Automation for Separation with CDOs: Dynamic Aircraft Arrival Routes

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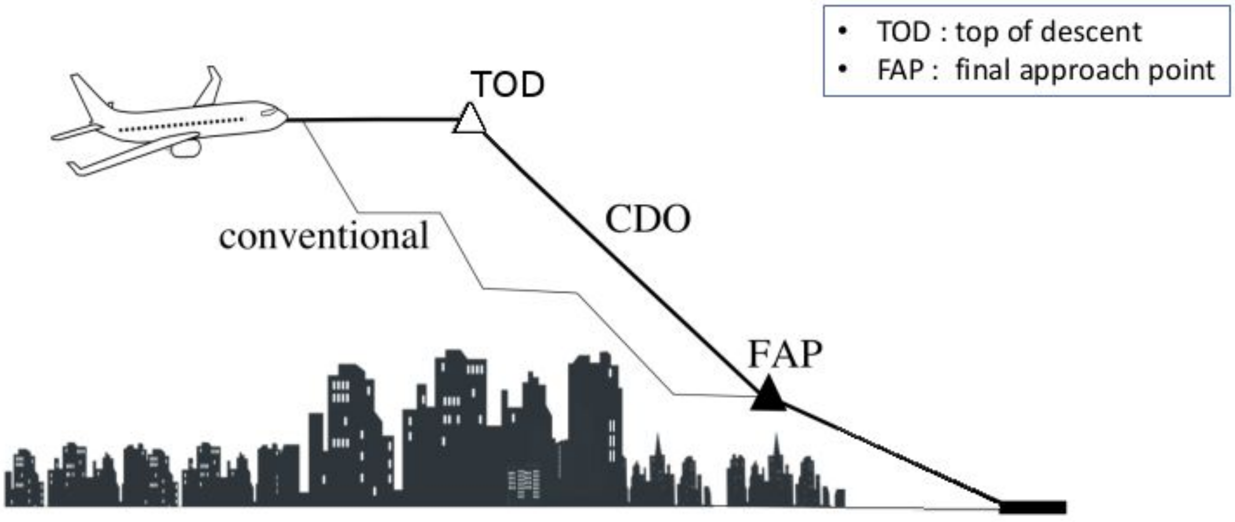
Motivation

- ✓ Air transportation grows: pros and cons
- ✓ Increased complexity and environmental effects
- ✓ Terminal Maneuvering Areas (TMAs) - most congested
- ✓ Optimization of arrival and departure procedures is needed
- ✓ Our solution:
  - Automatically separated arrivals to reduce complexity and ATCO's workload
  - CDOs (Continuous Descent Operations): promising solution to mitigate environmental effects, according to ICAO and EUROCONTROL: *"CDOs allow aircraft to follow a flexible, optimum flight path that delivers major environmental and economic benefits—reduced fuel burn, gaseous emissions, noise and fuel costs—without any adverse effect on safety"*

CDOs

✓ CDOs have shown important environmental benefits w.r.t. conventional (step-down) approaches in TMAs

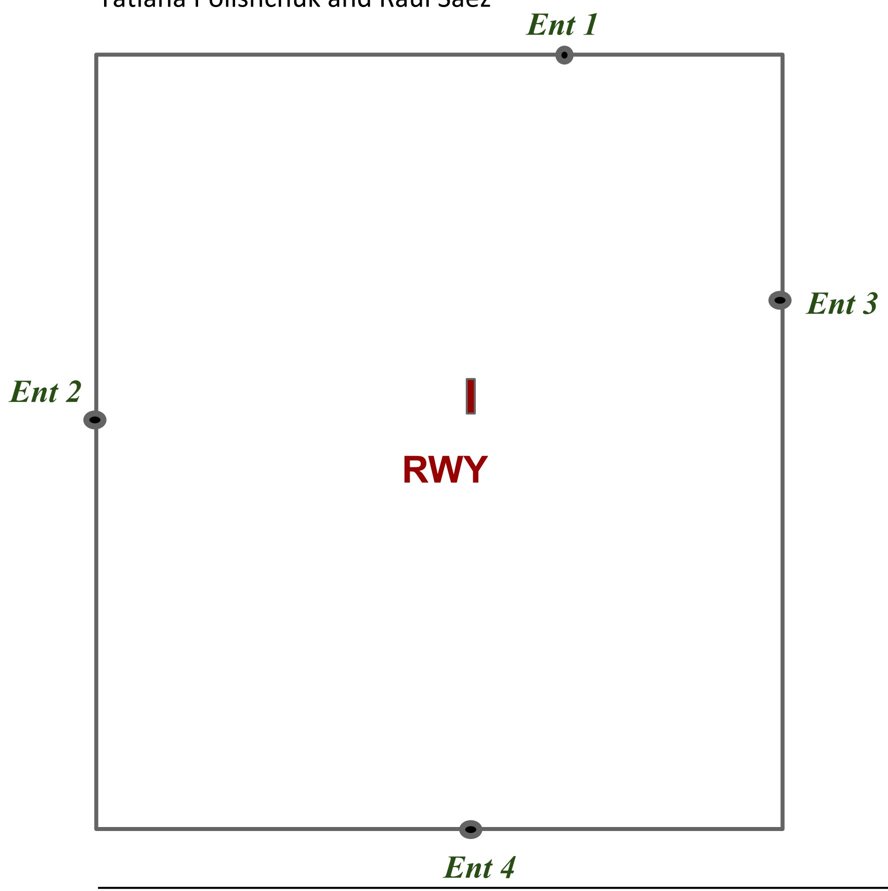


Previous Work

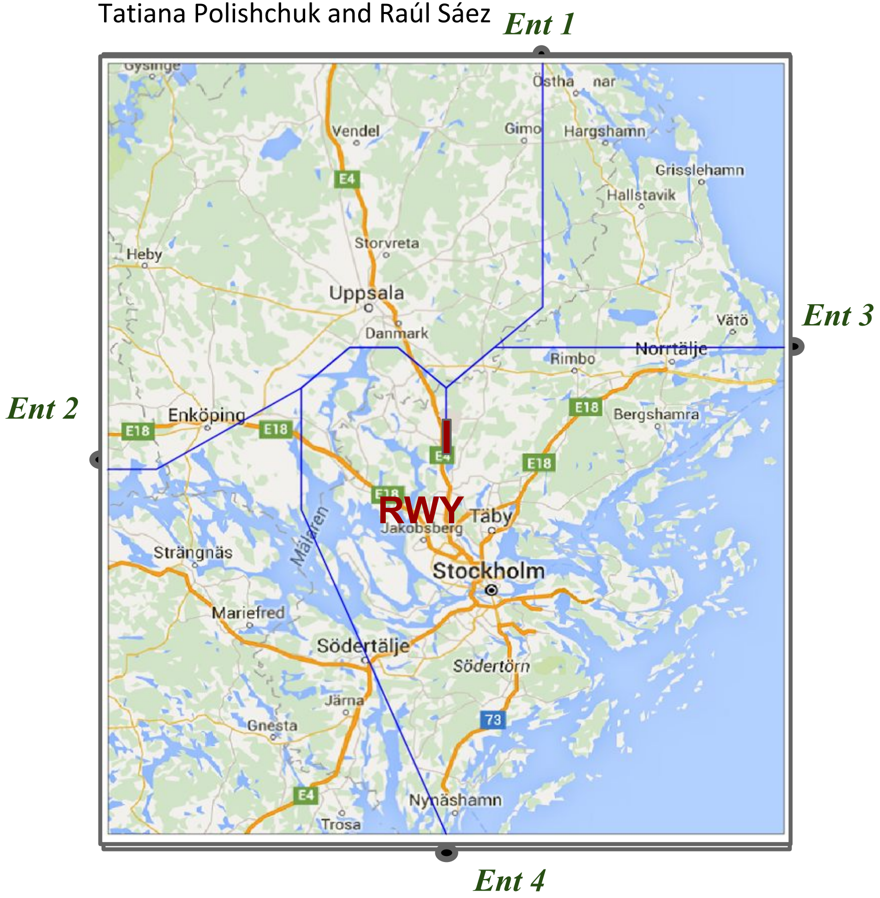
- ✓ LiU-LFV: optimal STARs + time-separated demand-weighted *arrival routes (dynamic, for pre-tactical planning)*
- ✓ UPC: CDO-enabled optimized arrival procedures (*engine-idle, low noise)*

New: automated time-separated demand-weighted ***CDO-enabled*** optimized ***arrival routes***

Input



- ✓ Location and direction of the airport runway
- ✓ Locations of the entry points to the TMA
- ✓ Aircraft arrival times at the entry points for a fixed time period
- ✓ Cruise conditions (altitude, true airspeed, distance to entry point + path distance inside TMA) and aircraft type for CDO profile generation



Output

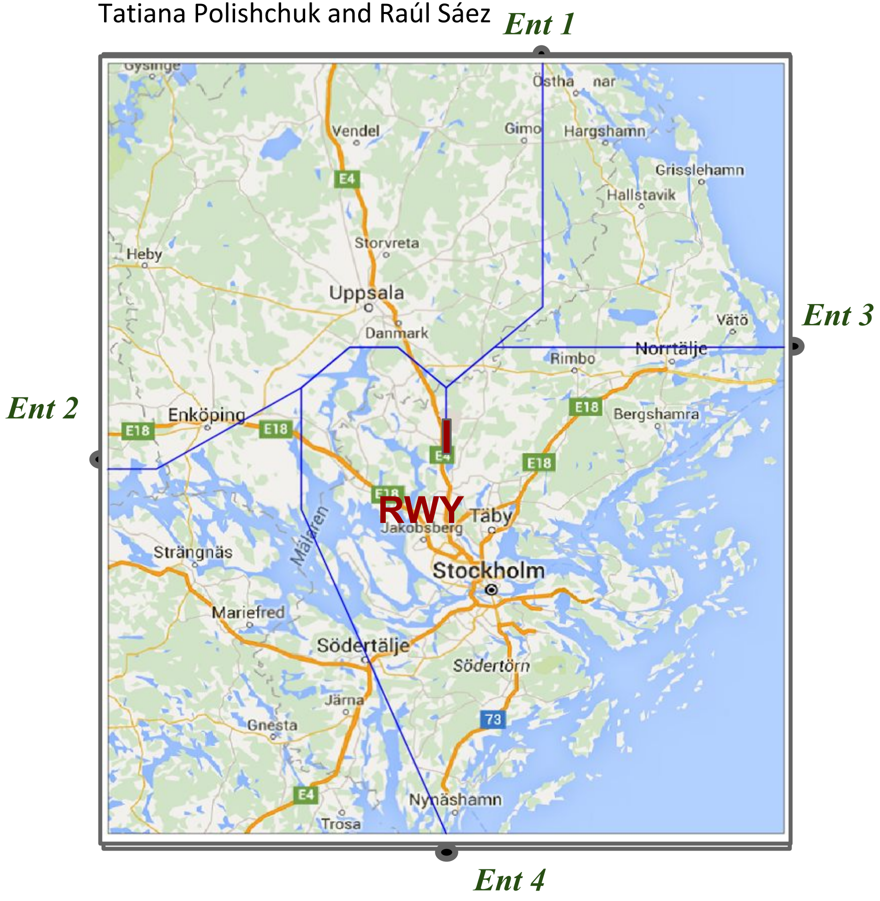
Optimal arrival tree

that merges traffic

from the entries to the runway

ensuring safe aircraft separation

for the given time period



Output

Optimal arrival tree

that merges traffic

from the entries to the runway

ensuring safe aircraft separation

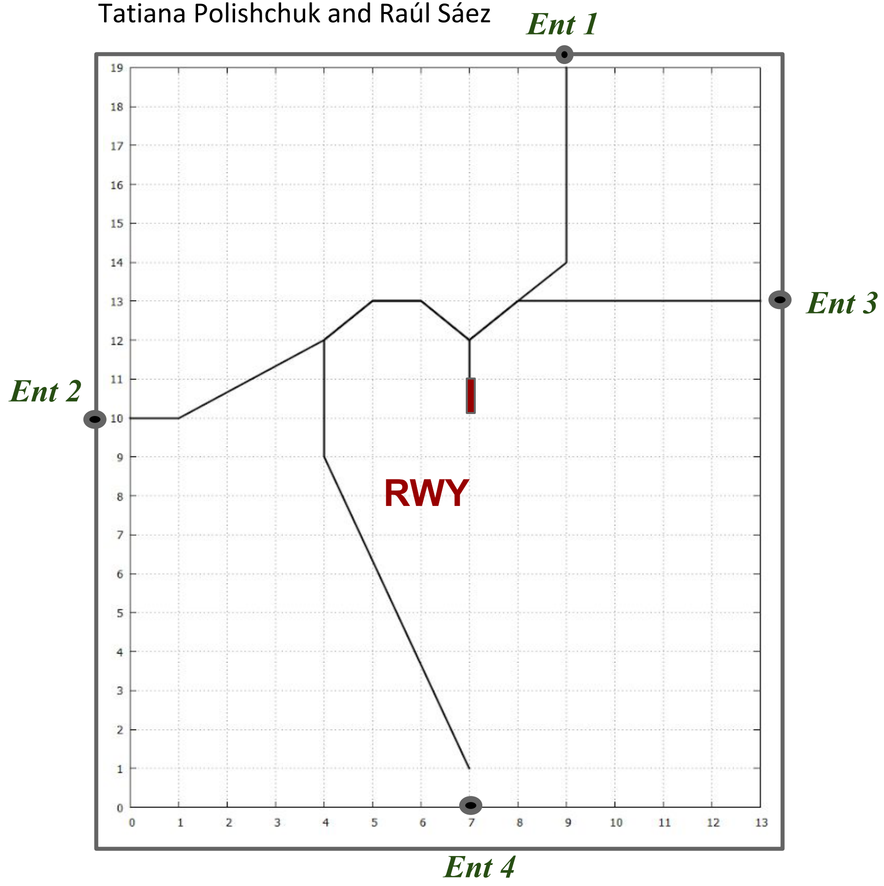
for the given time period

=

a set of time-separated **CDO-enabled** aircraft trajectories

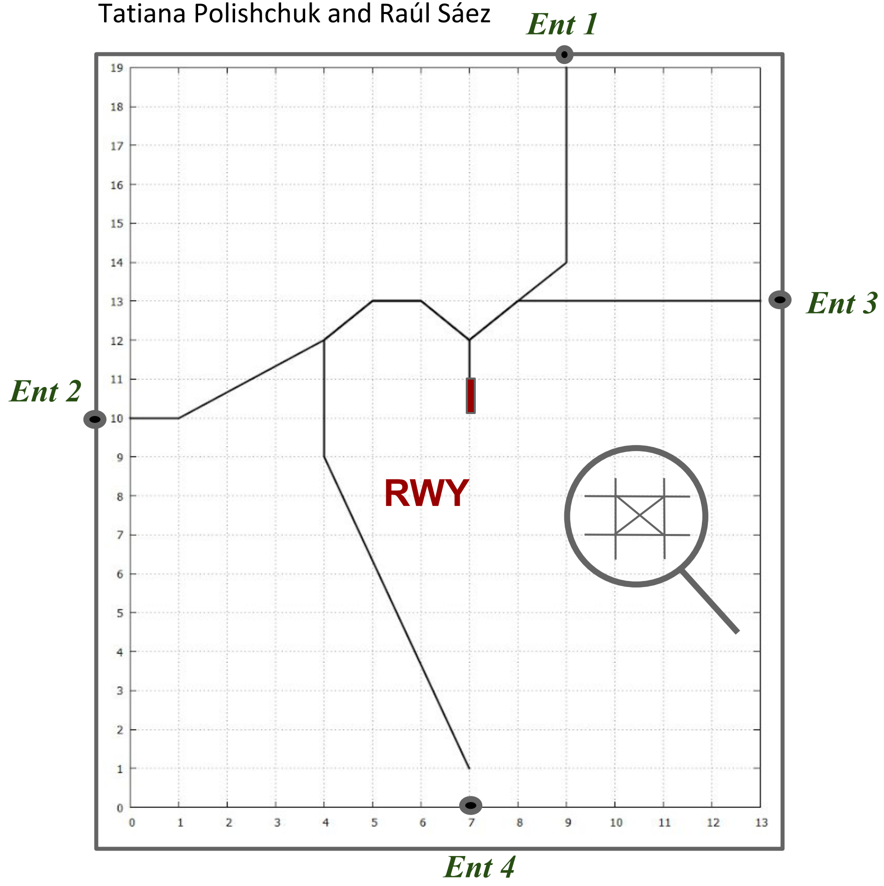
optimized w.r.t. the traffic demand

during the given period



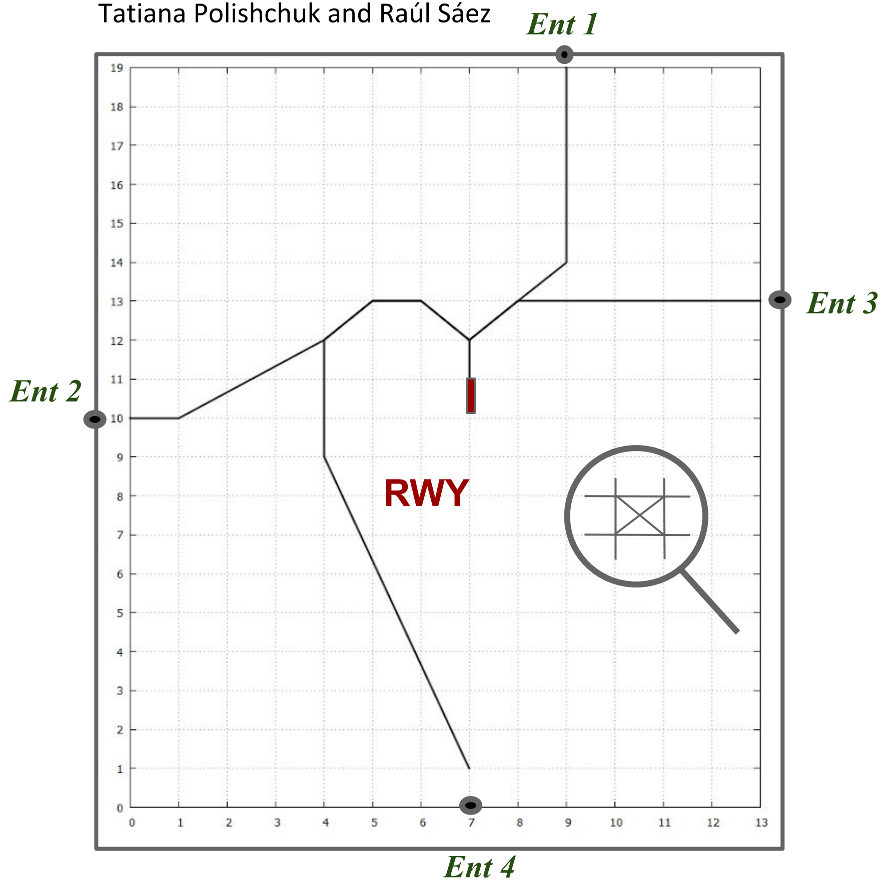
Grid-Based MIP Formulation

- ✓ Square grid in the TMA
- ✓ Snap locations of the entry points and the runway into the grid
- ✓ Grid cell side of the length l (*separation parameter*)



