



Causal Decision Support Tools for Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)

Clustering and Interaction Causal Solver Models

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4: Causal analysis and models

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1: Introduction to STREAM

- Project Consortium & Networks
- Project contents
- STREAM in 2012

Project Consortium & Networks



Advanced Logistics Group (ALG)



Boeing Research & Technology Europe
(BR&TE)



Universitat Autònoma de Barcelona
(UAB)

A project under



- Small project launched on 16th March 2011

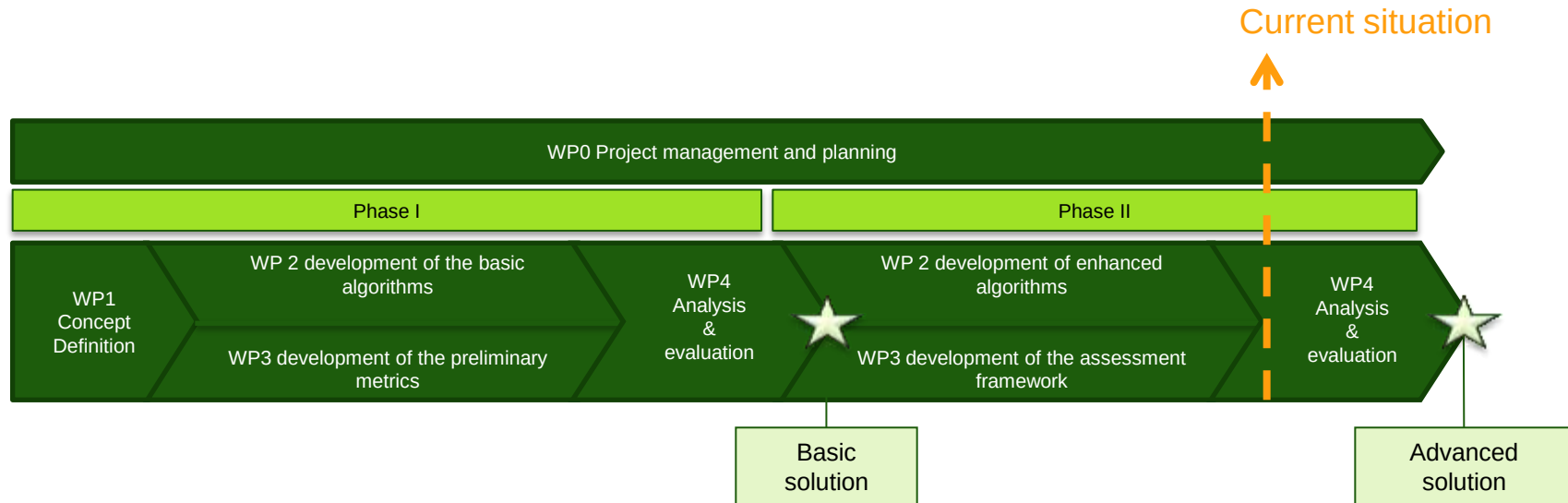
Project Contents: Objectives

High level objective

- To perform **conflict detection at pre-departure phase**, thus allowing the integration of appropriate conflict resolution manoeuvres at a strategic level

Derived intermediate objectives

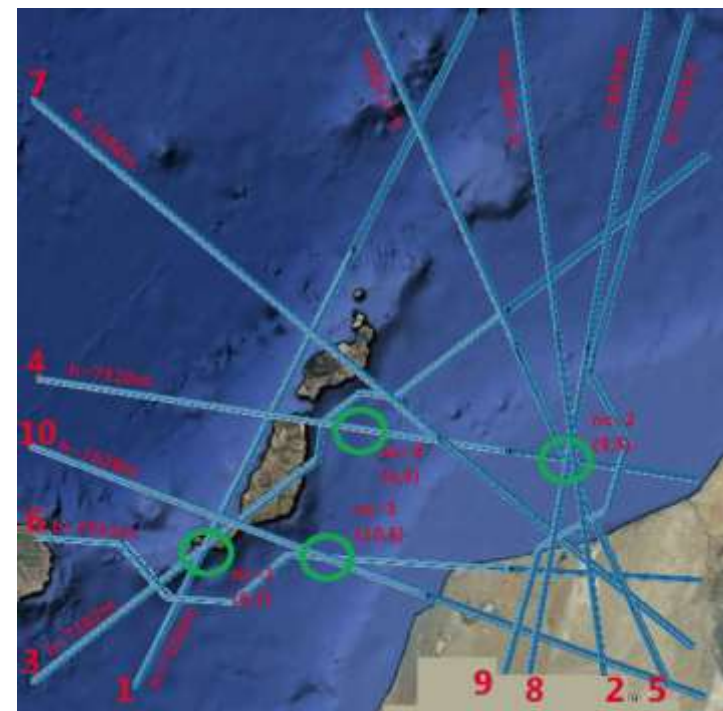
1. To develop **time-efficient algorithms** for the strategic detection and resolution of traffic conflicts:
 - capable of adopting a combination of **different resolution strategies**;
 - that **are computational efficient with respect to the number of trajectories** considered;
 - and manage a **high quantity of information describing 4D trajectories** and to ensure that resolutions maintain traffic complexity under control — at local (ACC), regional (FAB) and even global (ECAC) levels
2. To explore the **requirements on the reliability and robustness of traffic predictions** in order to allow the new strategic trajectory de-confliction algorithm that would efficiently modify SBTs
3. To define **metrics for assessing** the proposed algorithms performance towards an increased automation of the ATM system
4. To **perform simulations in a common environment** in order to assess the proposed algorithms and metrics



- STREAM is in its final phase: only 4 months to the end of the project
- An Advanced Solution for algorithms and metrics has been delivered (Phase 2)
- Phase 2 CD&R algorithms developments are in a mature status, integration and calibration of modules is performed
- From the lessons learnt in Phase 1, a new set of metrics has been defined for the execution of the Final Solution Simulations and Performance Assessment
- A direct routing scenario has been defined and tests are currently being undertaken

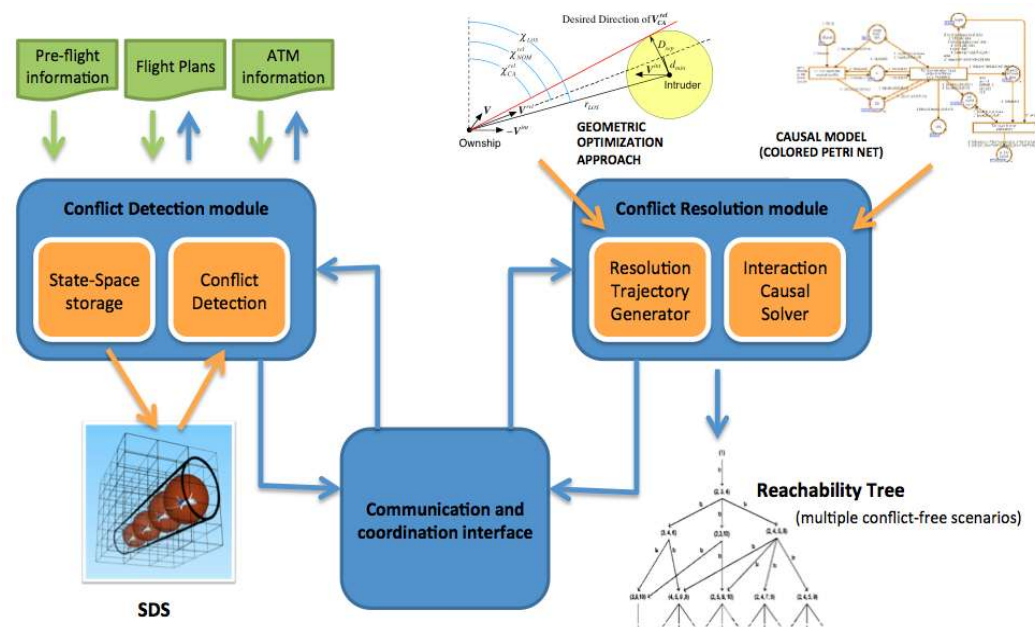
Deliverable D4.1 – Preliminary Performance Assessment (2012)

- Performance Evaluation of the initial CD&R Algorithms proposed by STREAM during 2011 (D2.1)
- Development of a Simulation Framework fed by the methodology and metrics proposed in 2011 (D3.1)
- Validation of the framework and performance evaluation leading to valuable inputs for the Algorithms development in Phase 2
- Use of a synthetic complex traffic scenario over Gran Canaria to test the CD&R capabilities and obtain meaningful results through the computed metrics
- Use of a pan-European scenario to stress the algorithms and explore further requirements for the Advanced Solution (new resolution strategies, geodesic projections, etc.)



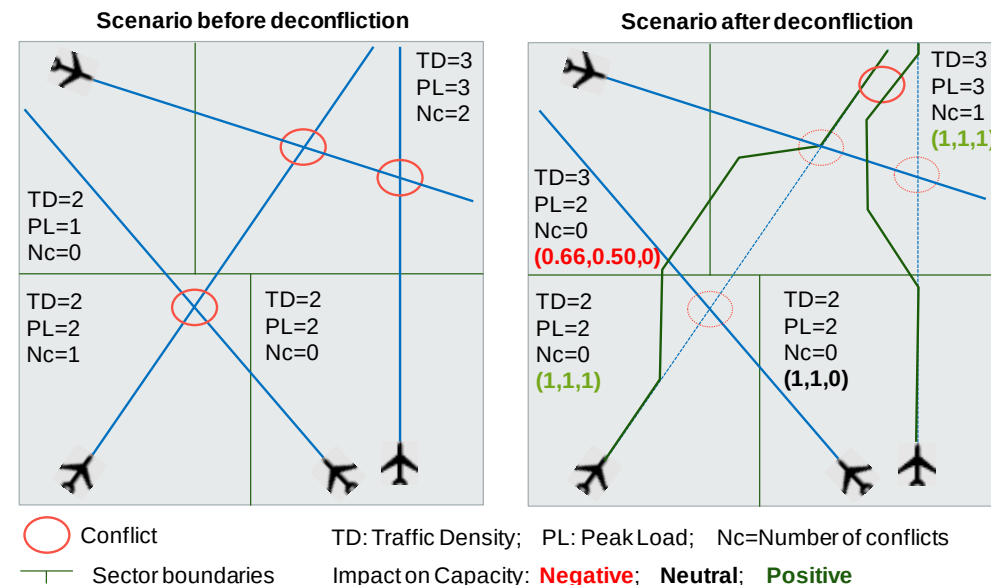
Deliverable D2.2 – Development of Advanced Algorithms (2012)

- The limitations of the initial solution (presented in 2011) for tackling European scale scenarios are addressed in this Final Solution.
- Scalability redesign of the SDS considering the curvature of the Earth and need to migrate to a 64-bit platform
- New sub-module to obtain multiple resolution efficient trajectories for each conflict through geometrical closed-form analytical formulae
- Another sub-module based on CPN models to analyse the network effects of those resolutions with a global optimization scope
- New models to tackle the uncertainty and hints about how these models could be implemented are shown
- A proof-of-concept application connecting STREAM algorithms with SWIM communication platform is also presented



Deliverable D3.2 – Final Metrics and Methodology (2012)

- Description of the framework proposed for the final evaluation of the CD&R algorithms to be presented in D4.2.
- In the definition of final set of metrics for the performance assessment, a new concept for the capacity metric is introduced: “Impact on capacity”. This metric does not quantify the capacity improvements related to specific controller workload, but it identifies positive/negative impacts in capacity for the airspace divided in arbitrary defined sectors.

