Automation for Separation with CDOs: Dynamic Aircraft Arrival Routes

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Motivation

- Air transportation grows:
  - Beneficial for growing global economy
  - Increased complexity for air traffic controllers (ATCOs)
  - Environmental effects
- Terminal Maneuvering Areas (TMAs) most congested

➡ Optimization of arrival and departure procedures is needed:
  - Lessen ATCO workload
  - Mitigate environmental impact

Our solution:

- Automatically temporally separated arrivals to reduce complexity and ATCO's workload
- Aircraft fly according to optimal continuous descent operations (CDOs):
  - 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 have shown important environmental benefits w.r.t. conventional (step-down) approaches in TMAs

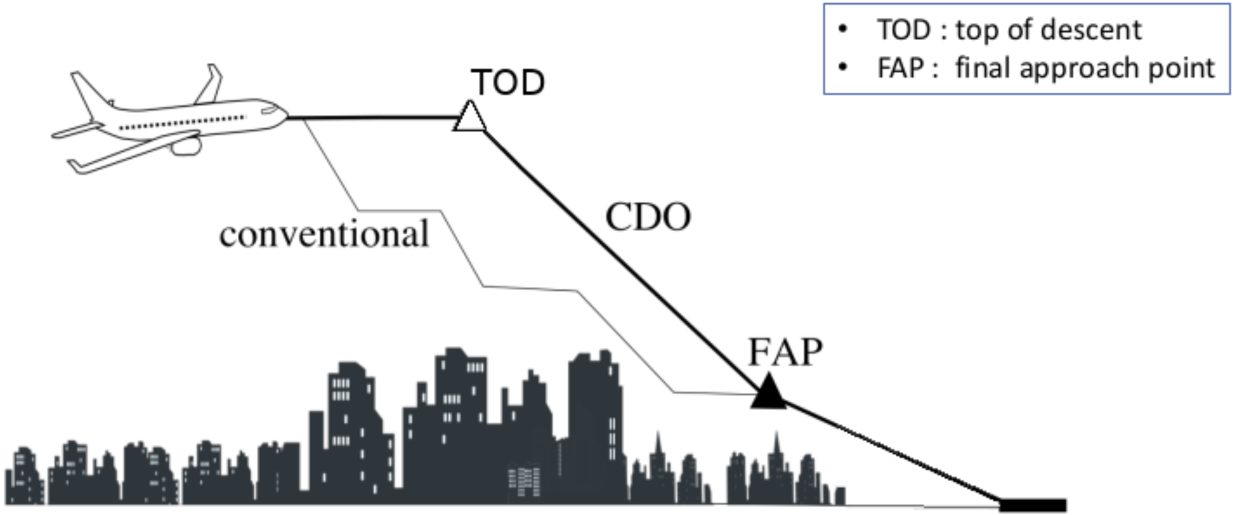


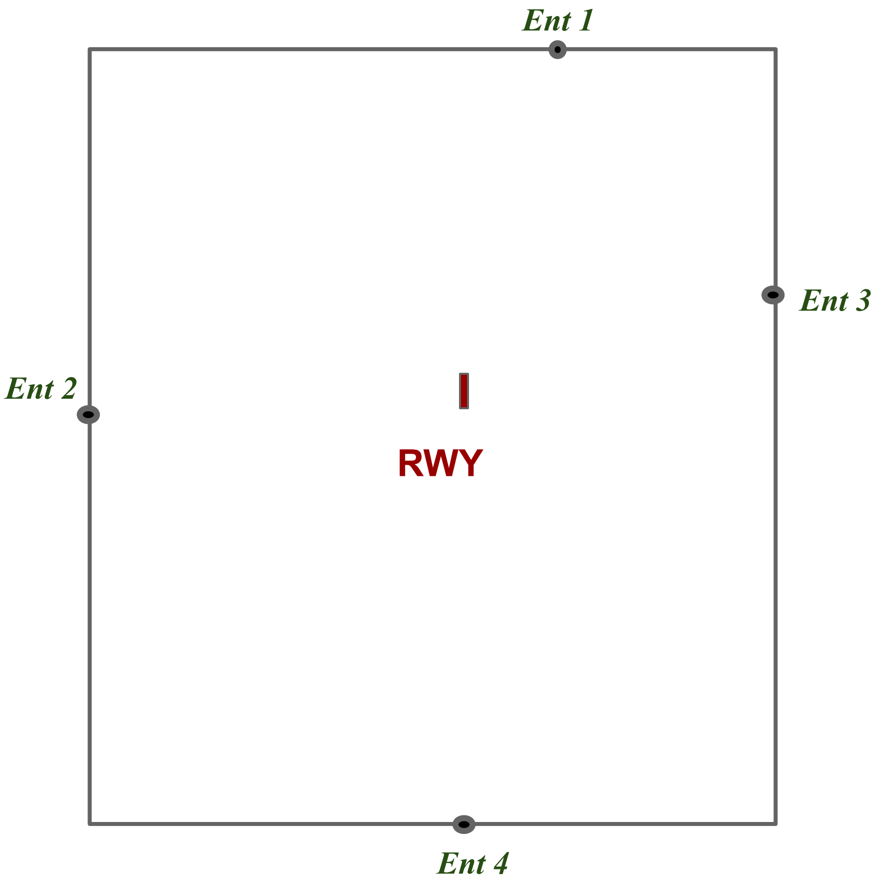
Figure source: Performance comparison between TEMO and a typical FMS in presence of CTA and wind uncertainties, by Ramon Dalmau, Xavier Prats, Ronald Verhoeven and Nico de Gelder, DASC 2016

Previous Work

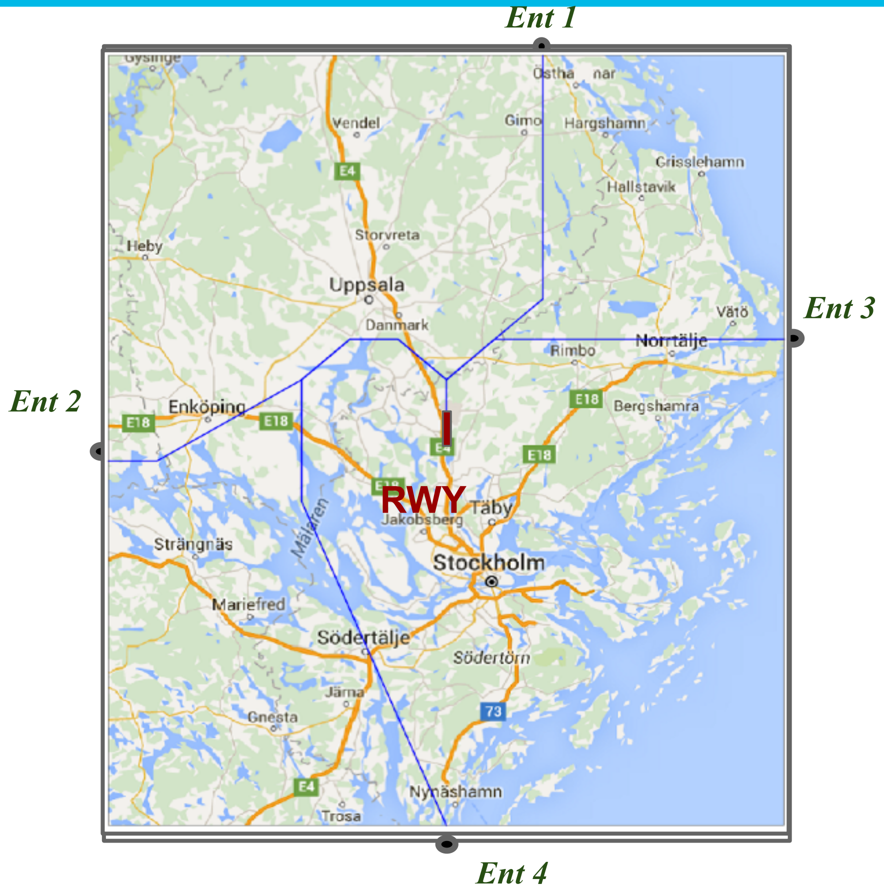
- LiU-LFV:
  - Optimal standard arrival routes (STARs)
  - Time-separated demand-weighted arrival routes (dynamic, for pre-tactical planning), assuming unit edge traversal time
- UPC: CDO-enabled optimized arrival procedures (engine-idle, low noise)
- Here: Automated time-separated demand-weighted CDO-enabled optimized arrival routes

Grid-based MIP Formulation

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



Optimal arrival tree that:

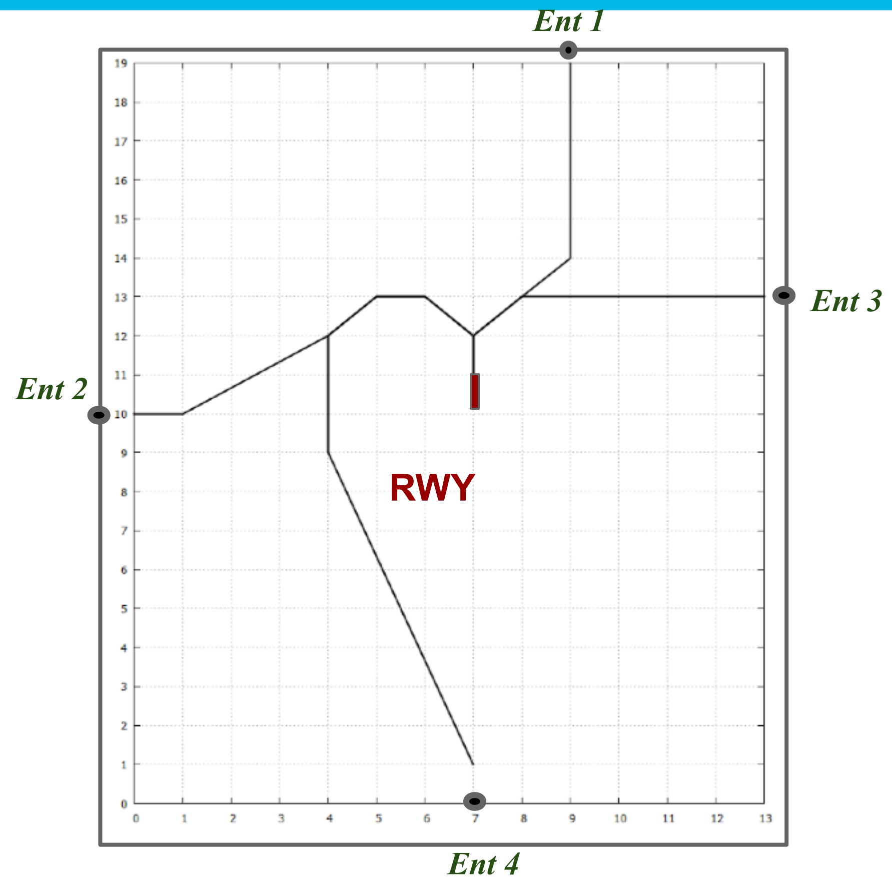
- Merges traffic from the entries to the runway
- Ensures safe aircraft separation for the given time period

⇨ A set of time-separated **CDO-enabled** tree-shaped aircraft trajectories optimized w.r.t. the traffic demand during the given period

Operational Requirements

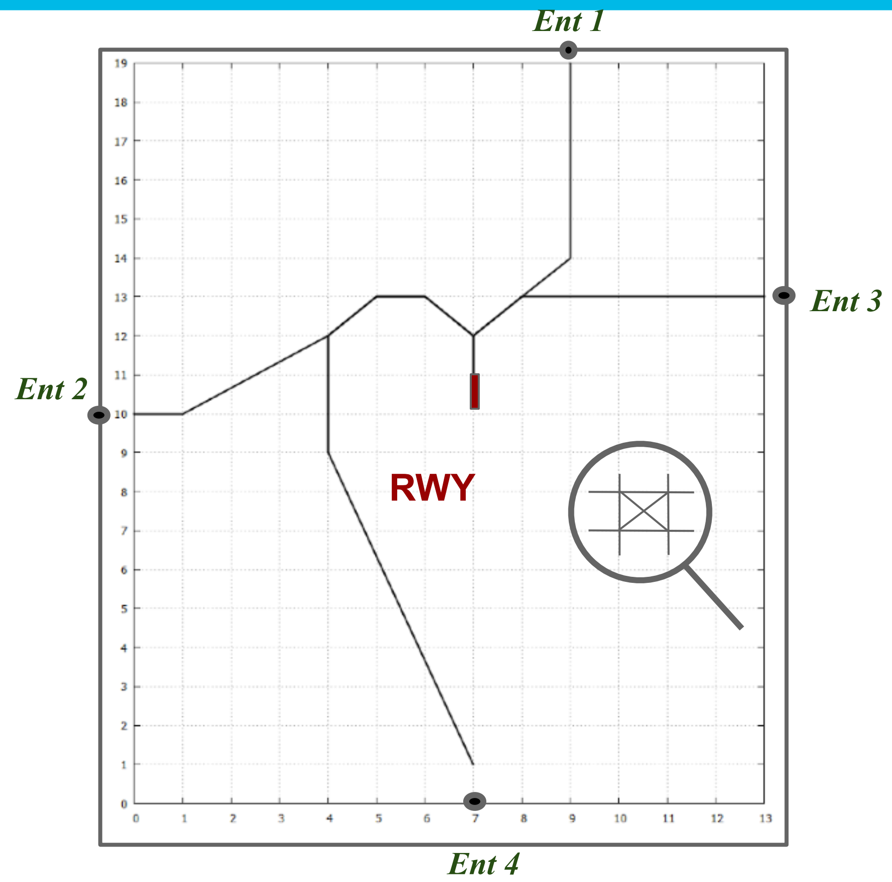
- **No more than two routes merge at a point:** in-degree ≤ 2
- **Merge point separation:** distance threshold L
- **No sharp turns:** angle threshold α, minimum edge length L
- **Temporal separation of all aircraft along the routes**
- **All aircraft fly energy-neutral CDO:**
  idle thrust, no speed brakes (noise avoidance)
- **Smooth transition** between consecutive trees when switching

Grid-based MIP Formulation



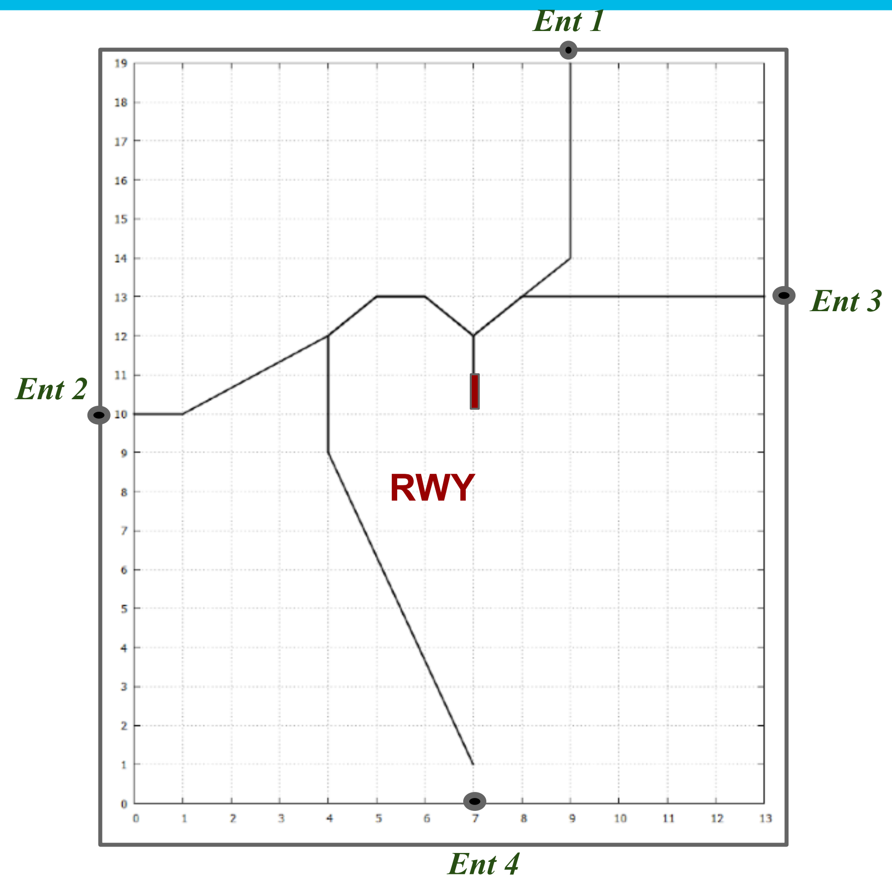
- Square grid in the TMA
- Snap locations of the entry points and the runway into the grid
- Grid cell side of the length L (separation parameter)

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

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

Short flight routes for aircraft

Demand-weighted path length: $\min \sum_{e \in E} \ell_e f_e$

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

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

Arrival tree should "occupy little space"