Grid-Based MIP Formulation

- ✓ Square grid in the TMA
- ✓ Snap locations of the entry points and the runway into the grid
- ✓ Grid cell side of the length l (*separation parameter*)
- ✓ Every node connected to its 8 neighbours



Grid-Based MIP Formulation

- ✓ Square grid in the TMA
- ✓ Snap locations of the entry points and the runway into the grid
- ✓ Grid cell side of the length l (*separation parameter*)
- ✓ Every node connected to its 8 neighbours
- ✓ Problem formulated as MIP

Based on flow MIP formulation for Steiner trees

Operational Requirements

- ✓ No more than two routes merge at a point
- ✓ Merge point separation
- ✓ No sharp turns
- ✓ Temporal separation of all aircraft along the routes
- ✓ All aircraft fly energy-neutral CDO:
  idle thrust, no speed brakes (noise avoidance)
- ✓ Smooth transition between consecutive trees when switching

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MIP Formulation

VARIABLES

x_e - decision variable - indicates whether edge *e* participates in arrival tree

f_e - gives the flow on edge *e = (i, j)*, non-negative

OBJECTIVES

Total path length: $\min \sum_{e \in E} \ell_e f_e$

Total tree weight: $\min \sum_{e \in E} \ell_e x_e$

⇒ $$\min \quad \beta \sum_{e \in E} \ell_e x_e + (1 - \beta) \sum_{e \in E} \ell_e f_e$$

MIP formulation: Constraints

- ✓ Flow constraints
- ✓ Degree constraints
- ✓ Turn angle constraints
- ✓ Auxiliary constraints to prevent crossings
- ✓ Temporal separation of all aircraft along the routes
- ✓ Realistic CDO speed profiles
- ✓ Consistency between trees of different time periods

MIP formulation: Constraints

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MIP formulation: Constraints

✓ RE: Flow constraints

$$\sum_{k:(k,i)\in E} f_{ki} - \sum_{j:(i,j)\in E} f_{ij} = \begin{cases} \sum_{b\in\mathcal{P}} w_b & i = r \\ -w_i & i \in \mathcal{P} \\ 0 & i \in V \setminus \{\mathcal{P} \cup r\} \end{cases}$$

, where $\mathcal{P}$ set of entry points
w_b - number of a/c entering TMA from the entry point $b \in \mathcal{P}$

$$x_e \geq \frac{f_e}{Q} \quad \forall e \in E$$

$$f_e \geq 0 \quad \forall e \in E$$

where Q is a large number (e.g., $Q = |\mathcal{P}|$)

$$x_e \in \{0,1\} \; \forall e \in E$$

T. Andersson, T. Polishchuk, V. Polishchuk, C. Schmidt. Automatic Design of Aircraft Arrival Routes with Limited Turning Angle. ATMOS 2016, Aarhus, Denmark.

MIP formulation: Constraints

✓ RE: Degree constraints

$$\sum_{k:(k,i)\in E} x_{ki} \leq 2 \quad \forall i \in V \setminus \{\mathcal{P} \cup r\}$$

$$\sum_{j:(i,j)\in E} x_{ij} \leq 1 \quad \forall i \in V \setminus \{\mathcal{P} \cup r\}$$

$$\sum_{k:(k,r)\in E} x_{kr} = 1$$

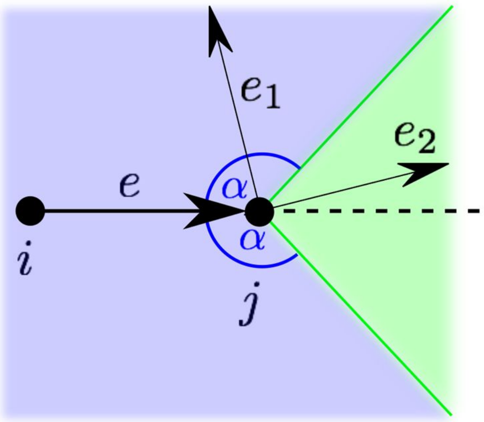
$$\sum_{j:(i,j)\in E} x_{ij} = 1 \quad \forall i \in \mathcal{P}$$

- maximum indegree
- maximum outdegree
- runway *r* has only 1 in-going enge
- only 1 out-going edge for entry points

T. Andersson, T. Polishchuk, V. Polishchuk, C. Schmidt. Automatic Design of Aircraft Arrival Routes with Limited Turning Angle. ATMOS 2016, Aarhus, Denmark.

MIP formulation: Constraints

✓ RE: Turn angle constraint



$$c_e x_e + \sum_{f \in \Gamma_e} x_f \leq c_e \quad \forall e \in E$$

for each edge $e = (i, j)$ used in the arrival tree, all outgoing edges at j must form an angle of at least α with *e*.

T. Andersson, T. Polishchuk, V. Polishchuk, C. Schmidt. Automatic Design of Aircraft Arrival Routes with Limited Turning Angle. ATMOS 2016, Aarhus, Denmark.

MIP formulation: Constraints

✓ RE: Auxiliary Constraints to Prevent Crossings

For all points except last column, last row, entries and rwy:

$$x_{i,i+1+n} + x_{i+1+n,i} + x_{i+n,i+1} + x_{i+1,i+n} \leq 1$$

$$\forall i \in V' \setminus \{\mathcal{P} \cup r\} : i+1+n, i+n, i+1 \notin \{\mathcal{P} \cup r\}$$

$$V' = V \setminus \{\text{last row}\} \setminus \{\text{last column}\}$$

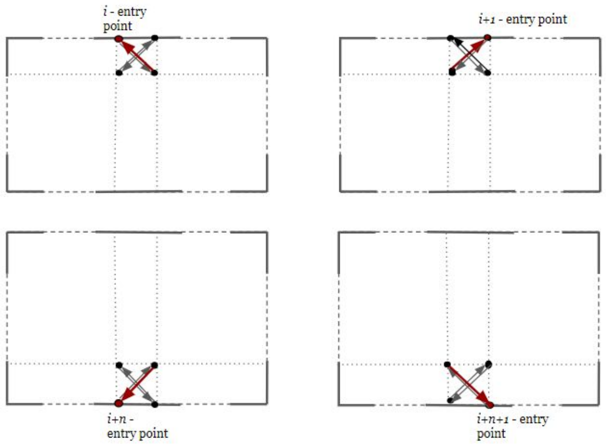
For different entry point locations:

$$x_{i,i+1+n} + x_{i+n,i+1} + x_{i+1,i+n} \leq 1 \; \forall i \in \mathcal{P}$$

$$x_{i,i+1+n} + x_{i+1+n,i} + x_{i+1,i+n} \leq 1 \; \forall i : i+1 \in \mathcal{P}$$

$$x_{i,i+1+n} + x_{i+n+1,i} + x_{i+n,i+1} \leq 1 \; \forall i : i+n \in \mathcal{P}$$

$$x_{i+1+n,i} + x_{i+n,i+1} + x_{i+1,i+n} \leq 1 \; \forall i : i+n+1 \in \mathcal{P}$$



J. Dahlberg, T. Andersson Granberg , T. Polishchuk, C. Schmidt, L. Sedov. Capacity-Driven Automac Design of Dynamic Aircraft Arrival Routes. DASC 2018, London, UK.

MIP formulation: Constraints

✓ RE: Temporal Aircraft Separation

More variables $y_{a,j,t}$ - binary, shows a/c *a* at node *j* at time *t*

$x_{e,b}$ - binary: edge *e* in the route from entry point *b*

Connect to x_e: $x_{e,b} \leq x_e \; \forall b \in \mathcal{P}, \forall e \in E$

Set:

$$y_{a,b,t_a^b} = 1 \;\; \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b$$

$$y_{a,b,t} = 0 \;\; \forall b \in \mathcal{P}, \forall a \in \mathcal{A} \setminus \mathcal{A}_b, \forall t \in T$$

$$y_{a,b,t} = 0 \;\; \forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b, \forall t \in T \setminus \{t_a^b\}$$

$$y_{a,j,t} \leq \sum_{\substack{k \in V: \\ (k,j) \in E}} x_{(k,j)} \forall b \in \mathcal{P}, \forall a \in \mathcal{A}, \forall j \in V \setminus \mathcal{P}, \forall t \in T$$

$$T = \{0, \dots, \overline{T}\}$$

Forward the information on the times at which *a* arrives at nodes along the route from *b* to the rwy

$$\sum_{j:(j,k) \in E} x_{(j,k),b} \times y_{a,j,t} = y_{a,k,t+u}$$

$$\forall b \in \mathcal{P}, \forall a \in \mathcal{A}_b, \forall k \in V \setminus \mathcal{P}, \forall t \in \{0, \dots, \overline{T} - u\}$$

Not linear ⇨ linearize …

Time separation:

$$\sum_{\tau=t}^{t+\sigma-1} \sum_{a \in \mathcal{A}} y_{a,j,\tau} \leq 1 \;\; \forall j \in V, \forall t \in \{0, \dots, \overline{T} - \sigma + 1\}$$

σ - separation parameter

J. Dahlberg, T. Andersson Granberg , T. Polishchuk, C. Schmidt, L. Sedov. Capacity-Driven Automac Design of Dynamic Aircraft Arrival Routes. DASC 2018, London, UK.

MIP formulation: Constraints

- ✓ Flow constraints
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- ✓ Realistic CDO speed profiles
- ✓ Consistency between trees of different time periods

MIP Formulation: Realistic CDO Speed Profiles

- ✓ The state vector $\boldsymbol{x}$ represents the fixed initial conditions of the aircraft: TAS $\boldsymbol{v}$, altitude $\boldsymbol{h}$ and distance to go $\boldsymbol{s}$
- ✓ To achieve environmentally friendly trajectories, **idle thrust** is assumed and **speed-brakes** use is **not allowed** throughout the descent → **energy-neutral** CDO
- ✓ The flight path angle is the only control variable in this problem → control vector $\boldsymbol{u}$

$$x = [v, h, s]$$
$$u = [\gamma]$$

MIP Formulation: Realistic CDO Speed Profiles

- ✓ A point-mass representation of the aircraft reduced to a “gamma-command” is considered, where vertical equilibrium is assumed → Dynamic constraints $\boldsymbol{f}$
- ✓ Path constraints **h** are enforced to ensure that the aircraft airspeed remains within operational limits, and that the maximum and minimum descent gradients are not exceeded
- ✓ Terminal constraints $\boldsymbol{\psi}$ fix the final states vector

Dynamic constraints

$$f = \begin{bmatrix} \dot{v} \\ \dot{h} \\ \dot{s} \end{bmatrix} = \begin{bmatrix} \frac{T_{idle} - D}{m} - g\gamma \\ v\gamma \\ v + w \end{bmatrix}$$

Path constraints

$$h = \begin{bmatrix} v_{CAS,min} - v_{CAS} \\ v_{CAS} - \mathrm{VMO} \\ M - \mathrm{MMO} \\ \gamma \\ \gamma_{min} - \gamma \end{bmatrix} \leq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Terminal constraints

$$\psi = \begin{bmatrix} v - v_f \\ h - h_f \\ s - s_f \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

MIP Formulation: Realistic CDO Speed Profiles

- ✓ The trajectory is divided in two phases: the latter part of the cruise phase prior the top of descent (TOD) and the idle descent
- ✓ The original cruise speed is not modified after the optimization process, so the two-phases optimal control problem can be converted into a single-phase optimal control problem
- ✓ BADA V4 is used to model the aircraft performance

$$J = \frac{f}{v_{cruise}} + \int_{t_0}^{t_f} (f_{idle} + \mathrm{CI}) dt$$

Sáez, R., Dalmau, R., & Prats, X. (2018 , Sep). Optimal assignment of 4D close-loop instructions to enable CDOs in dense TMAs. Proceedings of the 37th IEEE/AIAA Digital Avionics Systems Conference (DASC)

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MIP formulation: Constraints

✓ **NEW:** Integration of CDO-enabled Realistic Speed Profiles

Substitute: $y_{a,j,t}$ with $y_{a,j,p,n,t}$ - binary, indicates whether a/c *a* using speed profile *p* occupies the *n*-th vertex *j* at time *t*.

and the corresponding equations with

$$\sum_{p\in\mathcal{S}(a)} y_{a,b,p,1,t_a^b} = 1 \quad \forall b\in\mathcal{P}, \forall a\in\mathcal{A}_b$$

$$y_{a,b,p,k,t_a^b} = 0 \quad \forall b\in\mathcal{P}, \forall a\in\mathcal{A}_b, \forall p\in\mathcal{S}(a), \forall k\neq 1\in\mathcal{L}$$

$$y_{a,b,p,1,t} = 0 \quad \forall b\in\mathcal{P}, \forall a\in\mathcal{A}_b, \forall p\in\mathcal{S}(a), \forall t\in T\setminus\{t_a^b\}$$

$$y_{a,b',p,k,t} = 0 \quad \forall b'\neq b\in\mathcal{P}, \forall a\in\mathcal{A}_b, \forall p\in\mathcal{S}(a), \forall k\in\mathcal{L}, \forall t\in T$$

$$y_{a',b,p,1,t_a^b} = 0 \quad \forall b\in\mathcal{P}, \forall a'\neq a\in\mathcal{A}_b, \forall p\in\mathcal{S}(a)$$

$$y_{a,j,p,k,t} \leq \sum_{\substack{i\in V:\\(i,j)\in E}} x_{(i,j)} \forall j\in V\setminus\mathcal{P}, \forall a\in\mathcal{A}, \forall p\in\mathcal{S}(a),$$

Compute *l(b)* - path from b to the rwy

$$\ell(b) = \sum_{(i,j)\in E} x_{(i,j),b}$$

For each a/c a arriving from b we pick the speed profile from S(a) that has the length *l(b)*:

$$y_{a,b,\ell(b),1,t_a^b} = 1 \text{ and } y_{a,b,p,1,t_a^b} = 0 \forall p\neq\ell(b)$$

l(b) var, not a parameter ⇨ aux vars and constraints

…

Separation constraint:

$$\sum_{\tau=t}^{t+\sigma-1}\sum_{a\in\mathcal{A}}\sum_{p\in\mathcal{S}(a)}\sum_{k\in\mathcal{L}} y_{a,j,p,k,\tau} \leq 1 \quad \forall j\in V, \quad \forall t\in\{0,\dots,\overline{T}-\sigma+1\}$$

σ - separation parameter

MIP formulation: Constraints

✓ **NEW:** Consistency between trees of consecutive time periods

Define: x_{ij} and x_{ij}^{old} - edge indicators for current and previous periods

U - limits the number of differing edges

$$ax_{ij} \leq x_{ij} - x_{ij}^{old} \quad \forall (j,i) \in E$$

$$ax_{ij} \leq x_{ij}^{old} - x_{ij} \quad \forall (j,i) \in E$$

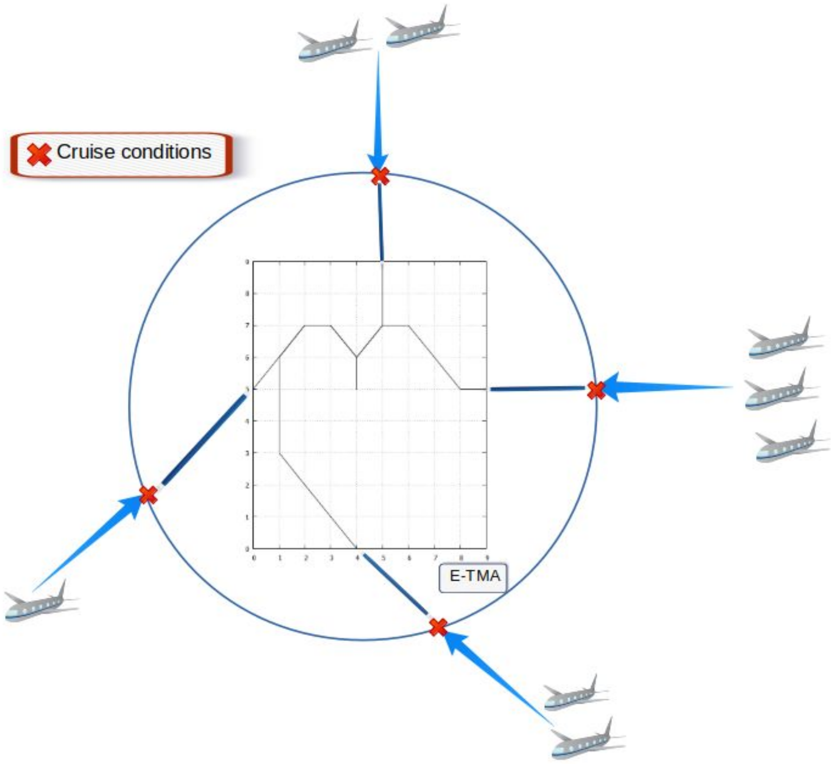
$$\sum_{(i,j) \in E} ax_{ij} \leq U$$

Experimental Study: Stockholm Arlanda Airport

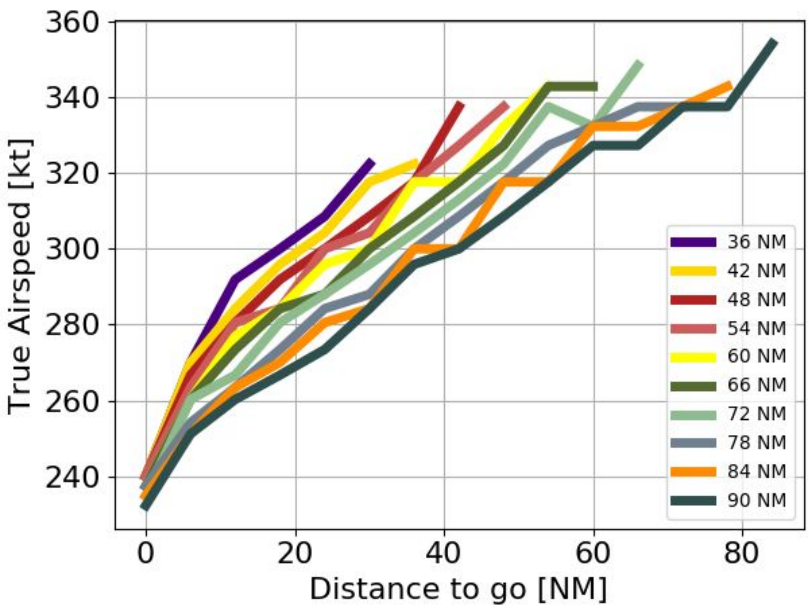
- ✓ Data: Stockholm Arlanda airport arrivals during one hour of operation
- ✓ Source: EUROCONTROL DDR2, BADA 4
- ✓ High-traffic scenario on October 3, 2017, time: 15:00 - 16:00
- ✓ Solved using GUROBI
- ✓ Run on a powerful Tetralith server, provided by SNIC, LIU: Intel HNS2600BPB nodes with 32 CPU cores and 384 GiB RAM

