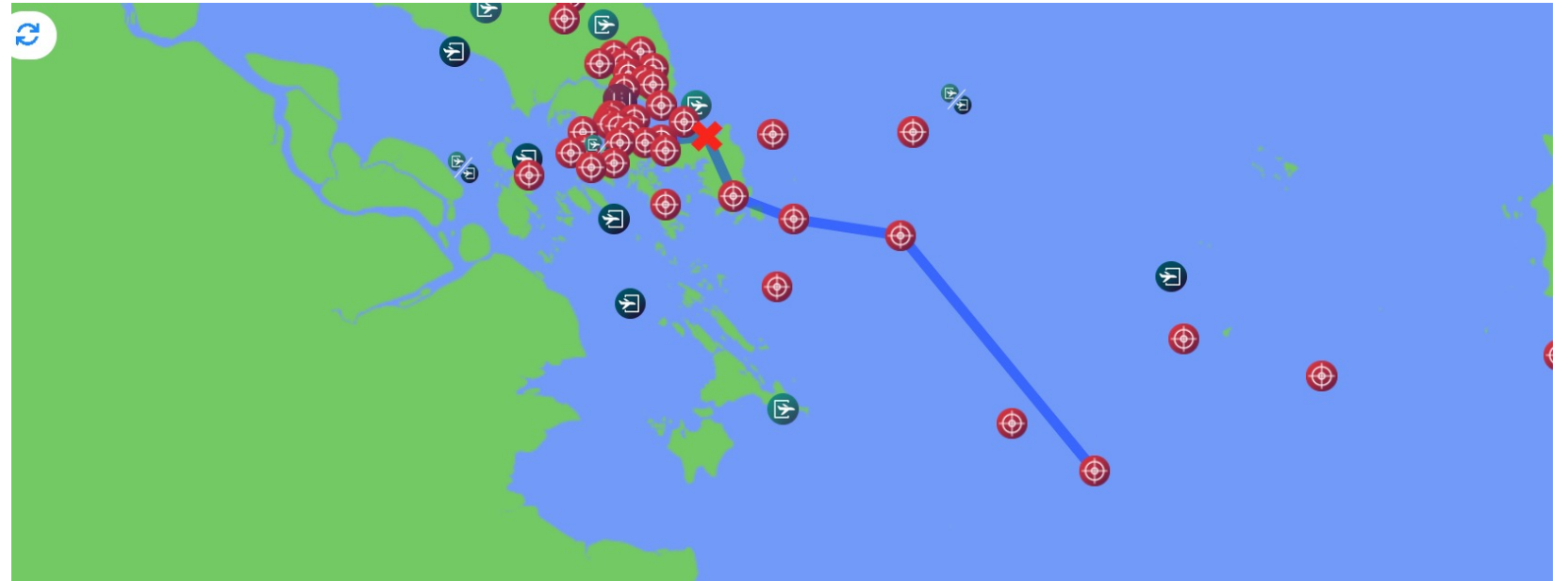
MABAL to SANAT

PASPU to SAMKO

REPOV to SAMKO

SURGA to SANAT Waypoints affected : 1

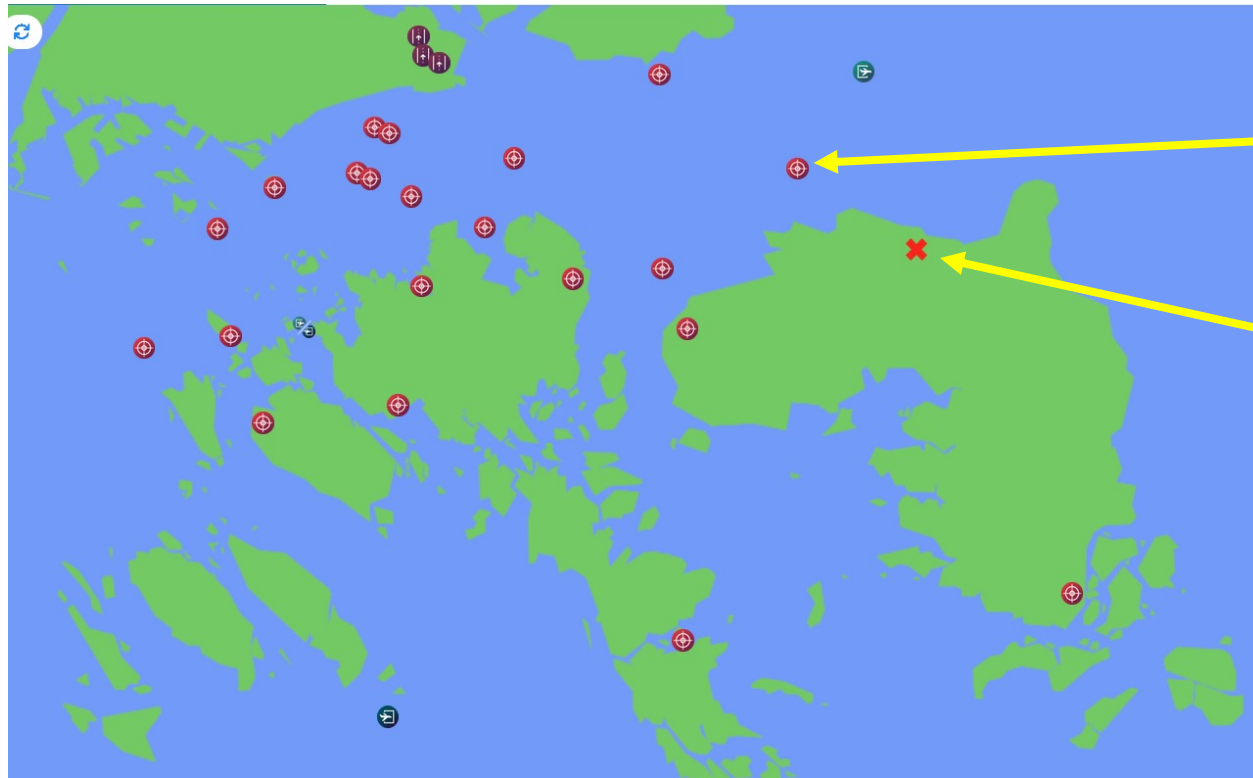
ELALO to SANAT



Two Design Choices

Design A:

- Re-route traffic around RUVIK



Shortname: RUVIK

Location Type: waypoint

Latitude: 1.2394

Longitude: 104.3425

Shortname: LAVAX

Location Type: waypoint

Latitude: 1.1639

Longitude: 104.4539

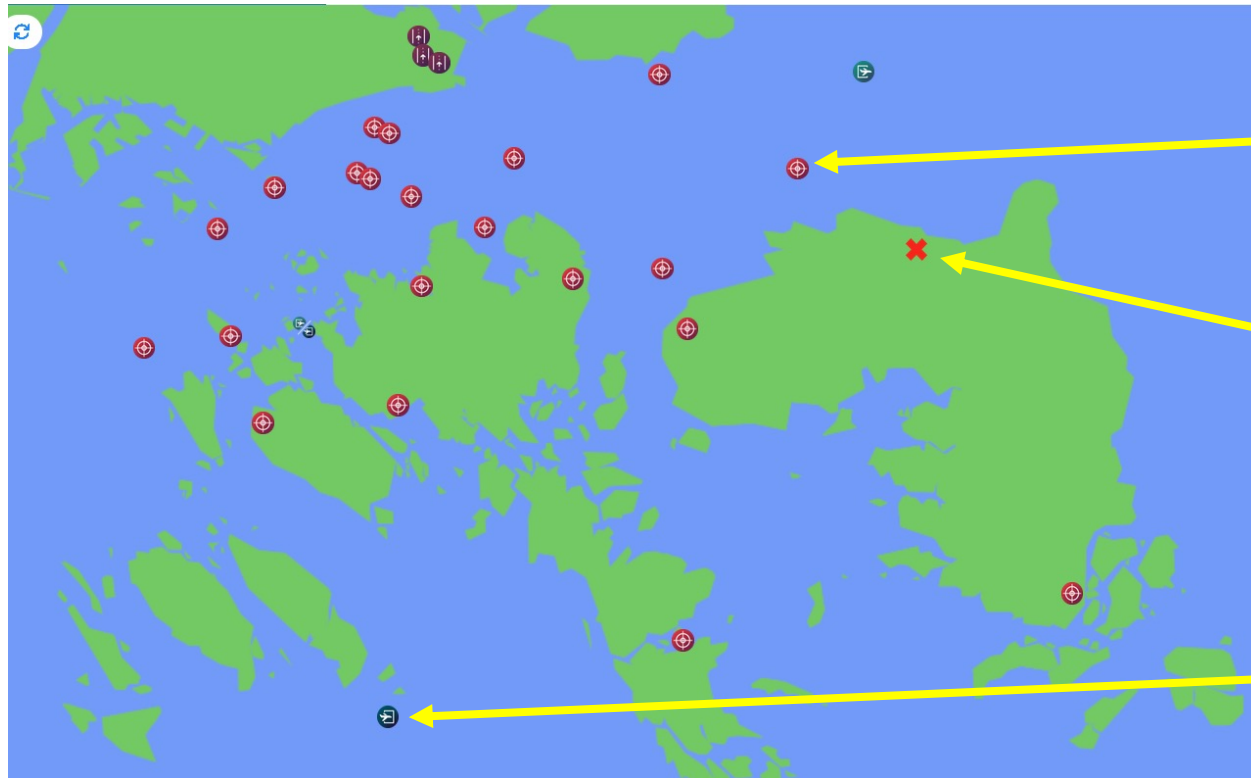
Two Design Choices

Design A:

- Re-route traffic around RUVIK

Design B:

- Re-route traffic around REMES



Shortname: RUVIK

Location Type: waypoint

Latitude: 1.2394

Longitude: 104.3425

Shortname: LAVAX

Location Type: waypoint

Latitude: 1.1639

Longitude: 104.4539

Shortname: REMES

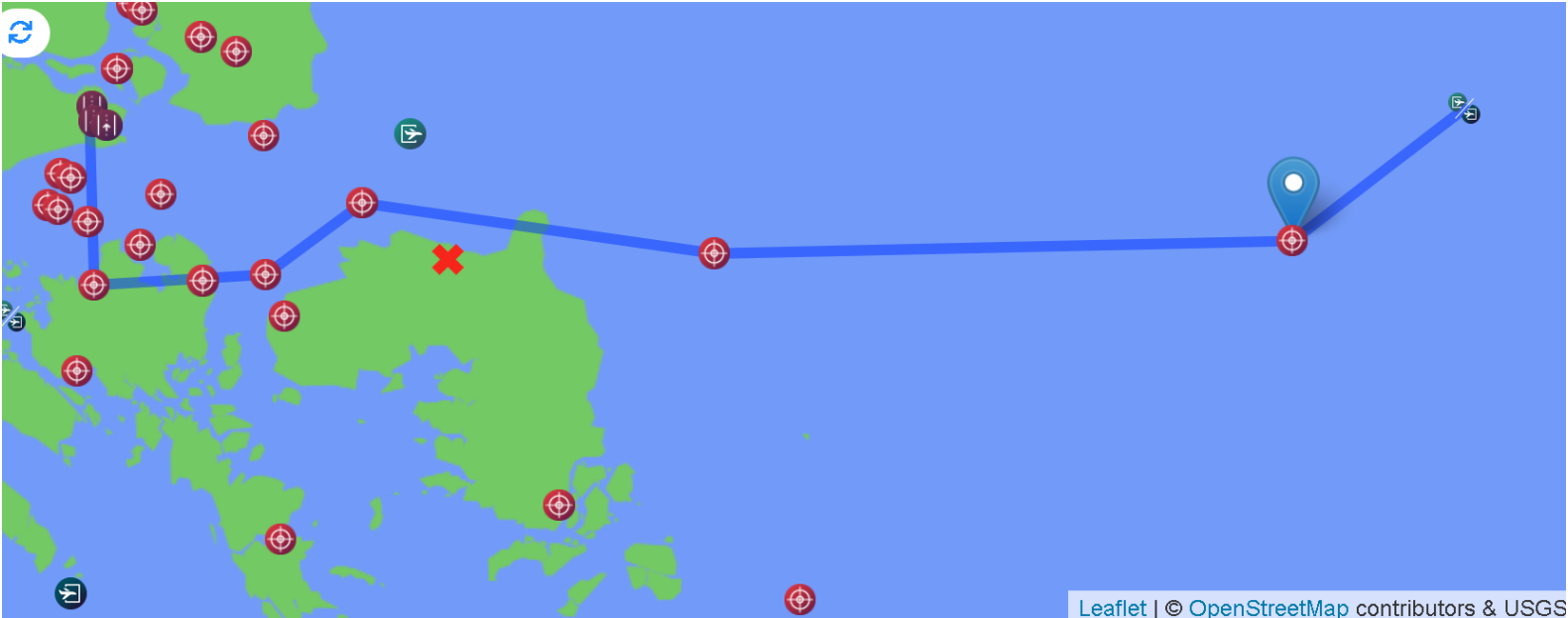
Location Type: entry

Latitude: 0.7283

Longitude: 103.9597