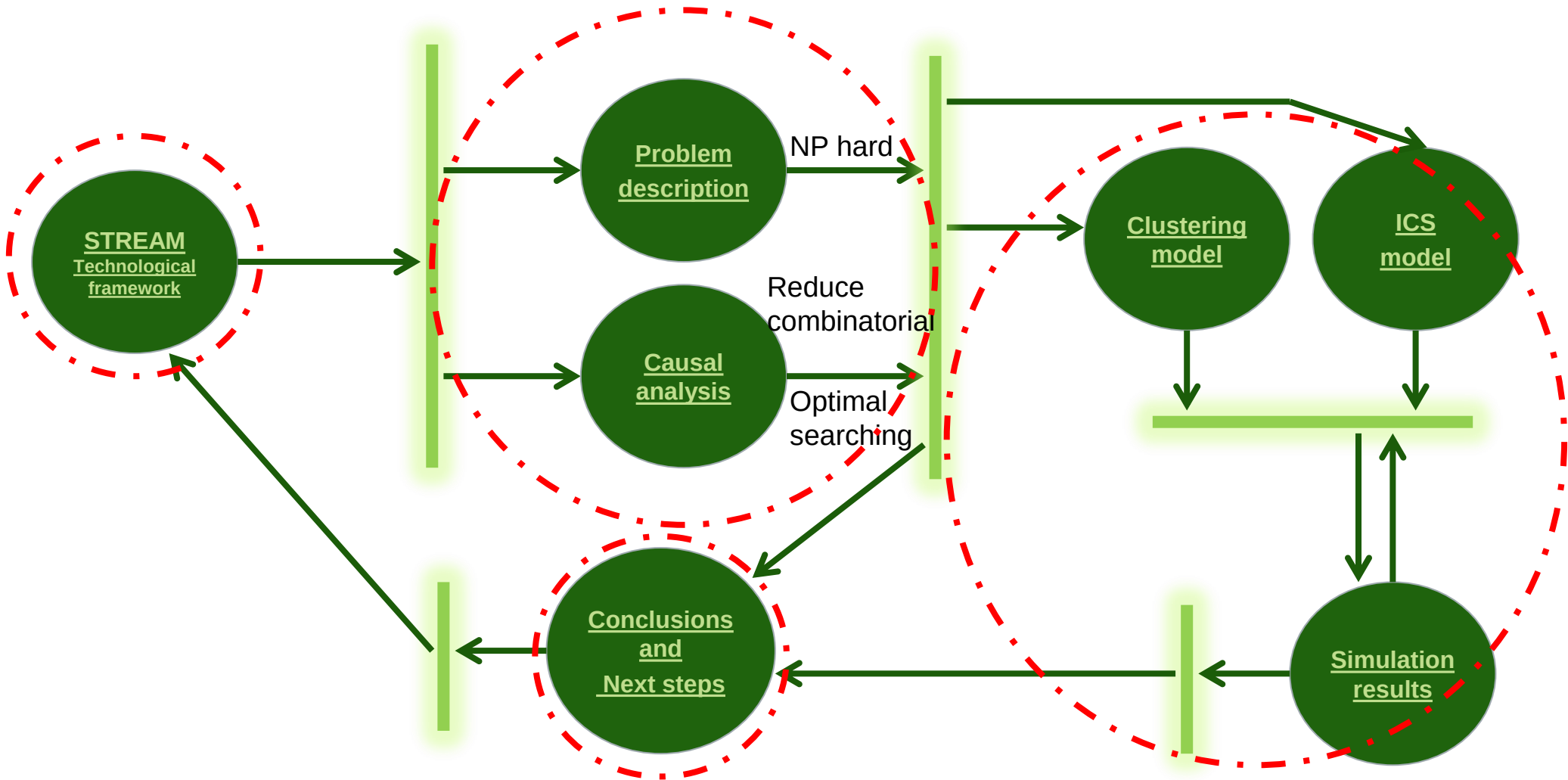


- The Fairness and equity metrics are alternatively defined to be aggregated in an Airspace User basis instead of a flight basis in order to better monitor and assess the performance of CD&R algorithms affecting all stakeholders.
- The methodology proposed for a fast-time air traffic simulation platform includes the generation of scenarios, generation of a baseline for comparison and computation of metrics for assessment; and it is adapted to encompass the “offline” study of the impact of Trajectory Prediction uncertainties.

2: Introduction to the paper

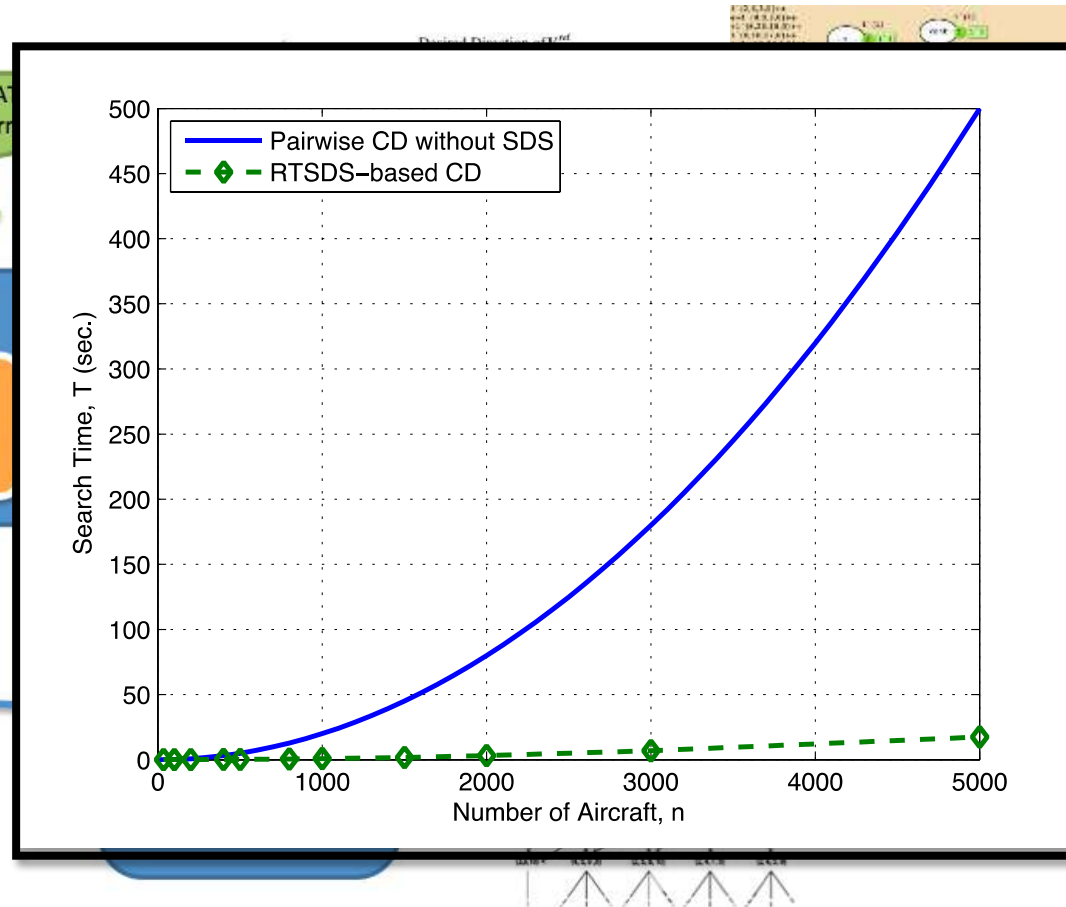
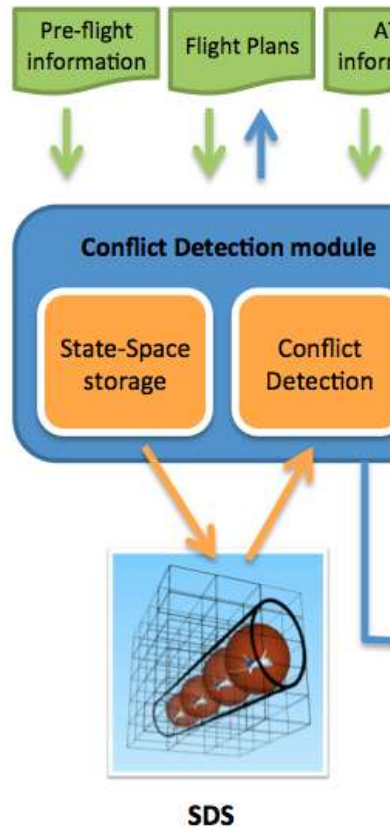
- Paper Outline
- Solution Framework

Paper Outline



STREAM

Solution framework



STREAM

Solution process

FLIGHT PLANS
(ORIGINAL TRAJECTORIES)



SDS



CONFLICT
DETECTION
(CD)

CONFLICTS



TRAJECTORIES
GENERATION
(TG)



ALTERNATIVE TRAJECTORIES

STATE SPACE GENERATION

AIRCRAFT	TRIALS TRAJECTORY										
1	1 _i	760 _i	520 _i	231 _i	452 _i	964 _i	741 _i	392 _i	175 _i	712 _i	672 _i
2	2 _i	784 _i	027 _i	146 _i							
3	3 _i	2045 _i									
4	4 _i	562 _i	543 _i	876 _i	436 _i	644 _i					
5	5 _i	324 _i	168 _i								
⋮	⋮	658	588	108	649	455	876	855	244	333	
⋮	⋮	765	257	848	478						
⋮	⋮	536									
⋮	⋮	651	342								
⋮	⋮	066	780	454	852	923					
⋮	⋮	246									
⋮	⋮	538	099	654							
⋮	⋮	976	576	374	456	984	194				
⋮	⋮	123	830	012	681	354	951	787			
N-1	N-1 _{o,i}	786 _{o,i}	511 _{o,i}								
N	N _o	866 _o	555 _o	786 _o	487 _o	001 _o					

CONFLICTS				
nc	idt1	idt2	tw_ini	tw_end
1	3	6	410	509
2	19	18	470	490
3	9	5	690	800
...	...	...	...	...
54	240	2	1100	1110
...	...	...	...	...
60	3432	7	1500	1590
...	...	...	...	...

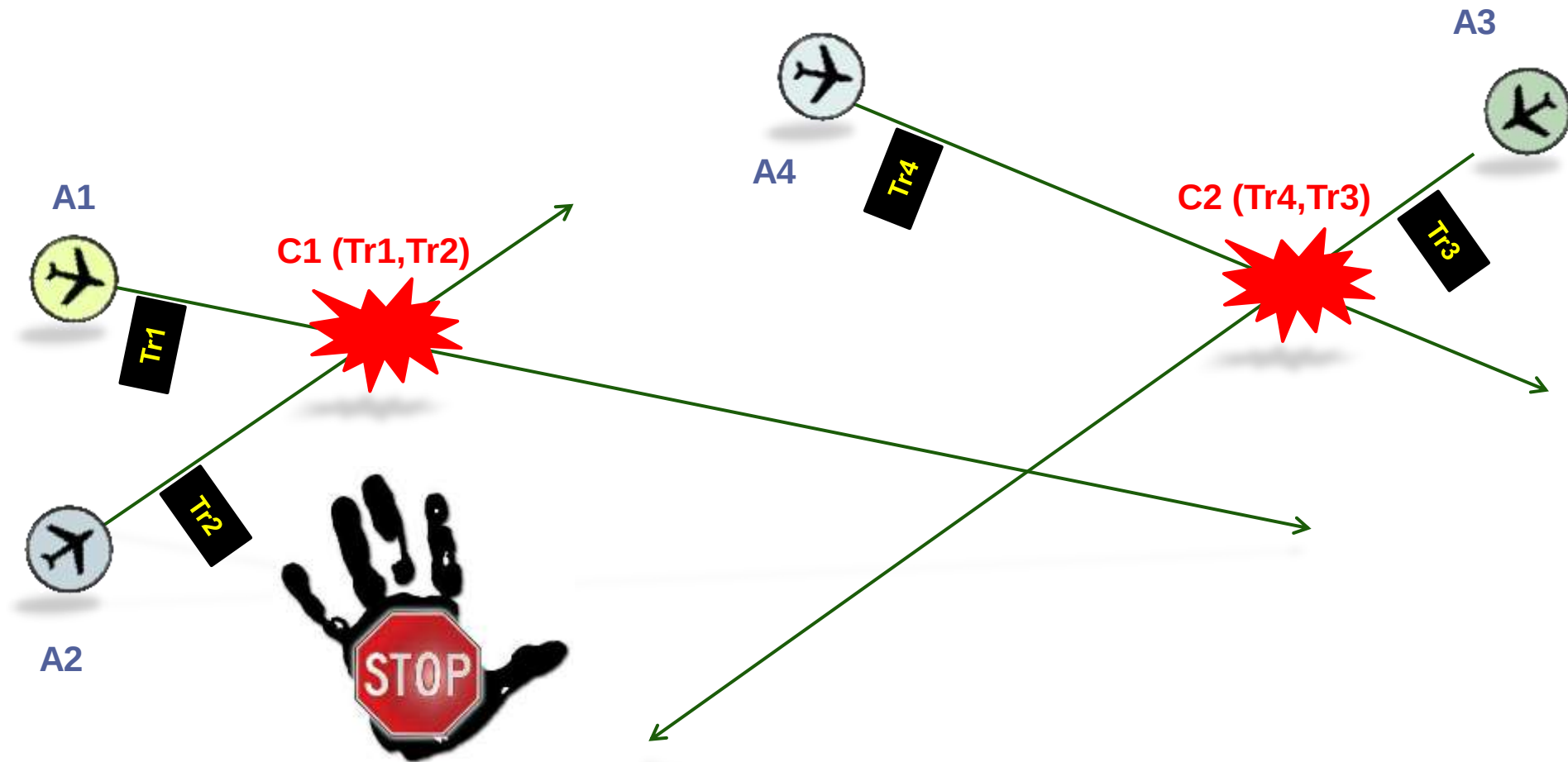
INTERACTION
CAUSAL SOLVER
(ICS)