CDO speed profiles inside TMA

- ✓ Cruise conditions are obtained from DDR2
- ✓ TOD position and descent phase are optimized
- ✓ Same time at the entry point for different path lengths inside TMA



CDO speed profiles inside TMA

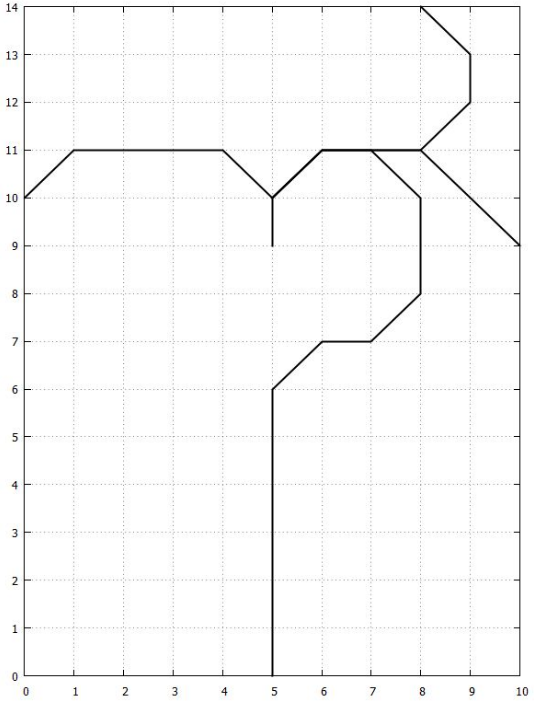


Example of A320 speed profiles for different path lengths inside TMA

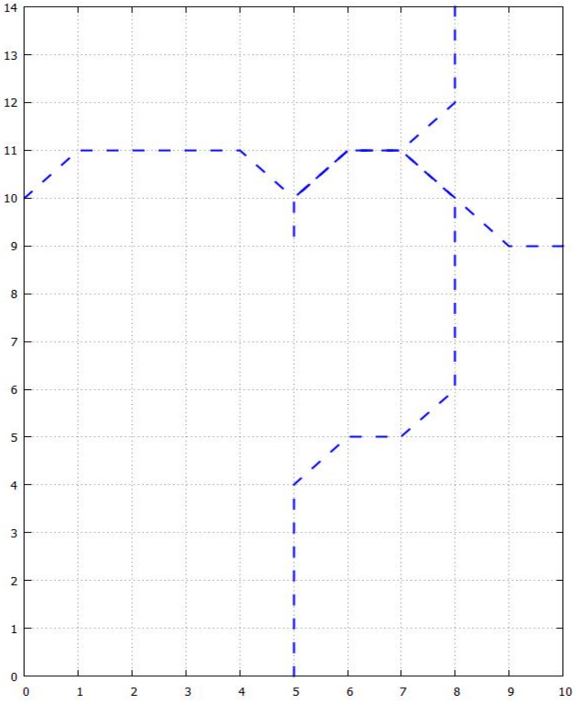
- ✓ A set of realistic alternative speed profiles for different possible route lengths inside TMA
- ✓ Generated for all a/c types arriving to Arlanda during the given period
- ✓ Used as input to MIP

Results: Stockholm Arlanda Airport

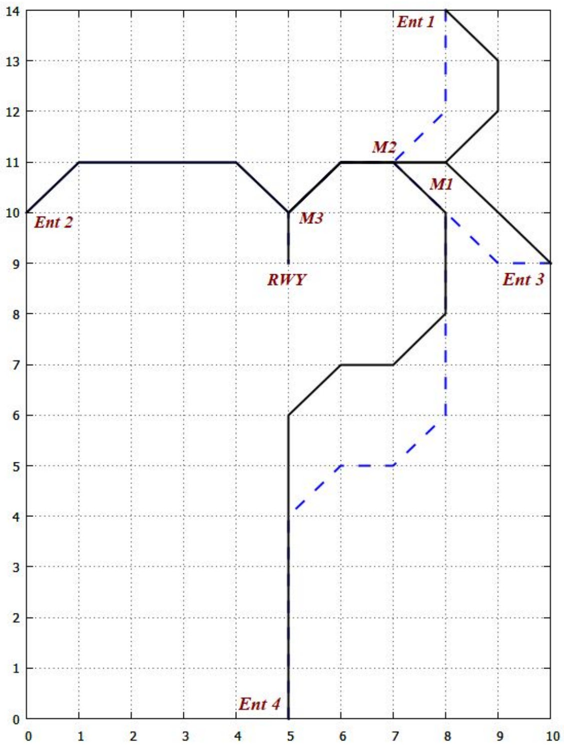
Tree 1: time: 15:00 - 15:30 (10 a/c)



Tree 2: time: 15:30 - 16:00 (7 a/c)

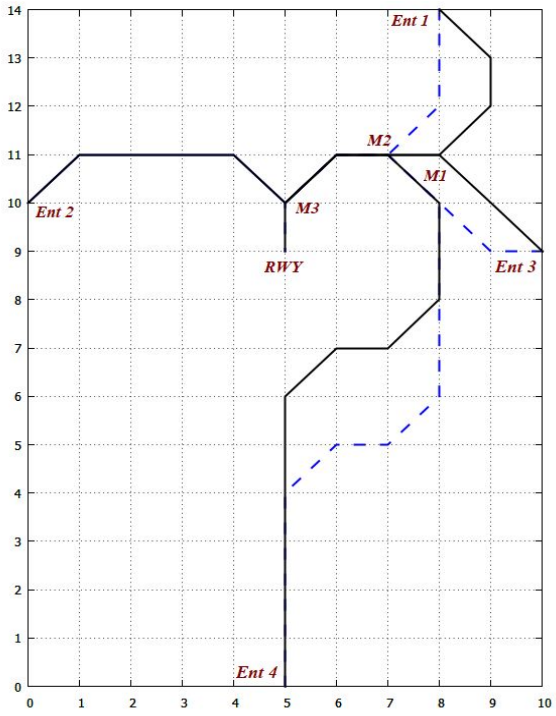


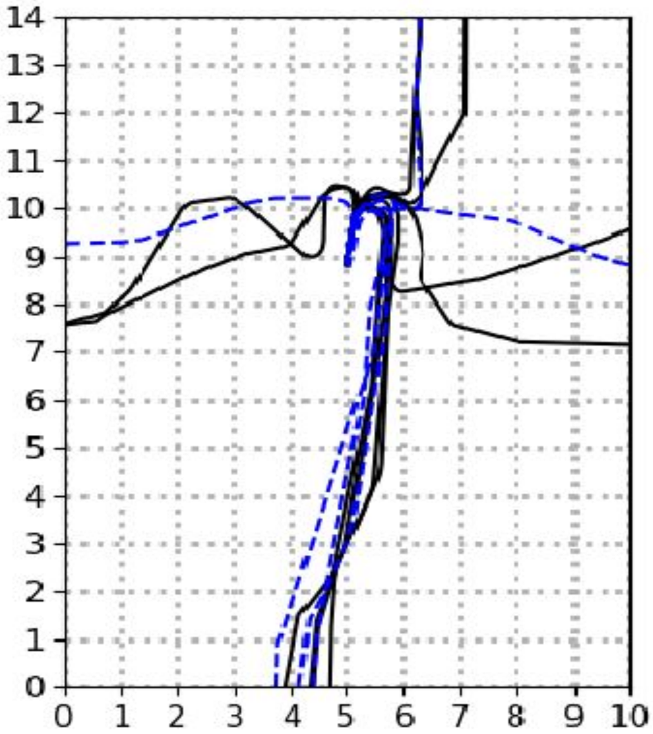
Results: Stockholm Arlanda Airport



- ✓ **Tree 1:** time: 15:00 - 15:30 (10 a/c)
- ✓ **Tree 2:** time: 15:30 - 16:00 (7 a/c)
- ✓ Optimized for 30 min intervals (longer periods may be sub-optimal. Note: time within TMA 5-18 min)
- ✓ U = 23 provides consistency between the trees
- ✓ Separation: 2 min, ~6 nm
- ✓ 17 out of 22 arrivals scheduled
- ✓ 5 filtered out, because of:
  - Initial violation of separation at entry points
  - Potential overtaking problem
  - In general, about 10-15% are not scheduled

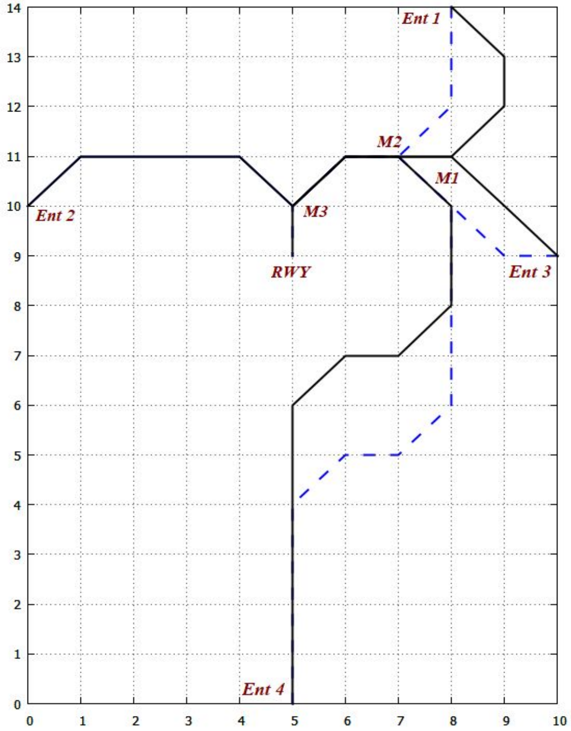
Comparison against historical trajectories (Open Sky Network)





Time Schedule

Arrivals		Simulated time [min]			
Aircraft	Entry point	Entry	M1	M2	M3
a1	Ent1 (North)	3	9	11	15
a2	Ent2 (West)	8	-	-	13
a3	Ent3 (East)	13	15	16	18
a4	Ent4 (South)	4	-	18	22
a5	Ent4	18	-	30	32
a6	Ent2	17	-	-	25
a7	Ent1	17	20	21	23
a8	Ent1	21	24	25	27
a9	Ent2	19	-	-	29
a10	Ent3	28	30	32	34
a11	Ent4	34	45	46	48
a12	Ent3	41	43	44	46
a13	Ent2	32	-	-	37
a14	Ent1	39	-	42	44
a15	Ent1	49	-	55	59
a16	Ent4	53	-	-	-
a17	Ent2	57	-	-	-



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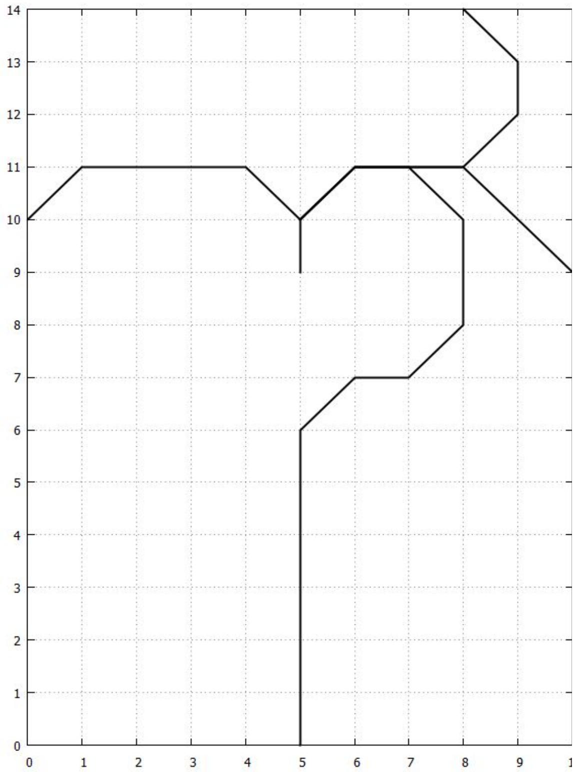
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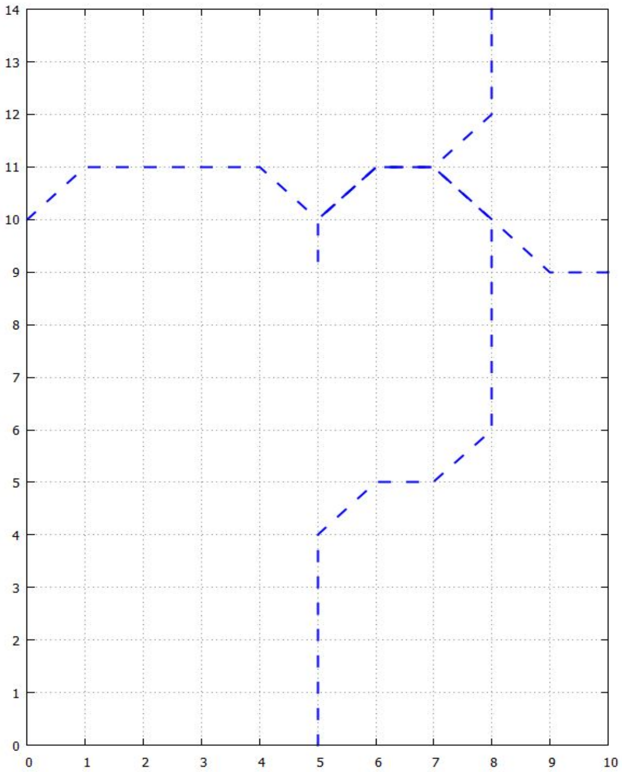
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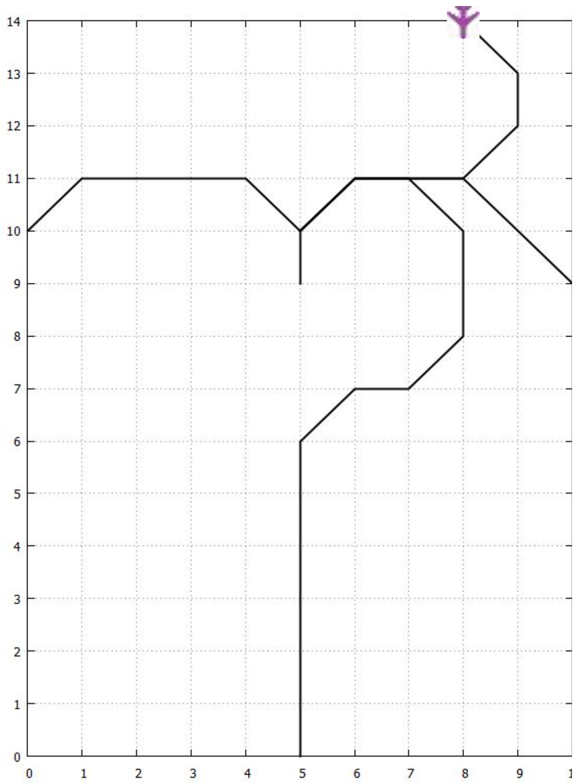
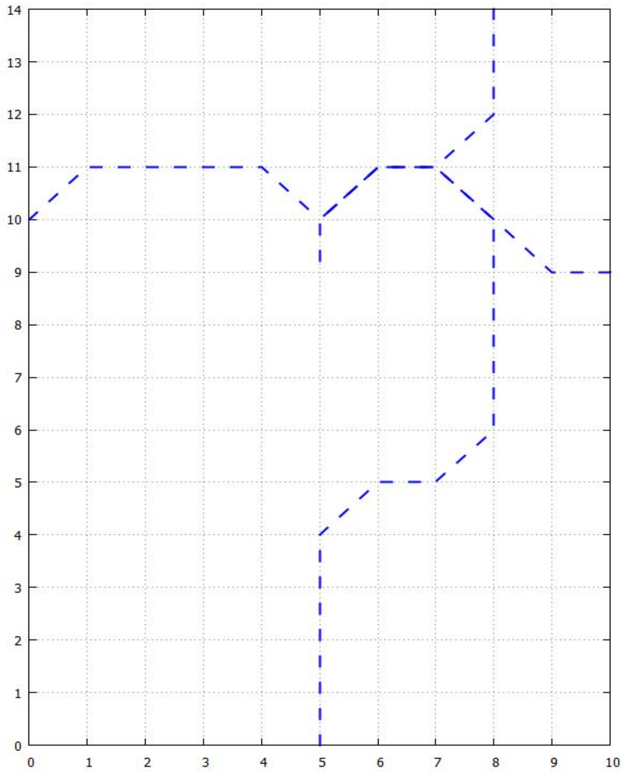
t = 15:03