- 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

$$\sum_{k:(k,i)\in E} f_{ki} - \sum_{j:(i,j)\in E} f_{ij} = \begin{cases} \sum_{k\in\mathcal{EP}} \varkappa_k & i = R \\ -\varkappa_i & i \in \mathcal{EP} \\ 0 & i \in V \setminus \{\mathcal{EP} \cup R\} \end{cases} \qquad (1)$$

Flow from all entry points reaches runway
Flow of #a/c leaves each entry point
Flow conservation

$$x_e \geq \frac{f_e}{|\mathcal{EP}|} \qquad \forall e \in E \qquad (2)$$

Edges with positive flow are in STAR

$$f_e \geq 0 \qquad \forall e \in E \qquad (3)$$

Flow non-negative

$$x_e \in \{0,1\} \qquad \forall e \in E \qquad (4)$$

Edge decision variables are binary

$$\sum_{k:(k,i)\in E} x_{ki} \leq 2 \qquad \forall i \in V \setminus \{\mathcal{EP} \cup R\} \qquad (5)$$

$$\sum_{j:(i,j)\in E} x_{ij} \leq 1 \qquad \forall i \in V \setminus \{\mathcal{EP} \cup R\} \qquad (6)$$

$$\sum_{k:(k,R)\in E} x_{kR} = 1 \qquad (7)$$

$$\sum_{j:(R,j)\in E} x_{Rj} \leq 0 \qquad (8)$$

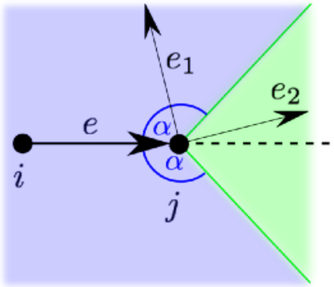
$$\sum_{k:(k,i)\in E} x_{ki} \leq 0 \qquad \forall i \in \mathcal{EP} \qquad (9)$$

$$\sum_{j:(i,j)\in E} x_{ij} = 1 \qquad \forall i \in \mathcal{EP} \qquad (10)$$

Degree constraints:
Outdegree of every vertex at most 1, maximum indegree is 2.
Runway only one ingoing, entry points only one outgoing edge.

$$a_e x_e + \sum_{f\in A_e} x_f \leq a_e \qquad \forall e \in E \qquad (11)$$

$a_e = |A_e|$



If an edge x_e the angle to the consecutive segment of a route is never smaller than $\boldsymbol{\alpha}$

Auxiliary Constraints to Prevent Crossings

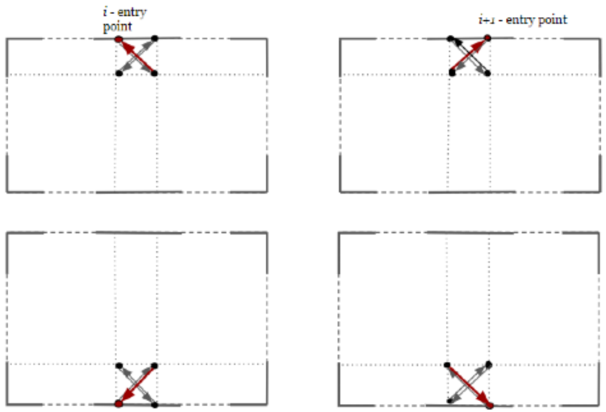
Why? Temporal Separation may enforce paths that are not shortest, hence, crossings may appear

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.

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

Temporal Aircraft Separation

Assumption: unit time u to cover a single edge

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 $\quad x_{e,b} \leq x_e \; \forall b \in \mathcal{P}, \forall e \in E$ plus several other constraints

Set:

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

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

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

$$y_{a,j,t} \leq \sum_{\substack{k \in V: \\ (k,j) \in E}} x_{(k,j)} \forall b \in \mathcal{P}, \forall a \in \mathcal{A}, \forall j \in V \setminus \mathcal{P}, \forall t \in T \qquad T = \{0, \ldots, \overline{T}\}$$

Aircraft arriving at entry point b ($\mathcal{A}_b$)

Time when aircraft a arrives at entry point b (t_a^b)

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

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

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

Not linear

$\Longrightarrow$ we linearise using a new variable $z_{a,j,k,b,t}$

$$\sum_{j:(j,k) \in E} z_{a,j,k,b,t} - y_{a,k,t+u} = 0$$

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

Temporal separation: $\displaystyle\sum_{\tau=t}^{t+\sigma-1} \sum_{a \in \mathcal{A}} y_{a,j,\tau} \leq 1 \quad \forall j \in V, \forall t \in \{0, \ldots, \overline{T} - \sigma + 1\}$ **σ** - separation parameter

- 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

- The state vector x represents the fixed initial conditions of the aircraft: TAS v, altitude h and distance to go 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 u

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

- A point-mass representation of the aircraft reduced to a "gamma-command" is considered, where vertical equilibrium is assumed → Dynamic constraints 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 ψ 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

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

Terminal constraints

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

- 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

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

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)

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

Integration of CDO-enabled Realistic Speed Profiles

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

Substitute the corresponding equations with:

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

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

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

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

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

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

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

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

Set of all speed profiles (different lengths) for aircraft a

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

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

ℓ(b) is a variable $\Longrightarrow$ We use auxiliary binary variables and constraints to achieve this.

Separation constraint:

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

σ - separation parameter

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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 in the two trees

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

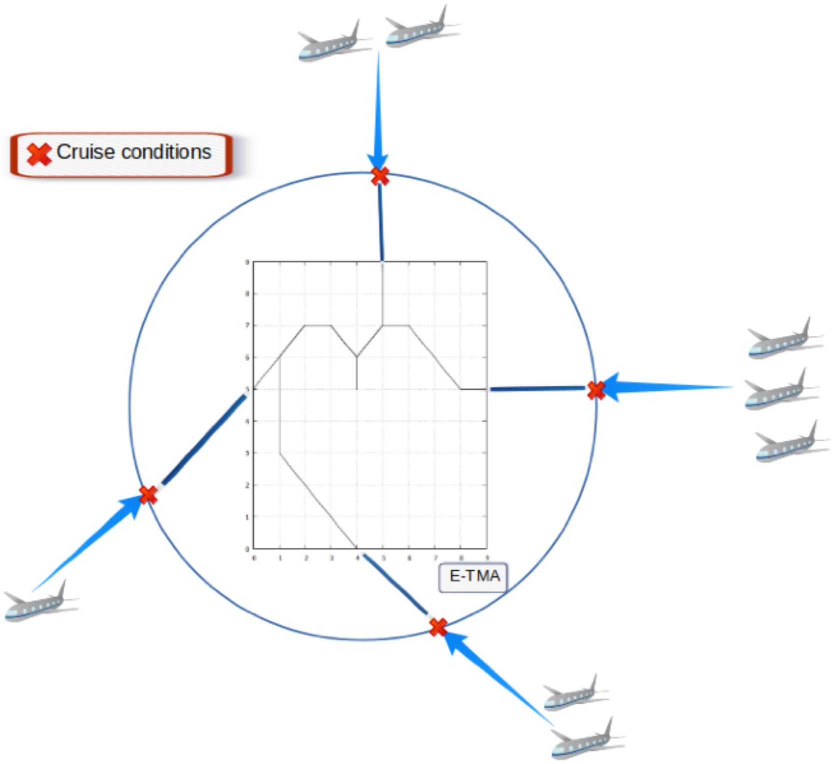
$$ax_{ij} \leq x_{ij}^{old} - x_{ij} \quad \forall (j,i) \in E$$

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

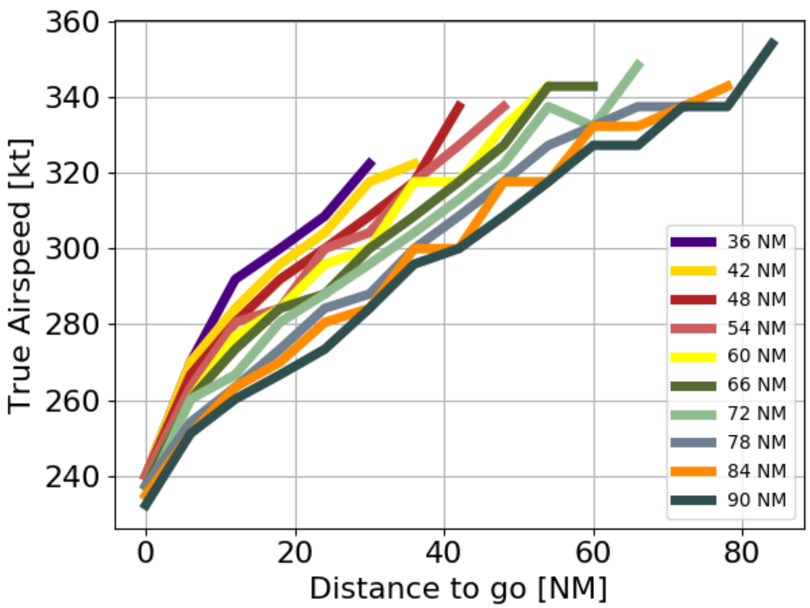
Experimental Study: Stockholm Arlanda Airport

- 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

- 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 profiles inside TMA

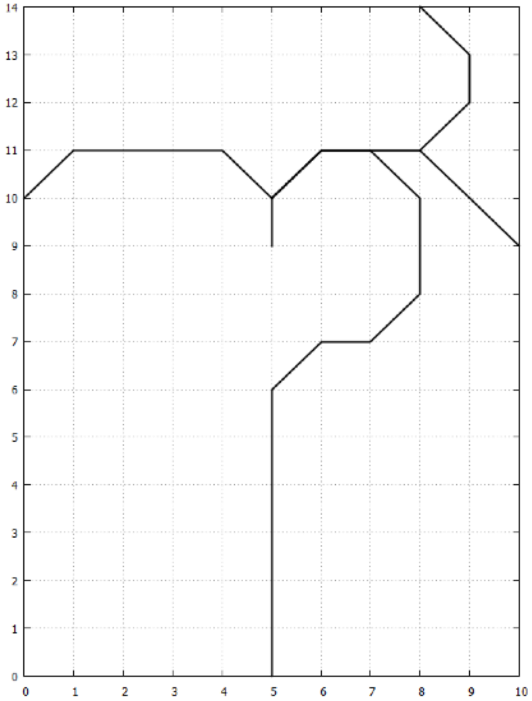


Example of A320 speed profiles for different path lengths inside TMA

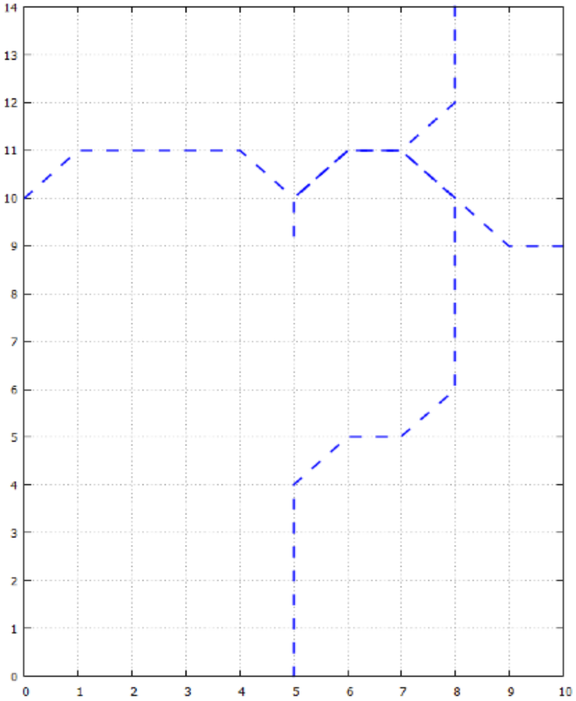
- A set of realistic alternative speed profiles for different possible route lengths inside TMA
- Generated for all a/c types arriving to Arlanda during the given period
- Used as input to MIP

Results: Stockholm Arlanda Airport

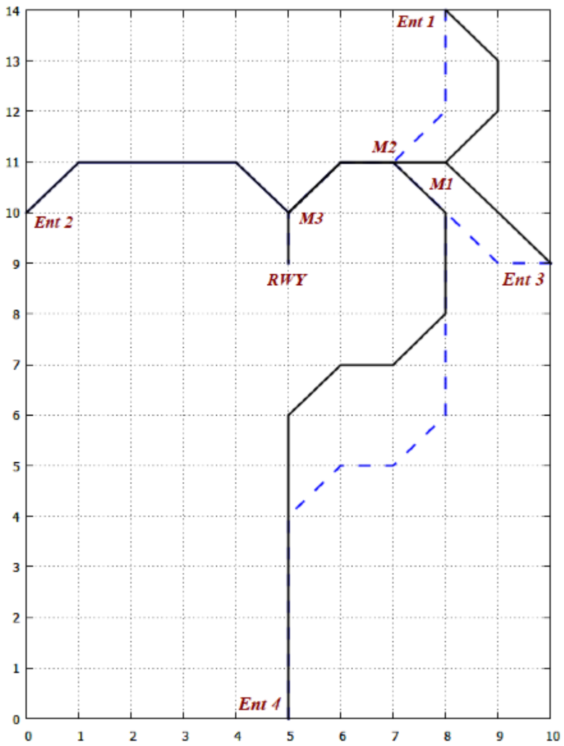
Tree 1: time: 15:00 - 15:30 (10 a/c)



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

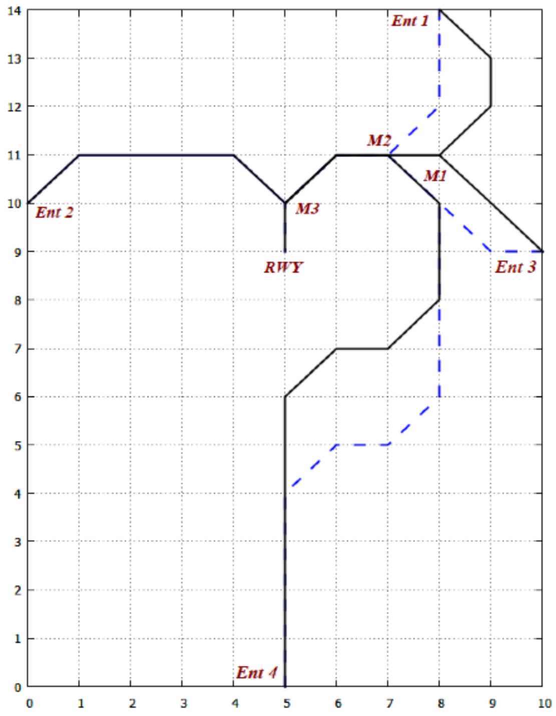


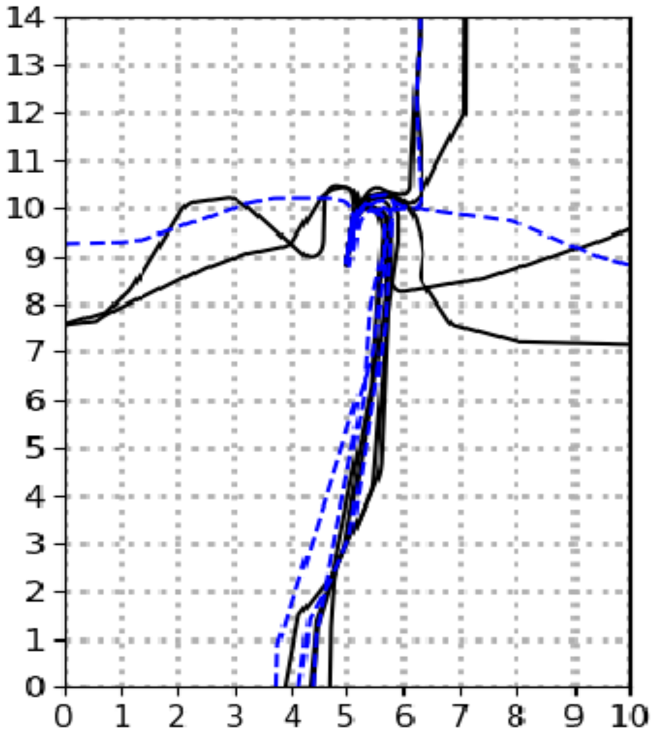
Results: Stockholm Arlanda Airport



- 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

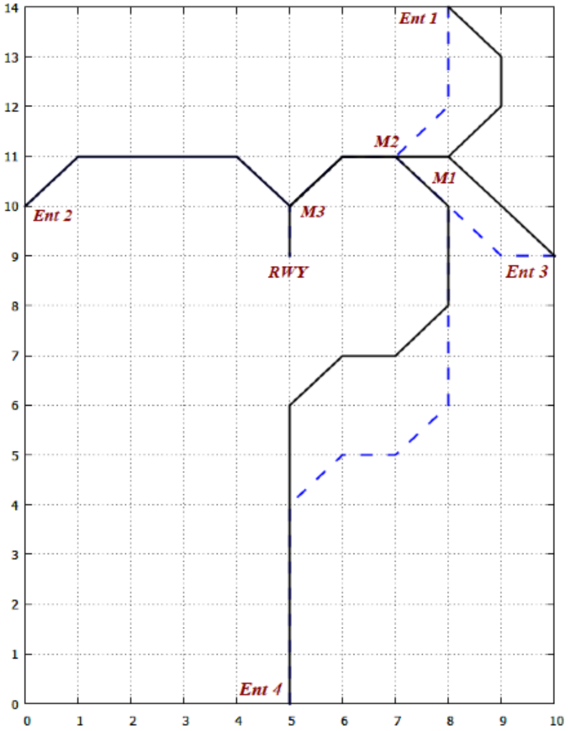
Comparison against historical trajectories (Open Sky Network)