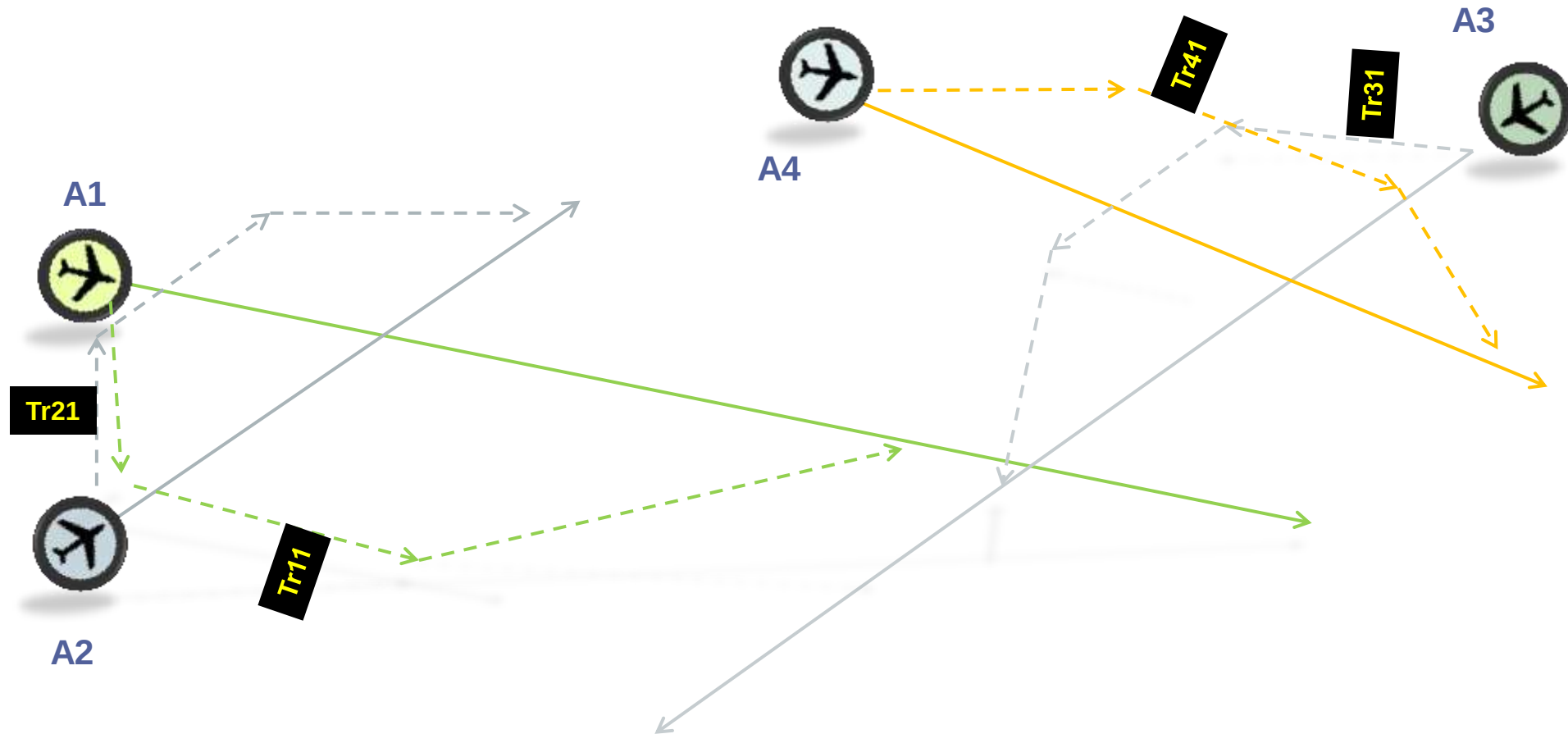
GEOMETRIC
OPTIMIZATION
APPROACH

3: Problem description

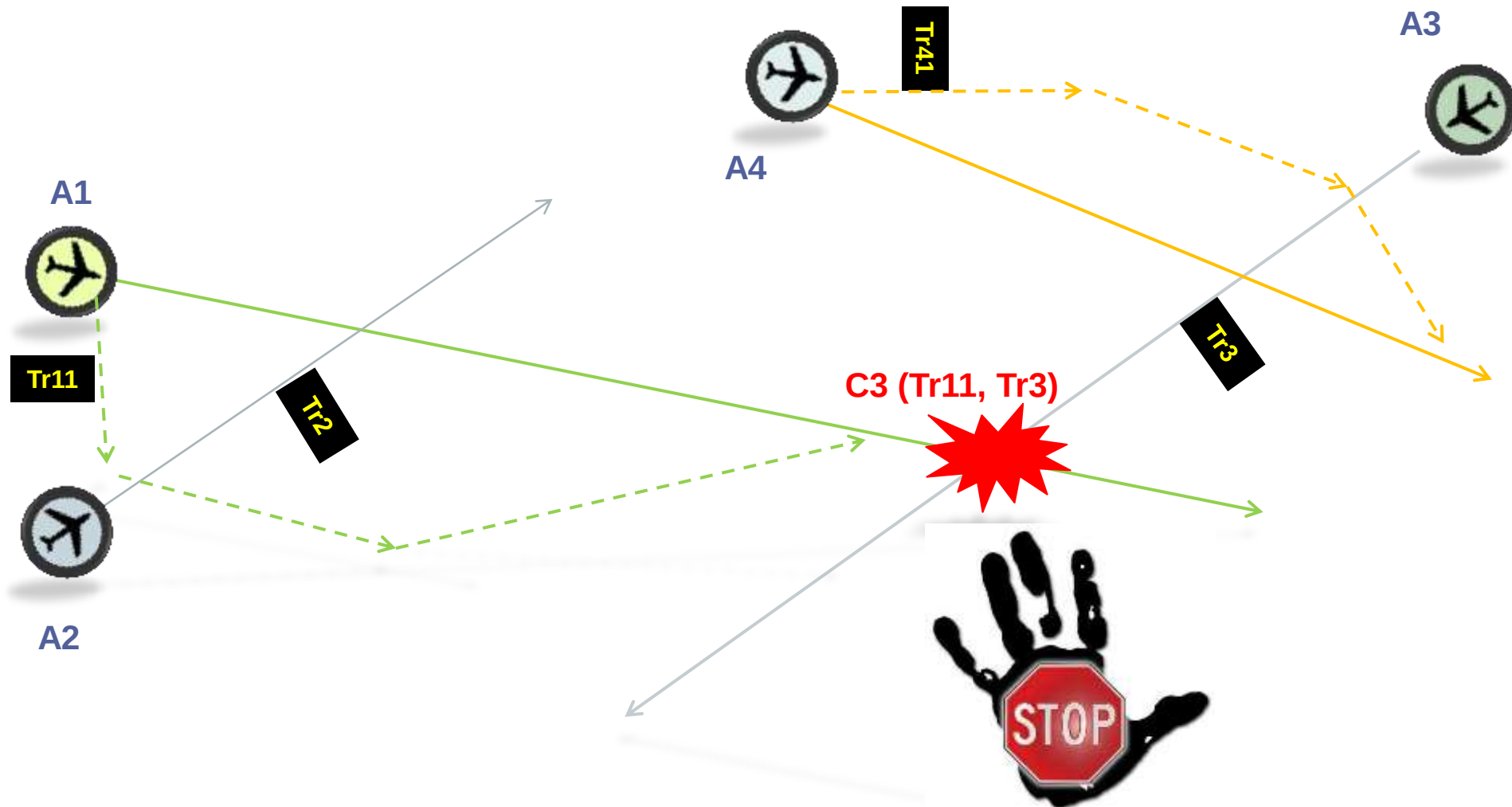
Problem description



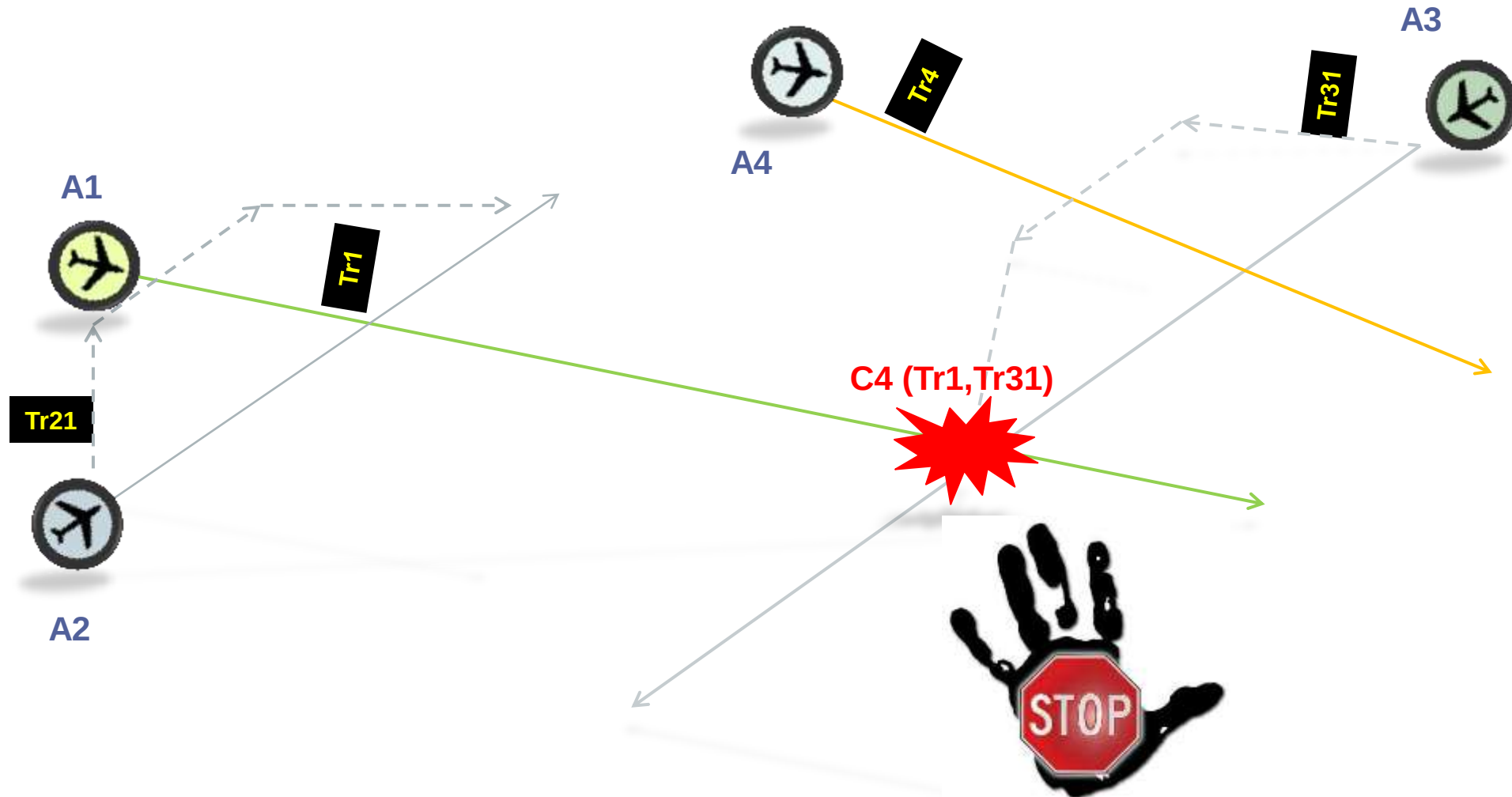
Problem description



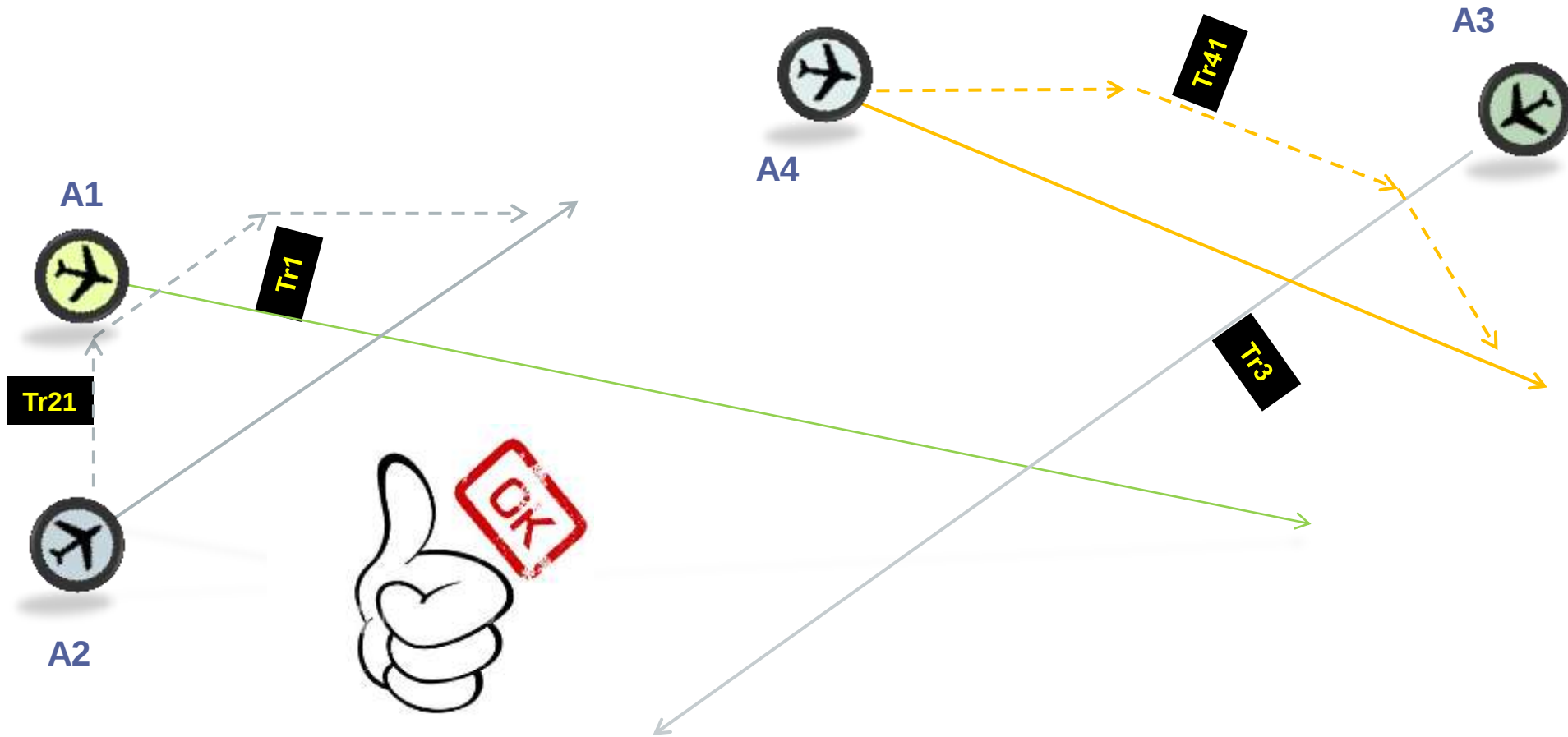
Problem description



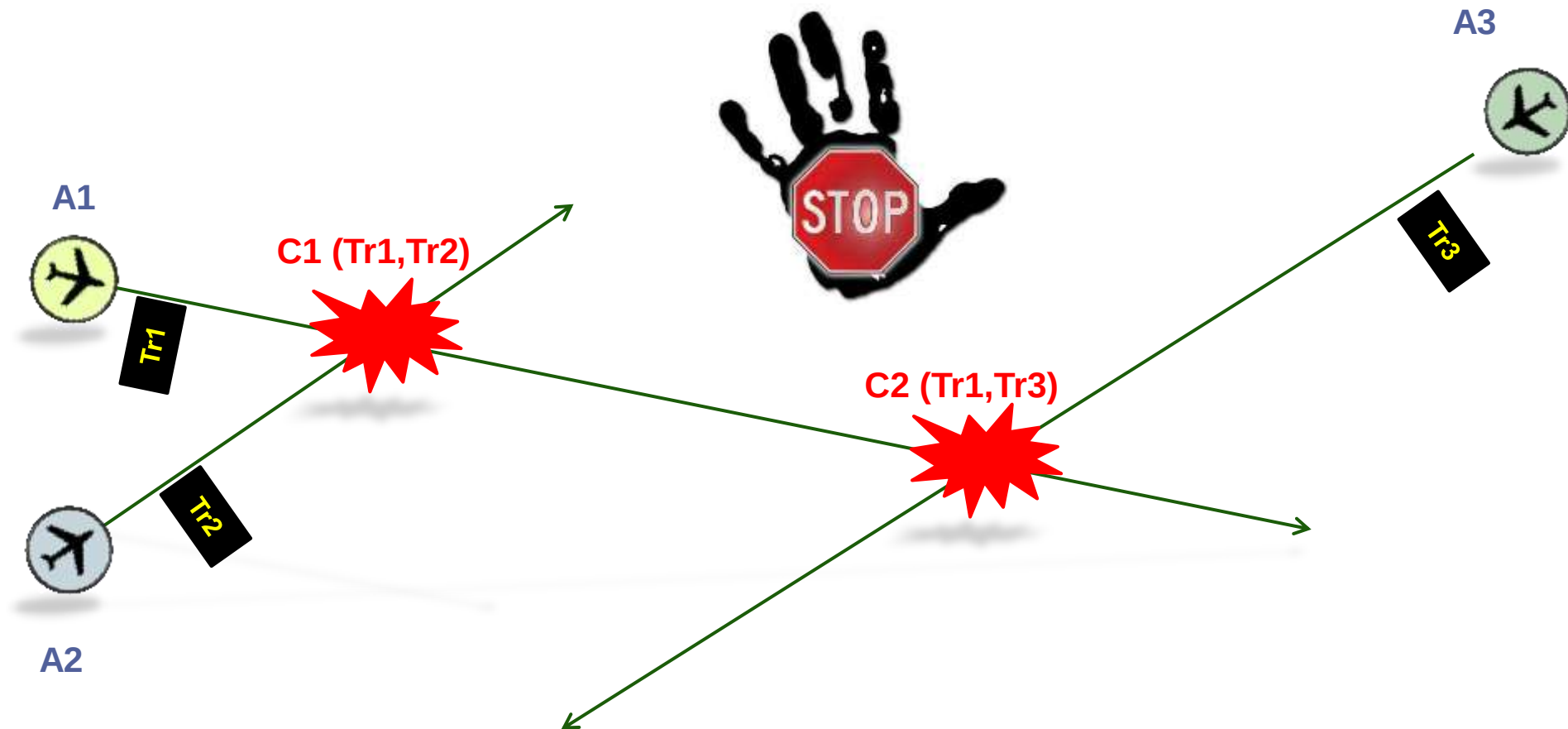
Problem description



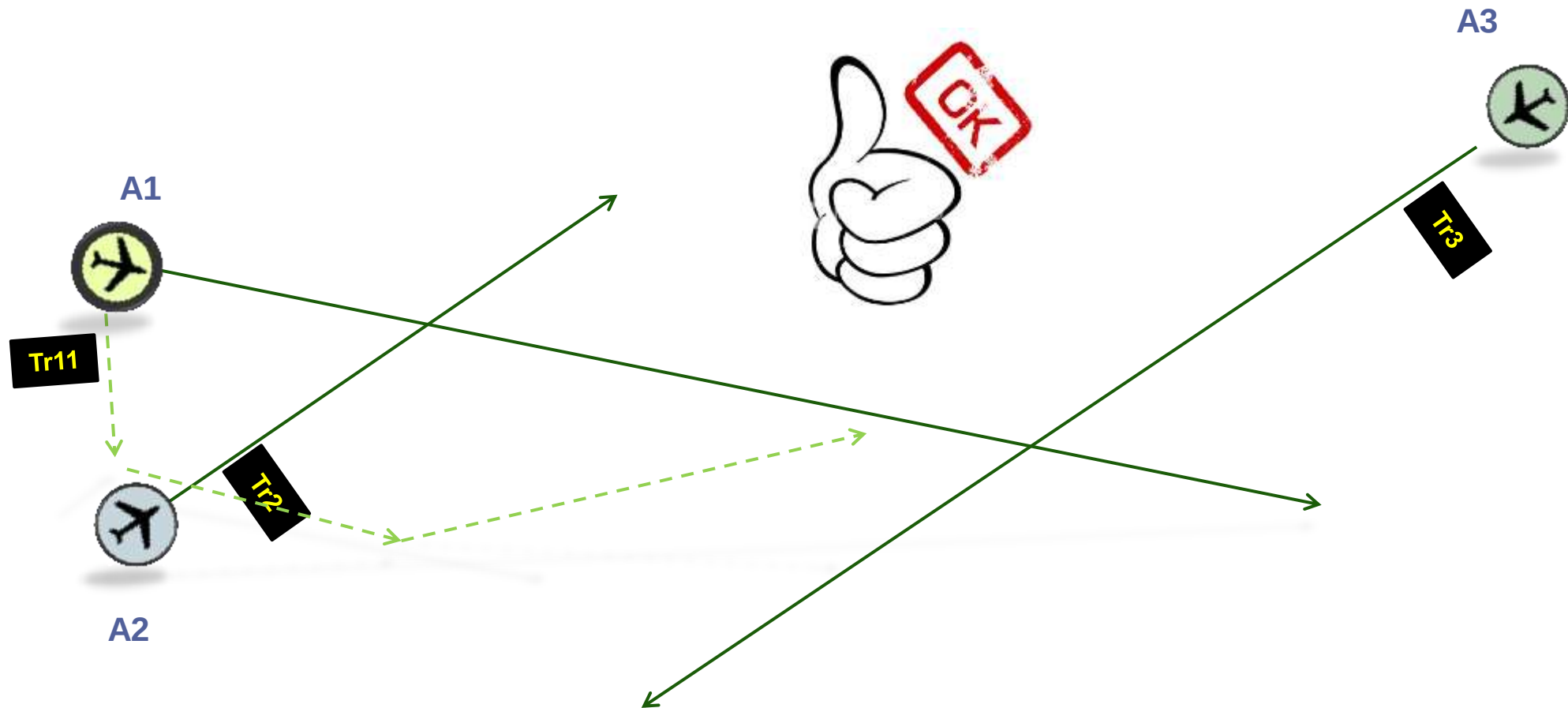
Problem description



Problem description

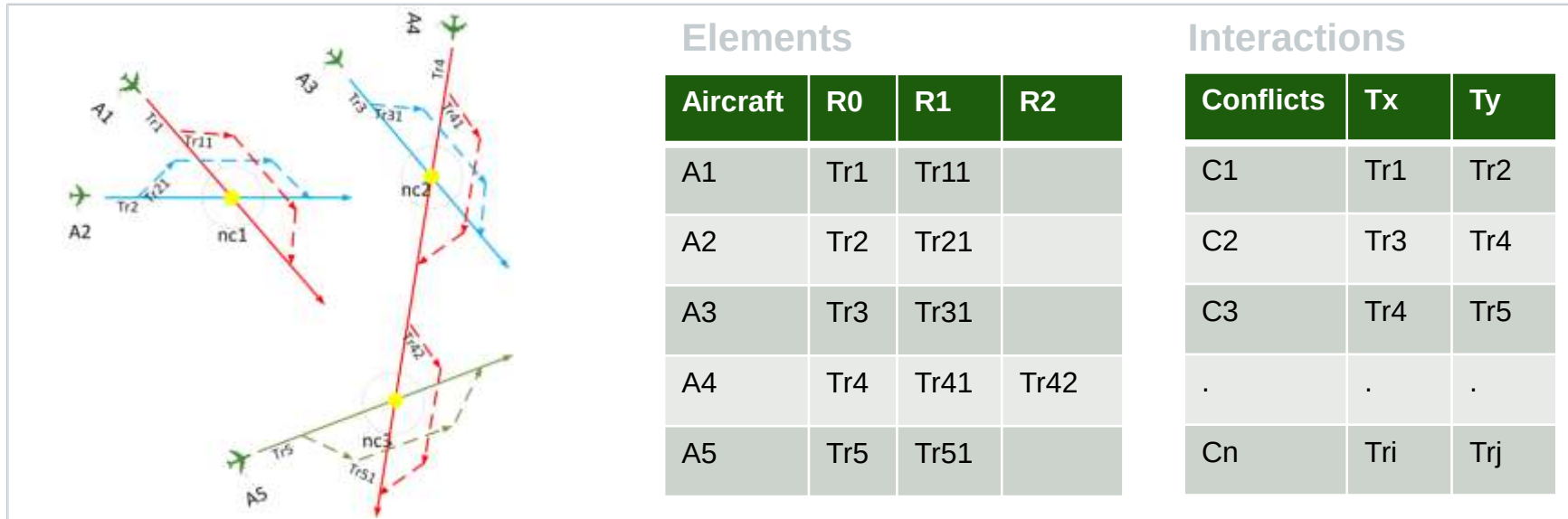


Problem description



Problem description

Inputs --> Outputs

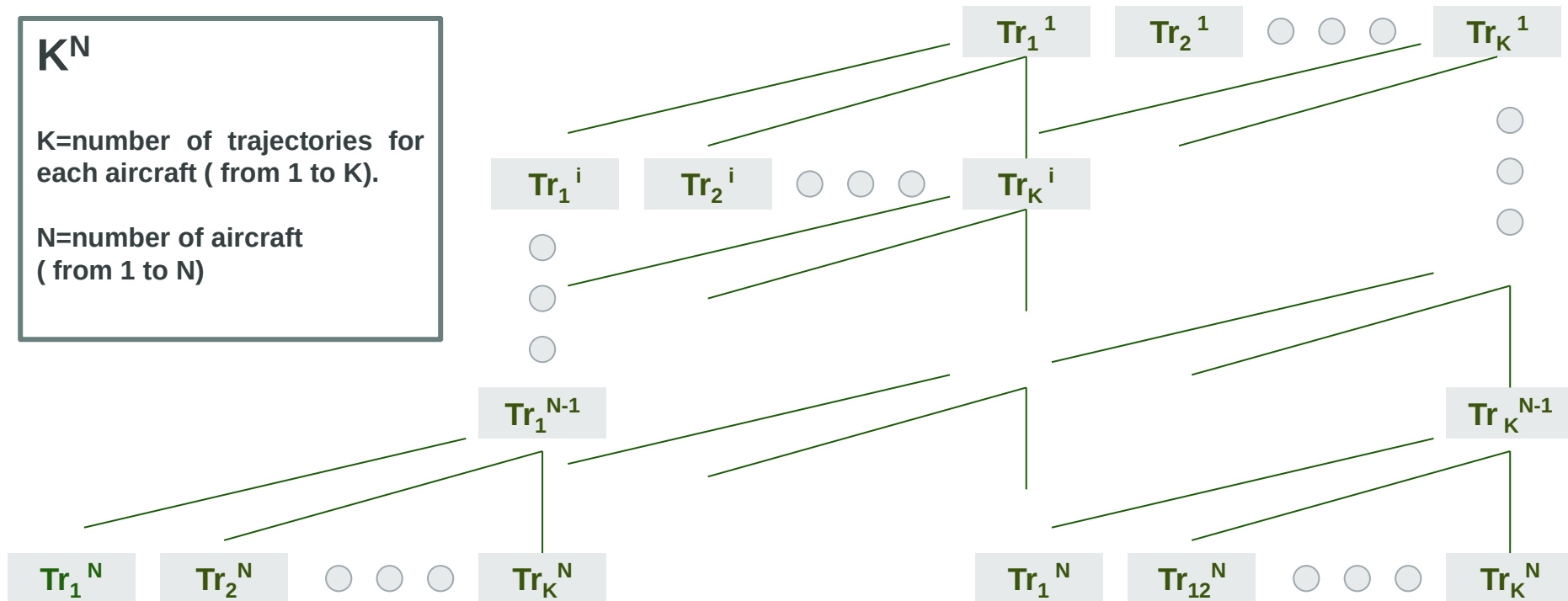


Solution requeriments:

1. One trajectory per aircraft
2. Conflict free (compatible trajectories)

Problem description

Total possible combinations considering an equal amount of alternative trajectories per aircraft.



$$K^N = (K_{A1})(K_{A2})(K_{A3})(K_{A4})\dots(K_{AN}) \text{ possible combinations}$$

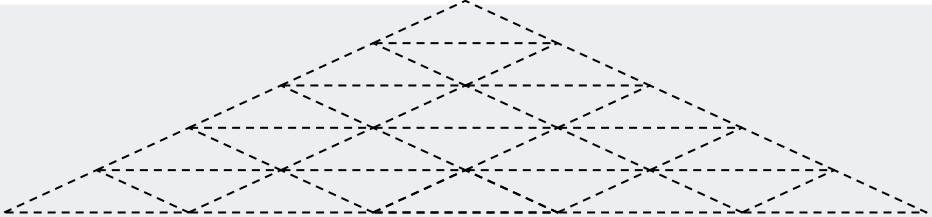
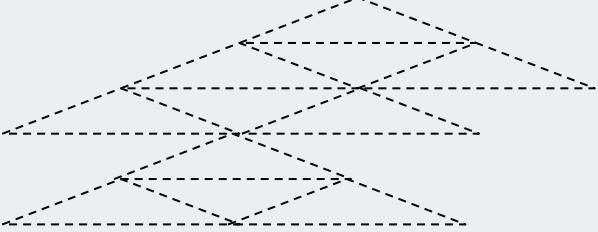
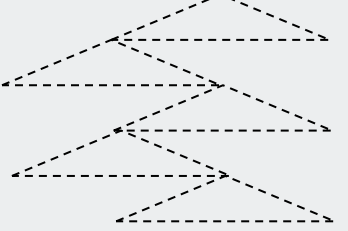
4: Causal analysis and models

- Causal analysis
- Clustering Model
- ICS Model

Causal analysis