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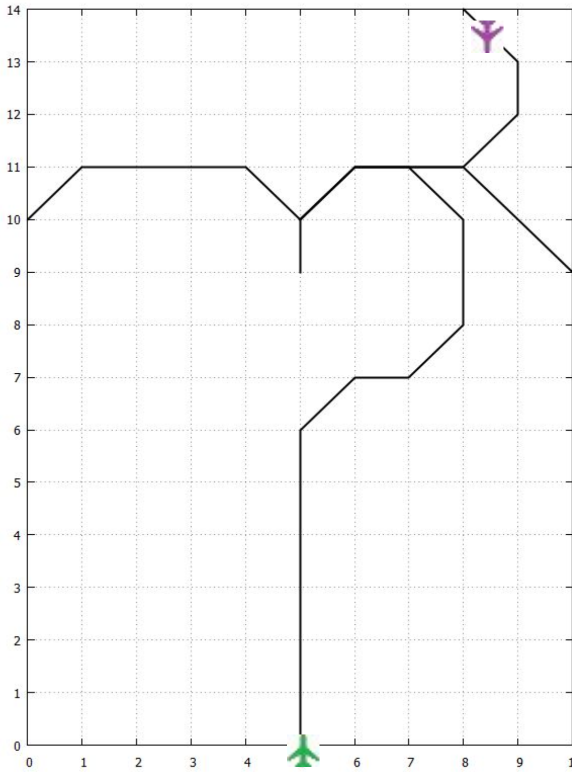
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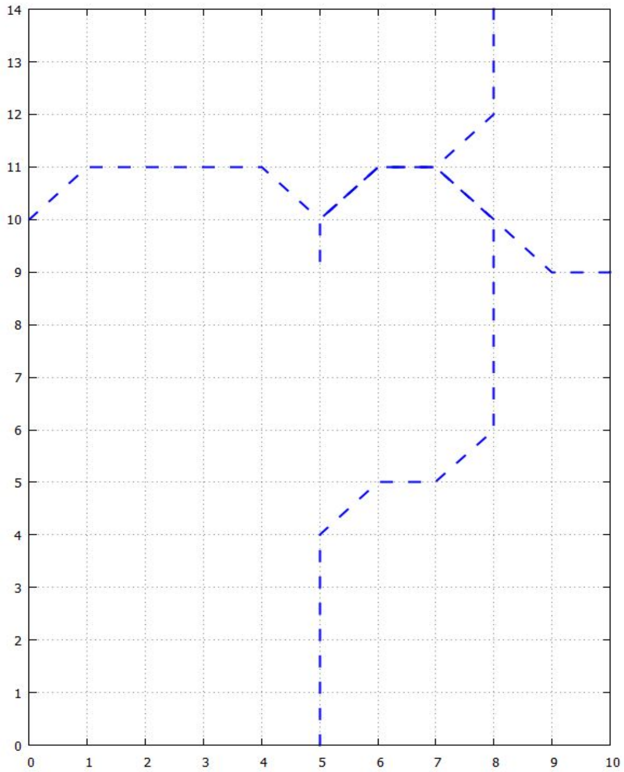
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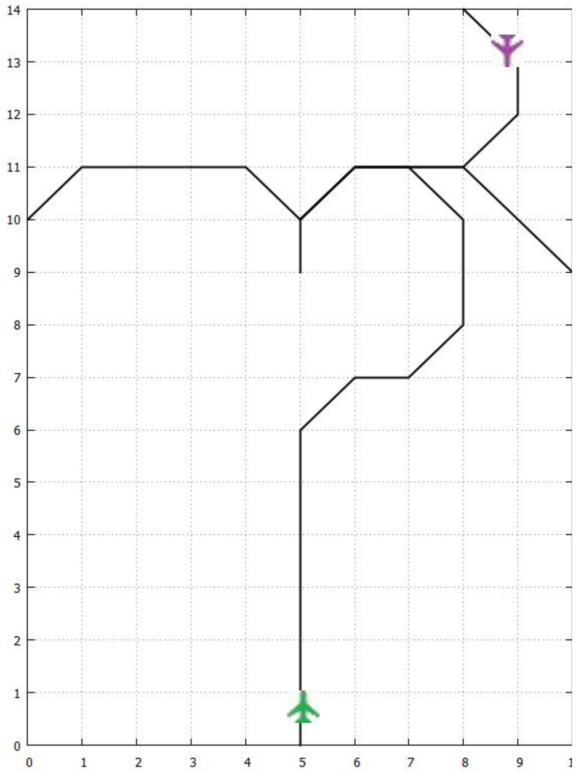
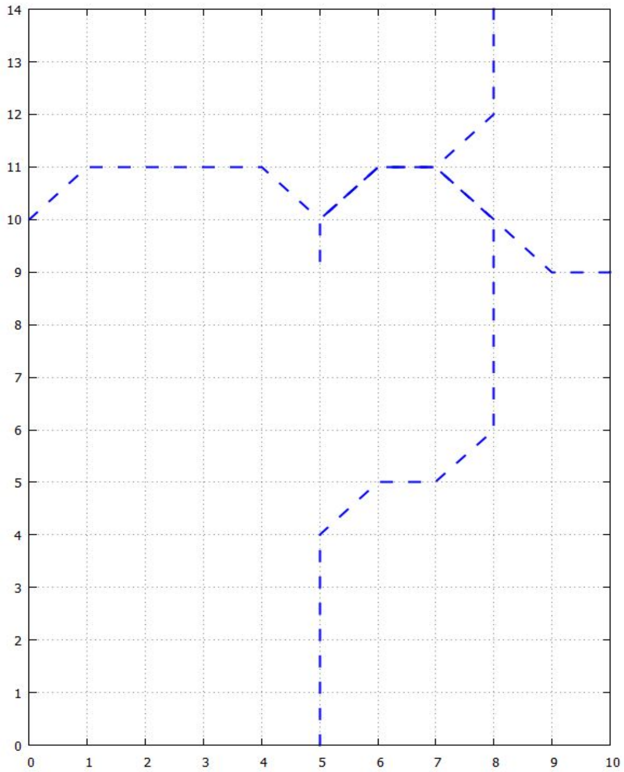
t = 15:05





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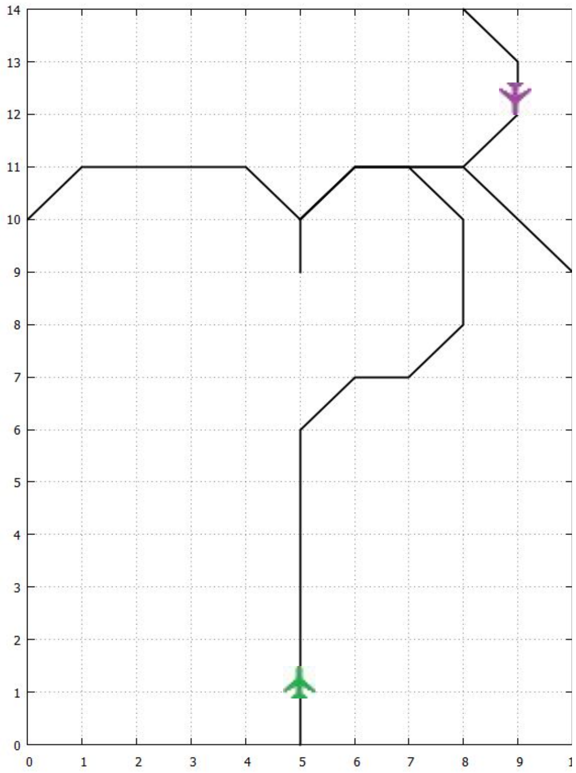

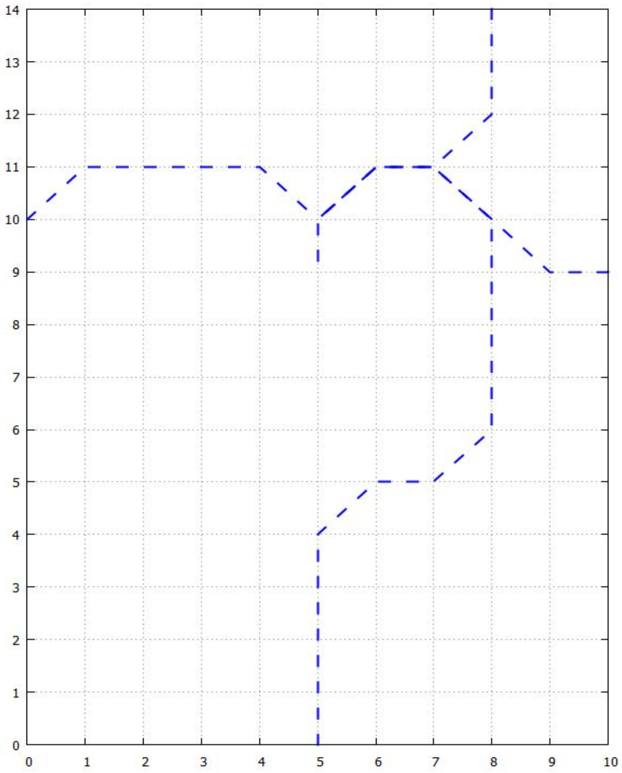

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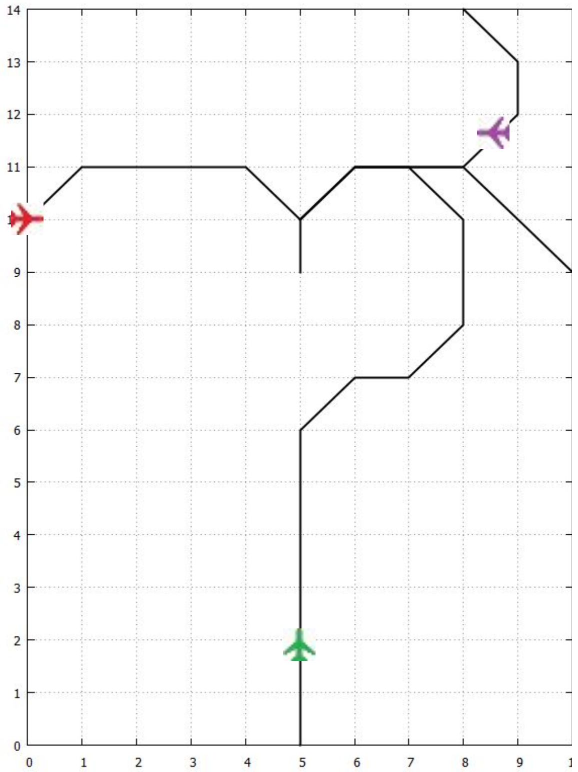