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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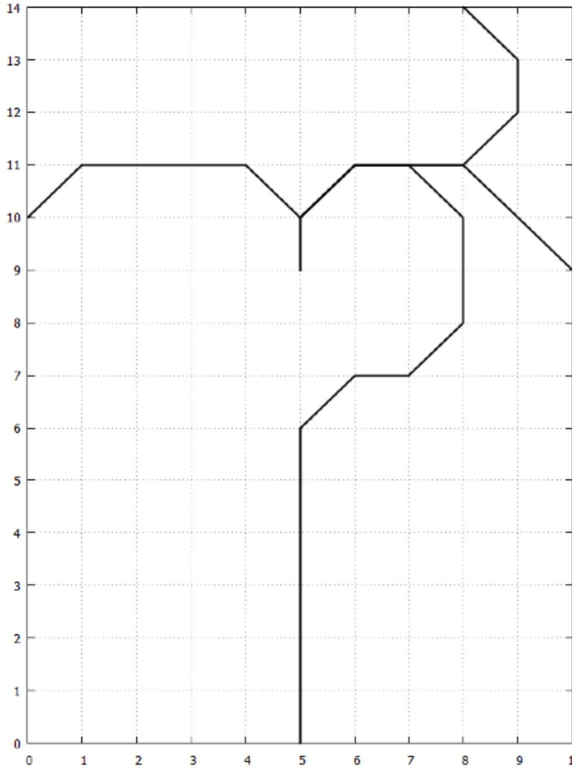

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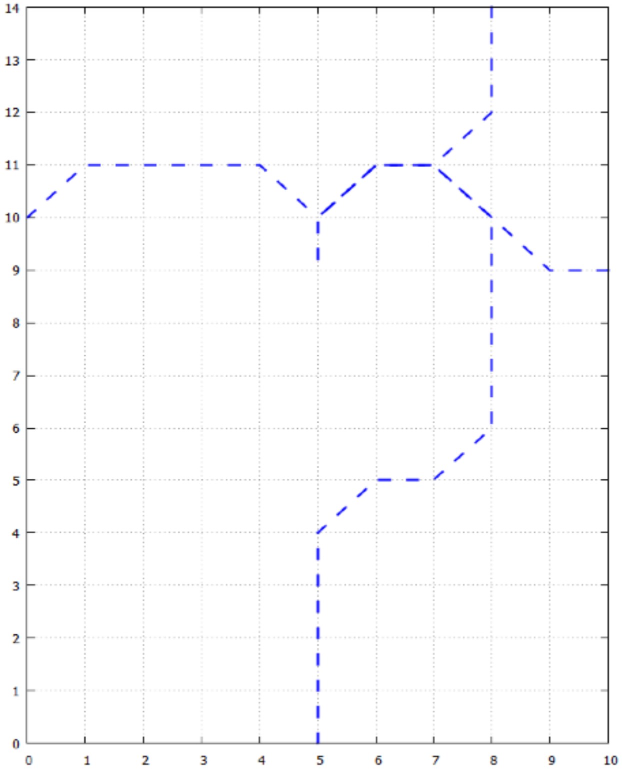

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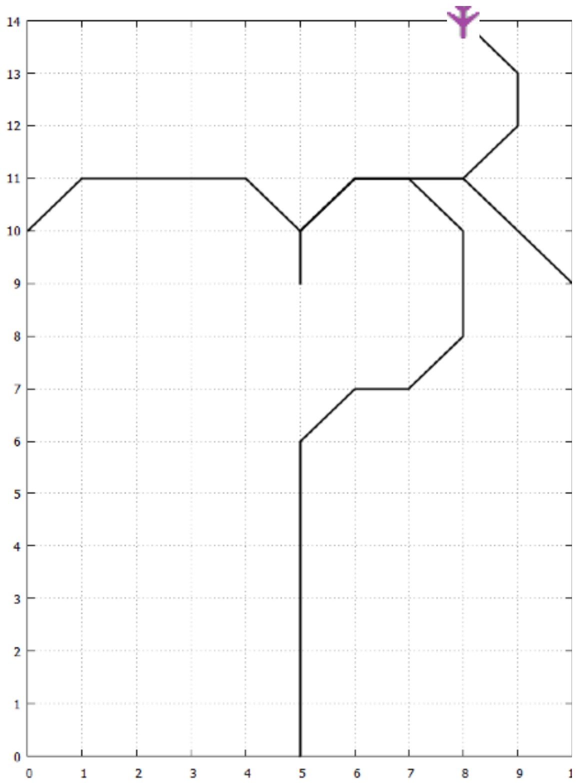

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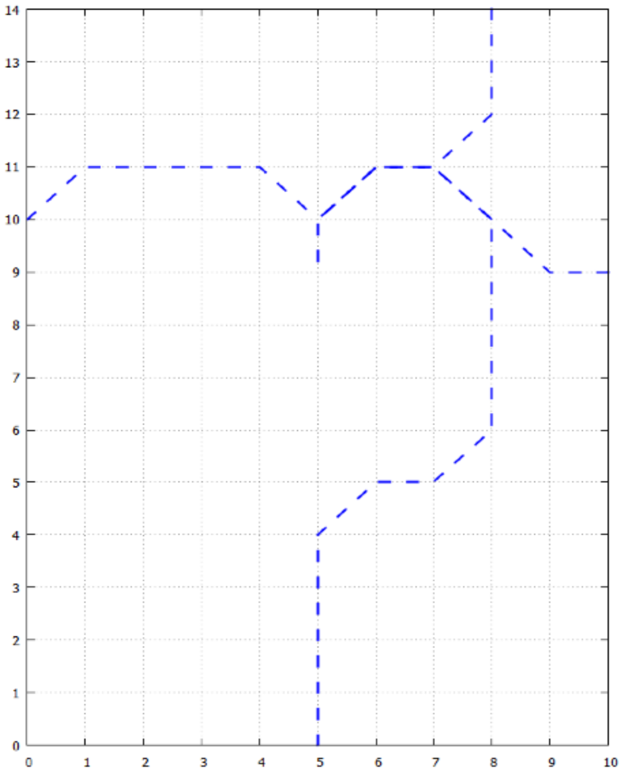

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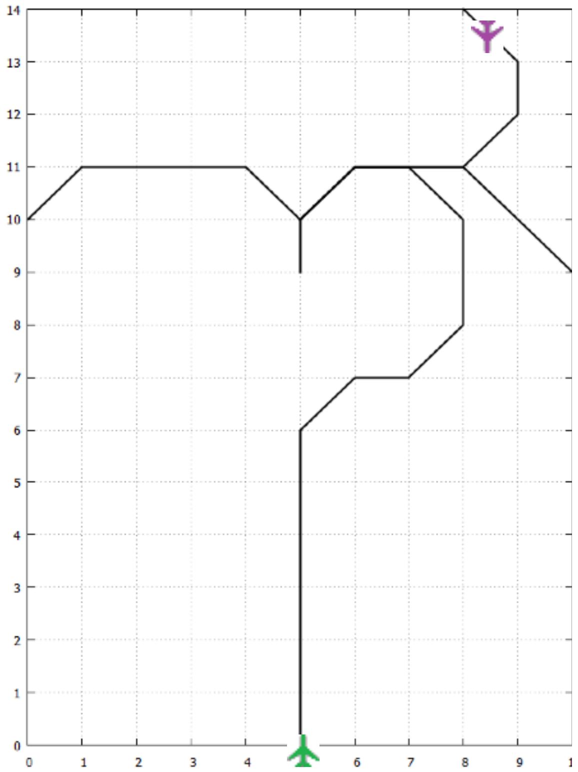

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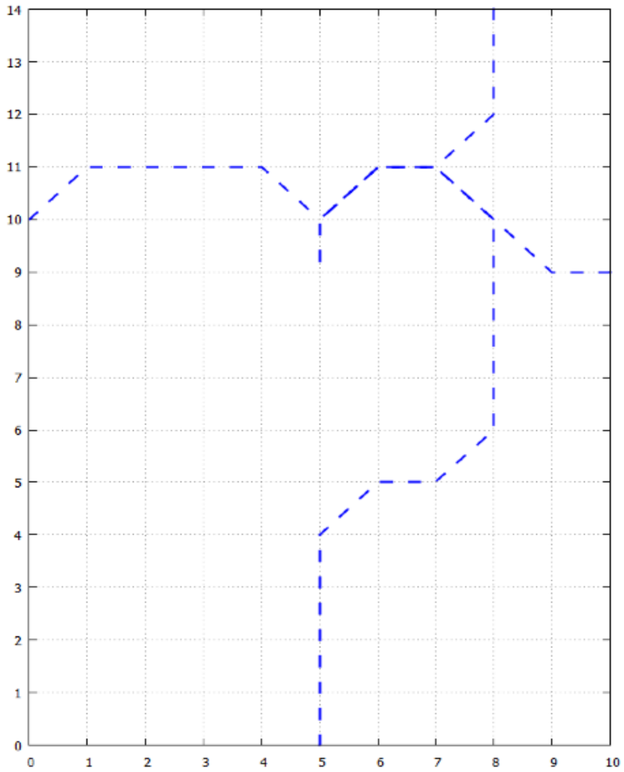

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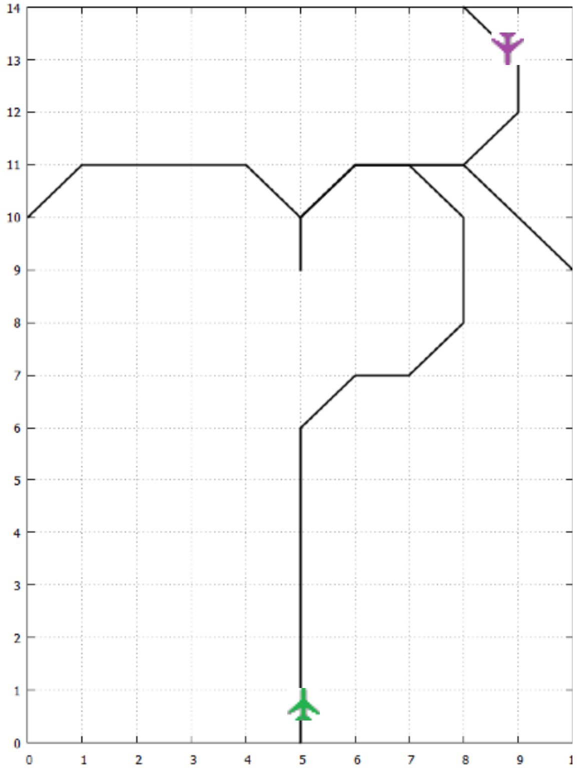
t = 15:05



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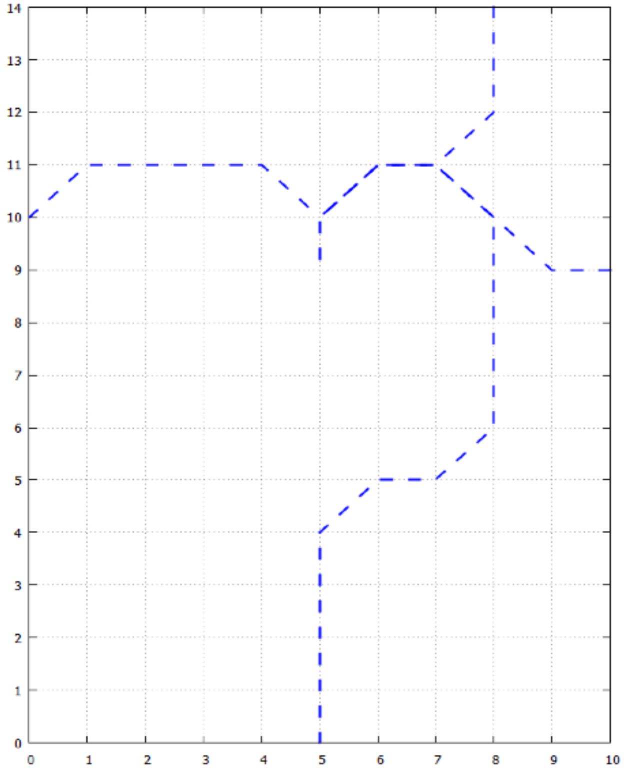

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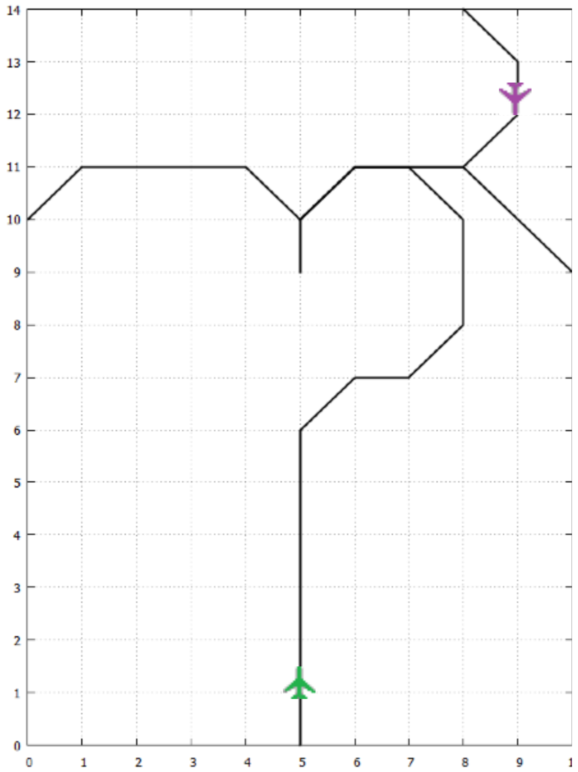

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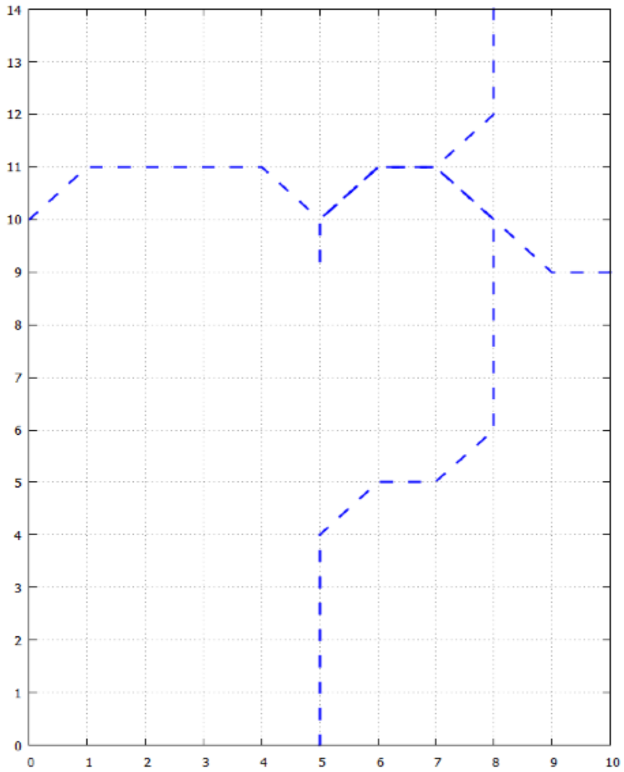

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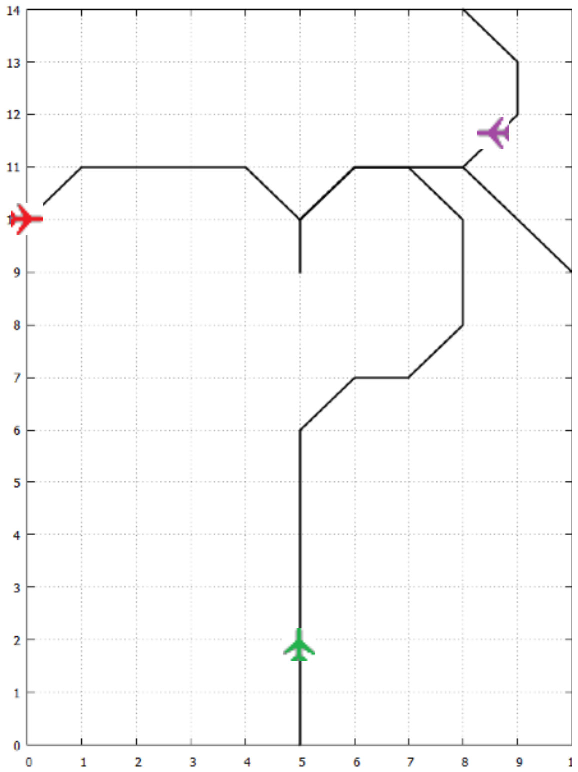