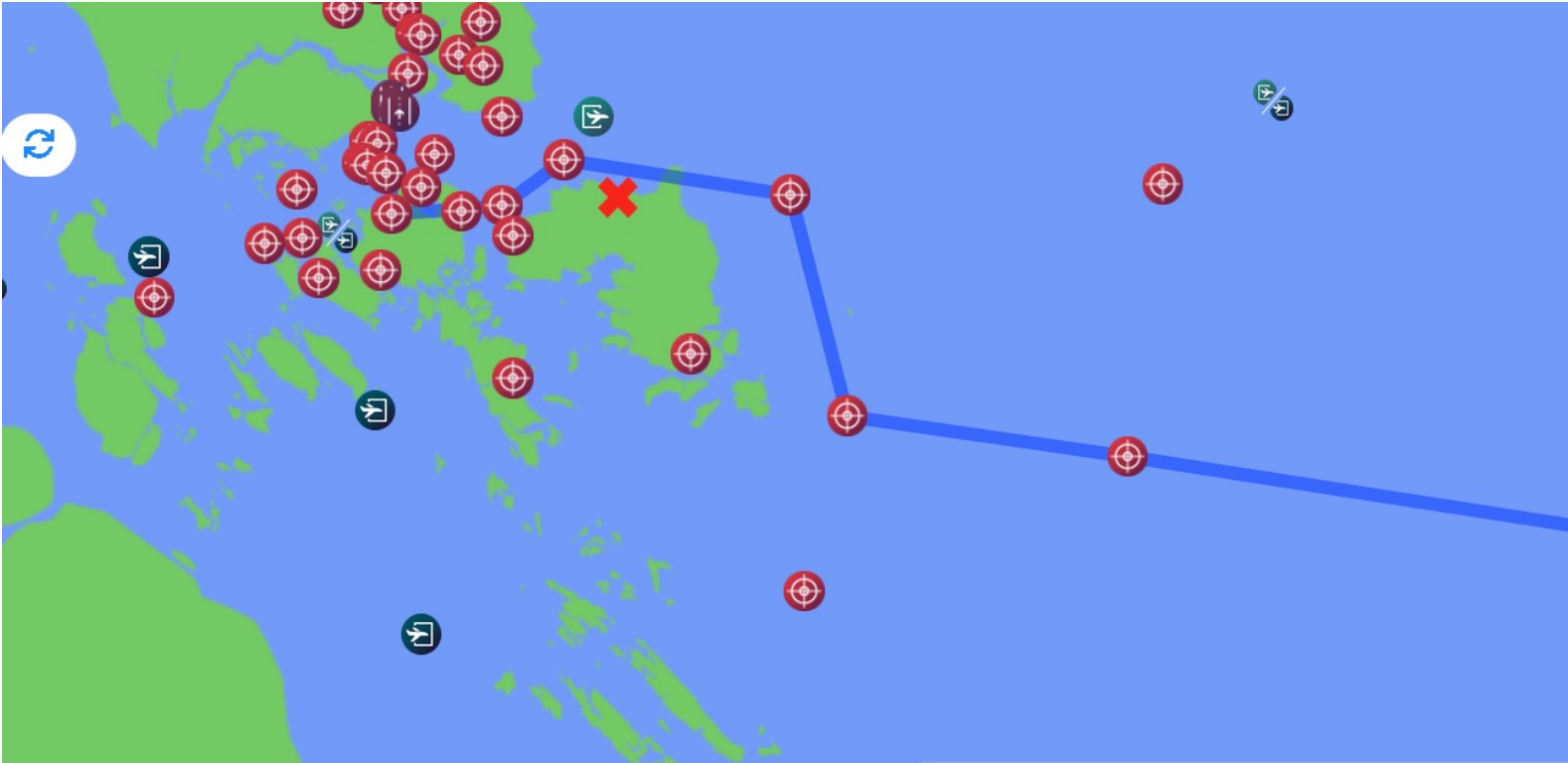
Design A for TOMAN

KARTO is a holding area



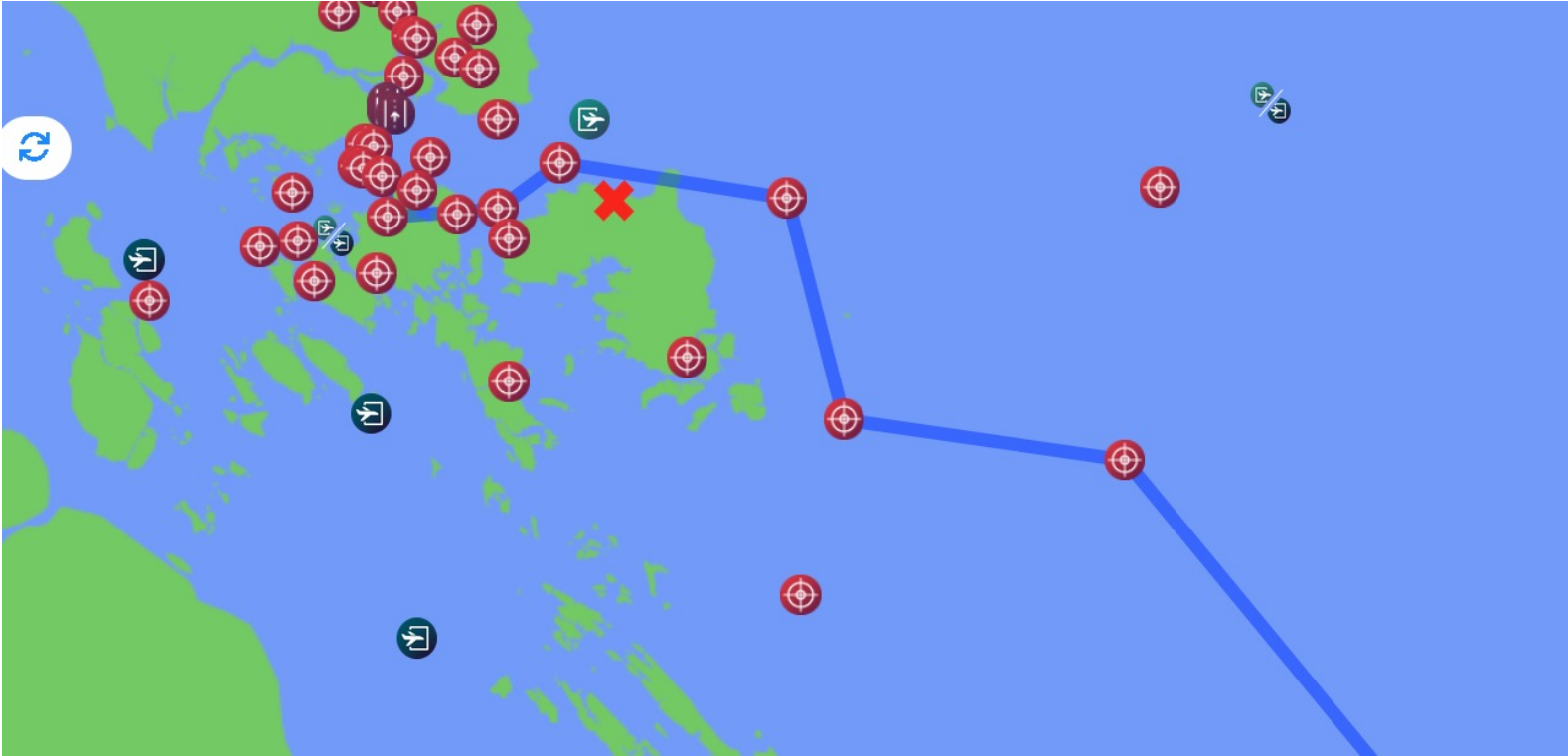
- TOMAN
- KARTO**
- KEXAS
- RUVIK
- IGNON
- SANAT
- WSSS_02L/02C/02R

Design A for OBDOS



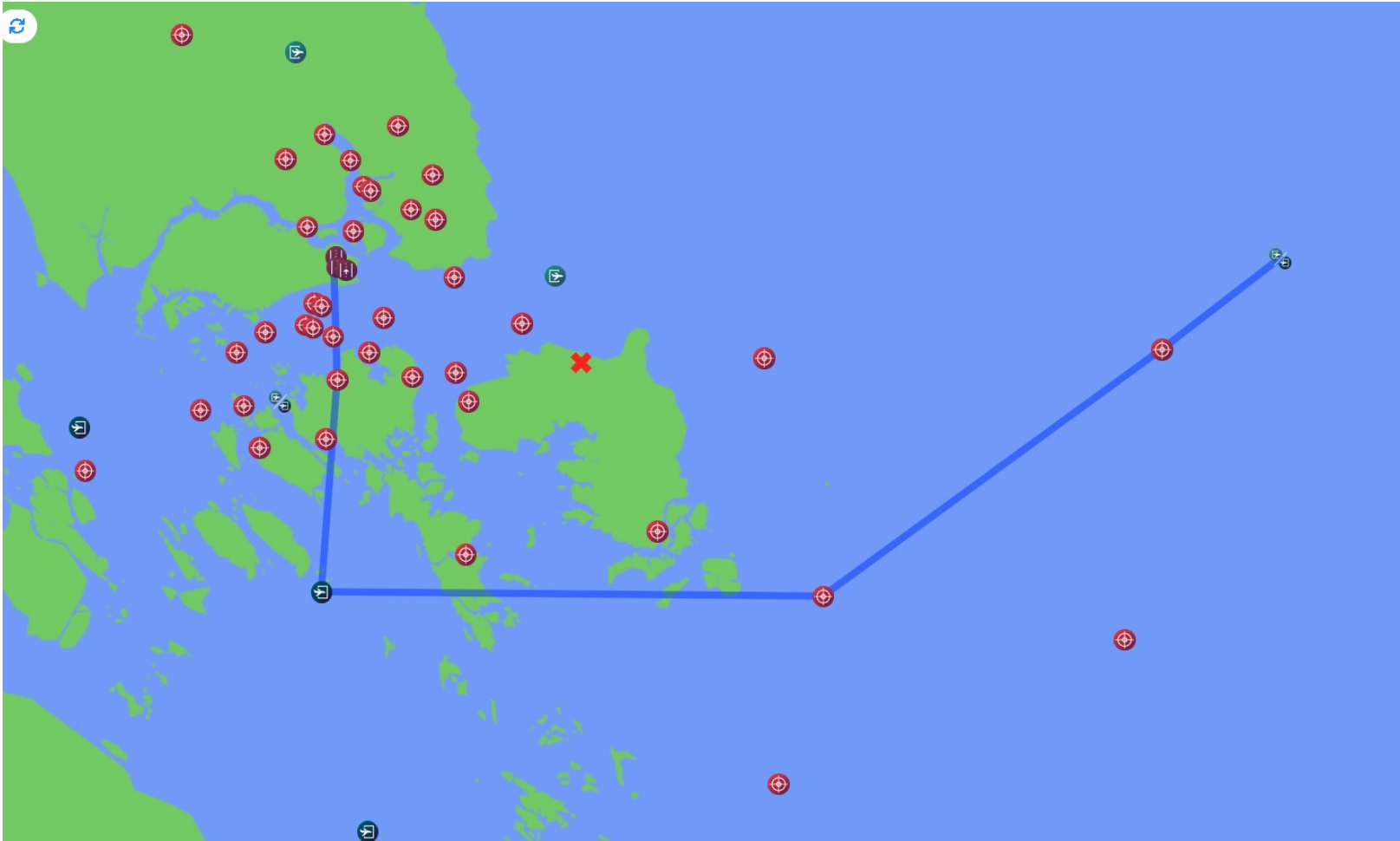
- OBDOS
- IKAGO
- IKIMA
- KEXAS
- RUVIK
- IGNON
- SANAT
- WSSS_02L/02C/02R