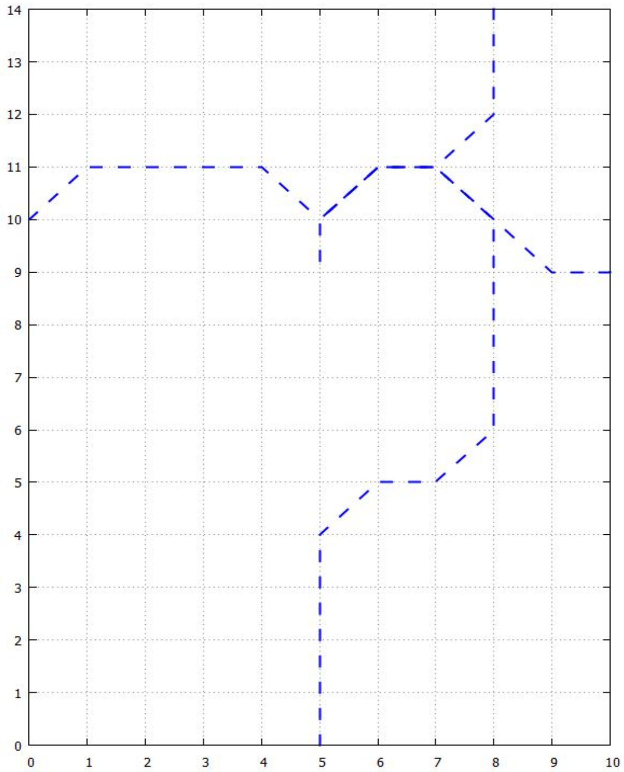

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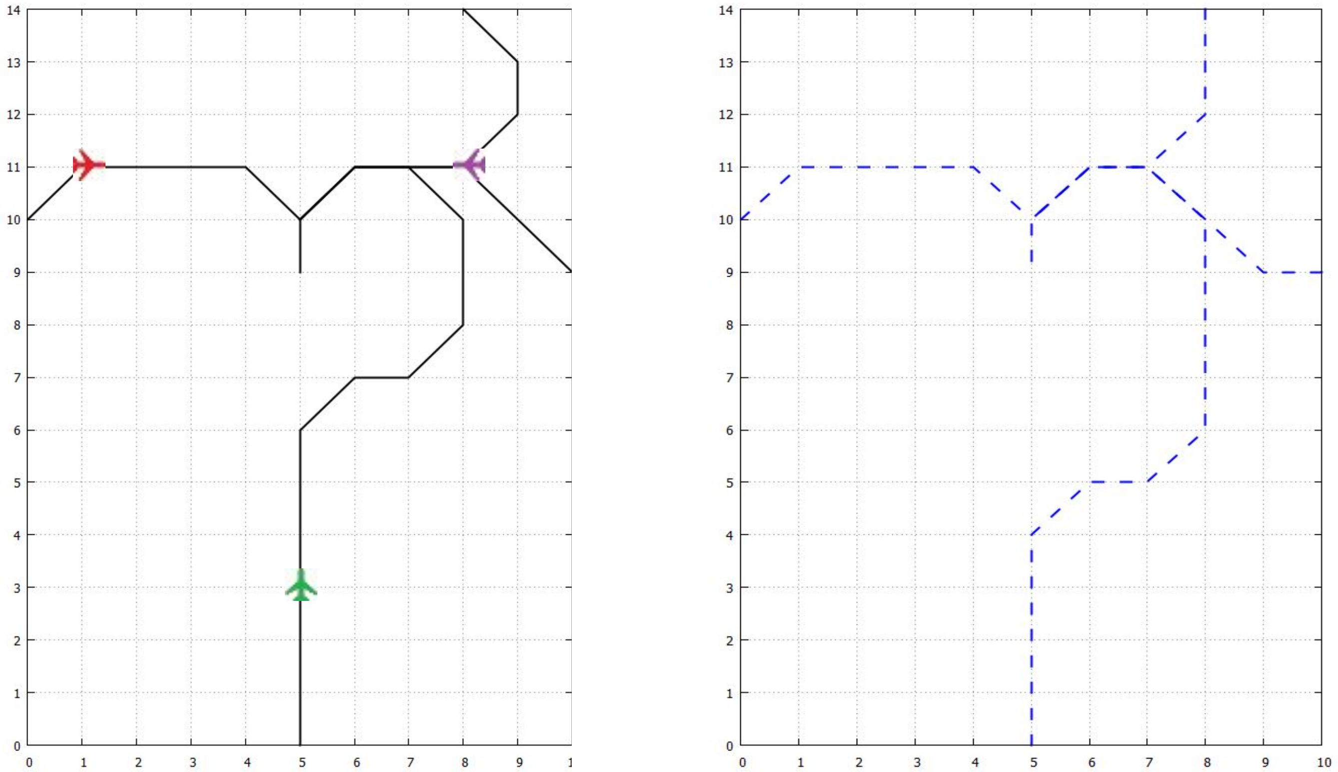
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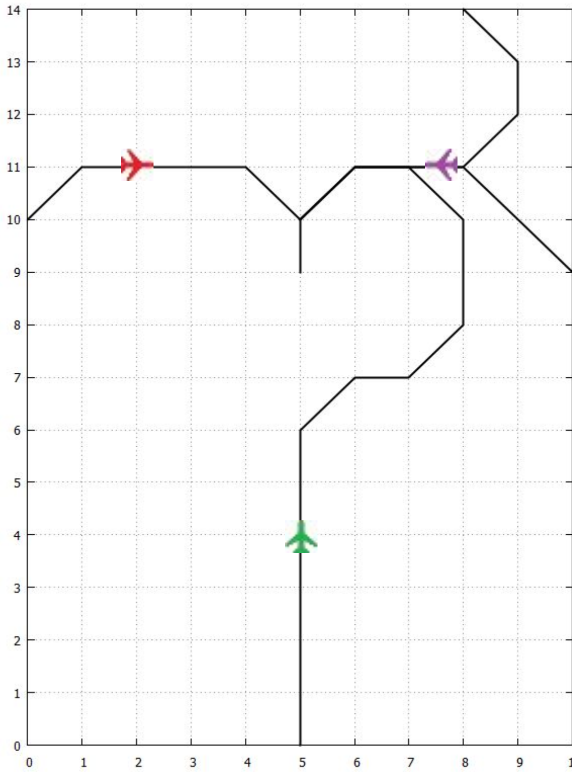
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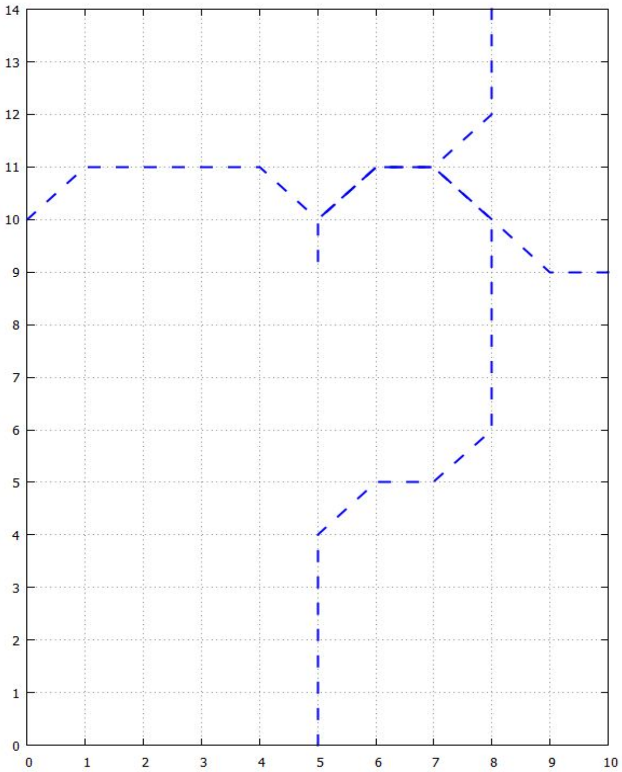
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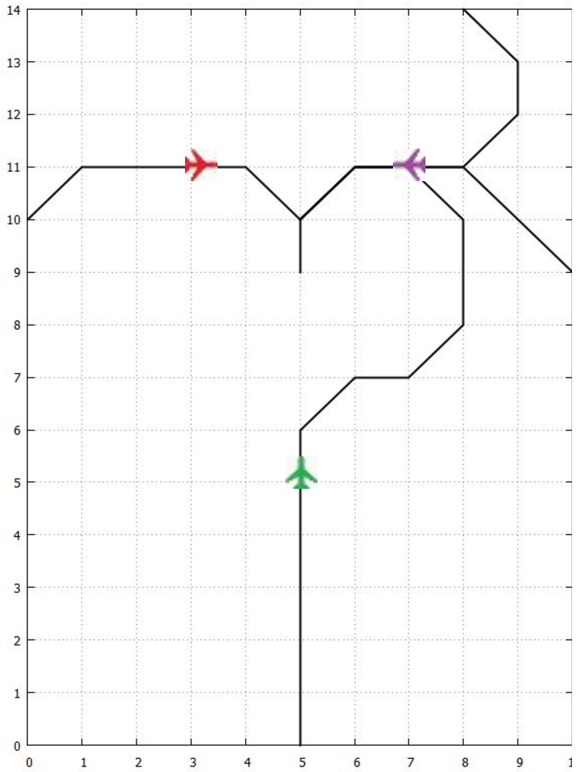
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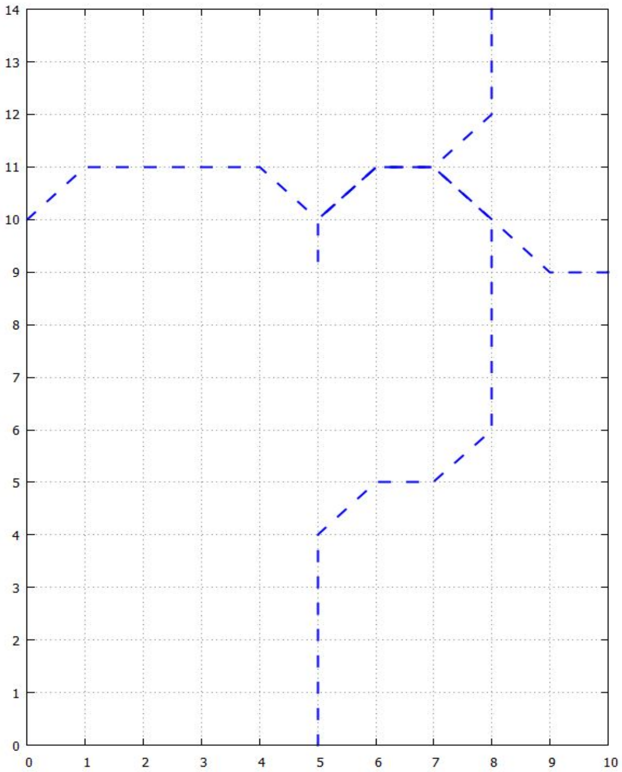
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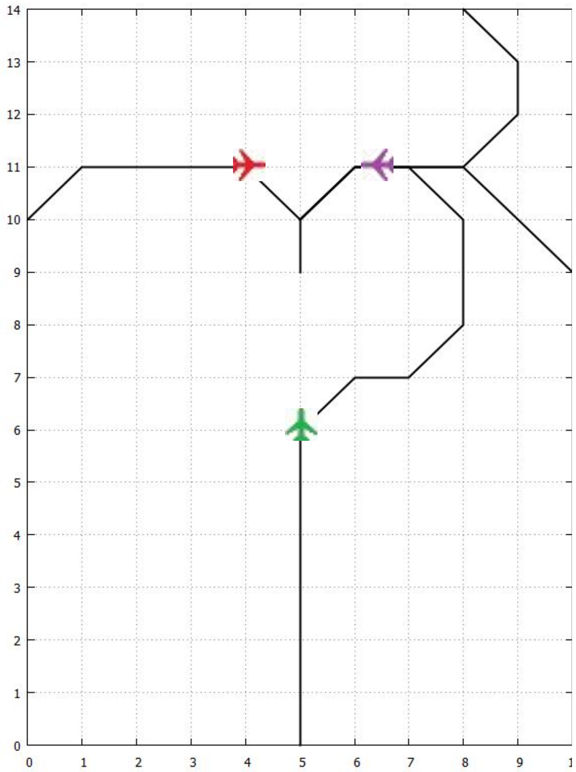
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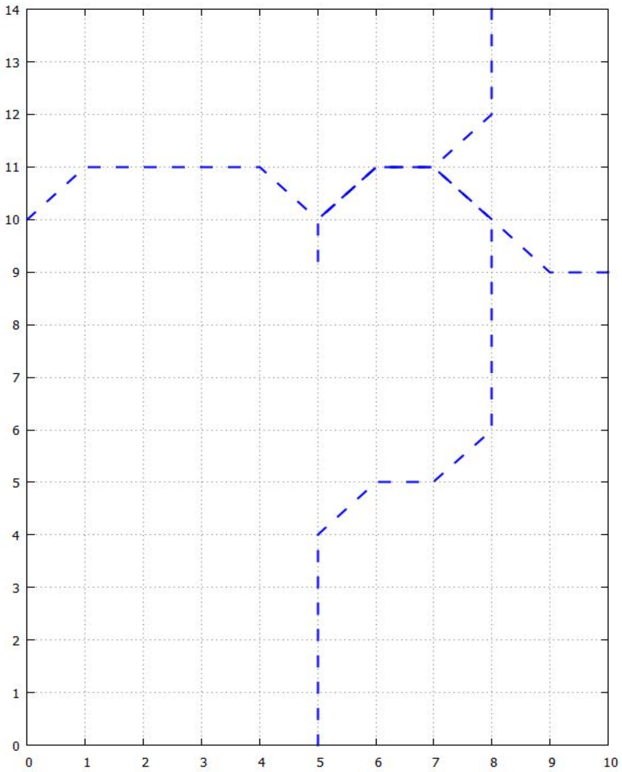
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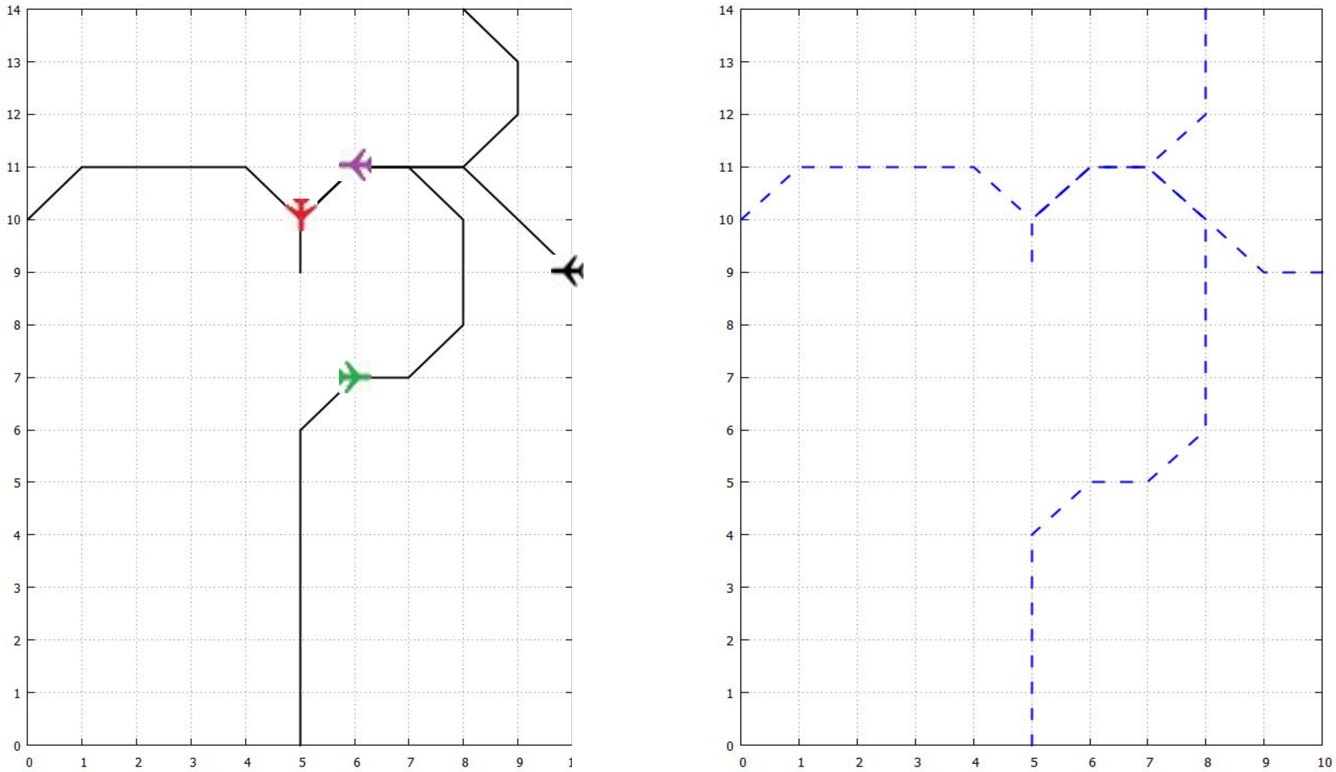
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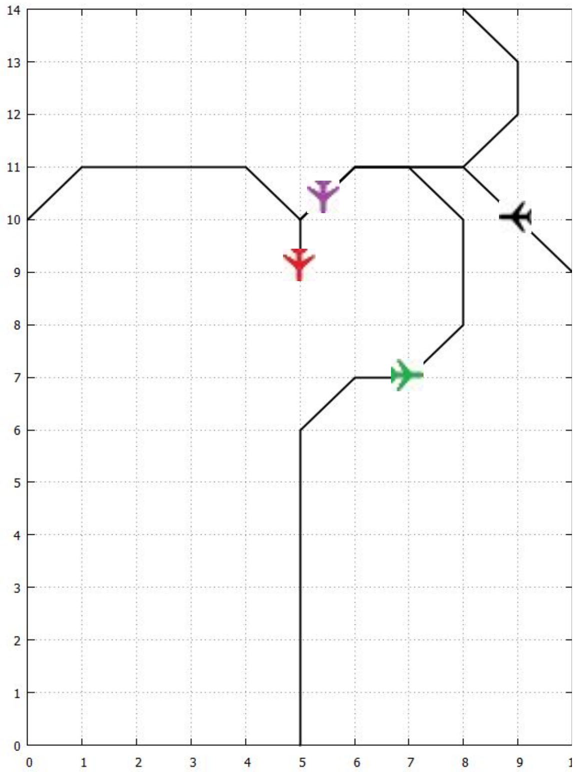
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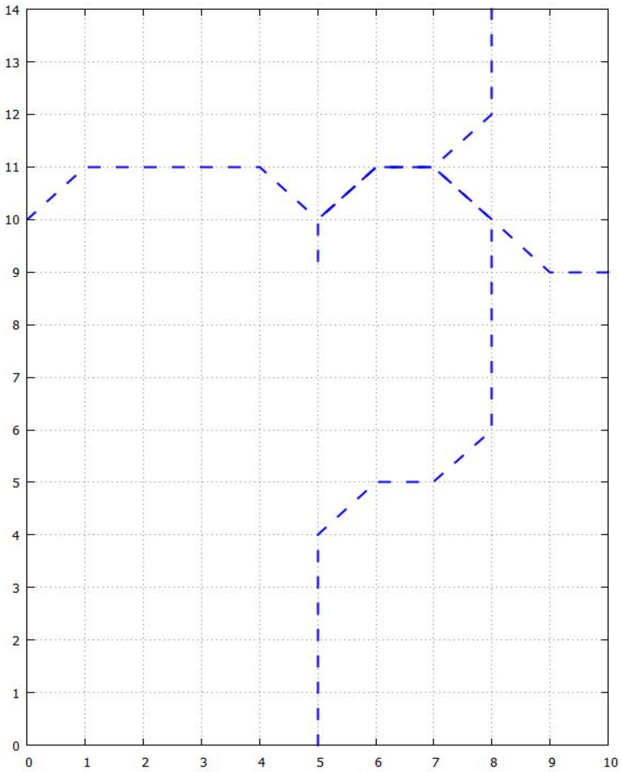
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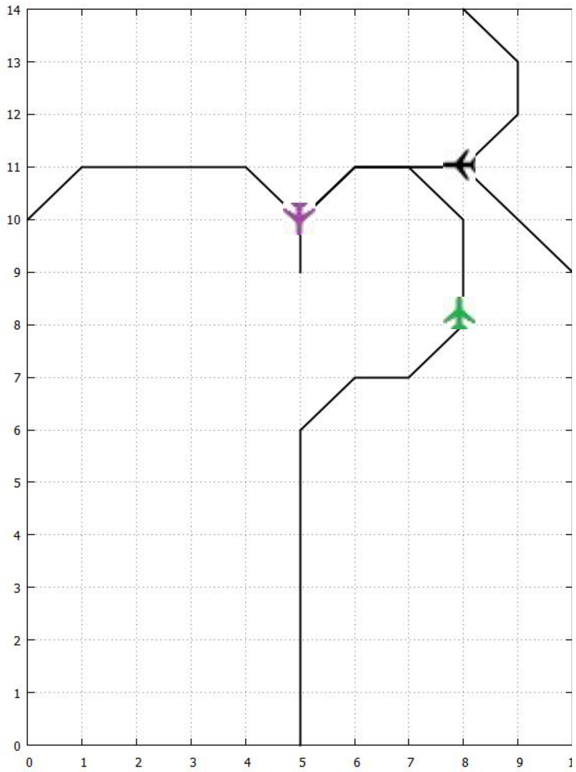
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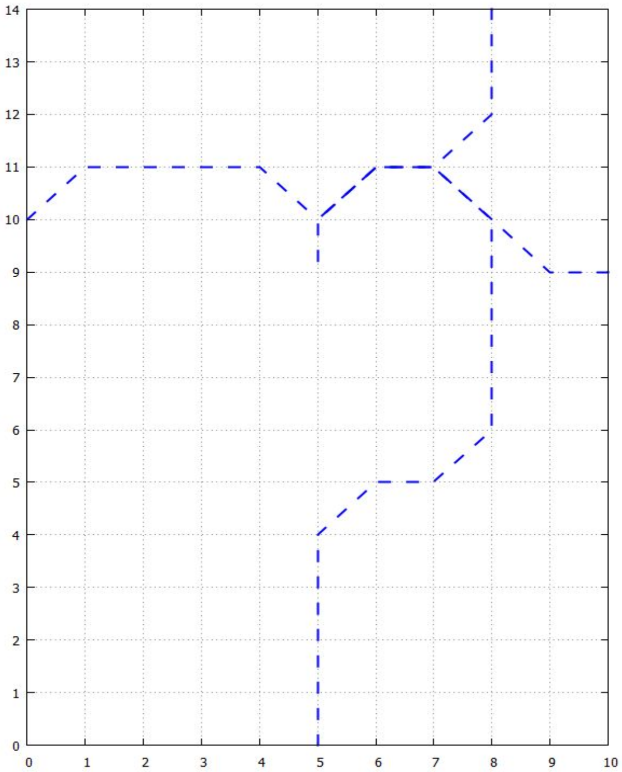
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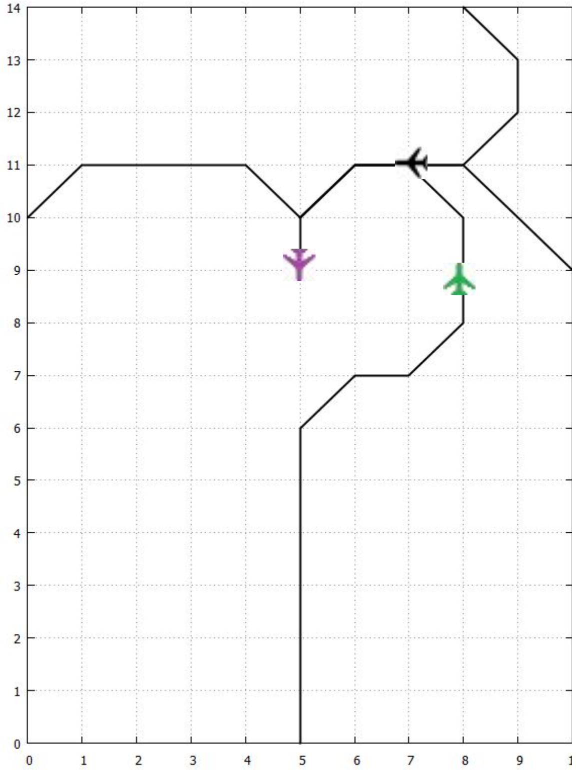
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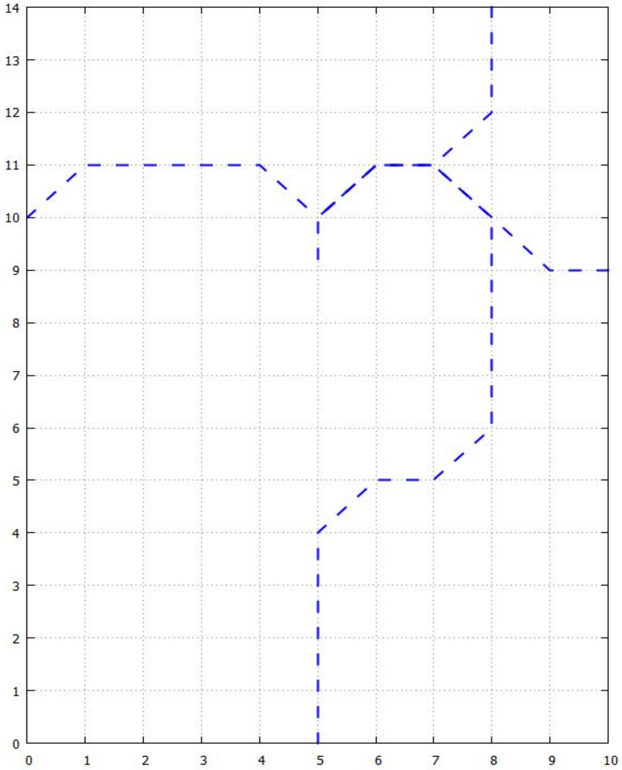
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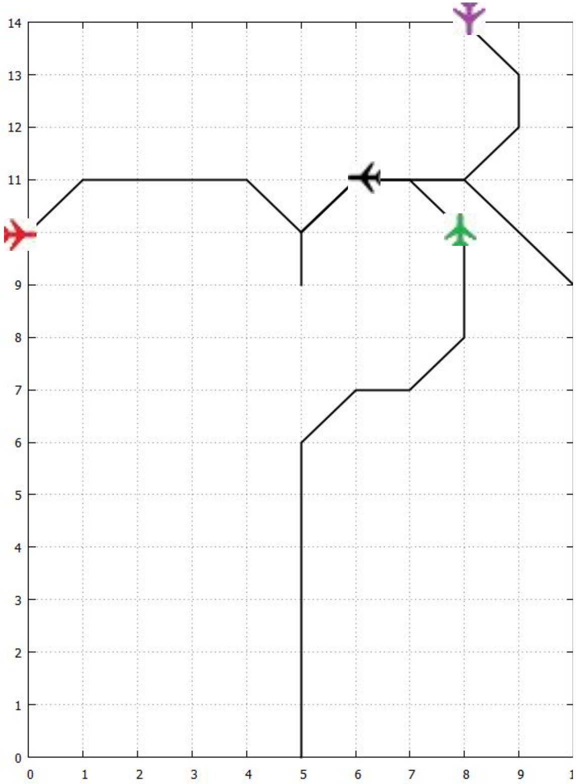