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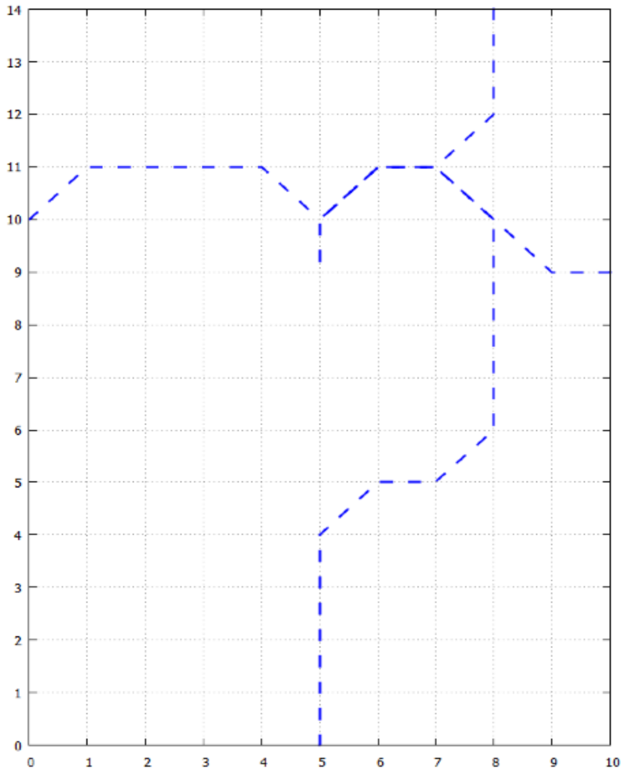

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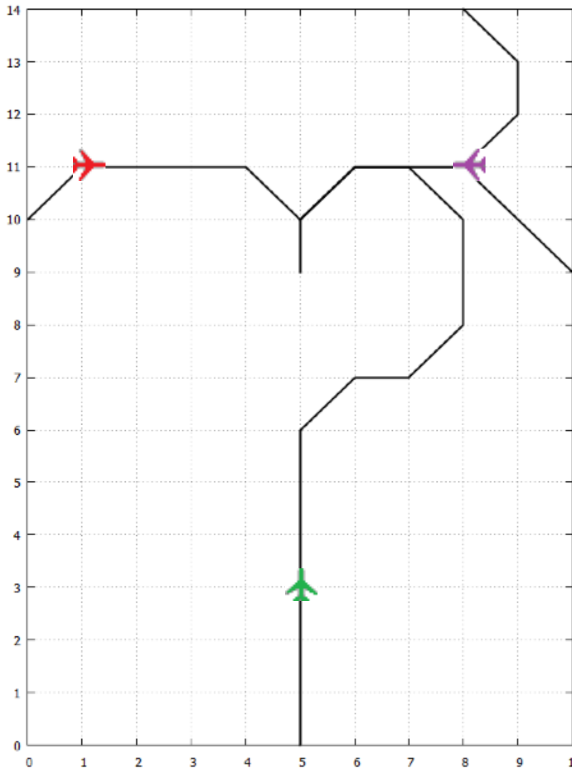

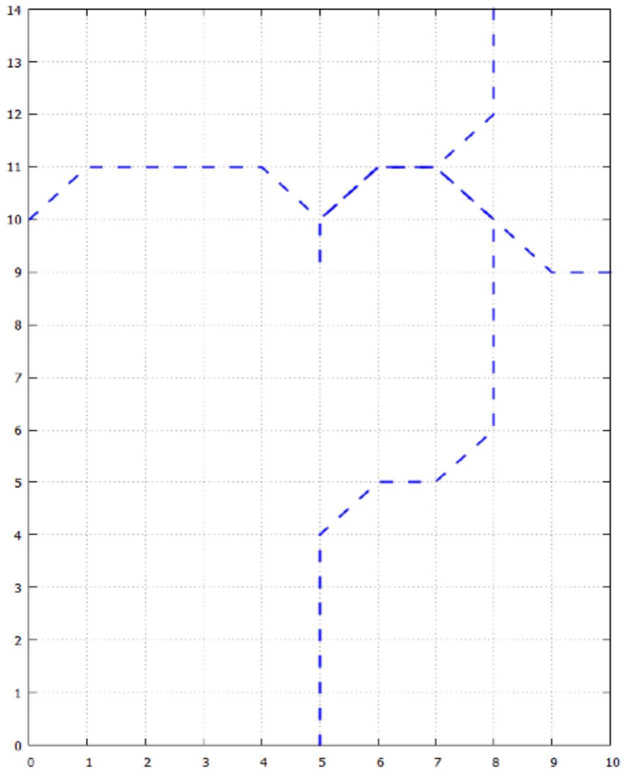

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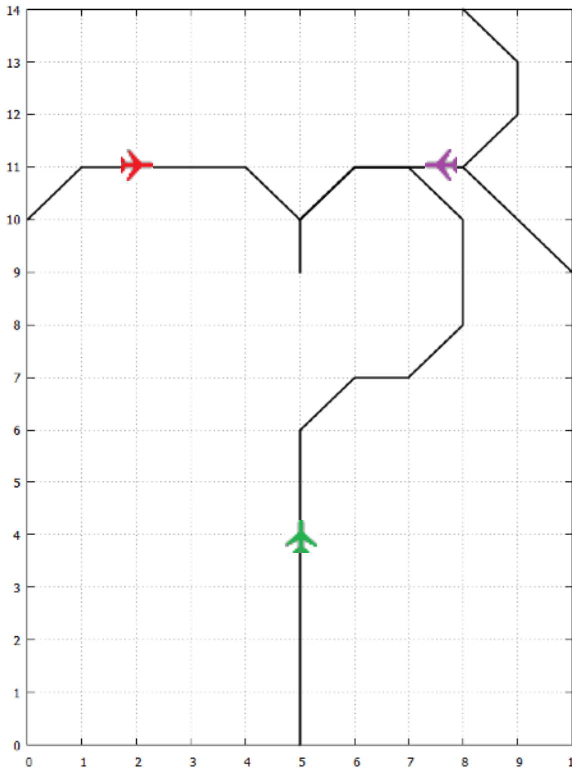

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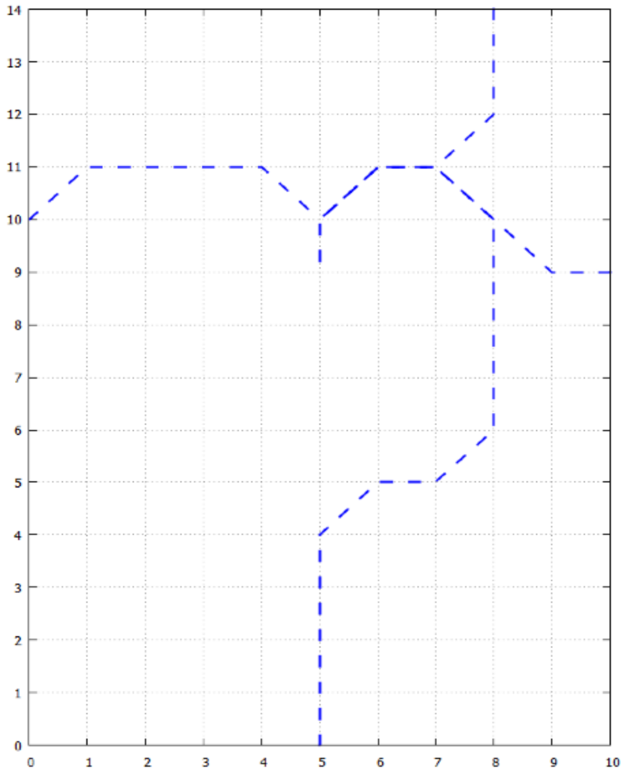

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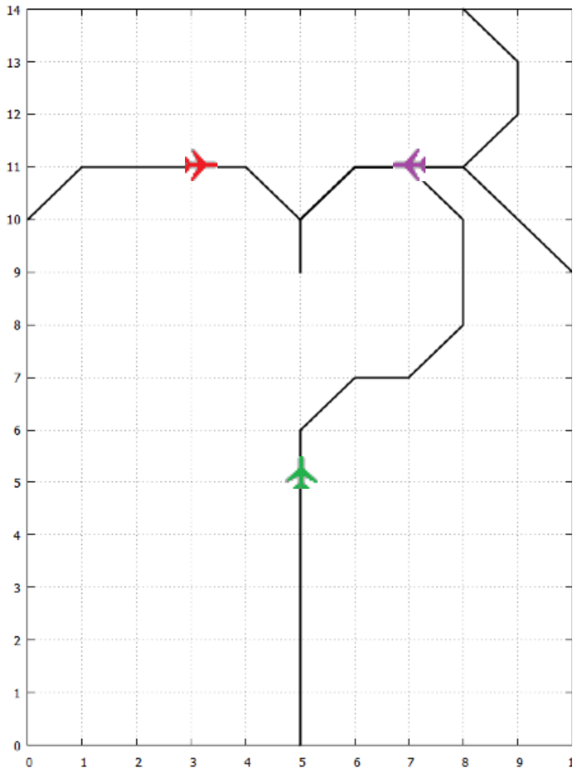
t = 15:11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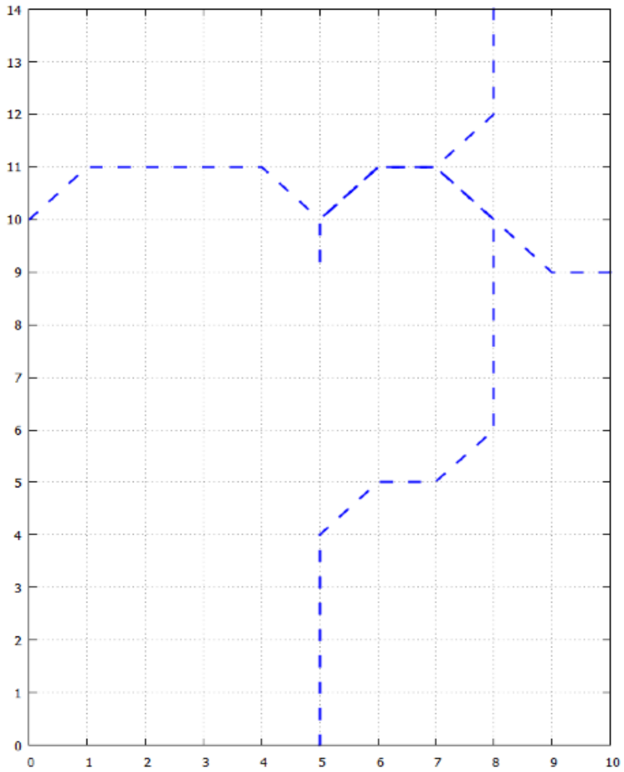
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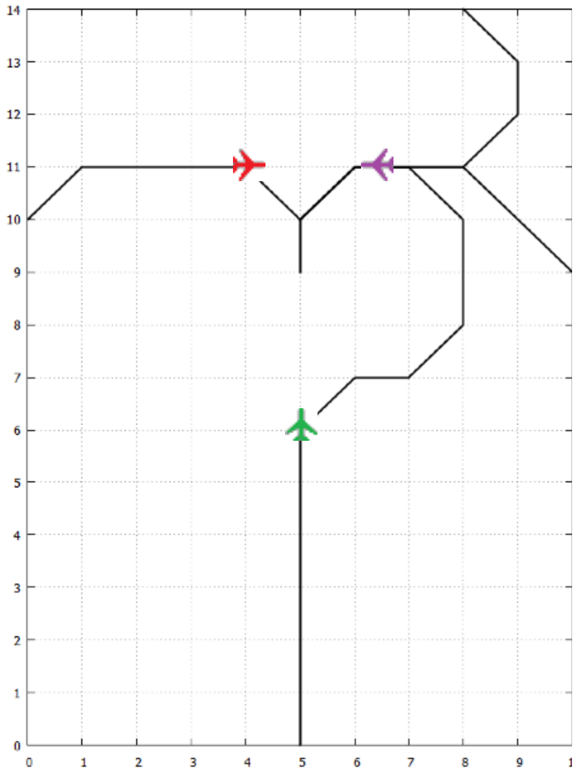

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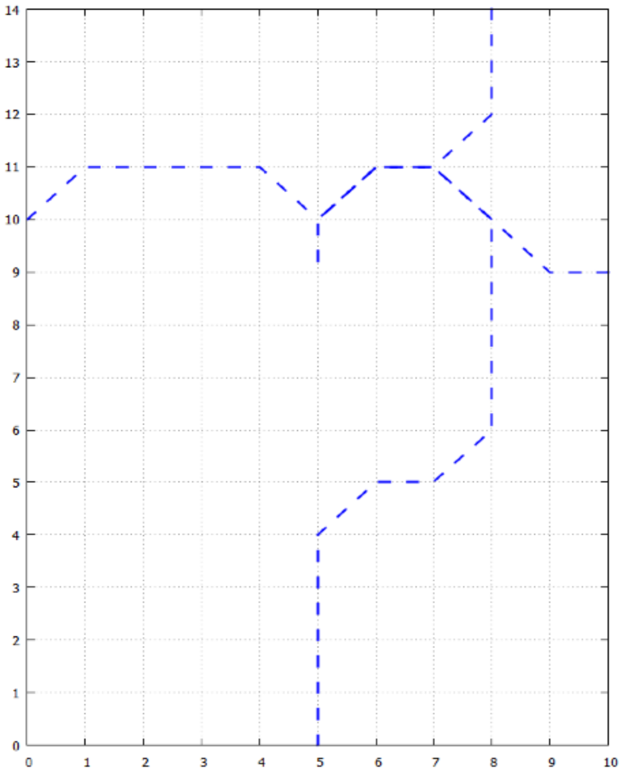

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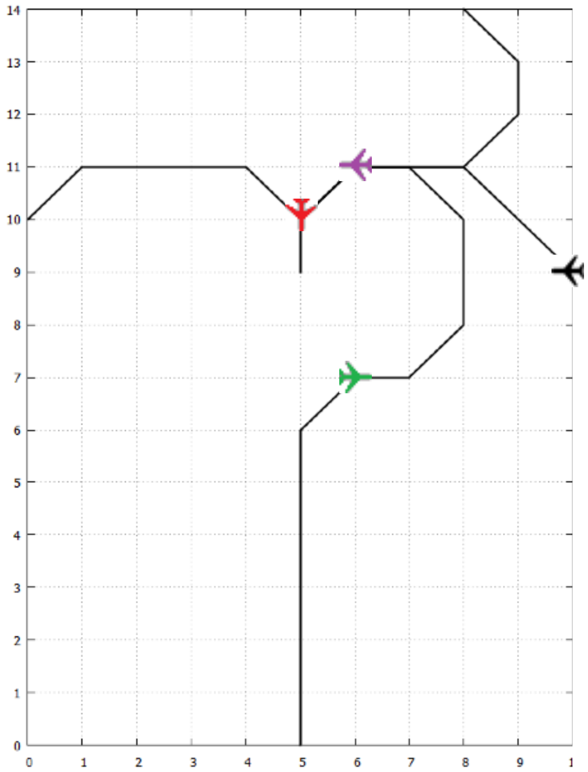
t = 15:13



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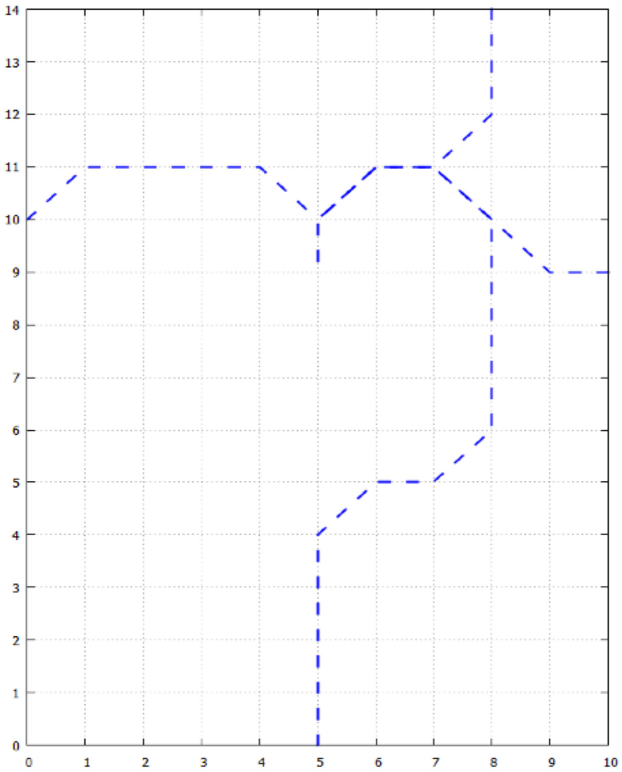