The search and construction of solutions is computed using three discrete events:

1. Trajectories selection.
2. Conflicts between trajectories.
3. Trajectories combination.

Approach	Solution space exploration
Pure combinatorial	
Causal	
Causal with Constraints propagation	

Causal analysis

Aircraft	R0	R1	R2	.	.	.	Rm
A1	Tr1	Tr11	Tr12				
A2	Tr2	Tr21	Tr22				
A3	Tr3	Tr31	Tr32				
A4	Tr4	Tr41	Tr42				
.	.	.	.				
.	.	.	.				
An	Tr	Trn1	Trn2				

Conflicts	Tx	Ty
C1	Tr1	Tr2
C2	Tr2	Tr4
C3	Tr31	Tr1
C4	Tr11	Tr32
.	.	.
.	.	.
Cm	Trx	Try

$K^N = (K_{A1})(K_{A2})(K_{A3})(K_{A4})...(K_{An})$ possible combinations

Causal analysis



Aircraft	R0	R1	R2	.	.	.	Rm
A1	Tr1	Tr11	Tr12				
A2	Tr2	Tr21	Tr22				
A3	Tr3	Tr31	Tr32				
A4	Tr4	Tr41	Tr42				
.	.	.	.				
.	.	.	.				
An	Trn	Trn1	Trn2				

Conflicts	Tx	Ty
C1	Tr1	Tr2
C2	Tr2	Tr4
C3	Tr31	Tr1
C4	Tr11	Tr32
.	.	.
.	.	.
Cm	Trx	Try

Causal analysis



Aircraft	R0	R1	R2	.	.	.	Rm
A1	Tr1	Tr11	Tr12				
A2	Tr2	Tr21	Tr22				
A3	Tr3	Tr31	Tr32				
A4	Tr4	Tr41	Tr42				
.	.	.	.				
.	.	.	.				
An	Trn	Trn1	Trn2				

Conflicts	Tx	Ty
C1	Tr1	Tr2
C2	Tr2	Tr4
C3	Tr31	Tr1
C4	Tr11	Tr32