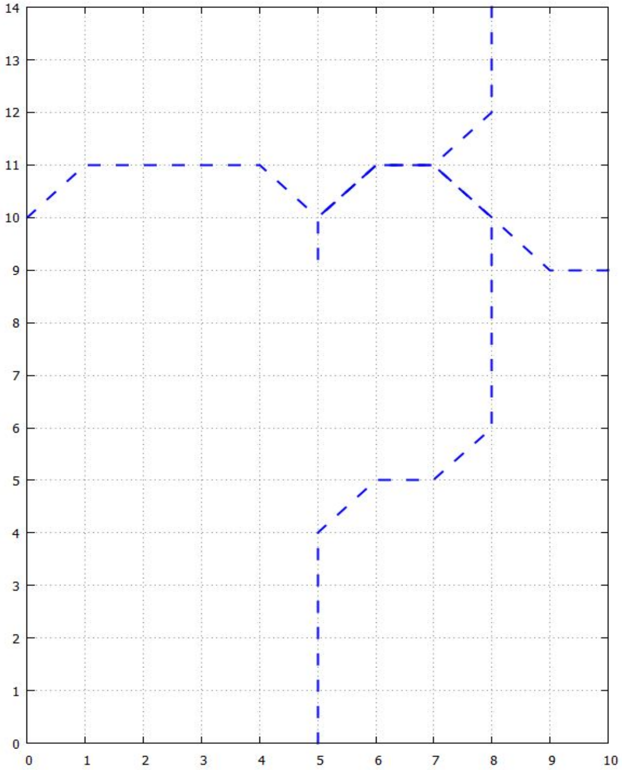

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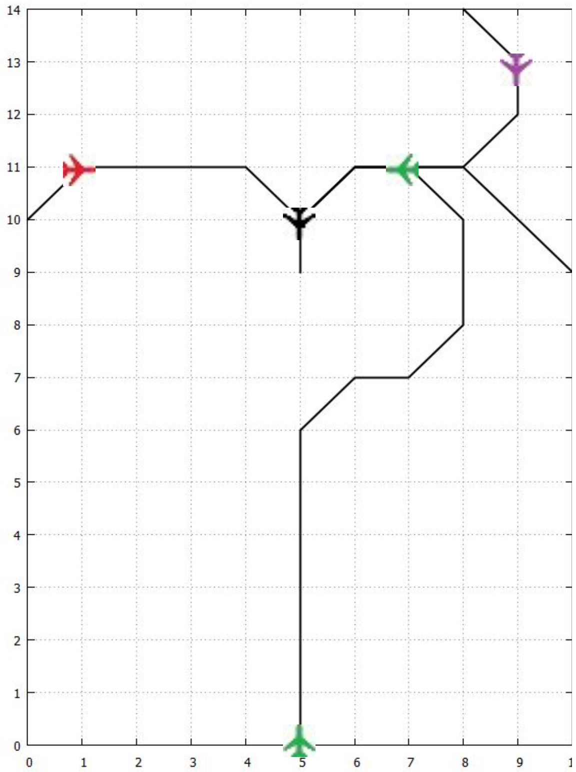
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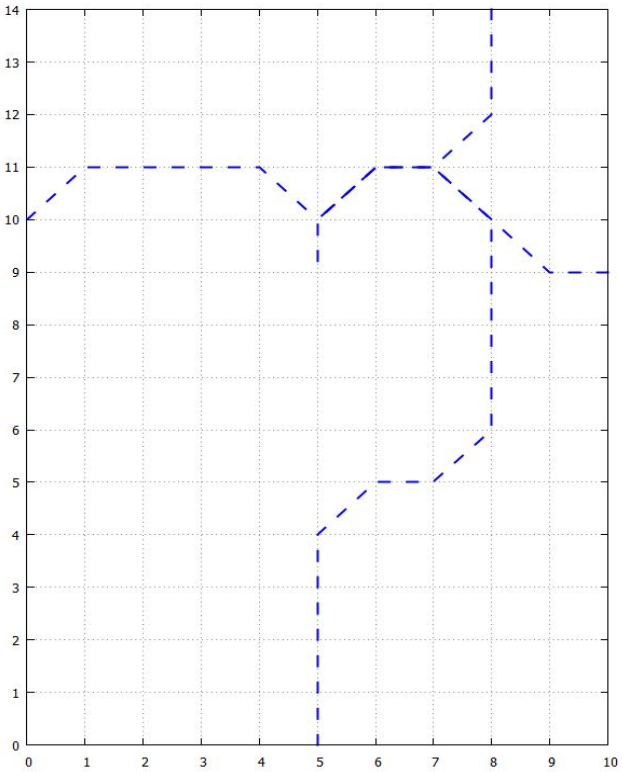
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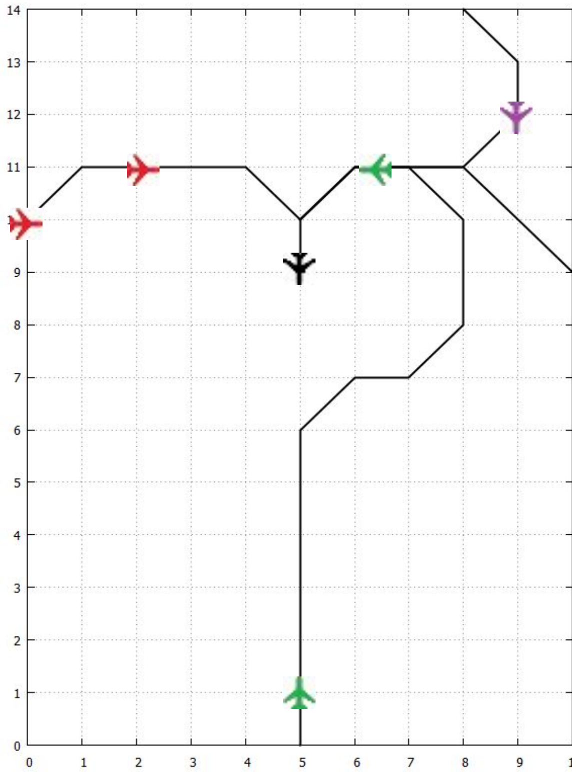

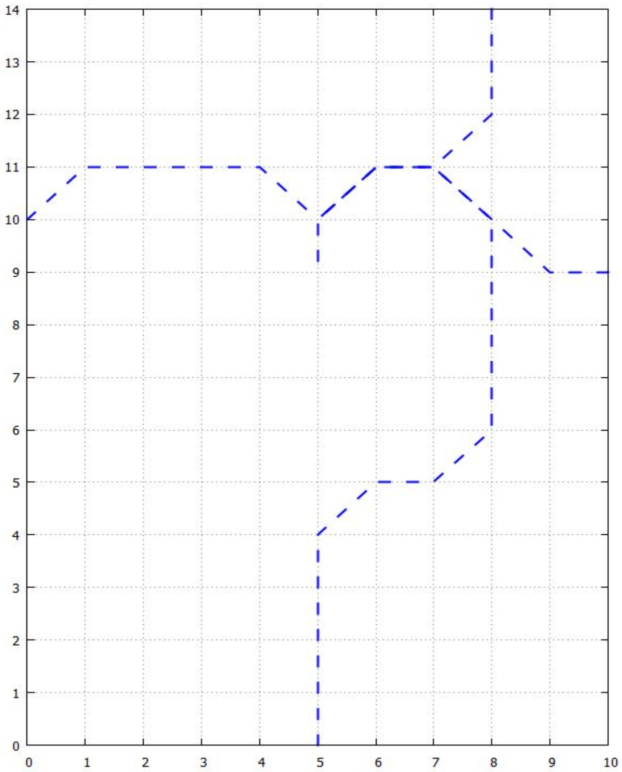

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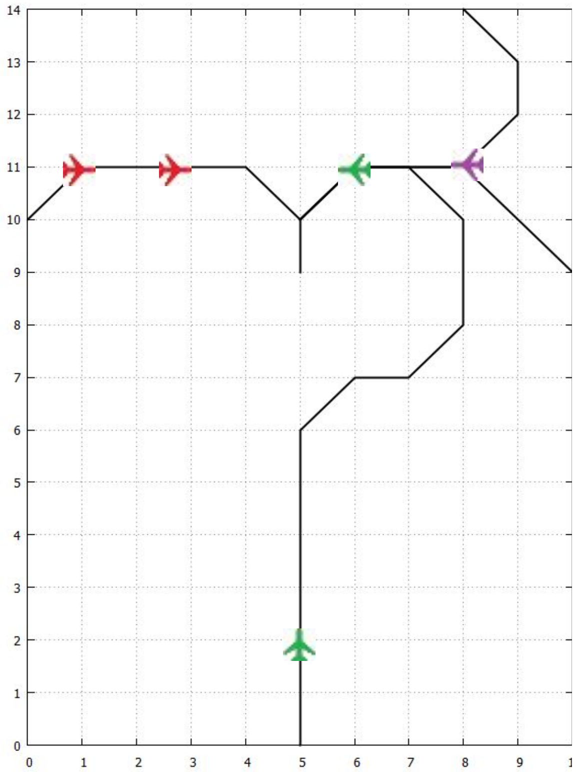
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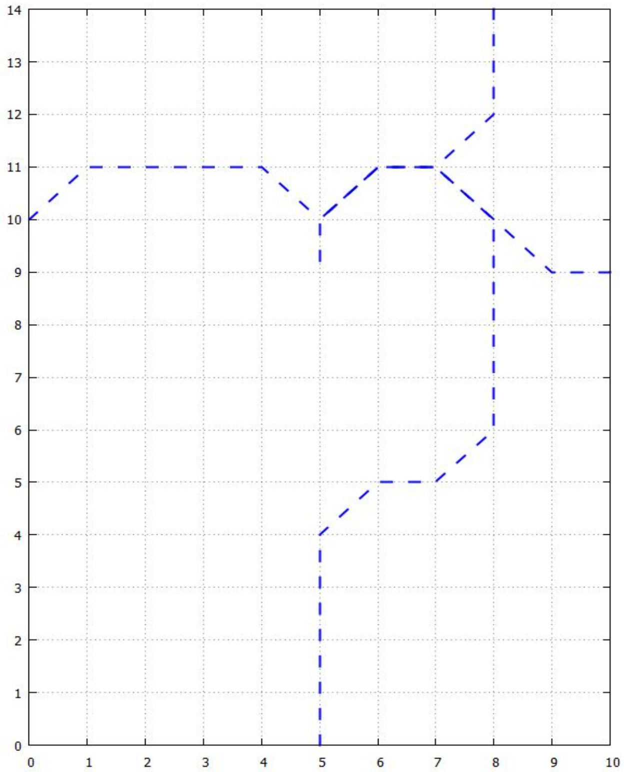
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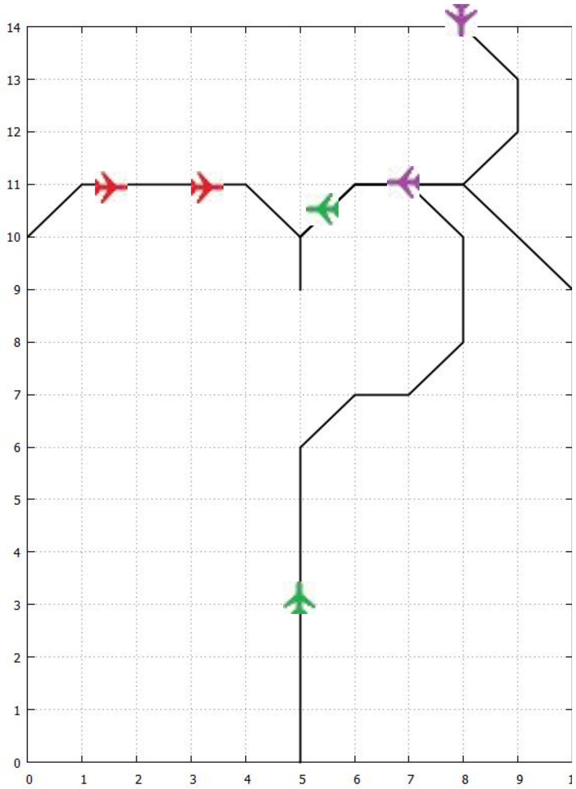
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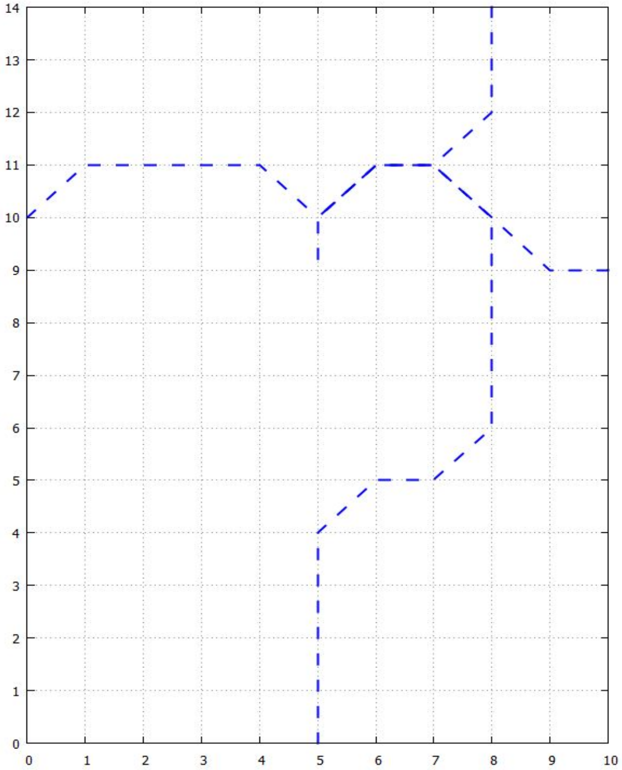
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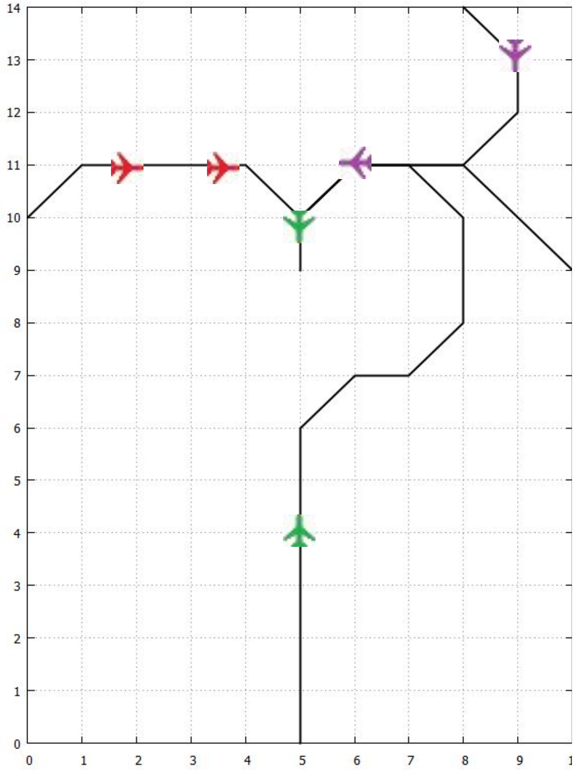