Design A for SURGA



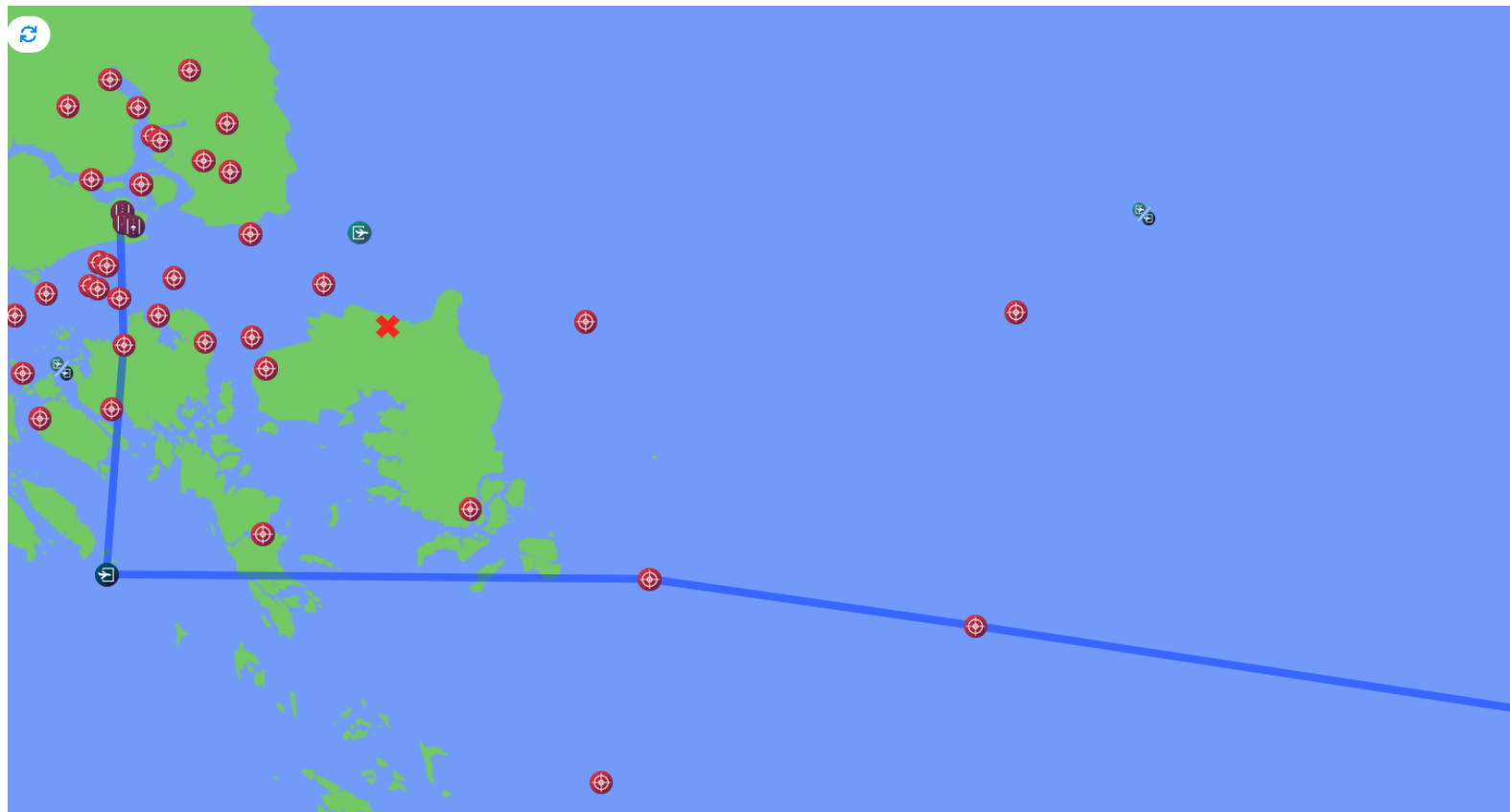
- SURGA
- IKAGO
- IKIMA
- KEXAS
- RUVIK
- SANAT
- WSSS_02L/02C/02R

Design B for TOMAN



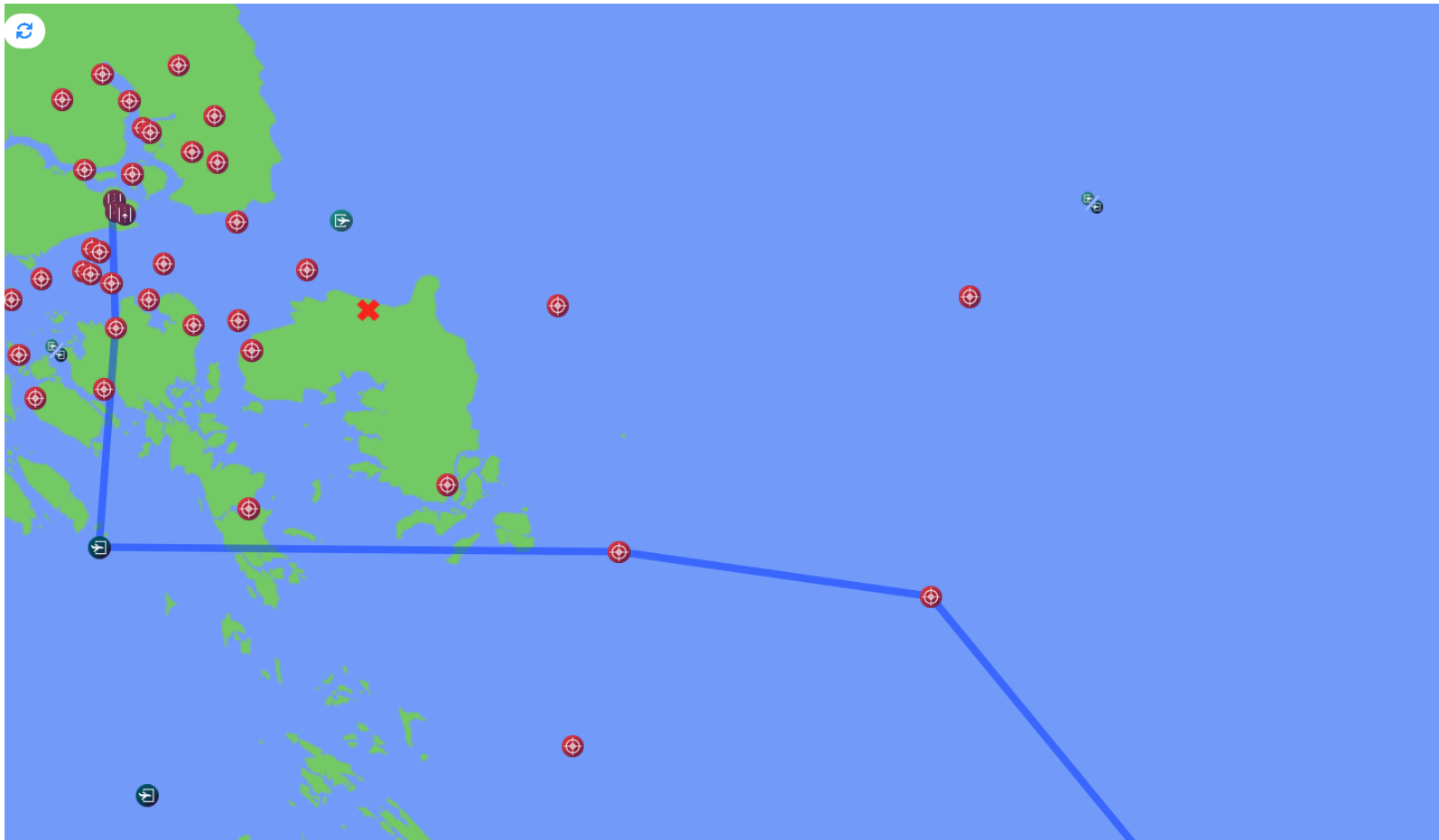
- TOMAN
- KARTO
- IKIMA
- REMES
- SANAT
- WSSS_02L/02C/02R