.	.	.
.	.	.
Cm	Trx	Try

Causal analysis



Aircraft	R0	R1	R2	.	.	.	Rm
A1	Tr1	Tr11	Tr12				
A2	Tr2	Tr21	Tr22				
A3	Tr3	Tr31	Tr32				
A4	Tr4	Tr41	Tr42				
.	.	.	.				
.	.	.	.				
An	Trn	Trn1	Trn2				

Conflicts	Tx	Ty
C1	Tr1	Tr2
C2	Tr2	Tr4
C3	Tr31	Tr1
C4	Tr11	Tr32
.	.	.
.	.	.
Cm	Trx	Try

$(1)(K_{A2}-K_{C_{Tr}})(K_{A3}-K_{C_{Tr}})(K_{A4}-K_{C_{Tr}}) \dots (K_{An}-K_{C_{Tr}})$ compatible combinations $< K^N$

Causal analysis

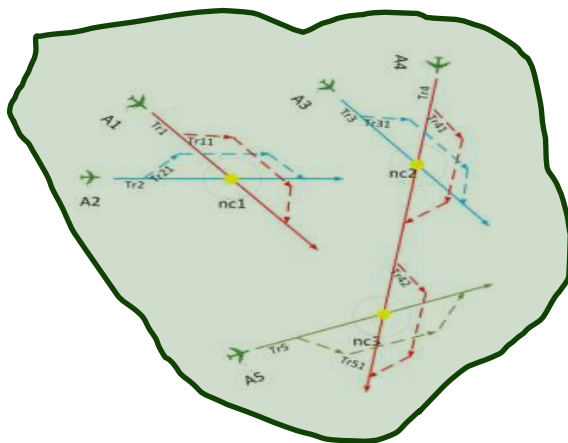
Aircraft	R0	R1	R2	.	.	.	Rm
A1	Tr1	Tr11	Tr12				
A2	Tr2	Tr21	Tr22				
A3	Tr3	Tr31	Tr32				
A4	Tr4	Tr41	Tr42				
.	.	.	.				
.	.	.	.				
An	Trn	Trn1	Trn2				

Conflicts	Tx	Ty
C1	Tr1	Tr2
C2	Tr2	Tr4
C3	Tr31	Tr1
C4	Tr11	Tr32
.	.	.
.	.	.
Cm	Trx	Try

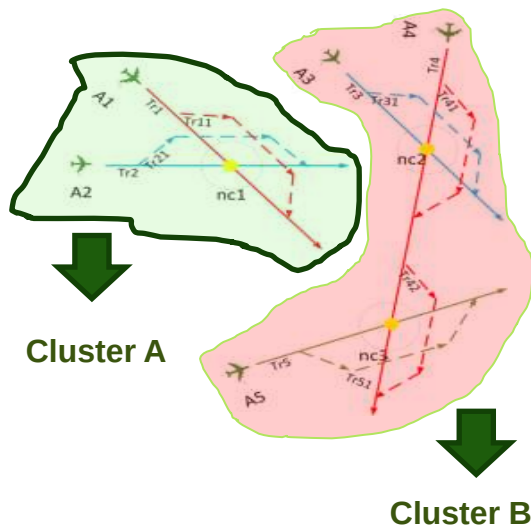
Combination of conflict free trajectories (construction of solutions)

Causal analysis

The combinatorial increases considerably with the amount of aircrafts and trajectories.



Partition in groups of aircrafts which do not share any conflict.



Feasible solution combinations



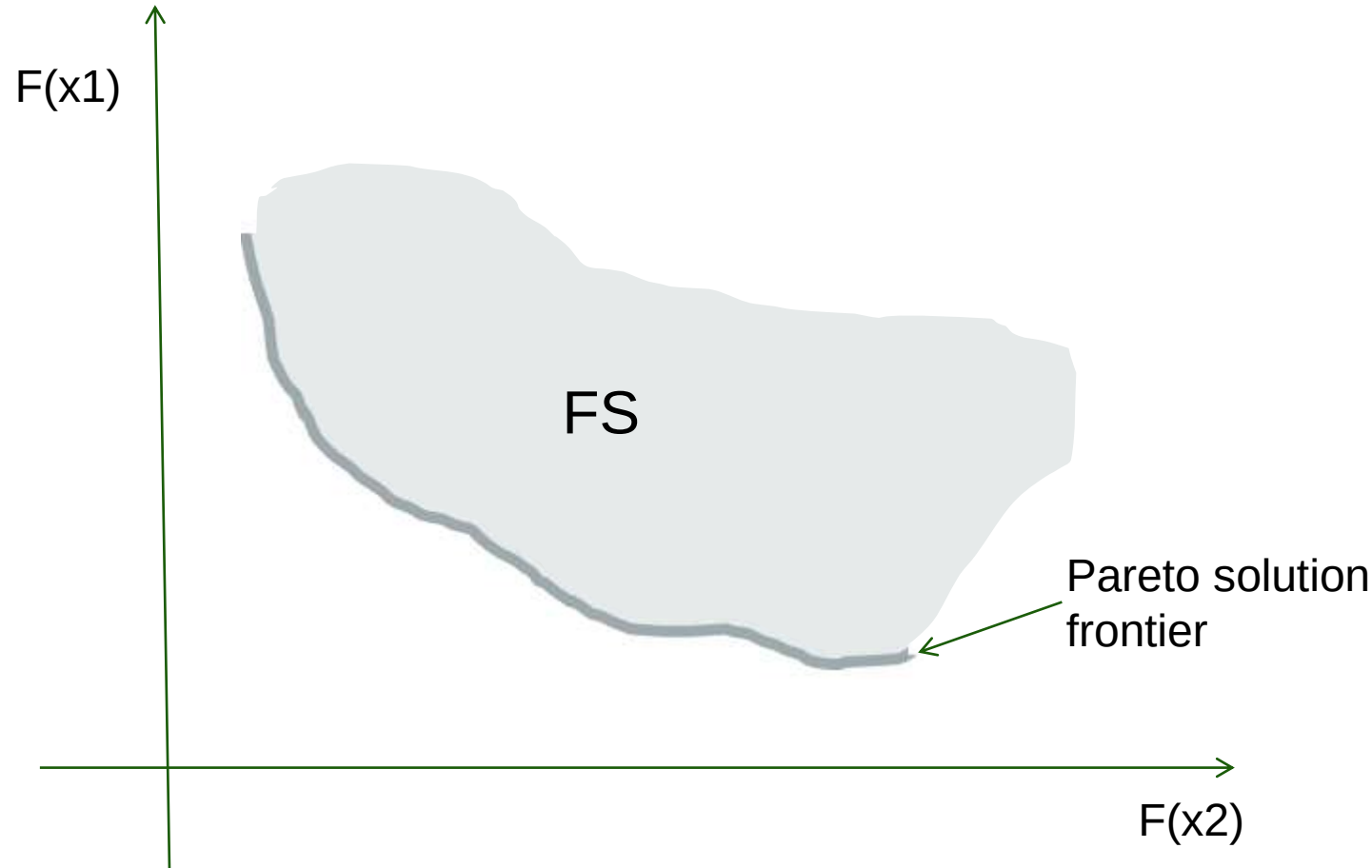
Avoiding unnecessary combinatorial.