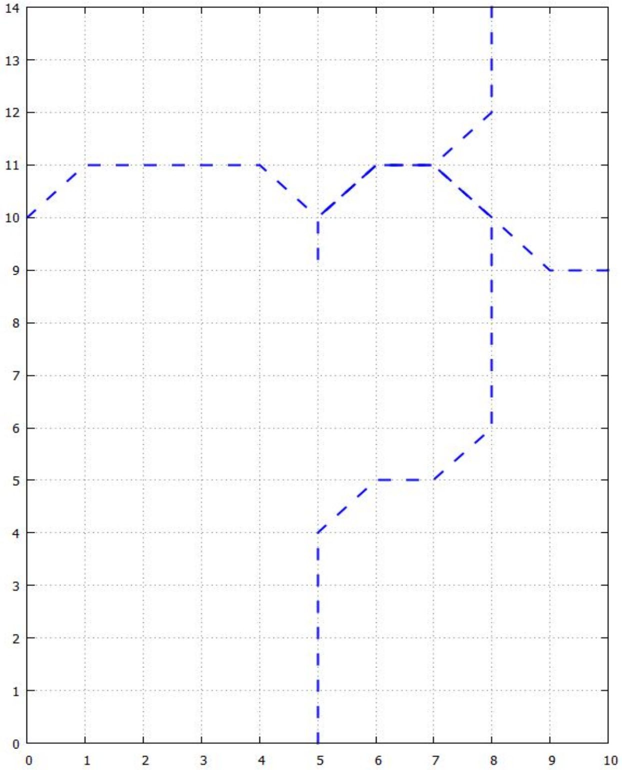

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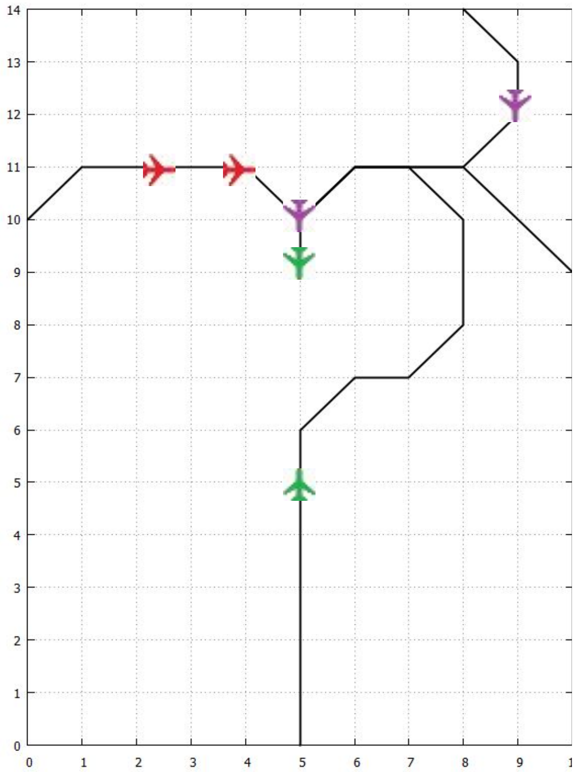
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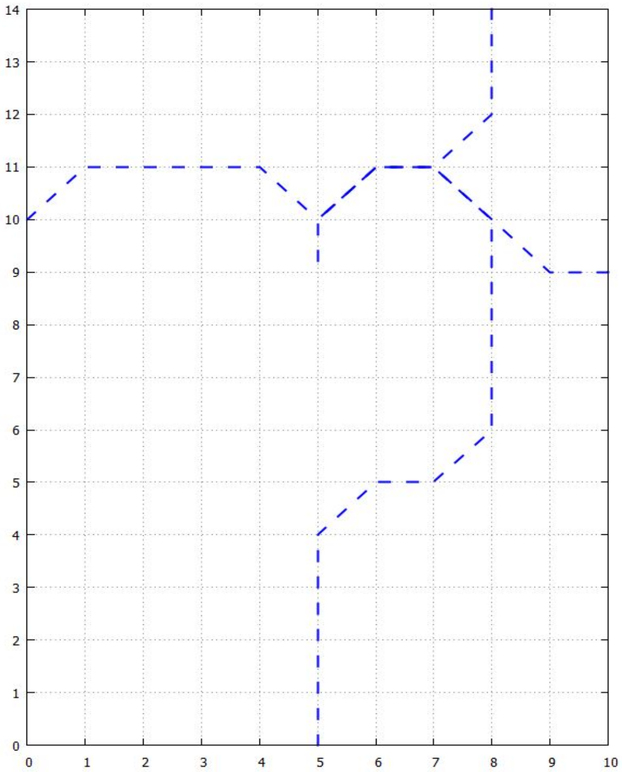
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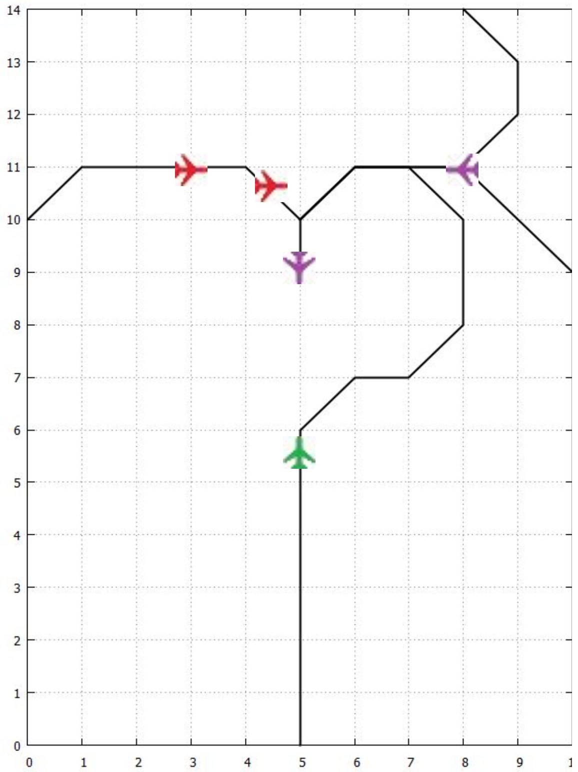

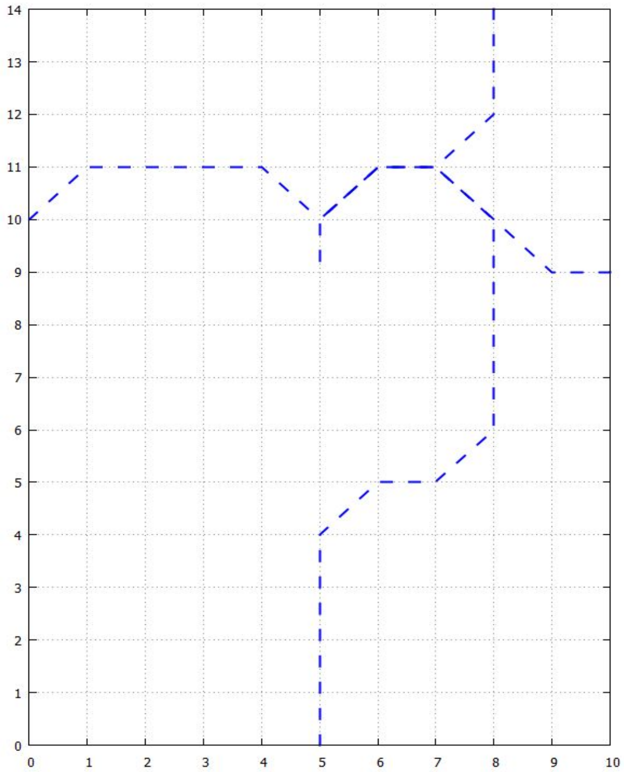

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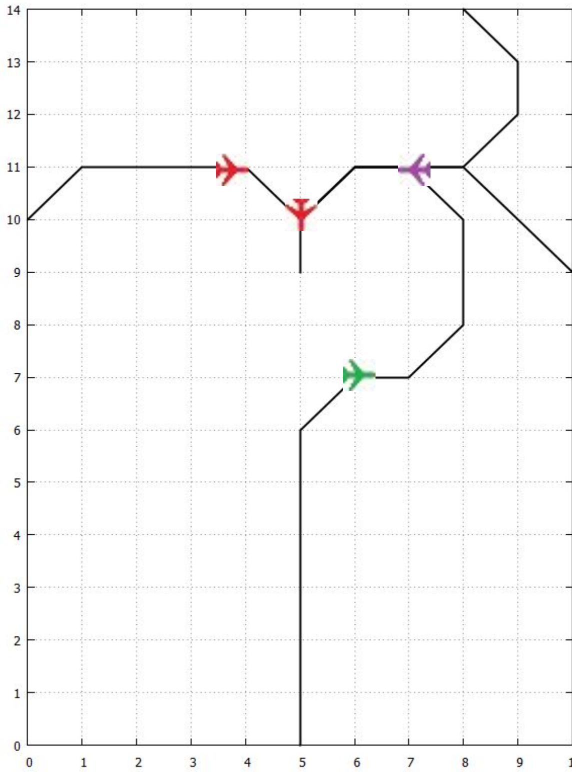
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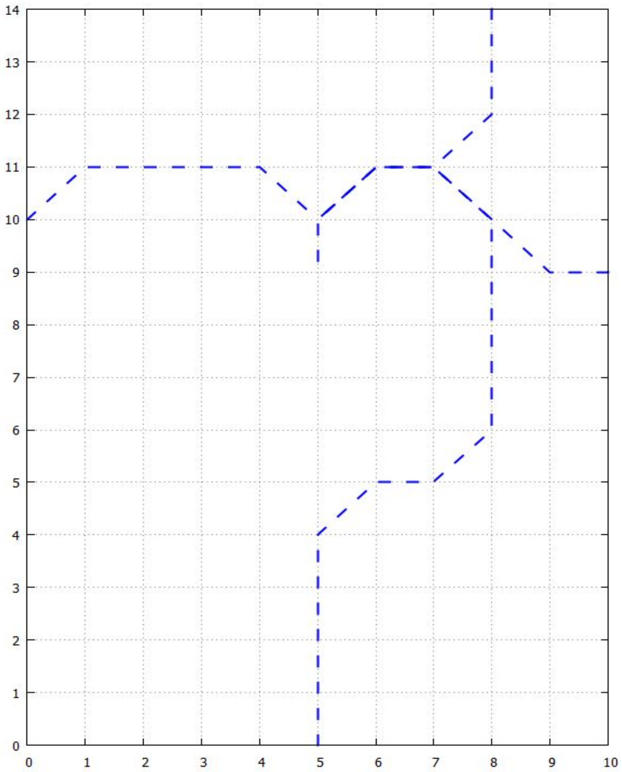
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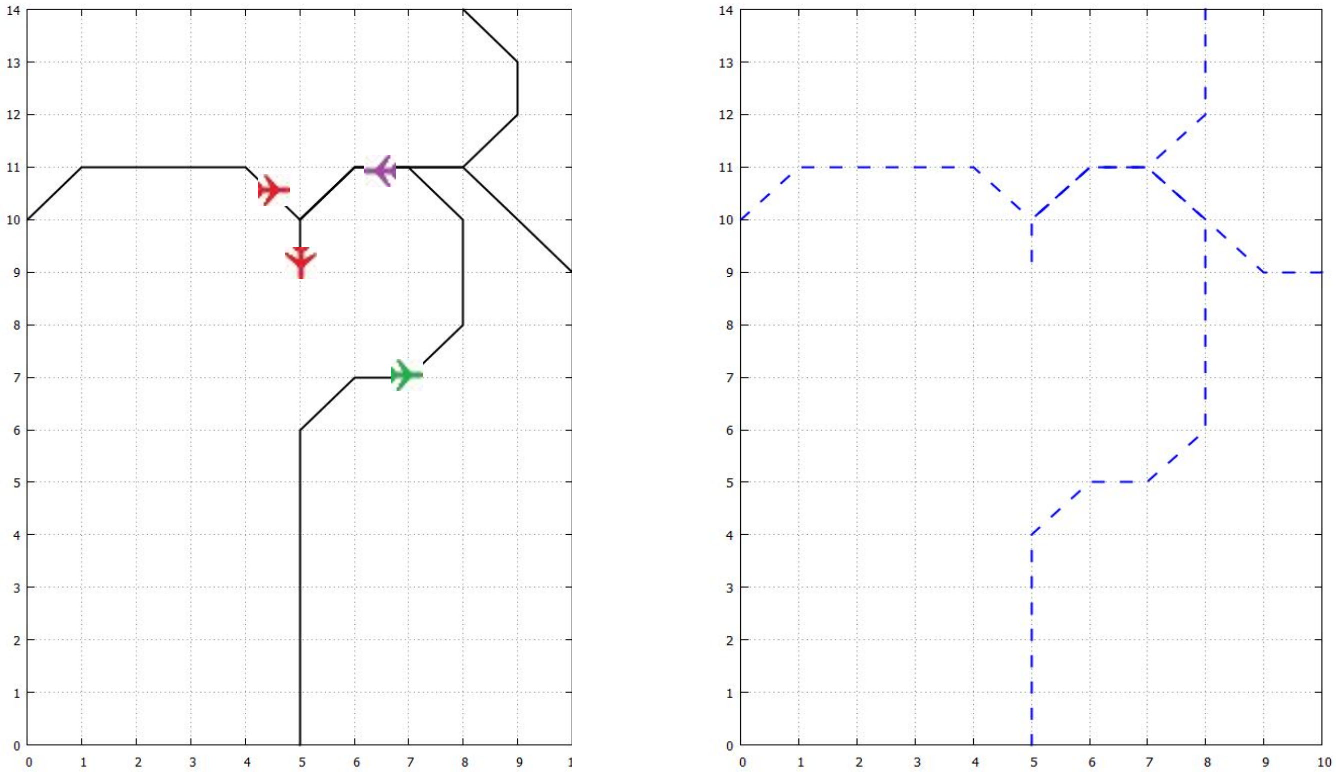

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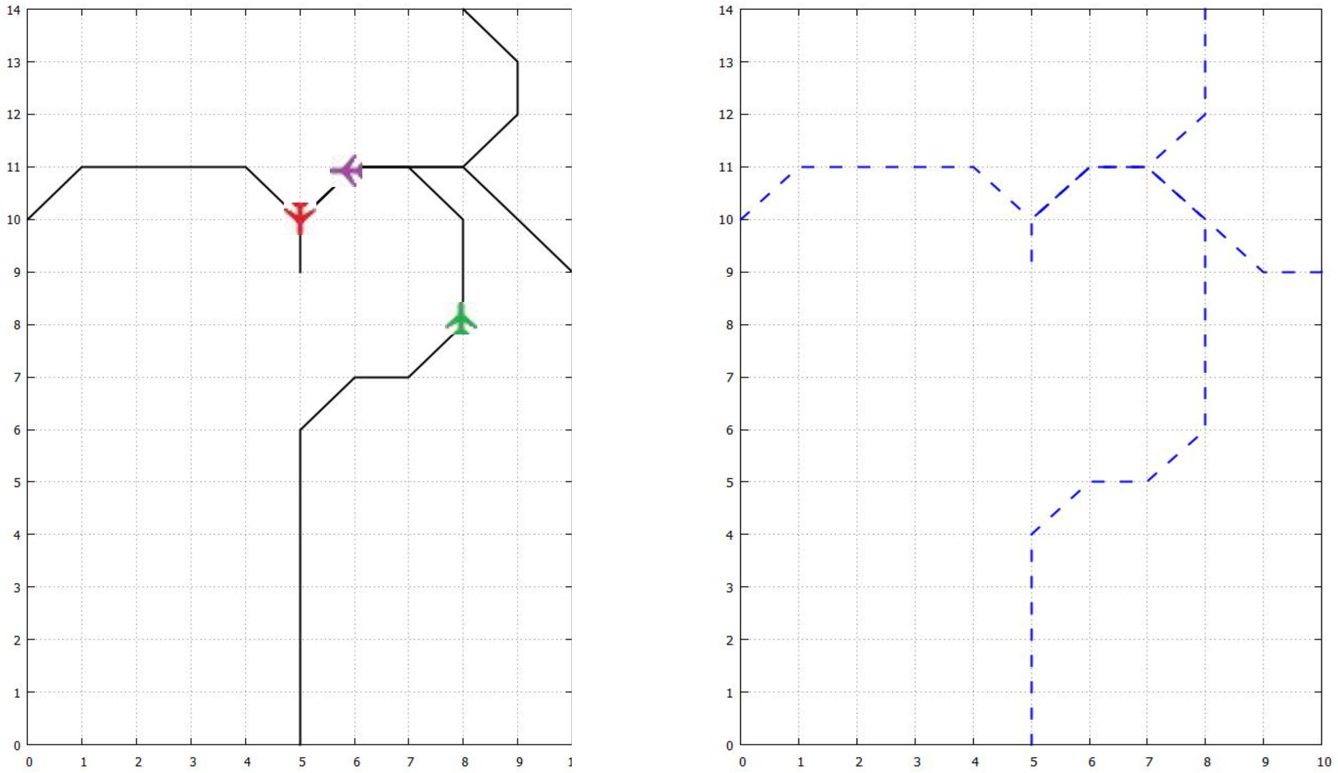