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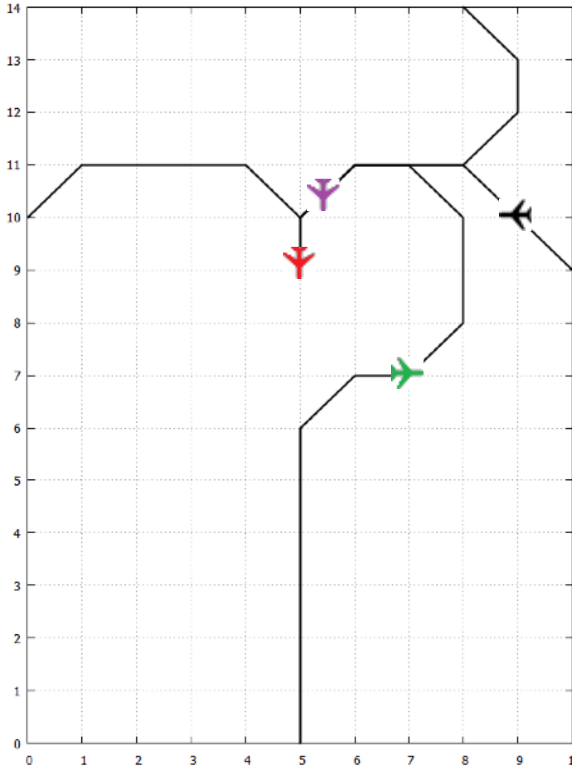

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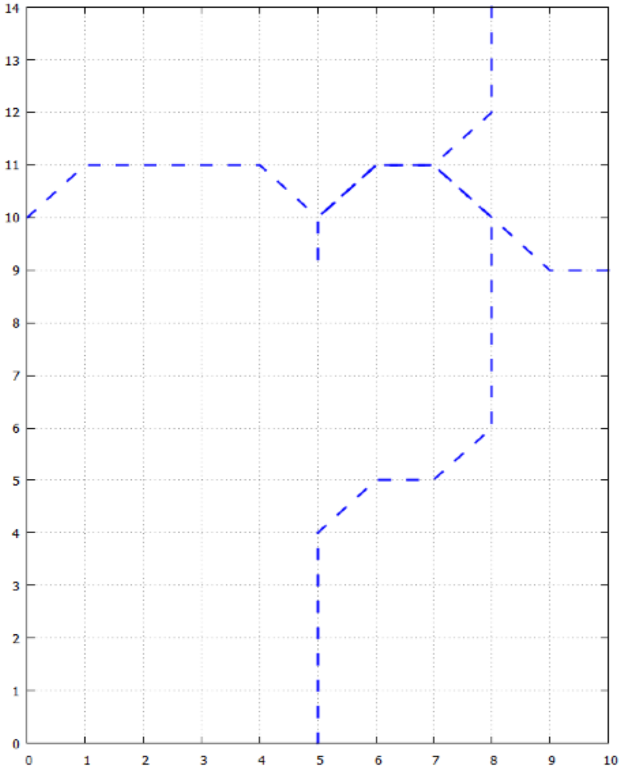

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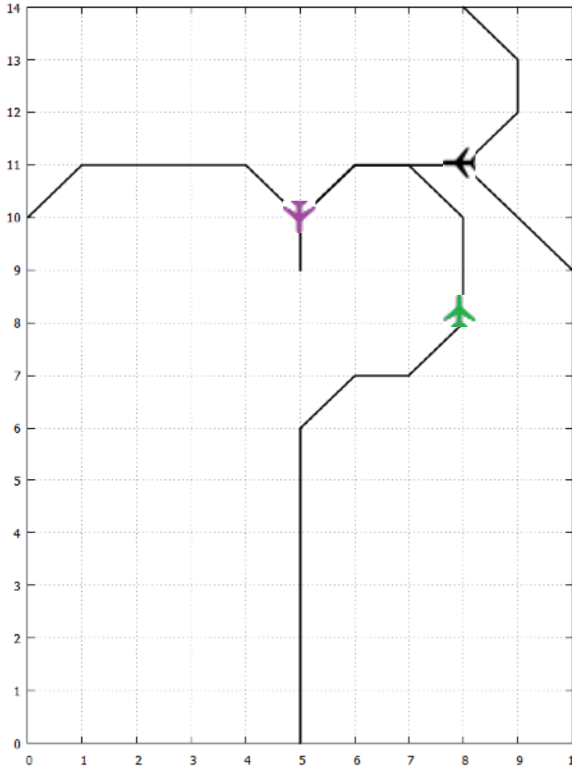
t = 15:15



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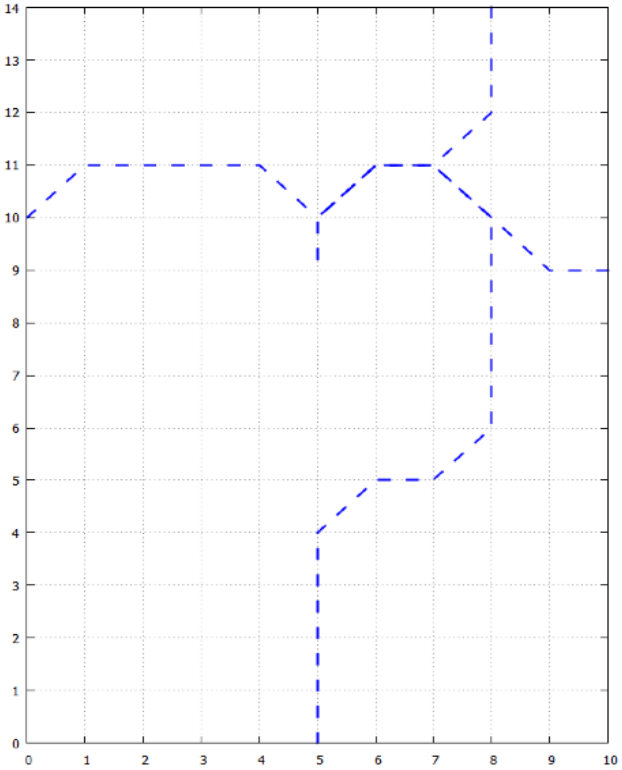

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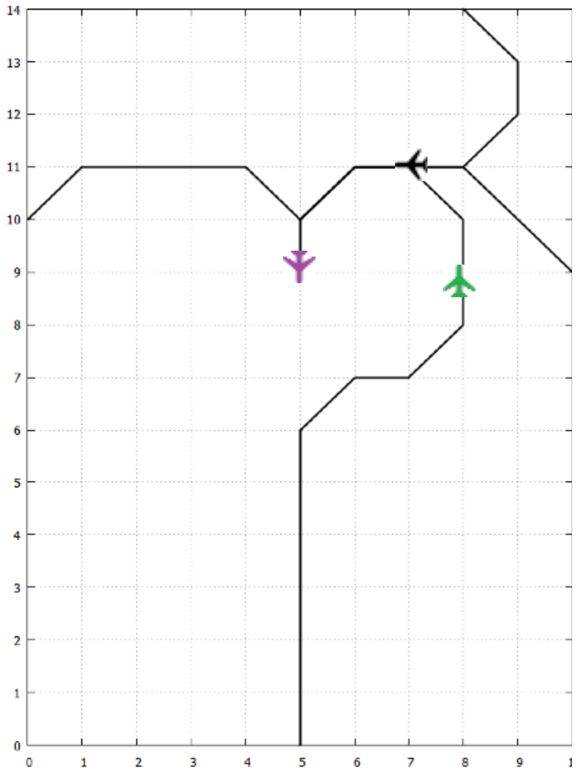

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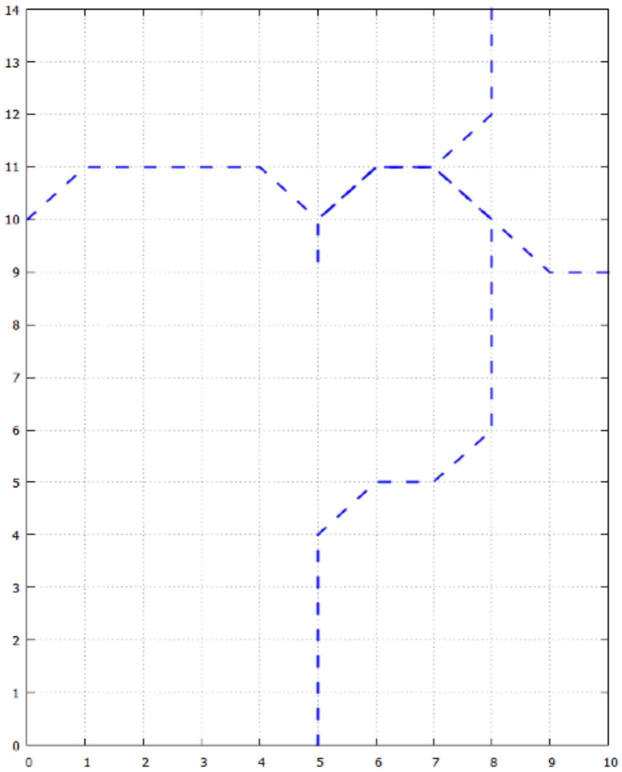

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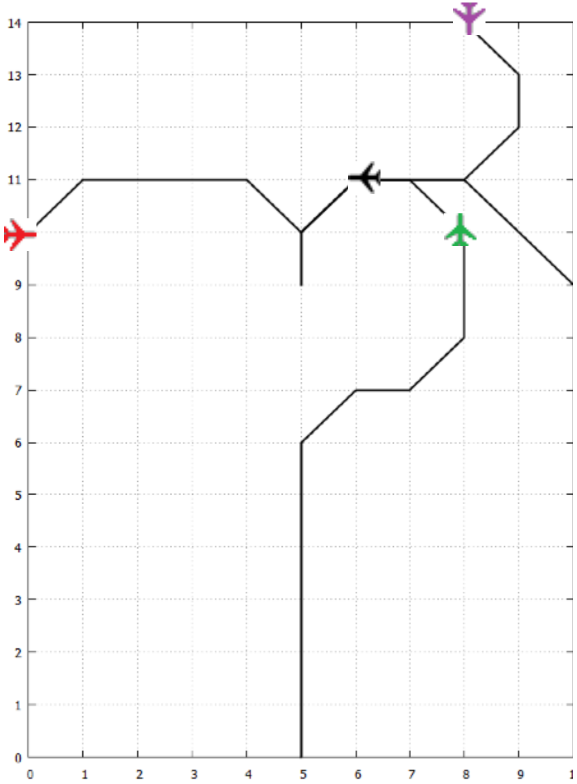
t = 15:17



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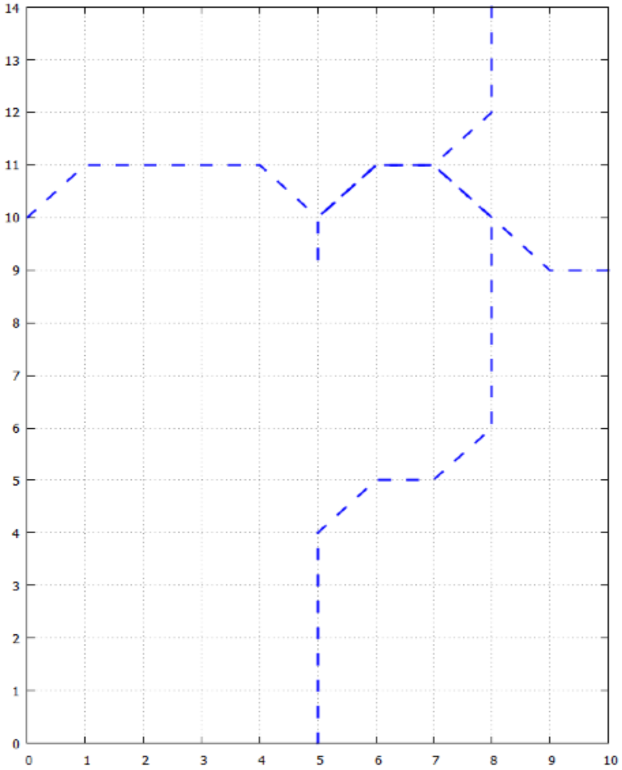

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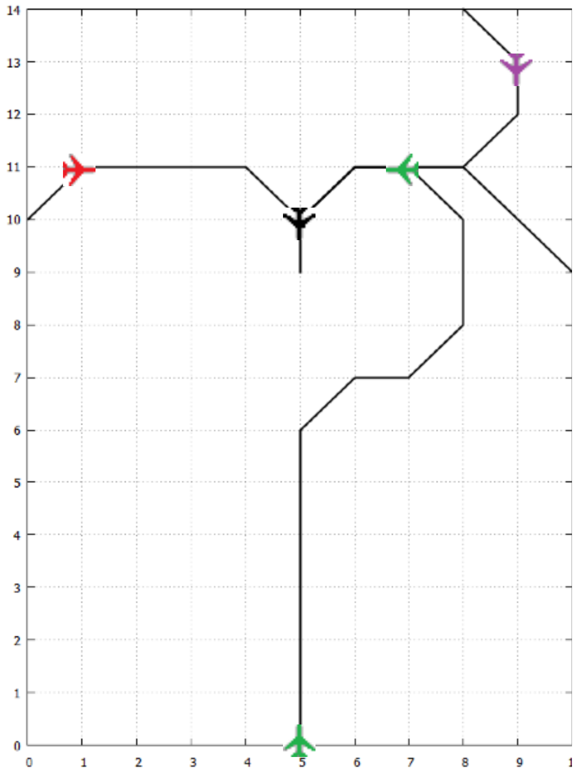

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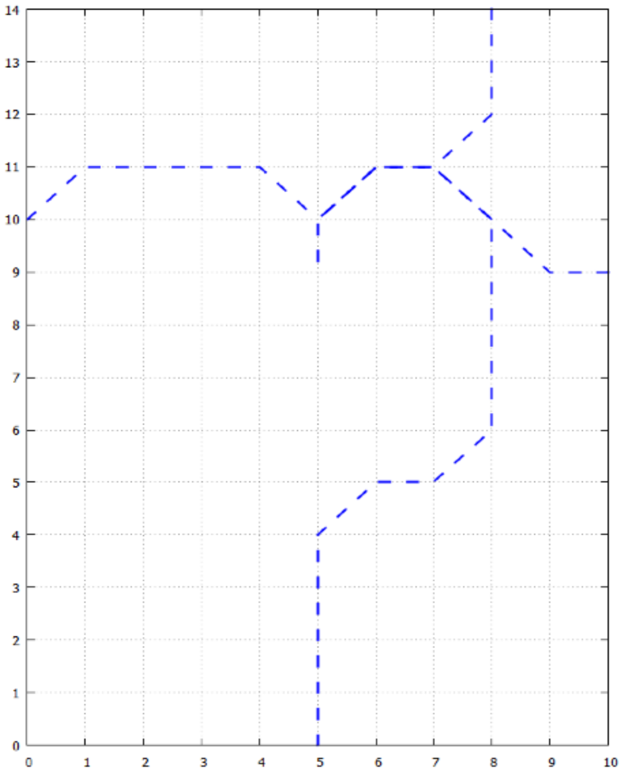

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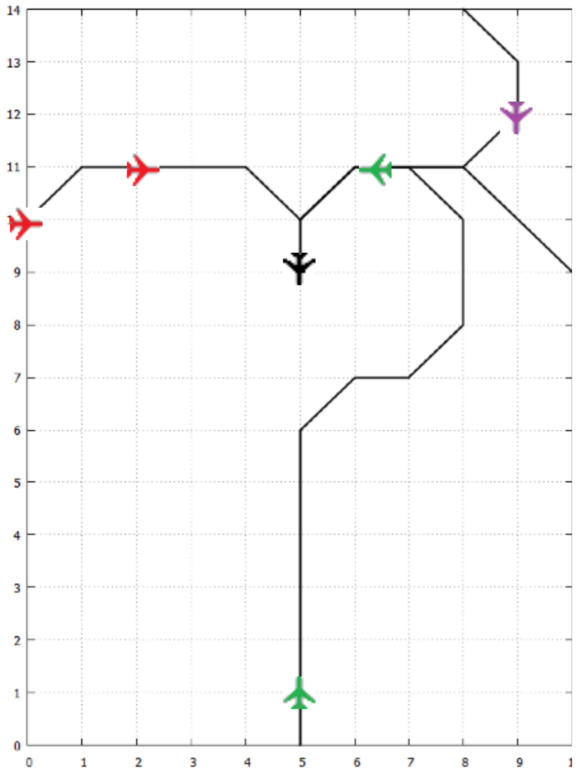