Design B for OBDOS



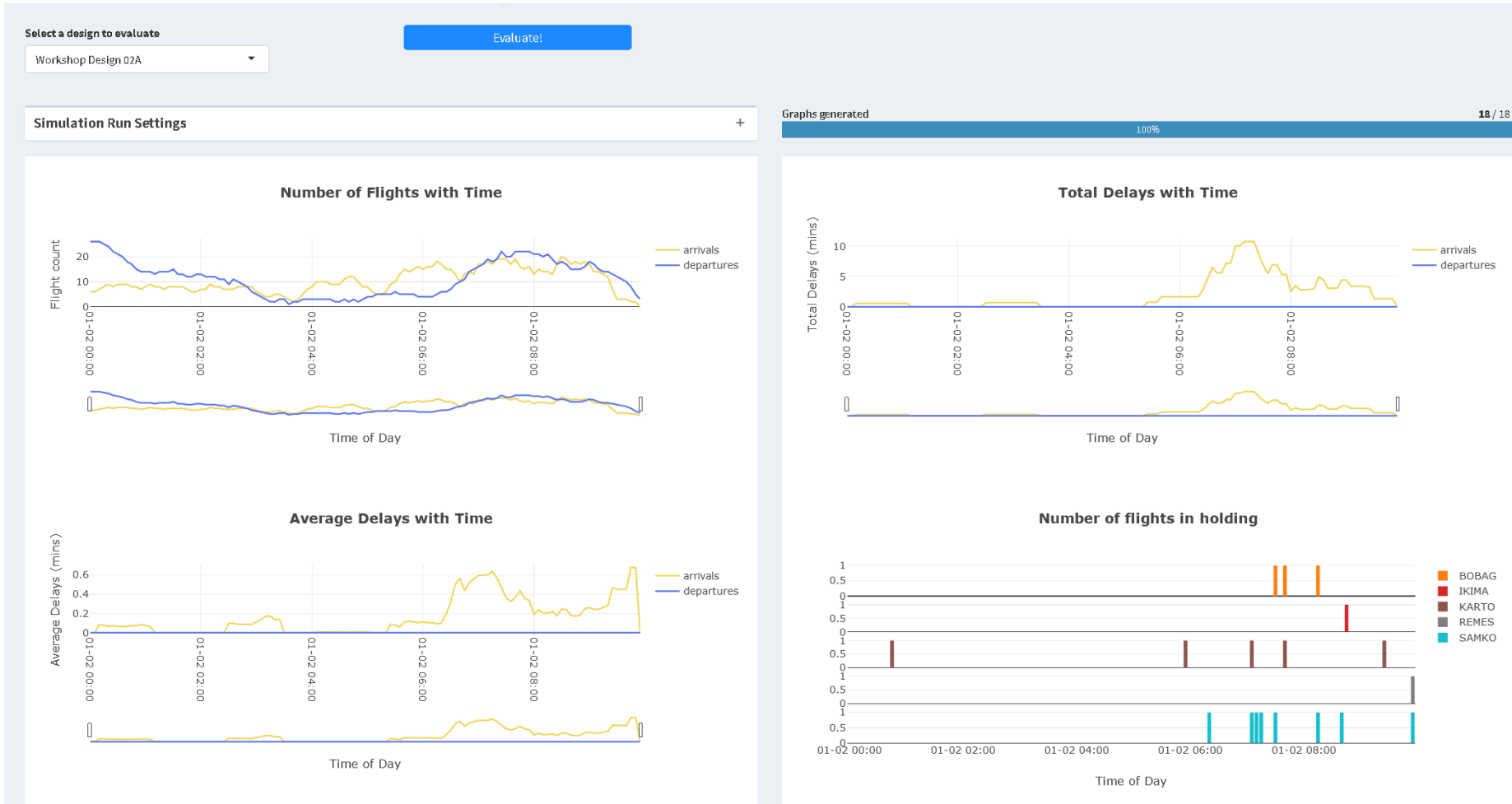
- OBDOS
- IKAGO
- IKIMA
- REMES
- SANAT
- WSSS_02L/02C/02R