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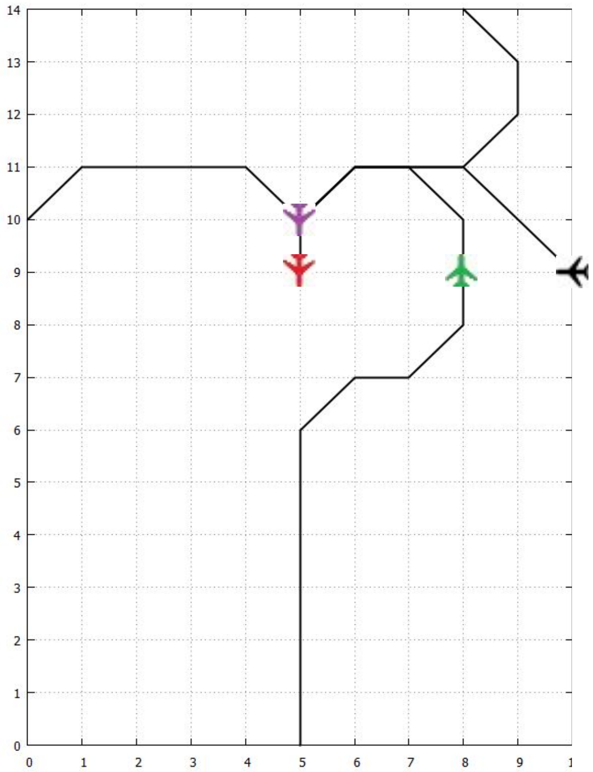
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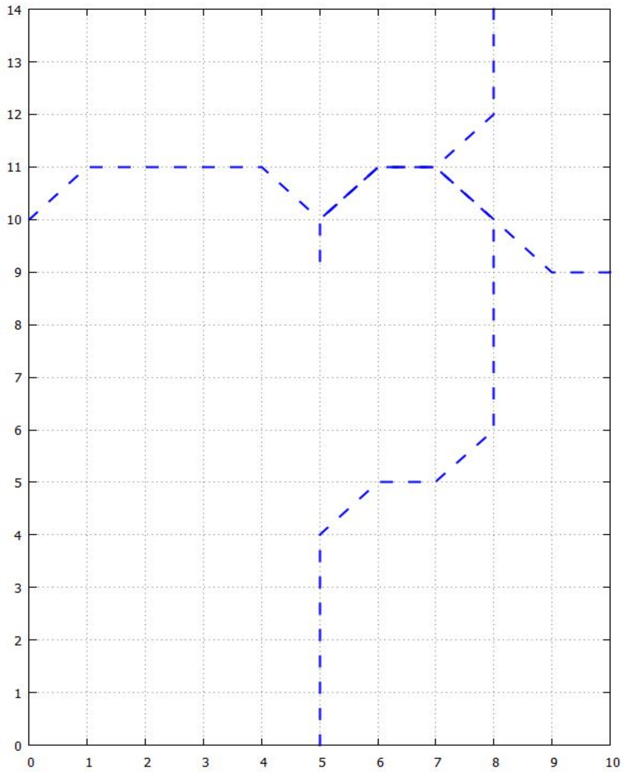
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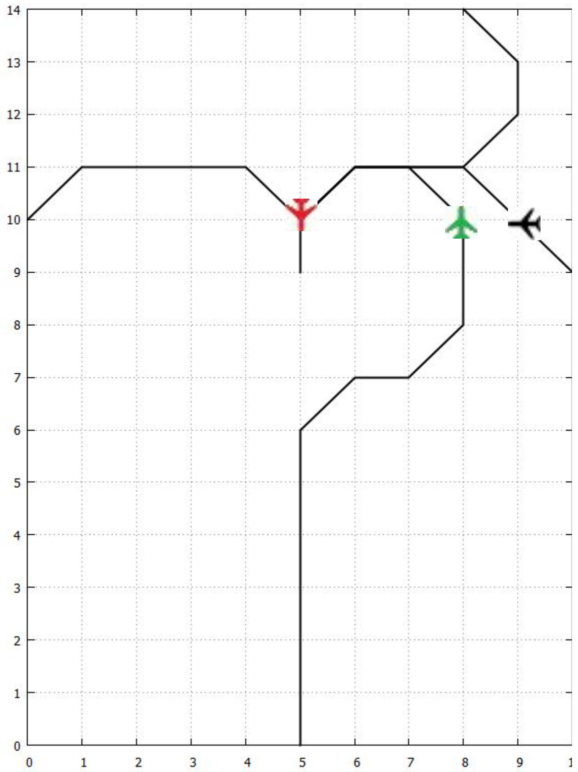
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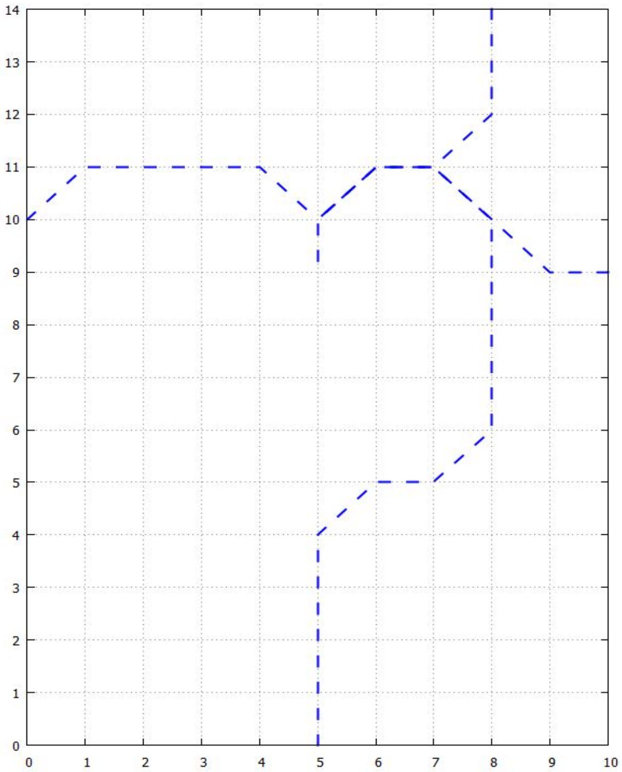
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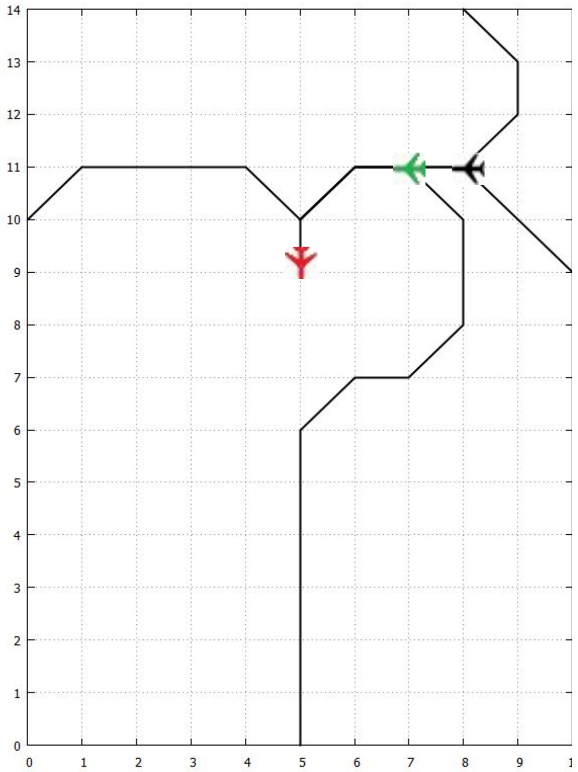
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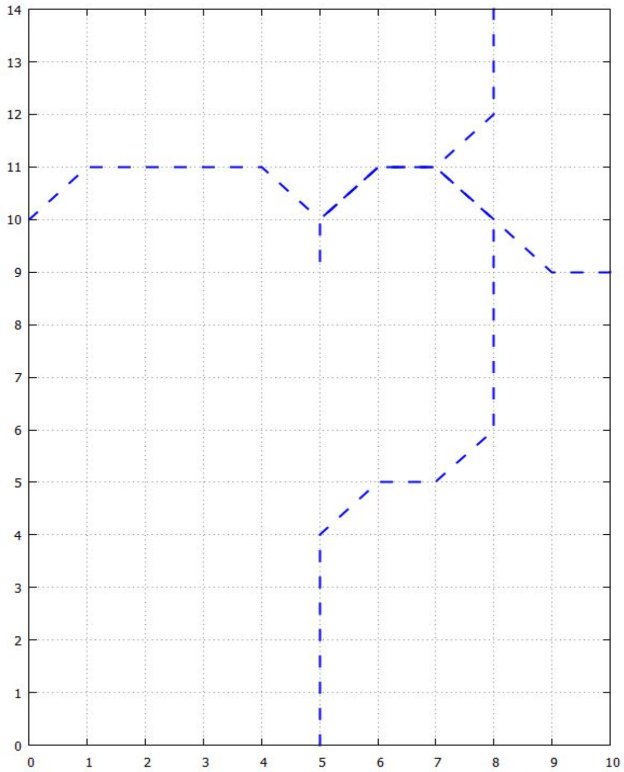
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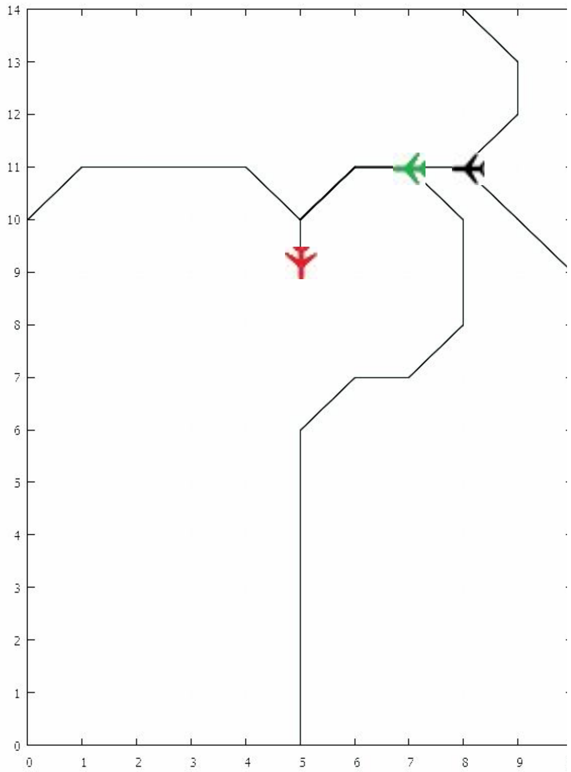

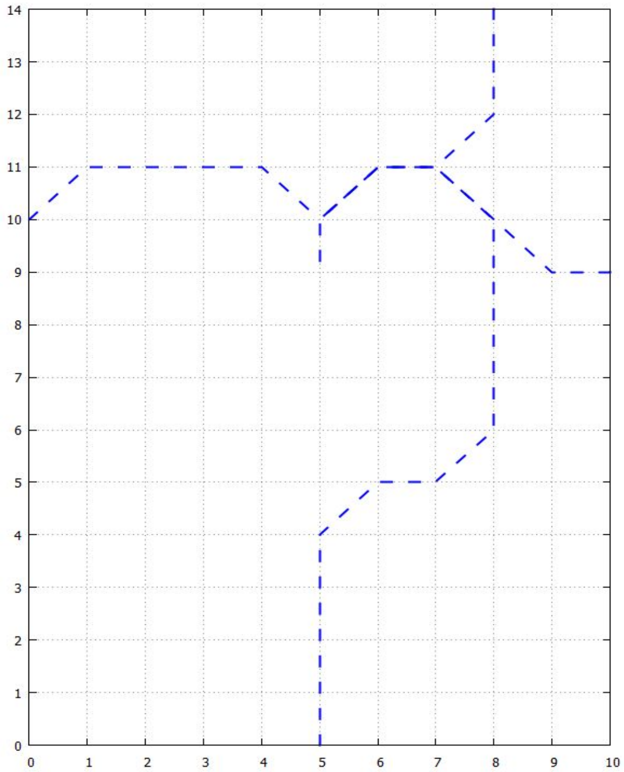

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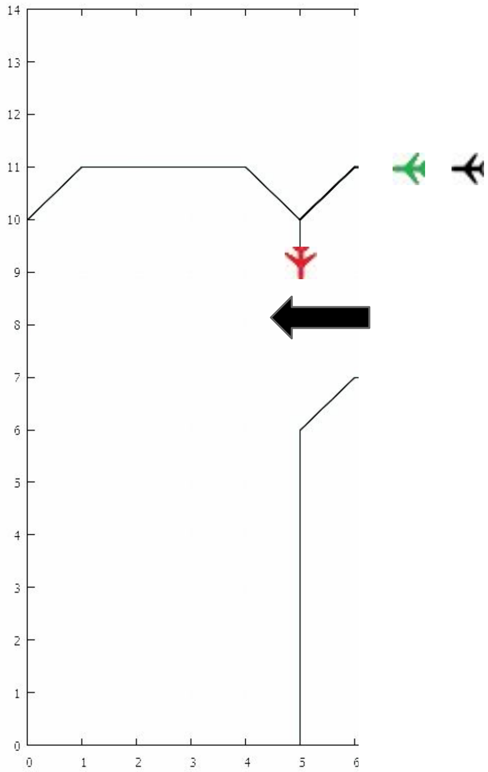
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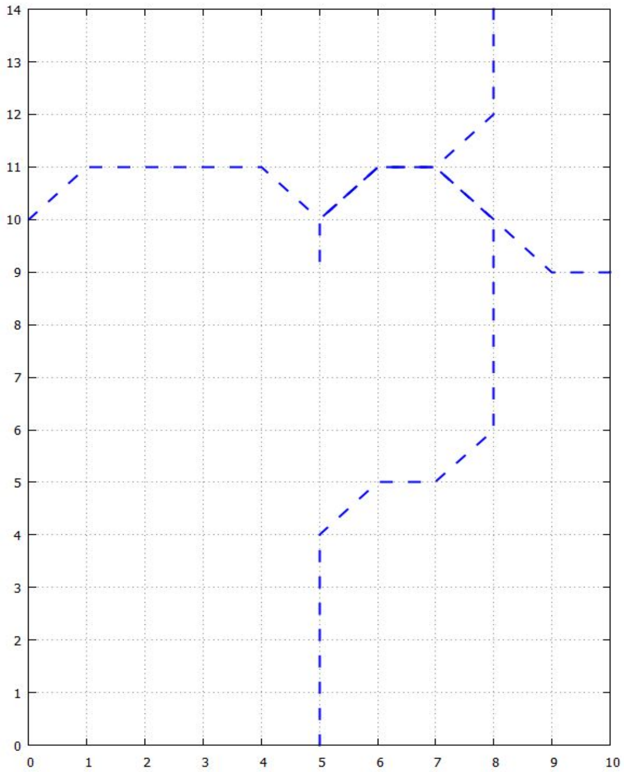
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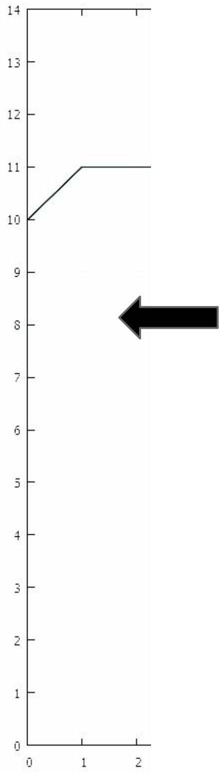
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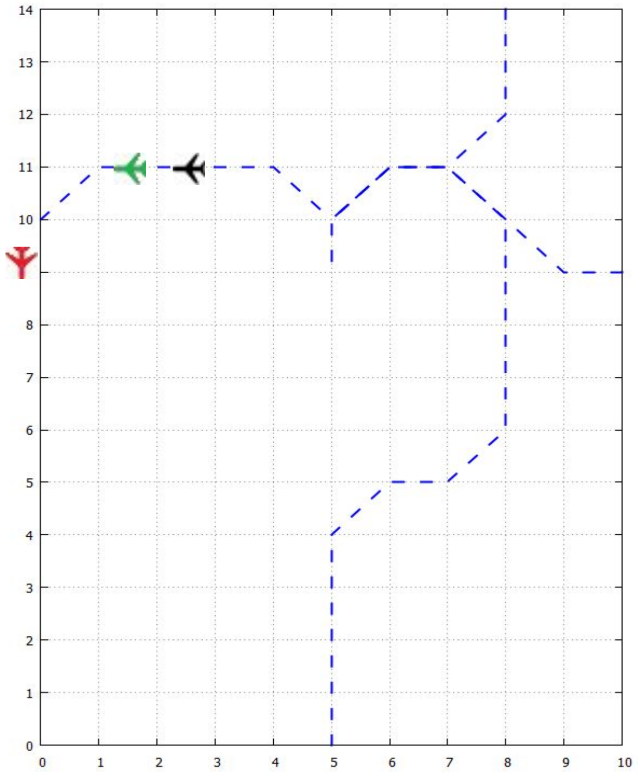
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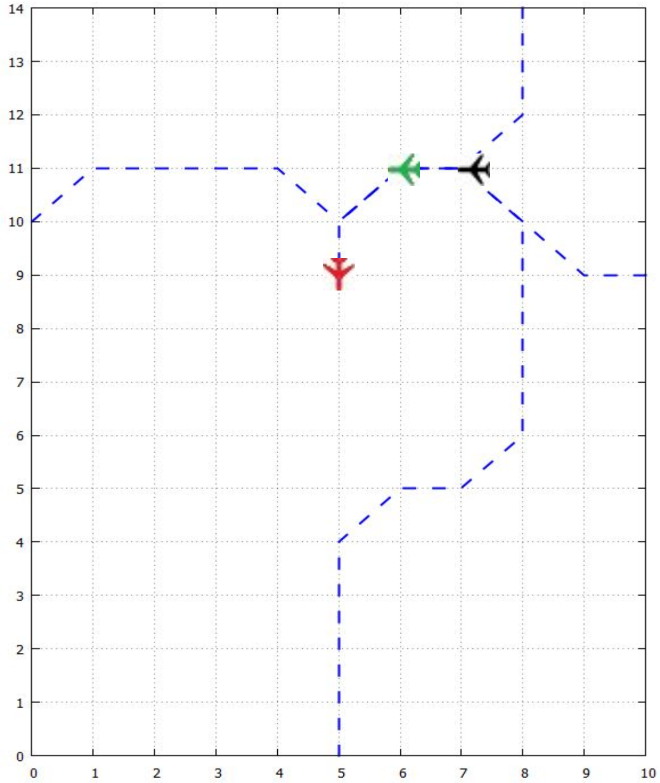

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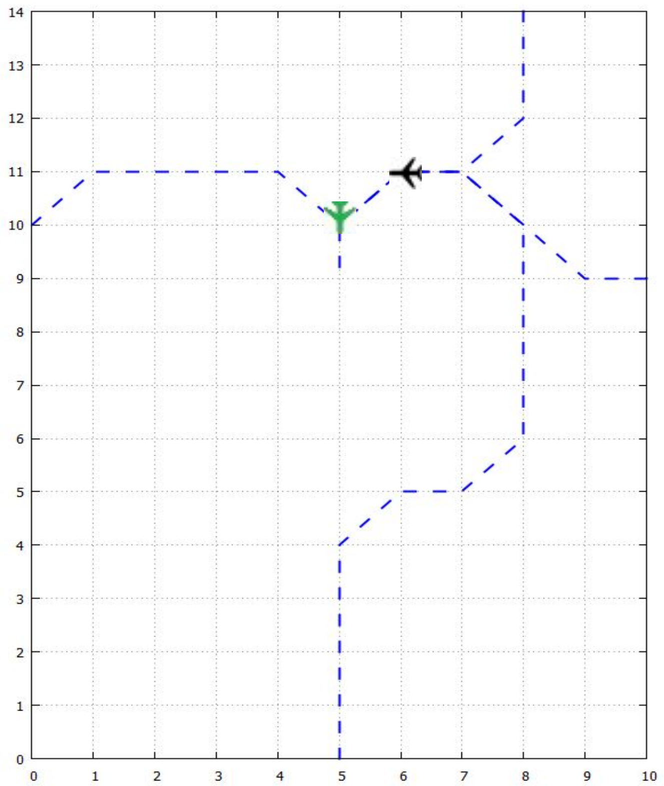

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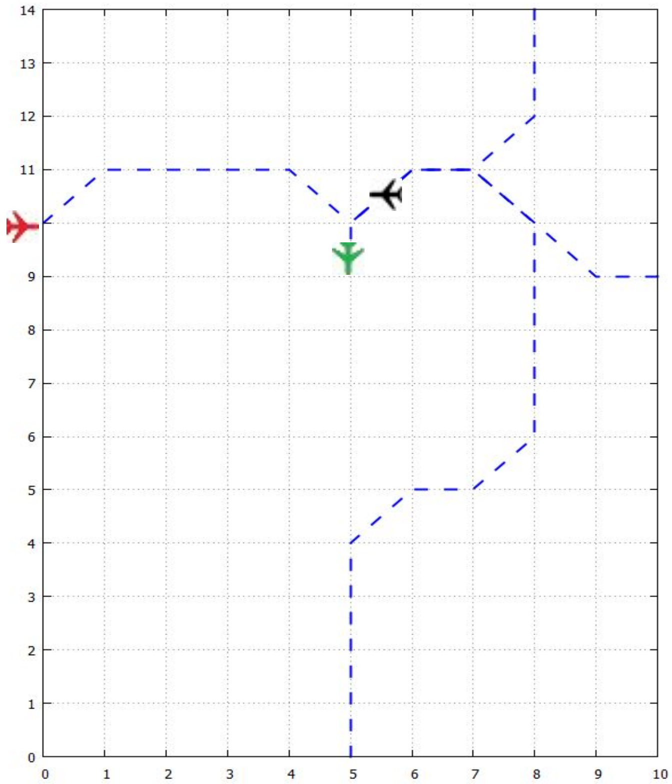

Conclusions

- ✓ Flexible optimization framework for dynamic route planning inside TMA
- ✓ Automated space and time separation
- ✓ Environmentally-friendly speed profiles (CDO)
- ✓ Applicable to any other realistic speed profiles
- ✓ May be used for TMA capacity evaluation

Future Work

- ✓ Account for uncertainties due to variations in arrival times
- ✓ Solve overtaking problem (allow non-optimal profiles, or route stretching)
- ✓ Consider fleet diversity
- ✓ Elaborate on implementation possibilities, link to the future operational enablers (data liks, technologies) for air-ground synchronisation (EPP)

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Thank you!

Questions?