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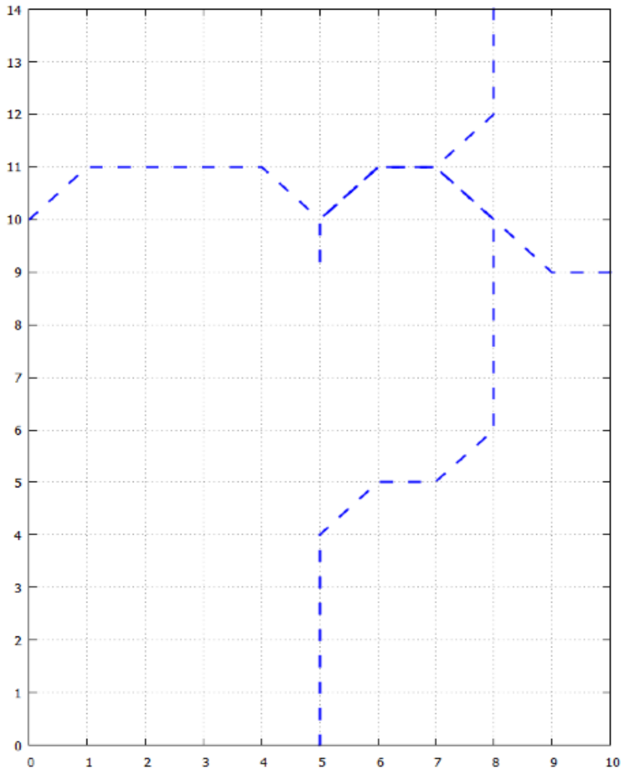

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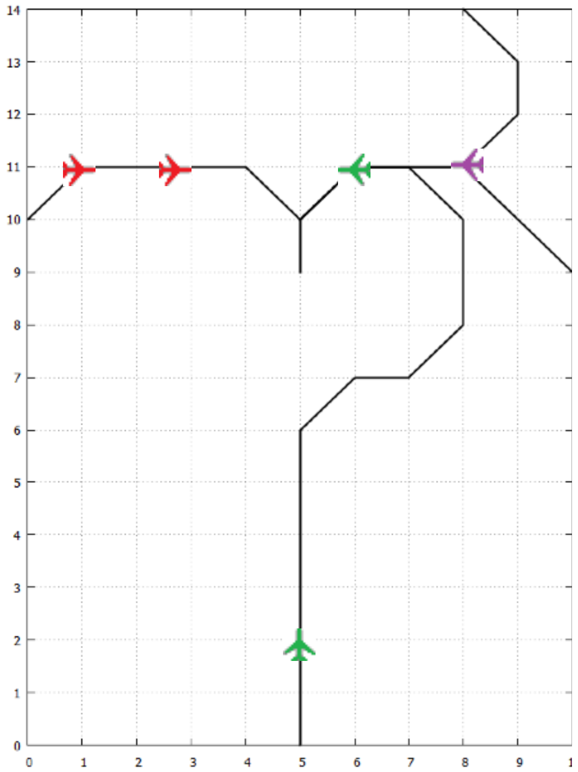
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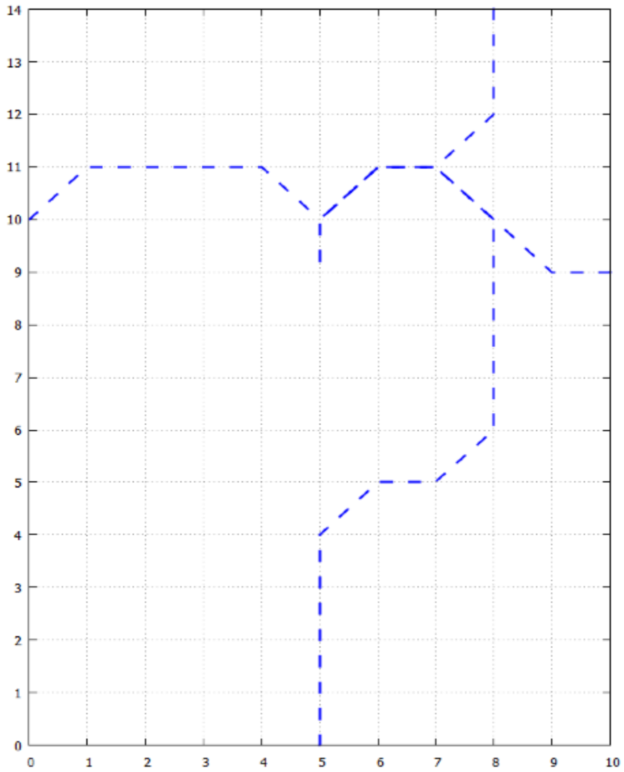
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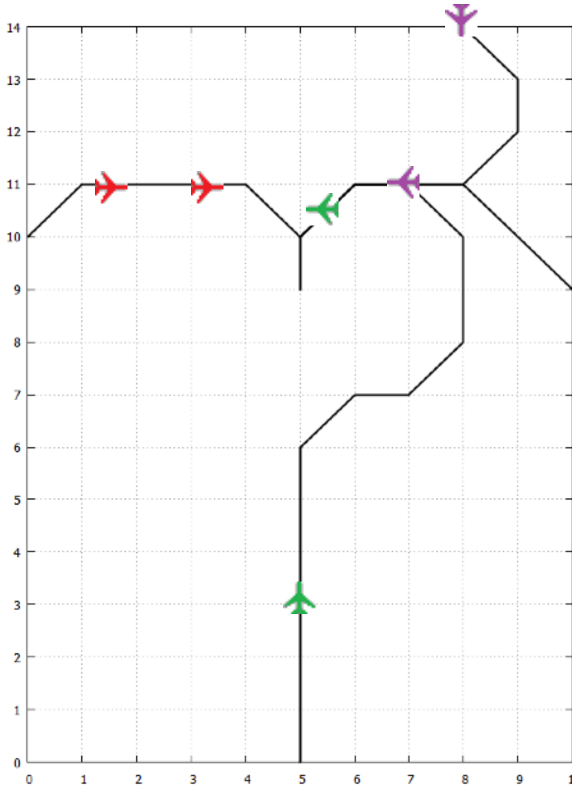

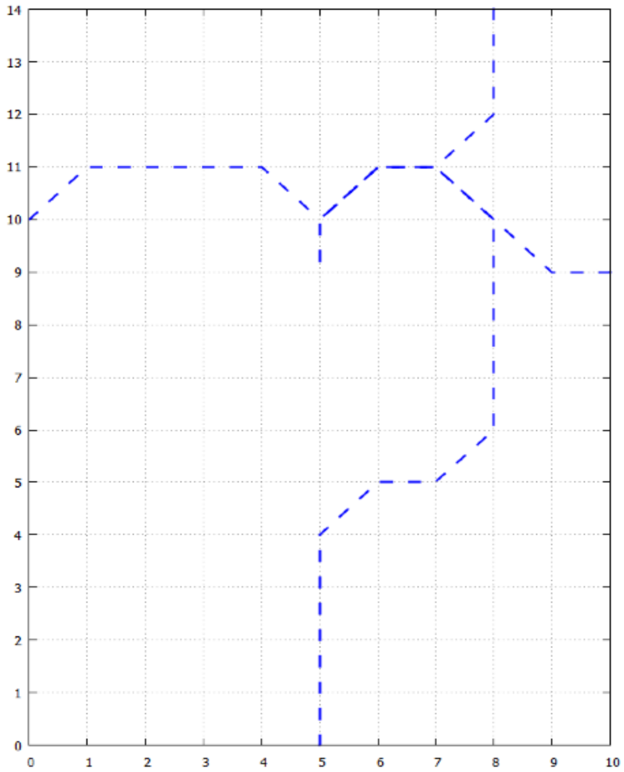

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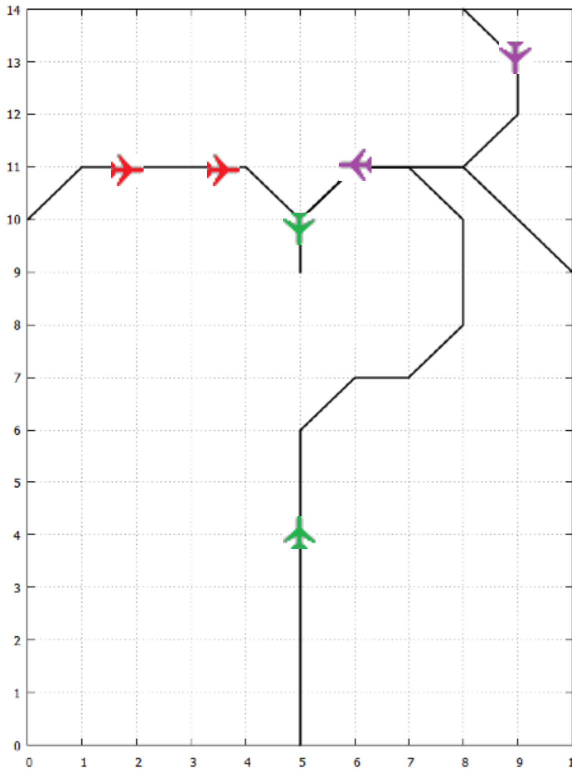

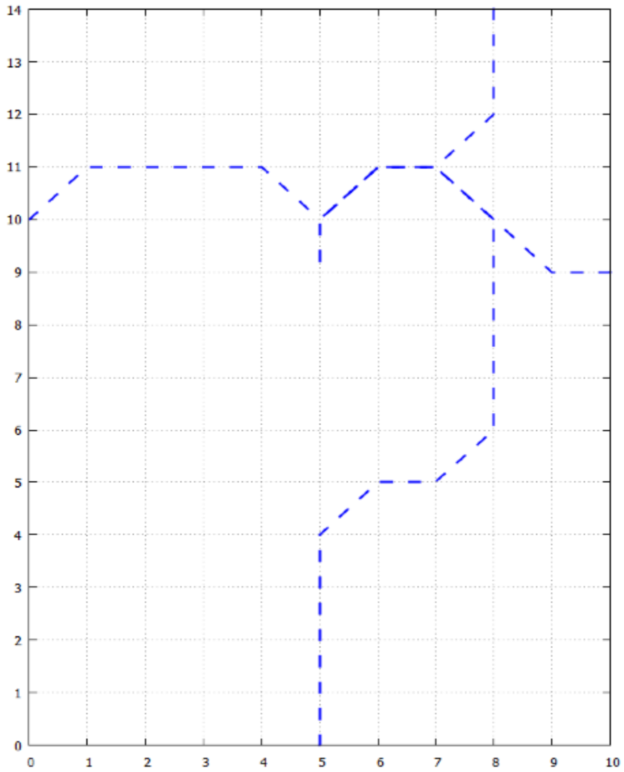

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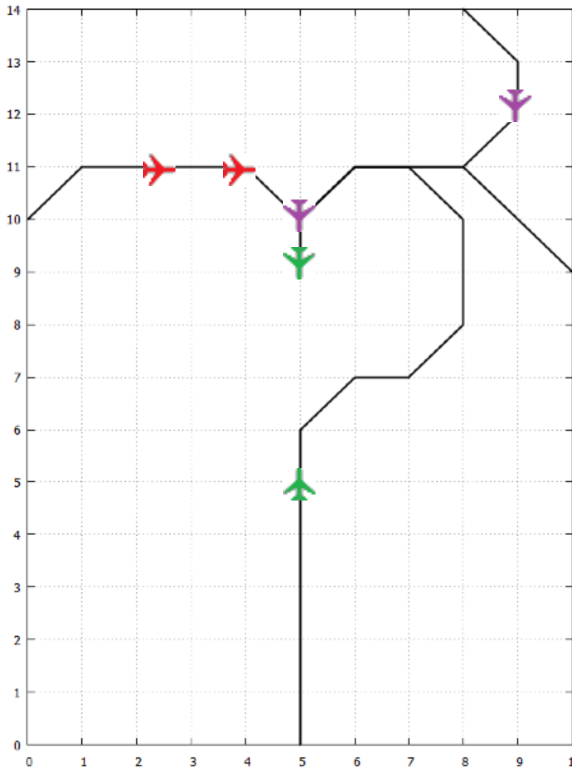

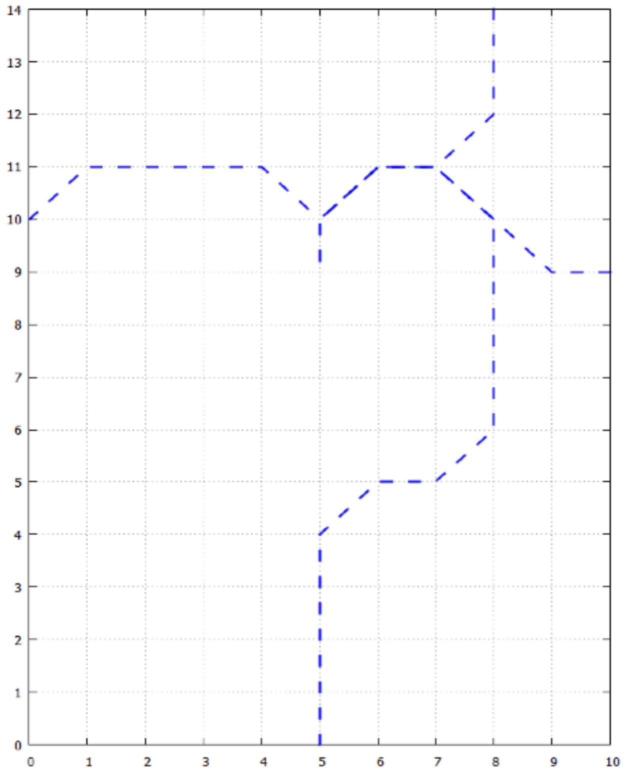

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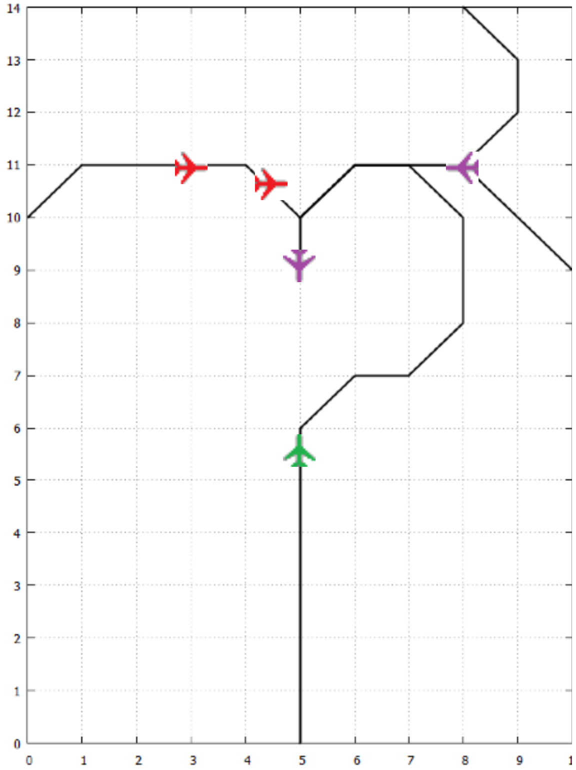
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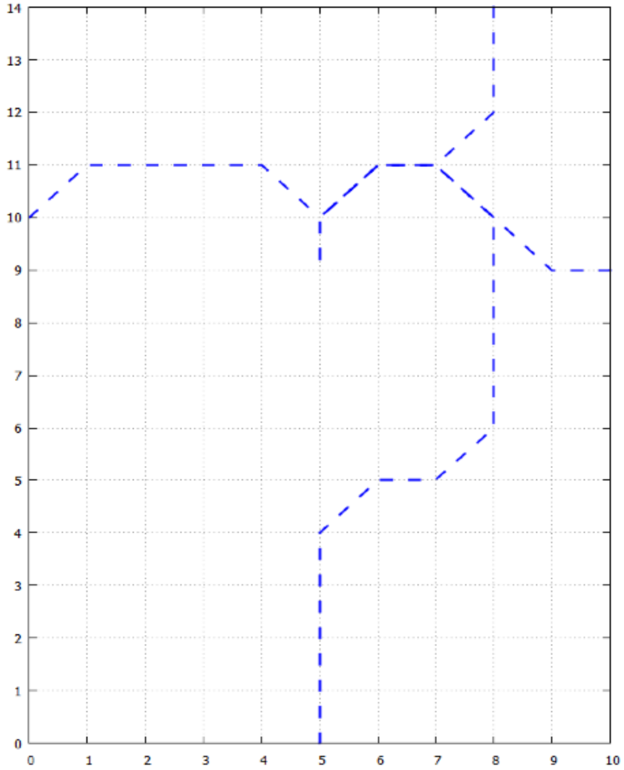
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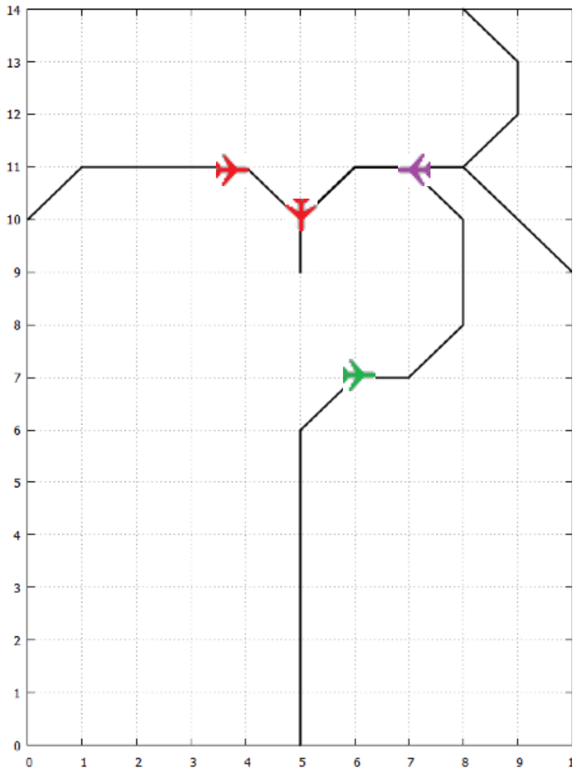