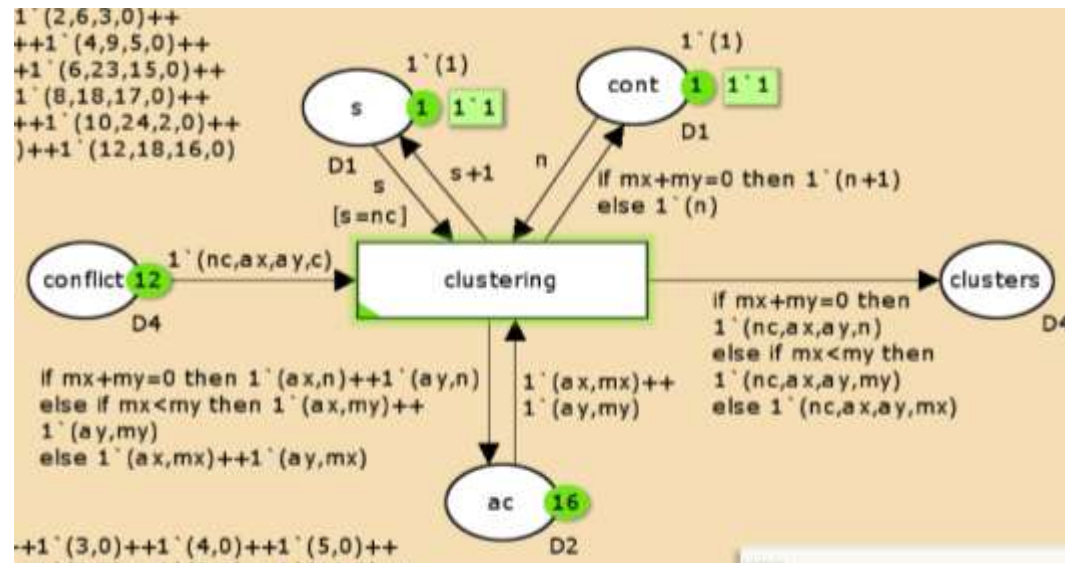
Feasible solution space (FS)

Local optimization of
resolution trajectories



Reduce the search of global
solutions to the Pareto frontier.





Interactions: Events for cluster construction.

1. Trajectories selection.
2. Conflicts between trajectories.
3. Trajectories combination.

5: Simulation Results

- STREAM solution performance

STREAM solution performance

The complete technological framework described before, including the clustering and interaction causal solver models, has been implemented in C++.



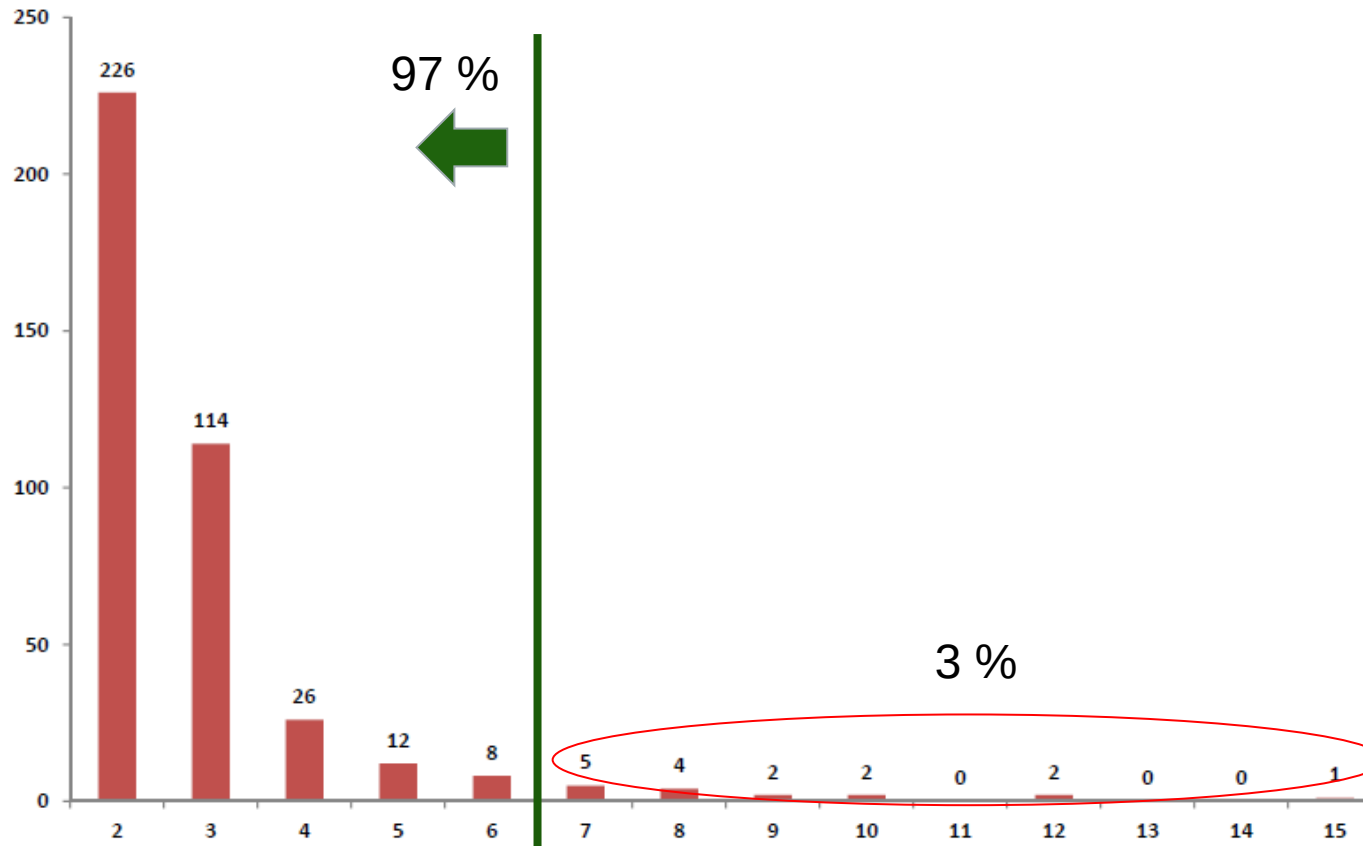
Test:

An European ATM Scenario of **3600 real trajectories** of 1 hour average-length (from TMA to TMA).

The hardware used in the simulations was a medium-range computer (10,000 MIPS) with 64GB RAM (around 40GB were used during the simulation).

STREAM solution performance

Results for the test scenario.



402 conflicts

97% ≤ 6 A/C

reduced size combinatorial

6: To conclude

- Conclusions
- Next steps

Conclusions

Air Traffic Networks are dynamic and adaptive systems, the causal analysis approach of interactions provides intelligence to explore their evolution.

Based on causal constraint propagation search, clustering and Pareto frontier exploration it is possible to downsize the combinatorial expansion problem, thus improving the computational performance and resolution capacity of the tool.

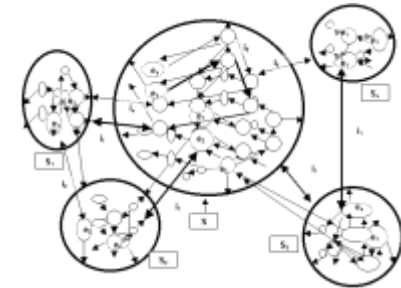
The technological framework developed under STREAM project is currently capable to efficiently find conflict free solutions for 97% of conflicts in a realistic scenario composed by 3600 trajectories over Europe.

Next Steps

Development and implementation of metrics for selection of optimal solutions at network level.

Development performance analyses with more complex and denser scenarios.

Improve the nominal model with the introduction of uncertainties.



Danke Schön!

Questions or comments?

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Extra material

Colored Petri Net formalism for modeling and simulation with discrete events.

CPN model makes it possible to determine:

All the system states that can be reached starting from a certain set of initial system operating conditions.

The transition sequence to drive the system from an specific initial state to a desired end state.

Complex systems are represented by:

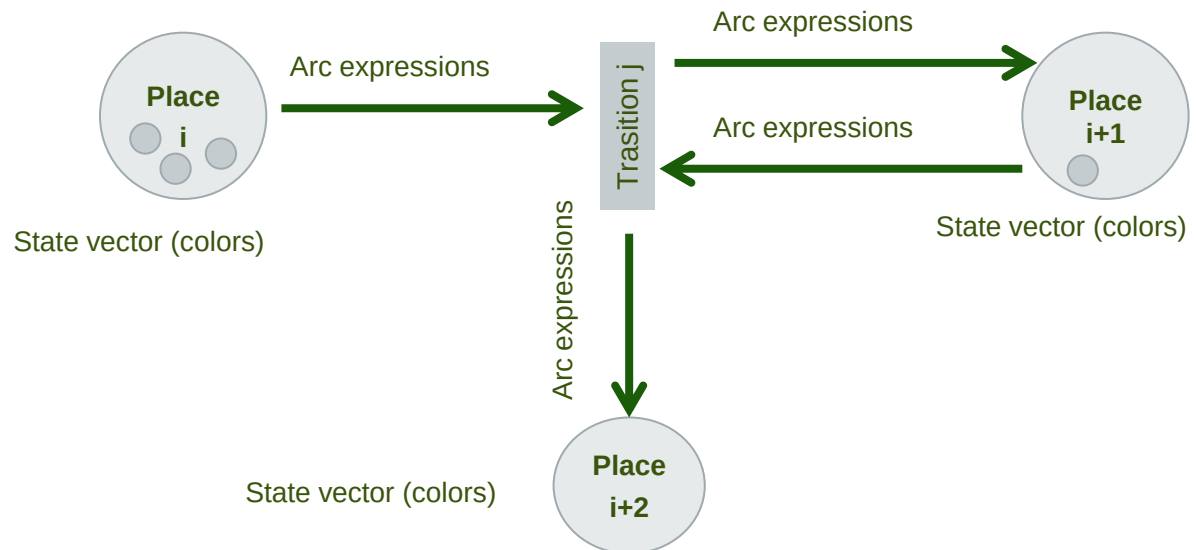
Places

Transitions

Arc expressions

Colors

State vectors



Clustering model

Description.

Colors	Description	
	Definition	Explanation
s	Int 1...N	Sequence number
nc	Int 1...N	Conflict number
ax,ay	Int 1...N	Aircraft id
n	Int 1...N	Cluster counter
c	Int 1...N	Cluster number on conflicts
mx,my	Int 1...N	Cluster number on aircraft

Places	Description	
	Colors	Explanation
conflict	nc,ax,ay,c	The tokens placed here correspond to all the conflicts (interactions between pairs of aircraft) of the global scenario or system.
ac	ax,mx ay,my	The tokens placed here correspond to all the aircraft in the global scenario or system.
s	s	This token is the sequence number for processing the conflicts.
cont	n	This token is the sequence number to assign conflicts.
clusters	nc,ax,ay,c	In this place, the tokens are removed from the set of conflicts once a cluster has been assigned.

Transitions	Explanation
clustering	Picking of conflicts and aircraft to assign the corresponding cluster number based on the preprocessed conflicts.

ICS model

Description.

Colors	Description	
	Definition	Explanation
r	Int 1...N	Sequence number
id	Int 1...N	Aircraft id
tr	Int 1...N	Trajectory id
k	Int 1...N	Total interactions for a trajectory
tx, ty	Int 1...N	Trajectory id
ac	Int 1...N	Aircraft id
n	Int 1...N	Total interactions for a trajectory
tc	Int 1...N	Trajectory id

Transitions	Explanation
T1	Chooses a trajectory for an aircraft
T2	Analyses the interactions of the trajectory with respect to the trajectories of other aircraft, eliminating those with any conflict. (tx case)
T3	Analyses the interactions of the trajectory with respect to the trajectories of other aircraft, eliminating those with any conflict. (ty case)
T4	Once all interactions of a trajectory have been processed the next aircraft is choose.
T5	Analyses if previous steps have eliminated the interactions, which no longer exist in the set of trajectories.