Design B for SURGA

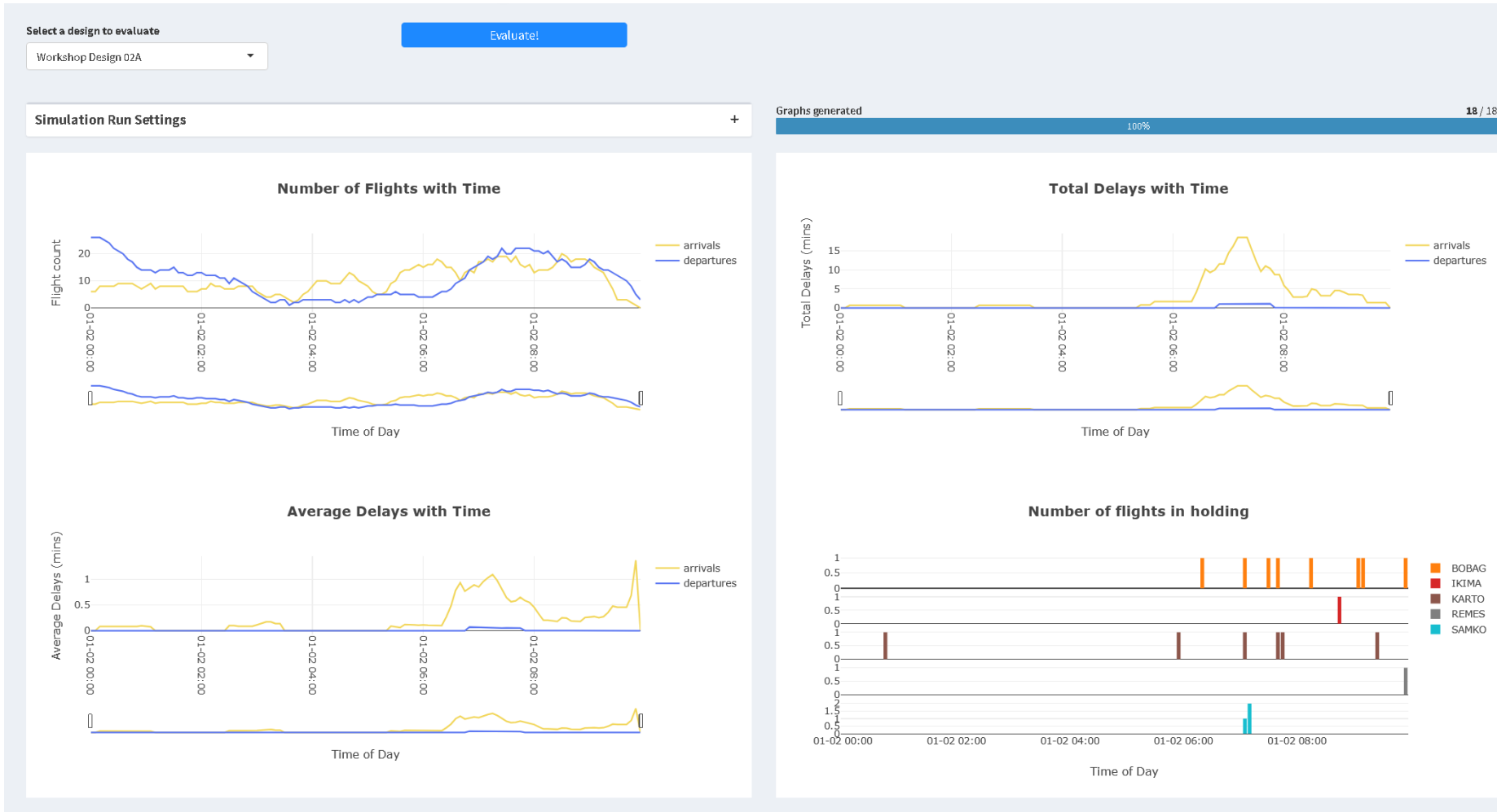


- SURGA
- IKAGO
- IKIMA
- REMES
- SANAT
- WSSS_02L/02C/02R

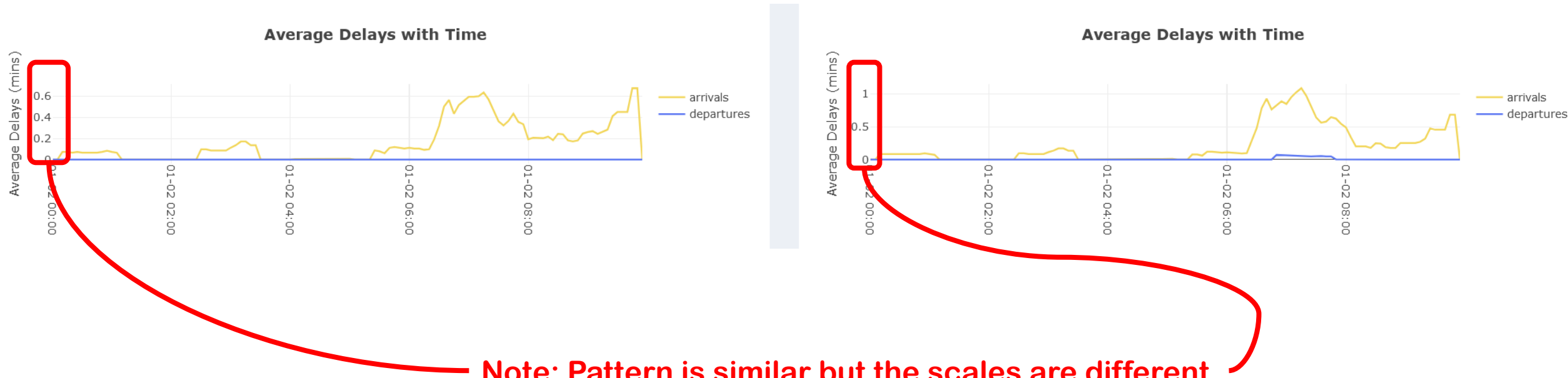
Evaluate Design A



Evaluate Design B

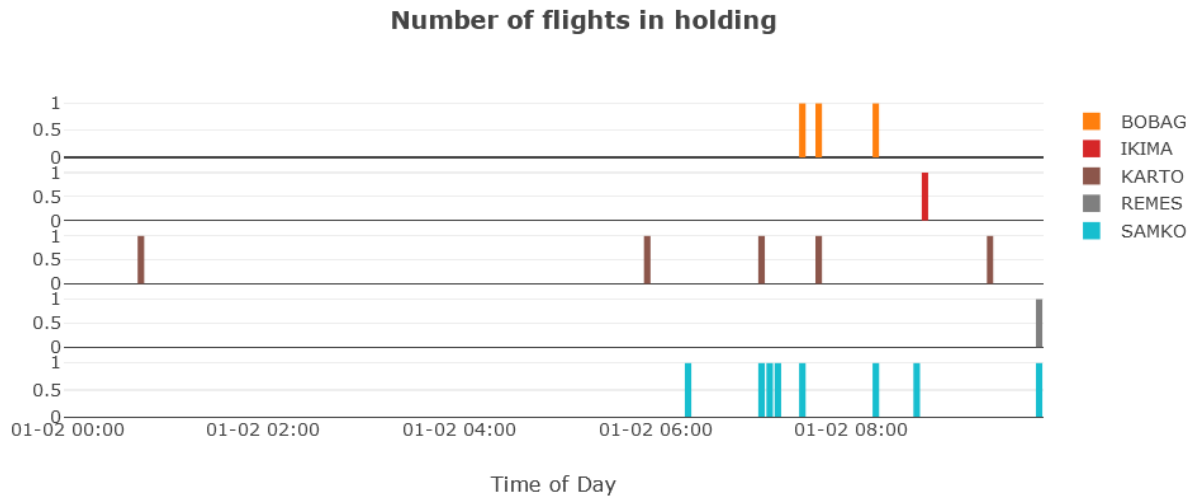


Side By Side Average Delays

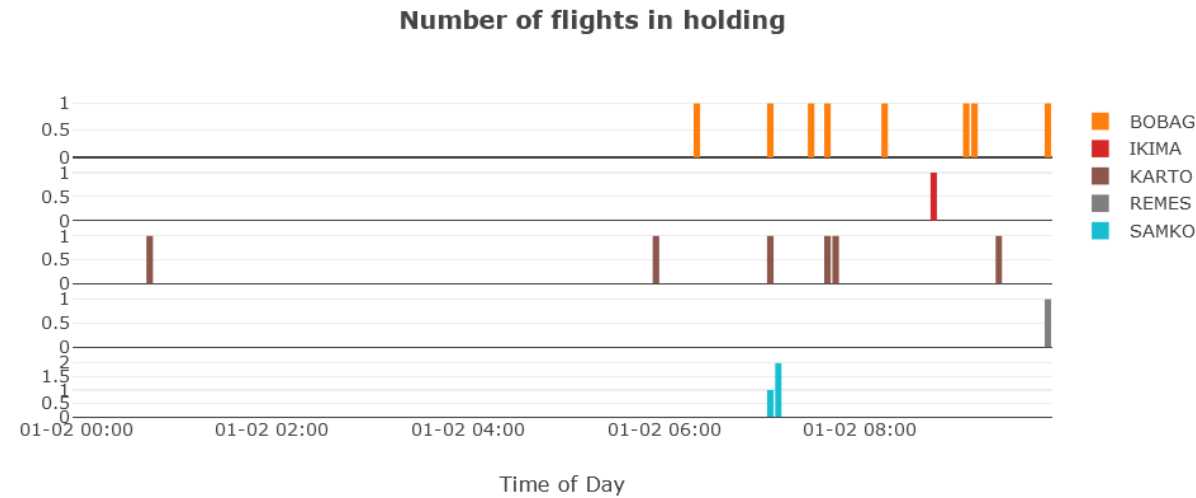


Side By Side: Number of Flights Holding

Plot for Workshop Design 02A

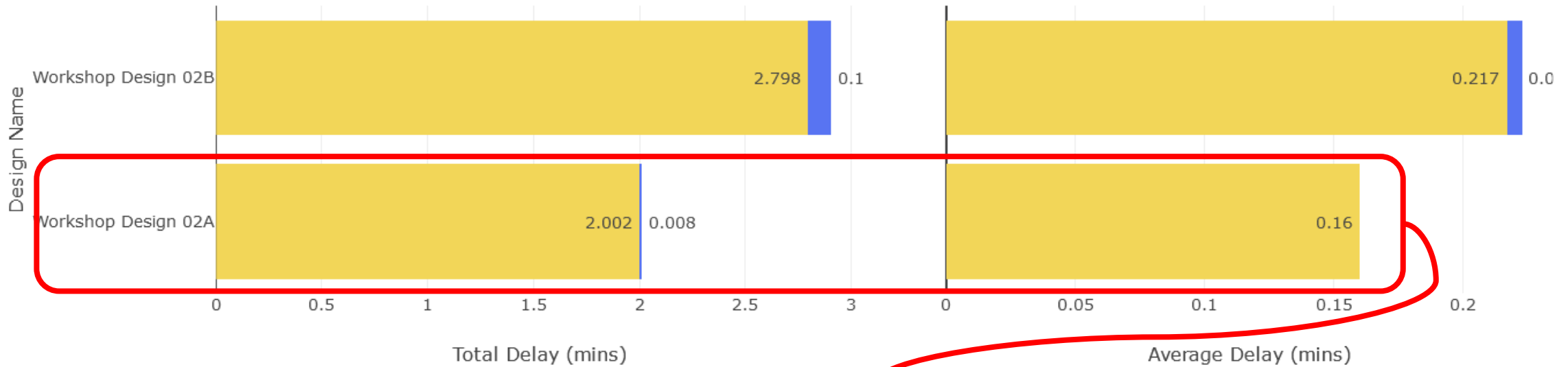


Plot for Workshop Design 02B



Assess Designs

Summary Statistics



Design A (through RUVIK) has lower total and average delay

The TMA Design Tool enables the user to

- Describe scenarios of airspace restriction events and future developments
- Develop alternative airspace designs (SID and STAR routes with holding areas)
- Simulate air traffic flows through each design using optimization to ensure appropriate separations at waypoints and use of vectoring or holding
- Compare designs side by side for their impact on simulated delays
- Rapidly identify best designs for further consideration

Attribution

- Storm cloud icon: <https://www.vecteezy.com/vector-art/441534-storm-vector-icon>
- Volcano icon: <https://www.vecteezy.com/vector-art/22929221-volcano-vector-icon-design>
- Spacecraft icon: <https://www.vecteezy.com/vector-art/1522059-spaceship-on-a-take-off-platform>
- Military jets: <https://www.vecteezy.com/vector-art/23825180-flying-modern-jet-formation-vector-design>
- Airport Runway: <https://www.vecteezy.com/vector-art/2127665-top-view-of-airport-runway-with-airplane-vector-illustration>
- Wildfires: <https://www.vecteezy.com/vector-art/10426272-fire-forest-natural-disaster>