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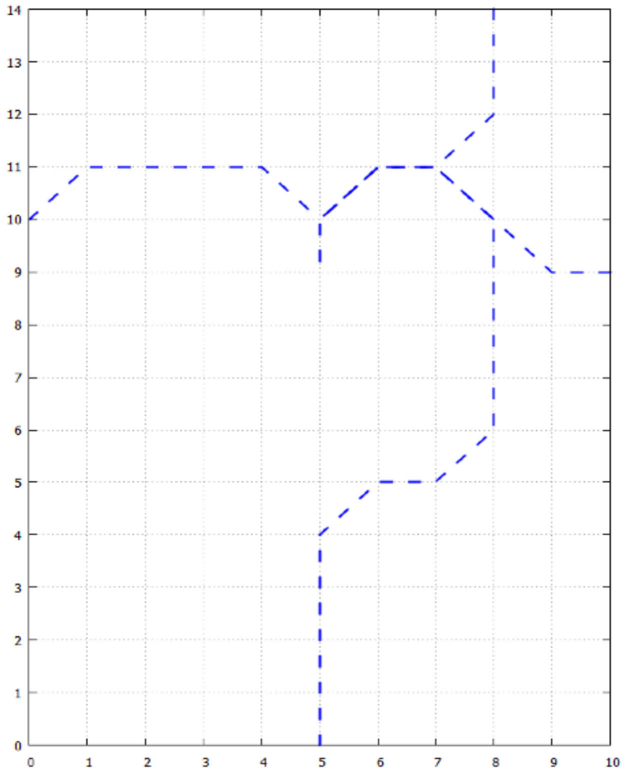

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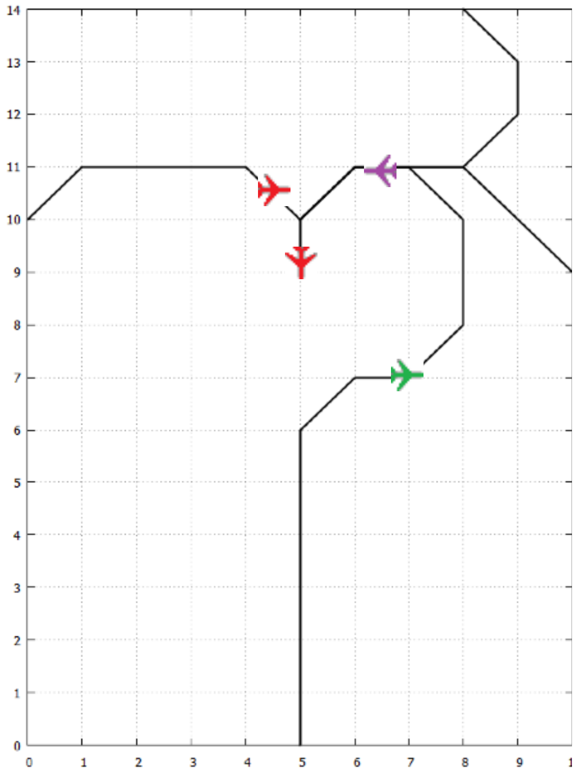

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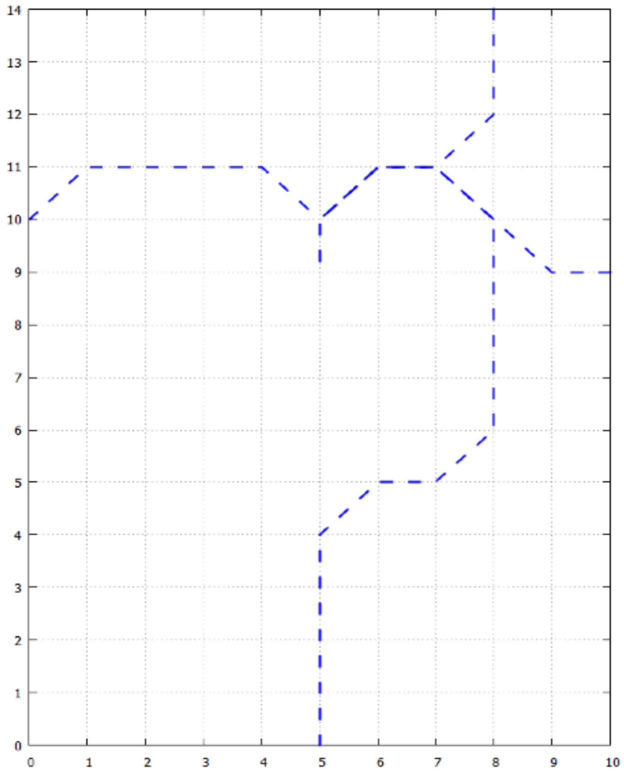

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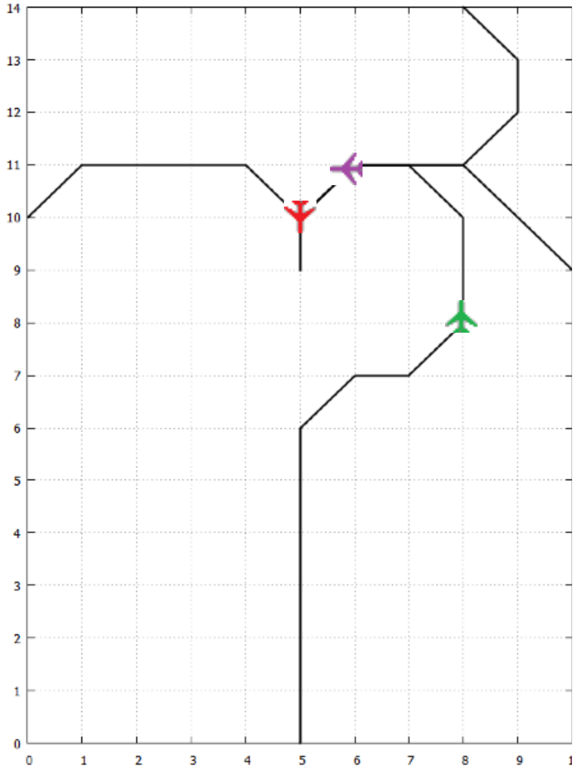
t = 15:27



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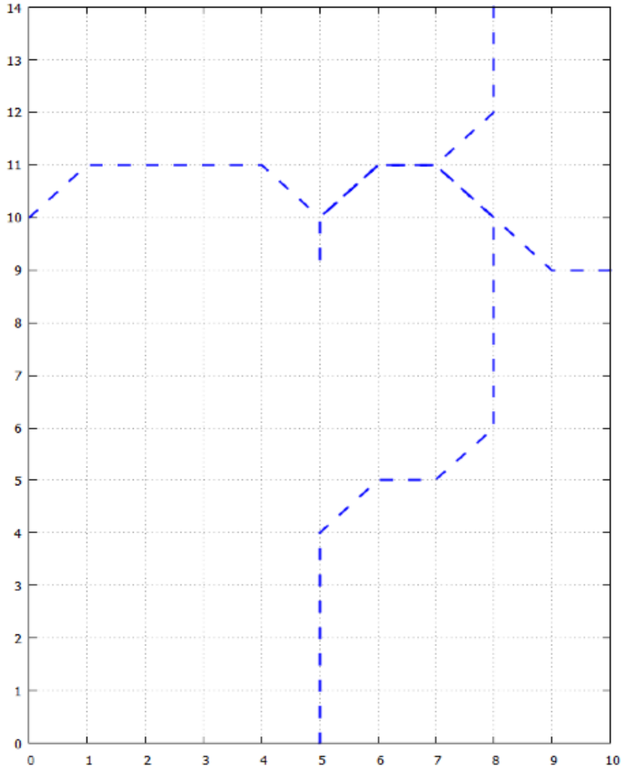

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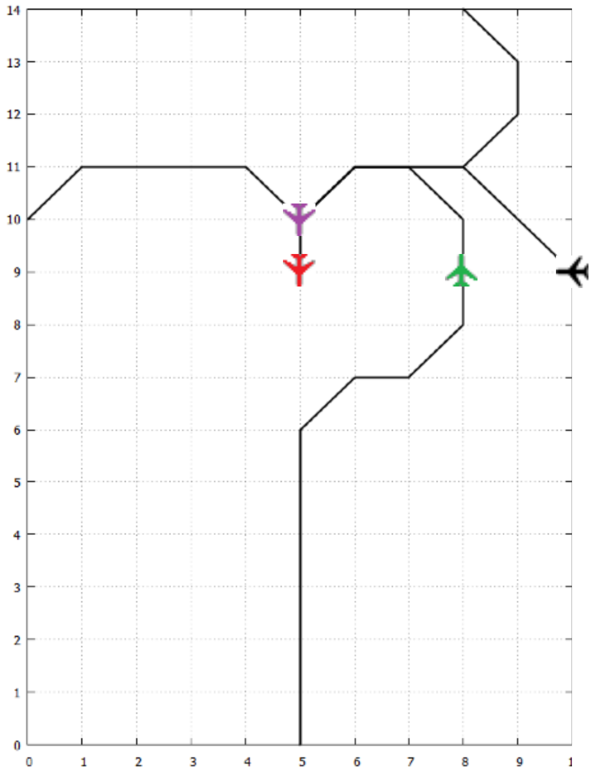
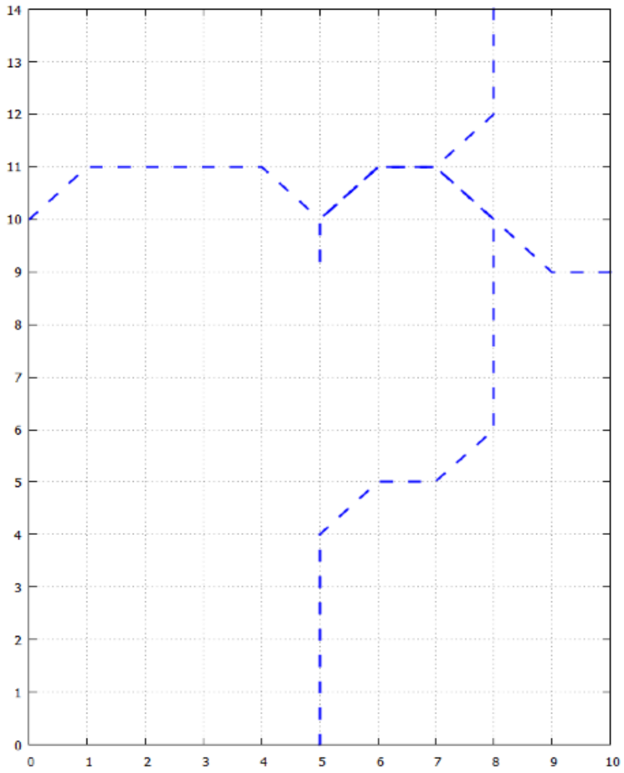
t = 15:28





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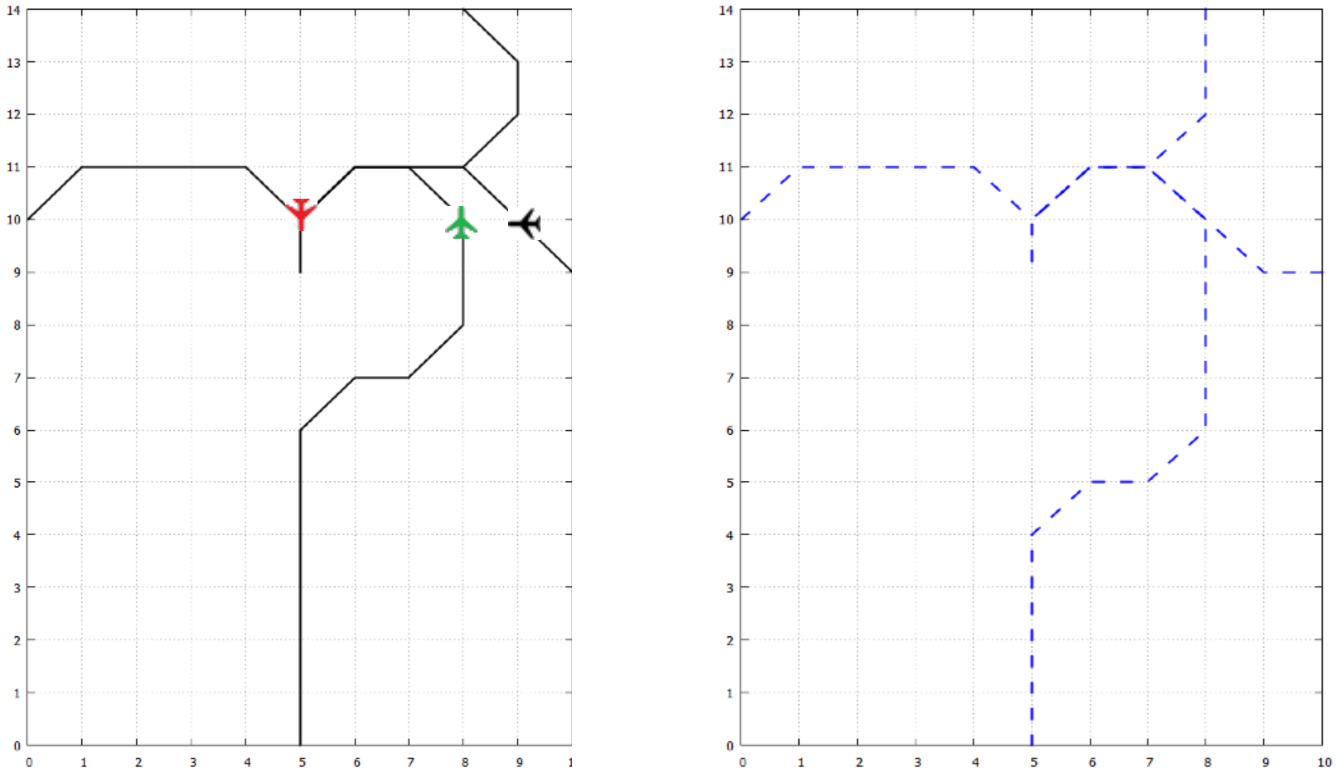

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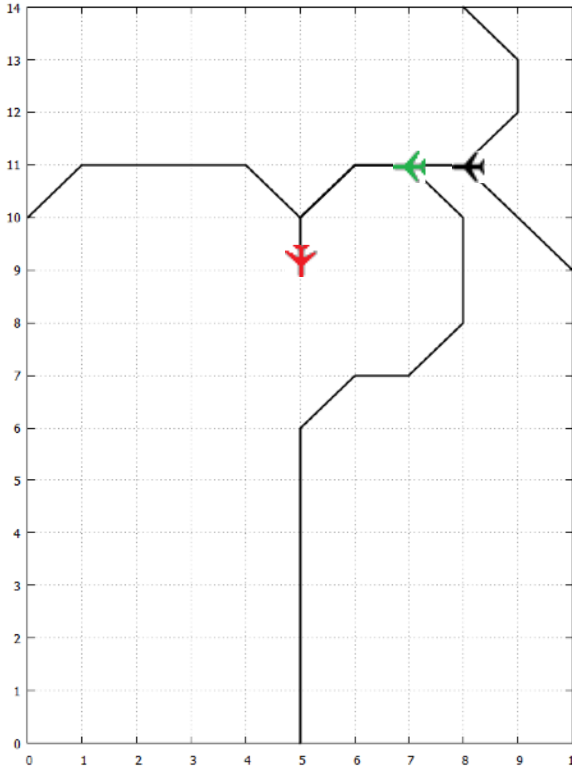
t = 15:30



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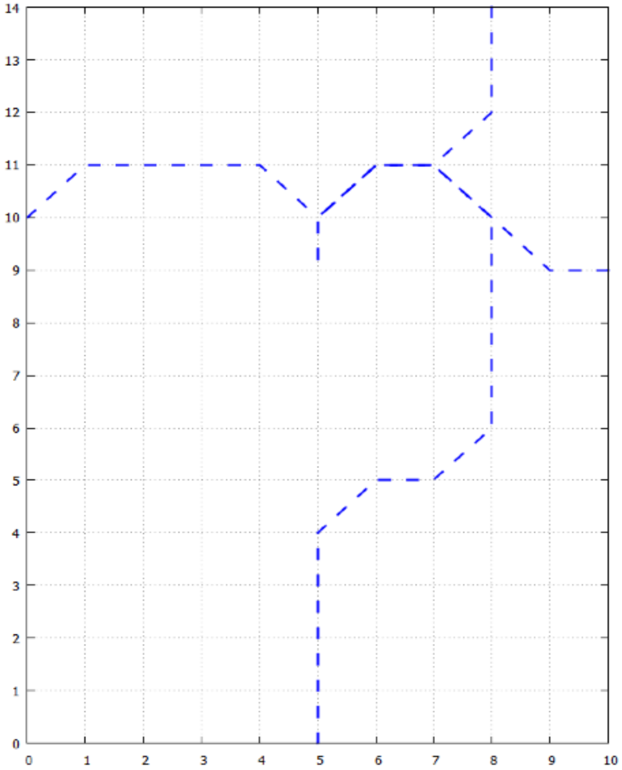