Places	Description	
	Colors	Explanation
p1	r, id	Tokens stored here represent the aircraft involved in the scenario for which a path should be assigned and in this case are processed according to the value of r from lowest to highest.
p2	tr, id, k	The tokens stored here correspond to the feasible paths, defined for each plane and which have the number of interactions.
p3	r	This token is a sequence number
p4	tr, id, k tx, ac, n ty, ac, n	When depositing a token in this place it is because you chose a path for an aircraft, for further analysis of the trajectory's compatibility with the rest of the aircraft.
p5	r	This place is assigned the following sequence and functions as a switch.
p6	r, tx, ty	In this place you have stored conflicts which identify interactions between pairs of trajectories.
p7	tr, id, k	Here the trajectories analyzed and processed (feasible scenarios and unconflicted) are stored.
p8	tr, id, k tx, ac, n ty, ac, n	In this place, the trajectories discarded based on interactions with the selected paths are stored.

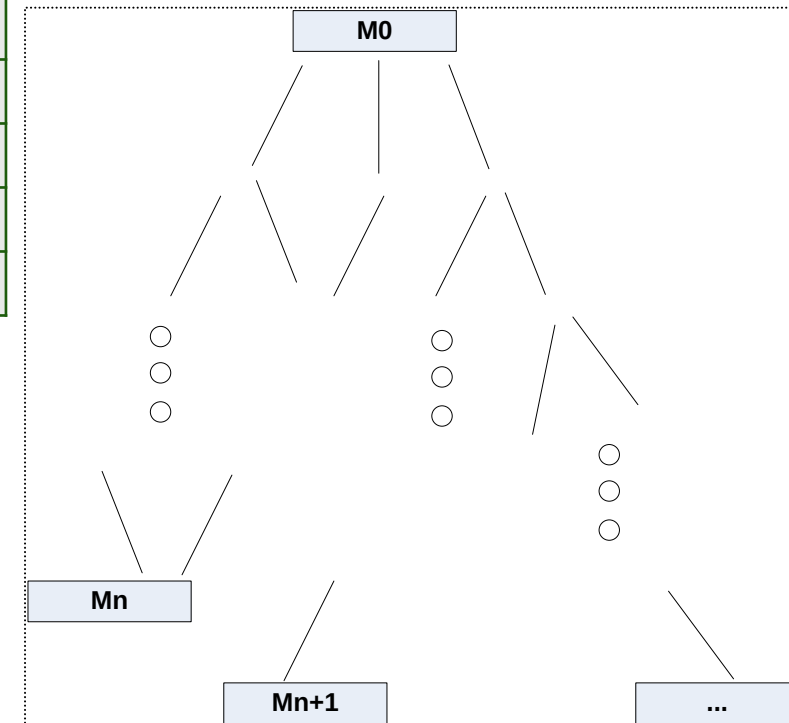
ICS example

Cluster 3

Space State construction

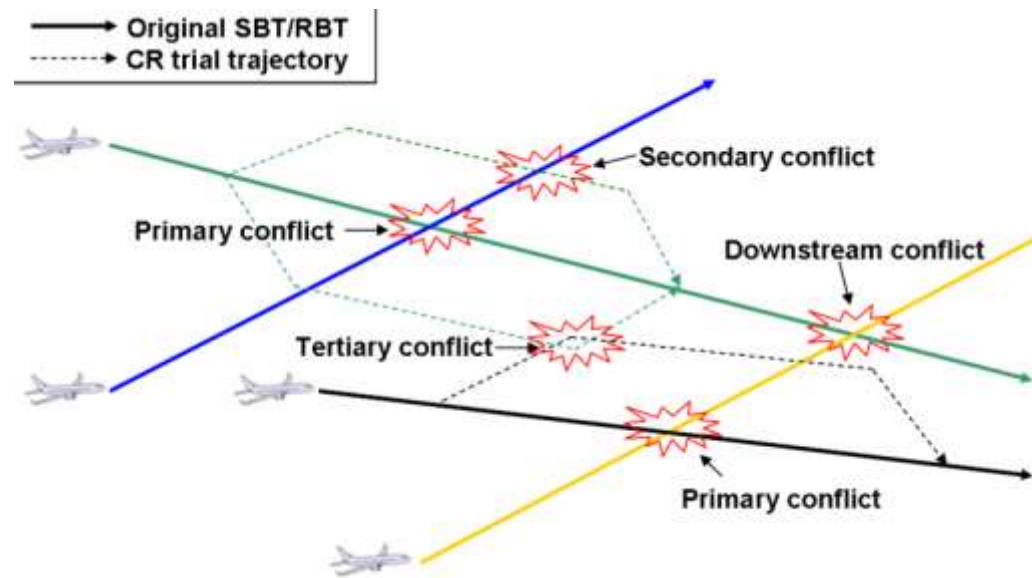
Cluster 3	P1	P2	P3	P4	P5	P6	P7	P8
M0	1`(1,16), 1`(2,17), 1`(3,18), 1`(4,19)	Tr`s	1`(1)			Conflict's		
■								
■								
■								
Mn		Tr`s	1`(5)			Conflict's	Sol n	
Mn+1		Tr`s	1`(5)			Conflict's	Sol n+1	

Reachability tree



Problem description

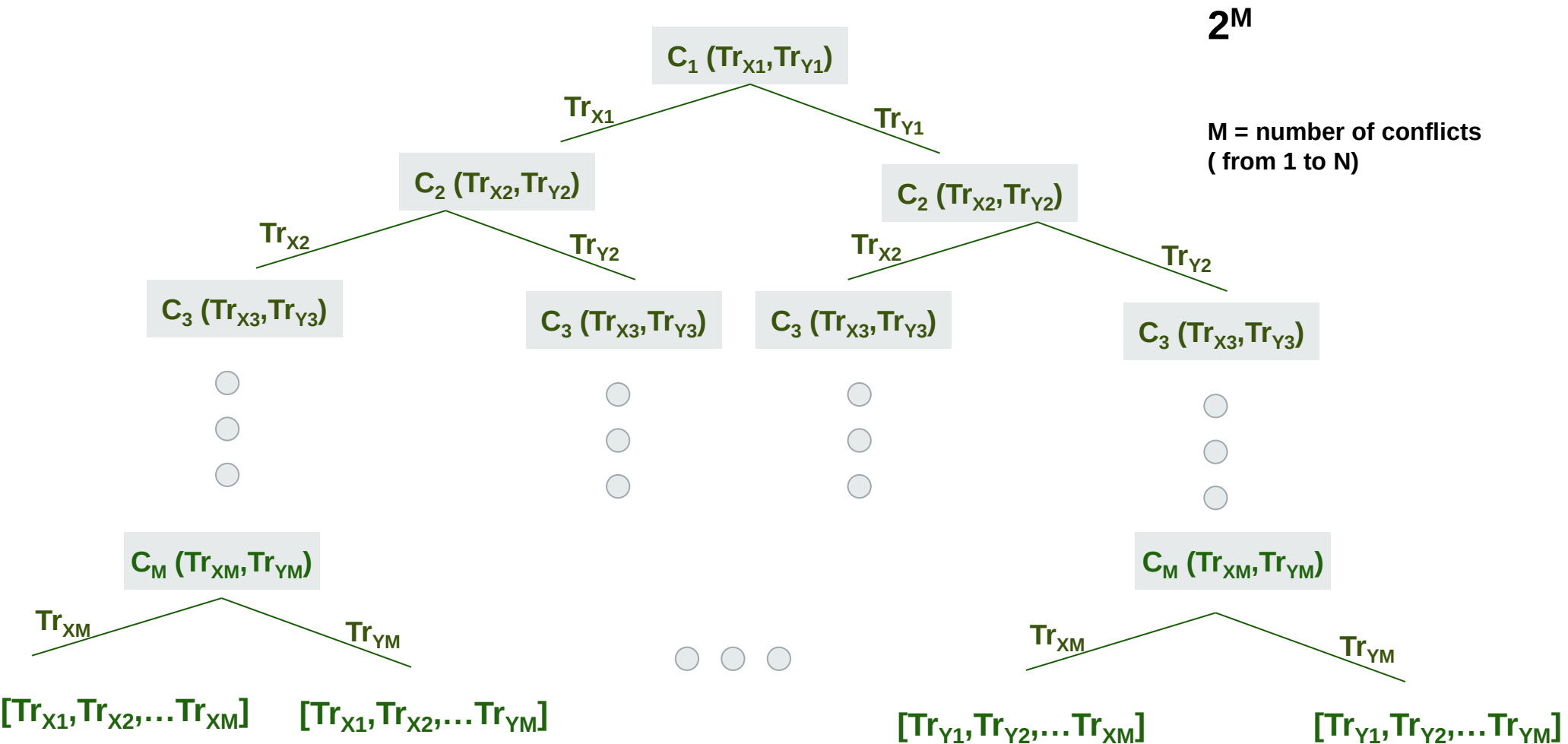
In some cases intended to solve a conflict can generate other conflicts that previously did not exist.



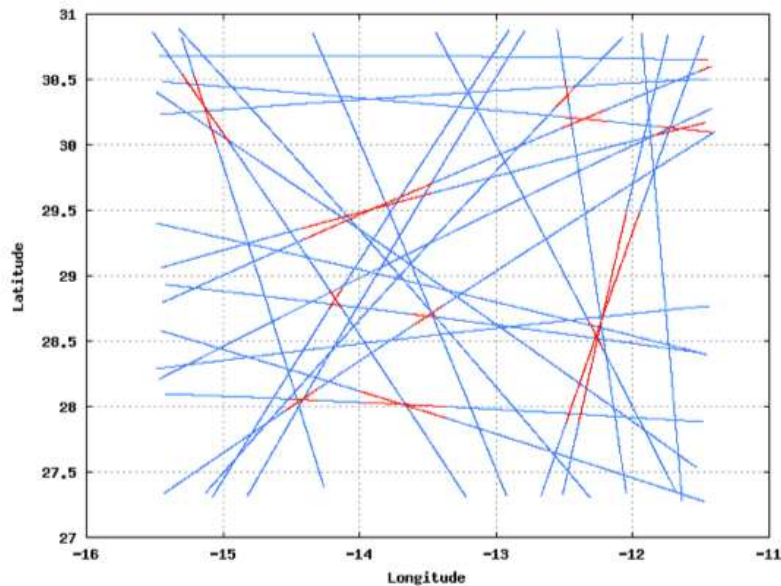
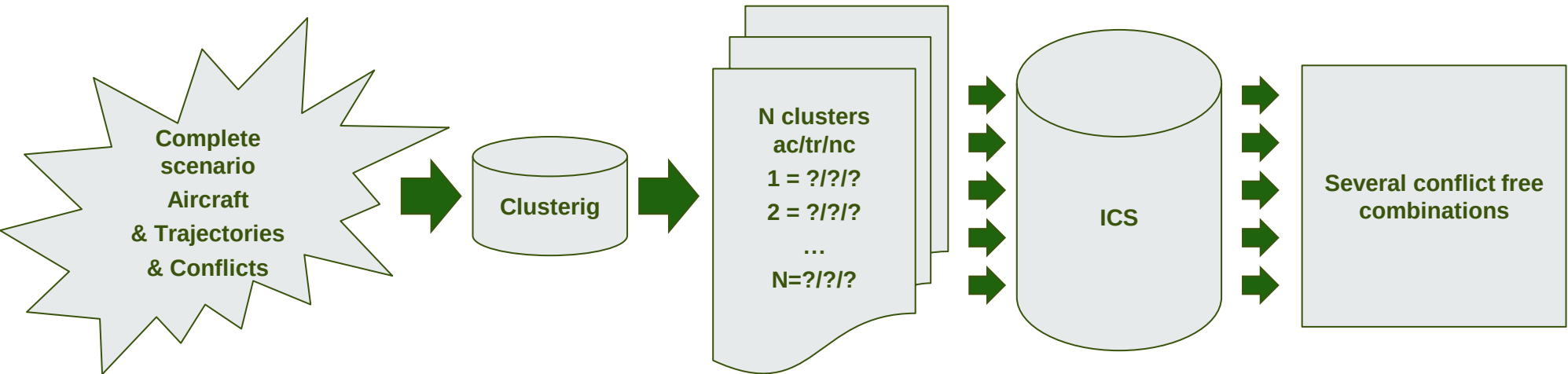
These network effects depend on space-time interactions within the element of the system.