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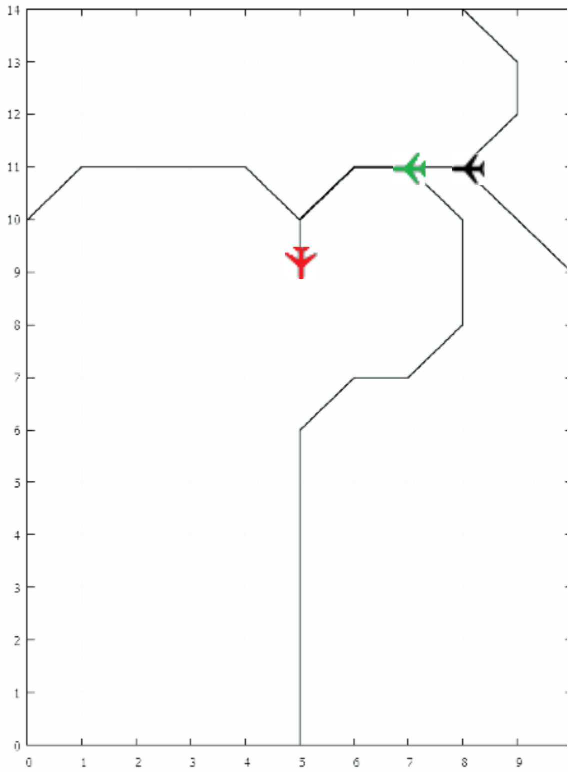

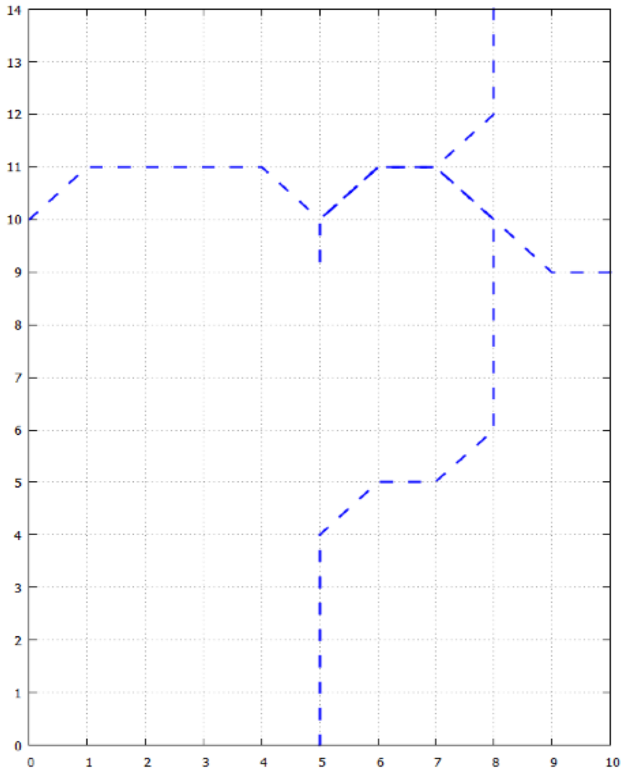

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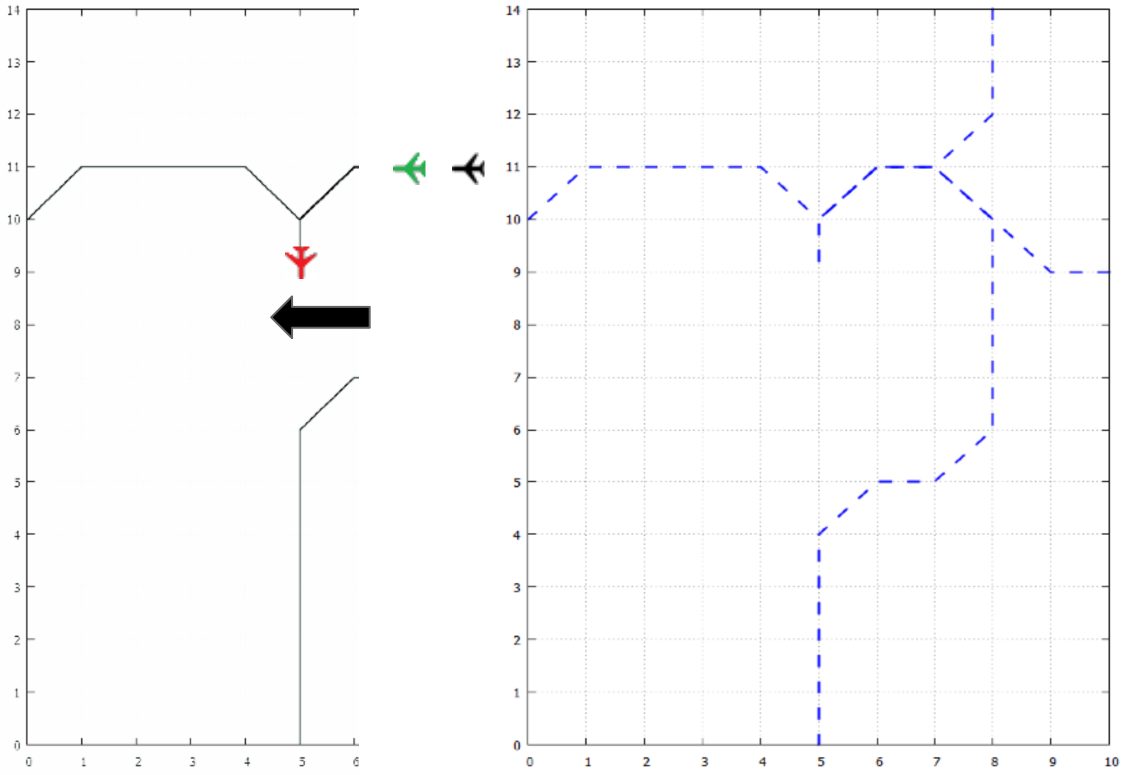

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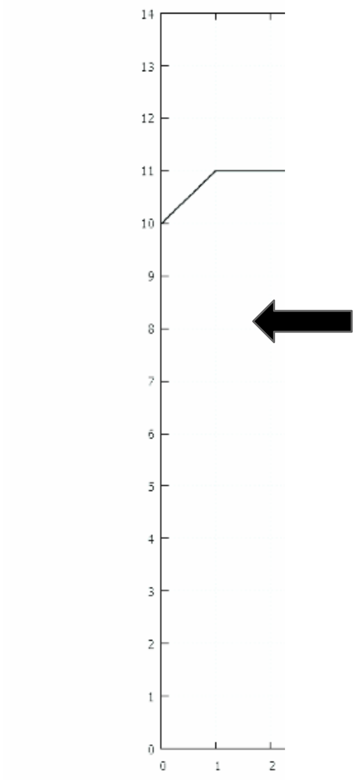

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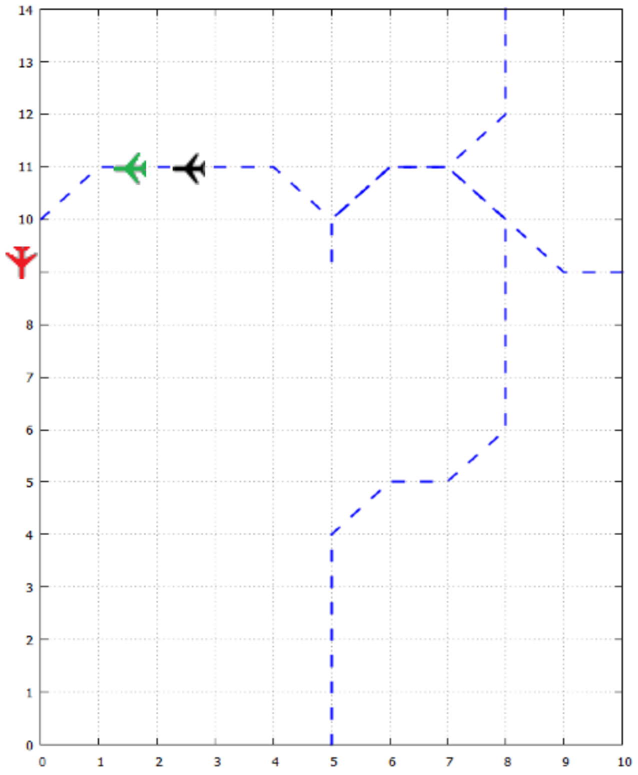

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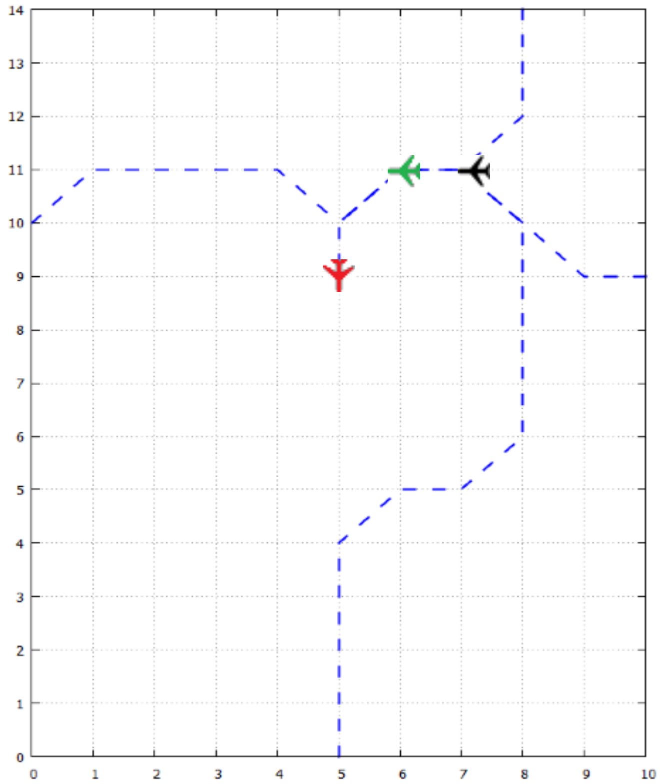

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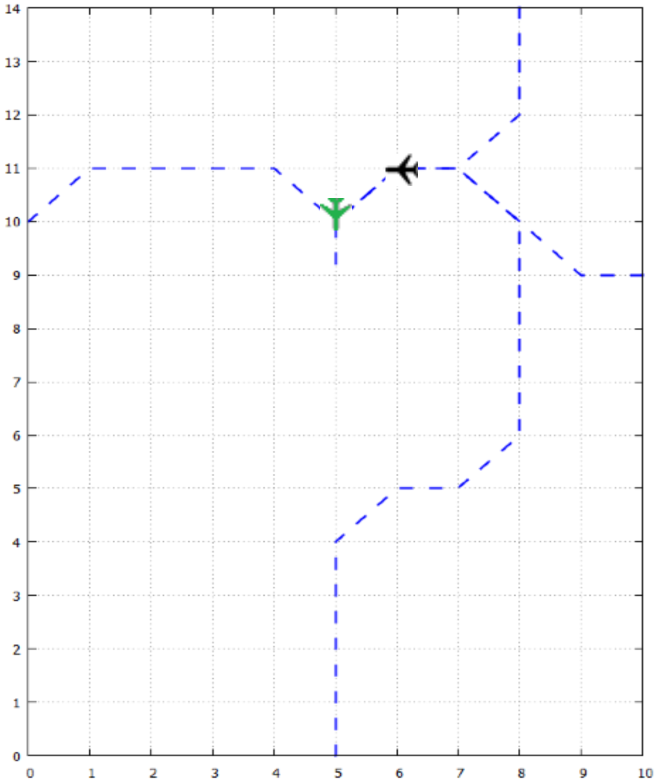

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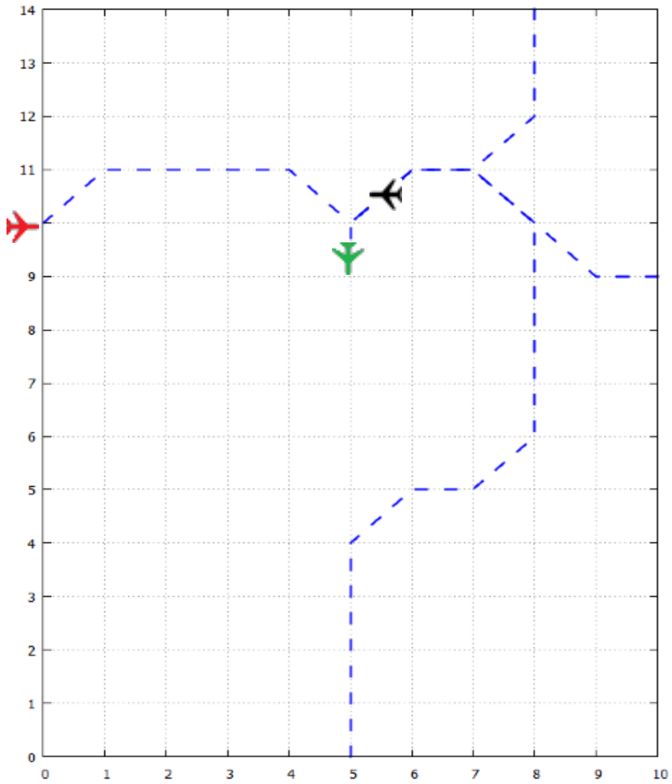


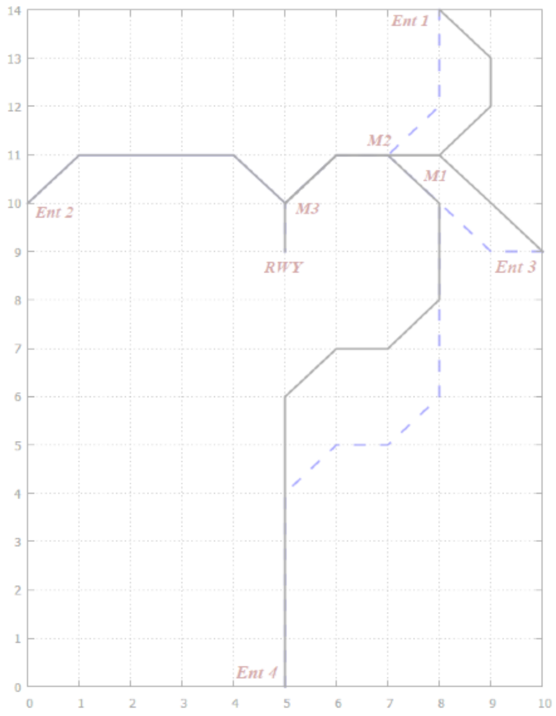
Conclusions and Future Work

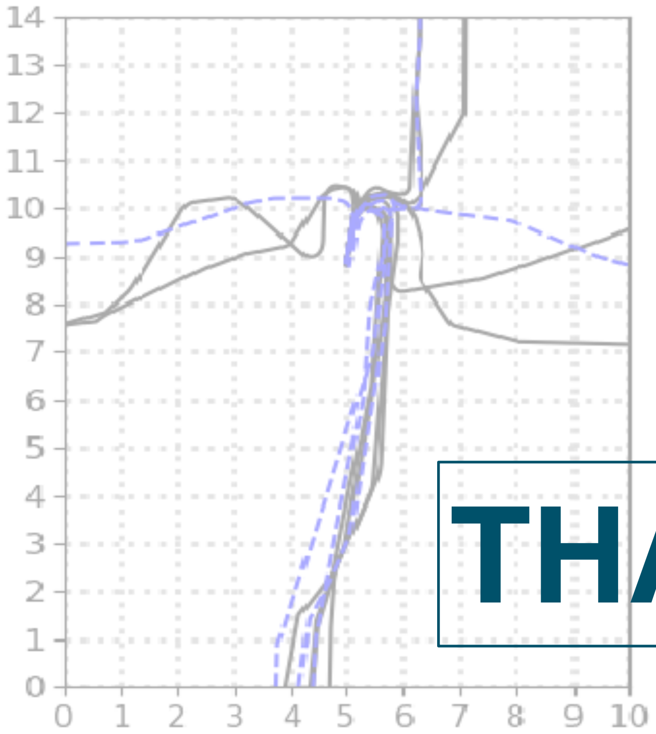
Conclusions

- Flexible optimization framework for dynamic route planning inside TMA
- Automated spatial and temporal 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 links, technologies) for air-ground synchronisation (EPP)





THANKS.