Problem description

Combinations of incompatible trajectories conducted by conflicts



Flow chart process

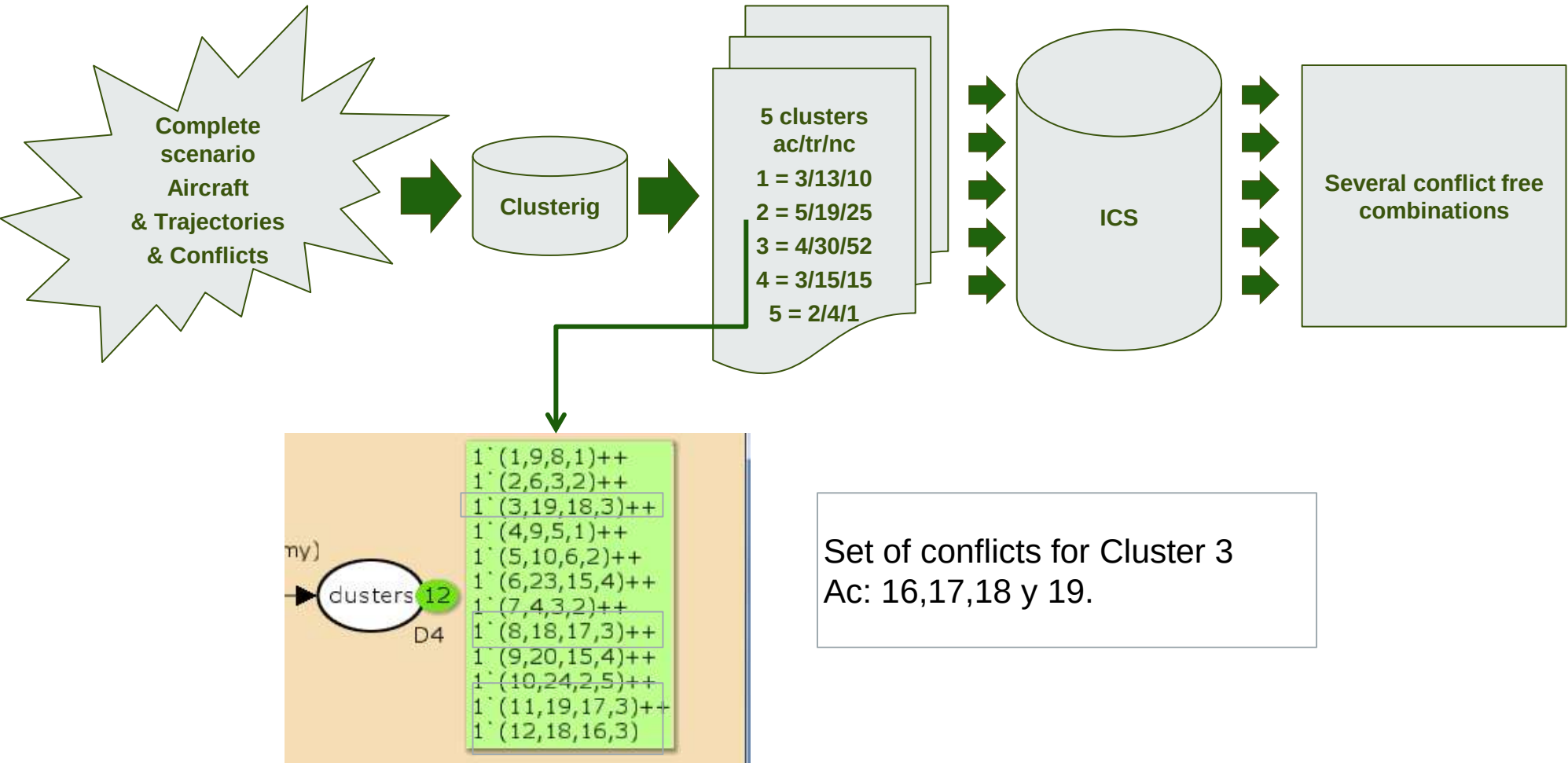


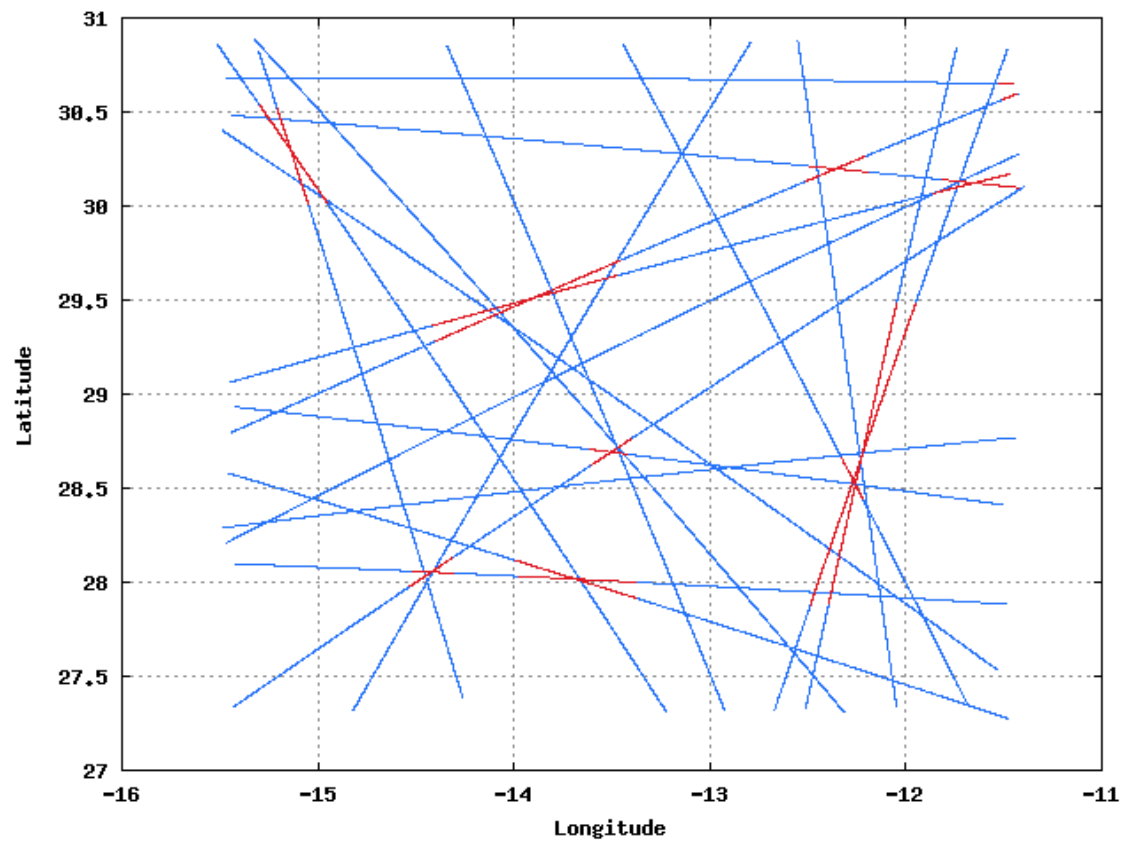
Demo synthetic scenario:

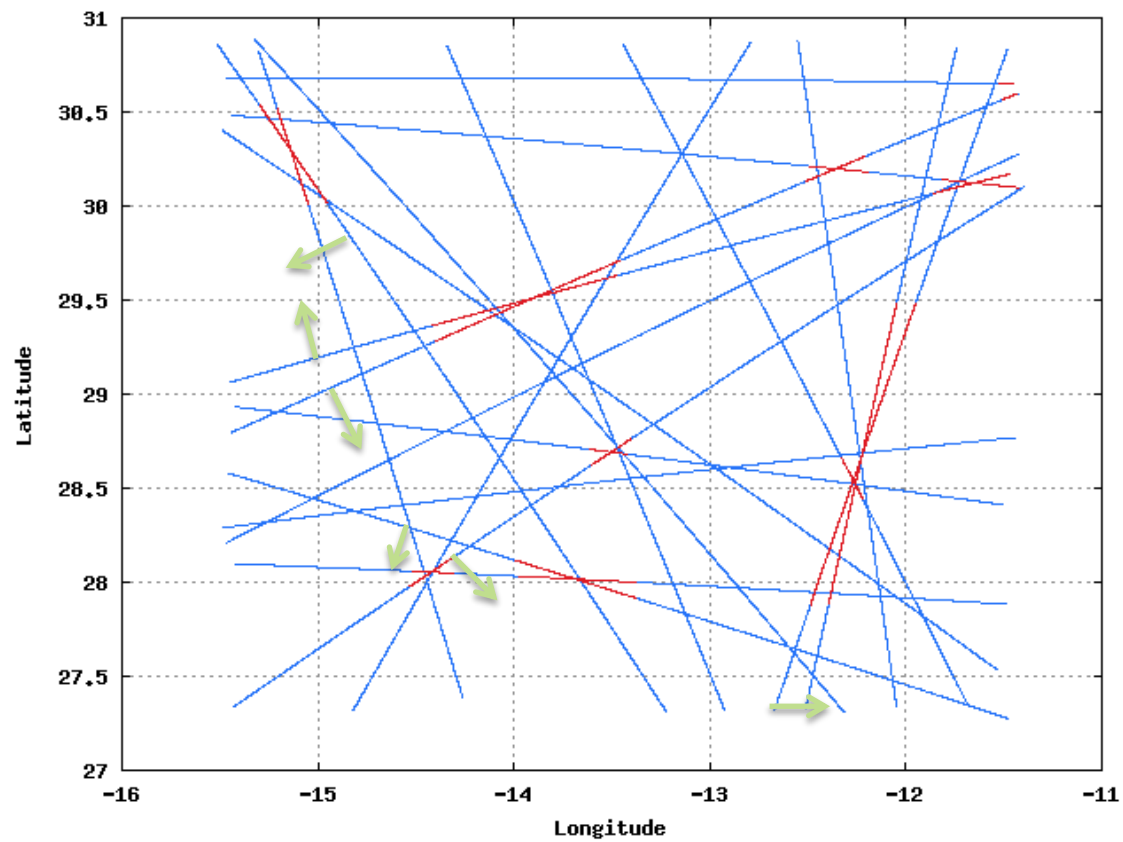
25 aircraft

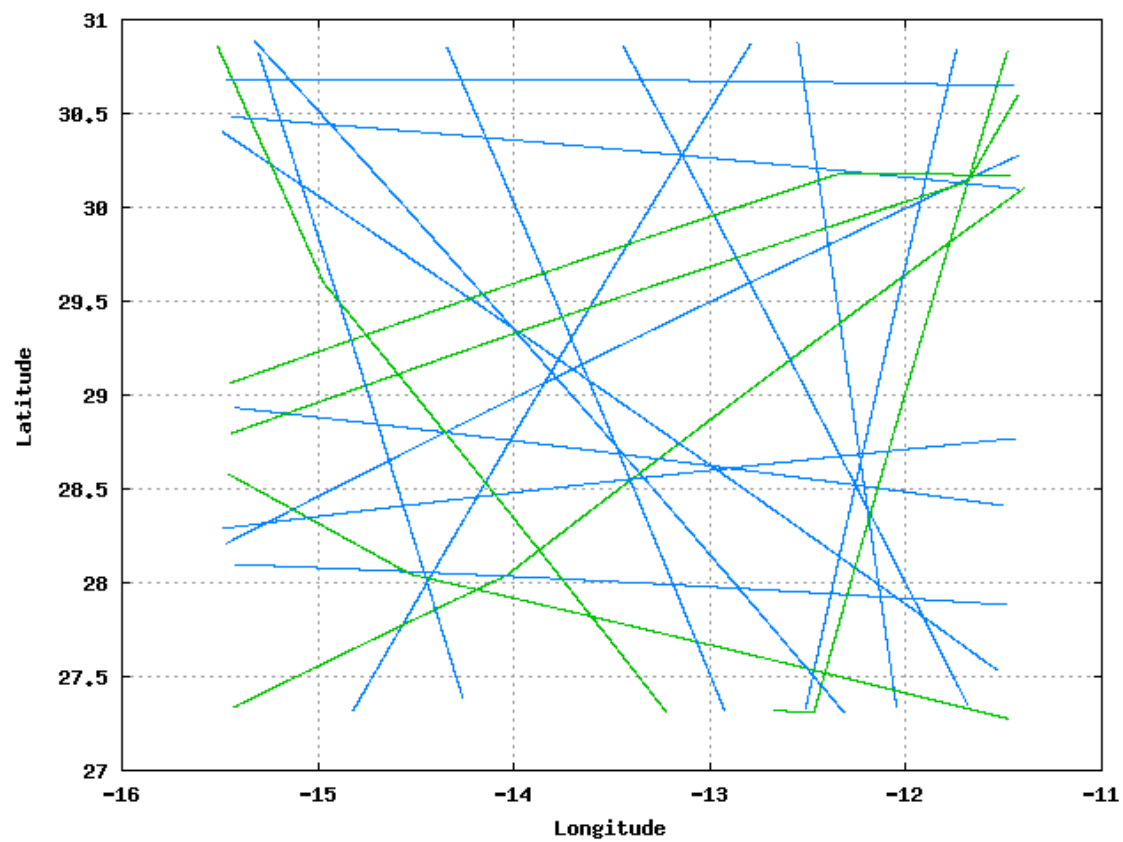
17 aircraft with 12 primary conflicts, and 91 secondary and tertiary conflicts.

Clustering example

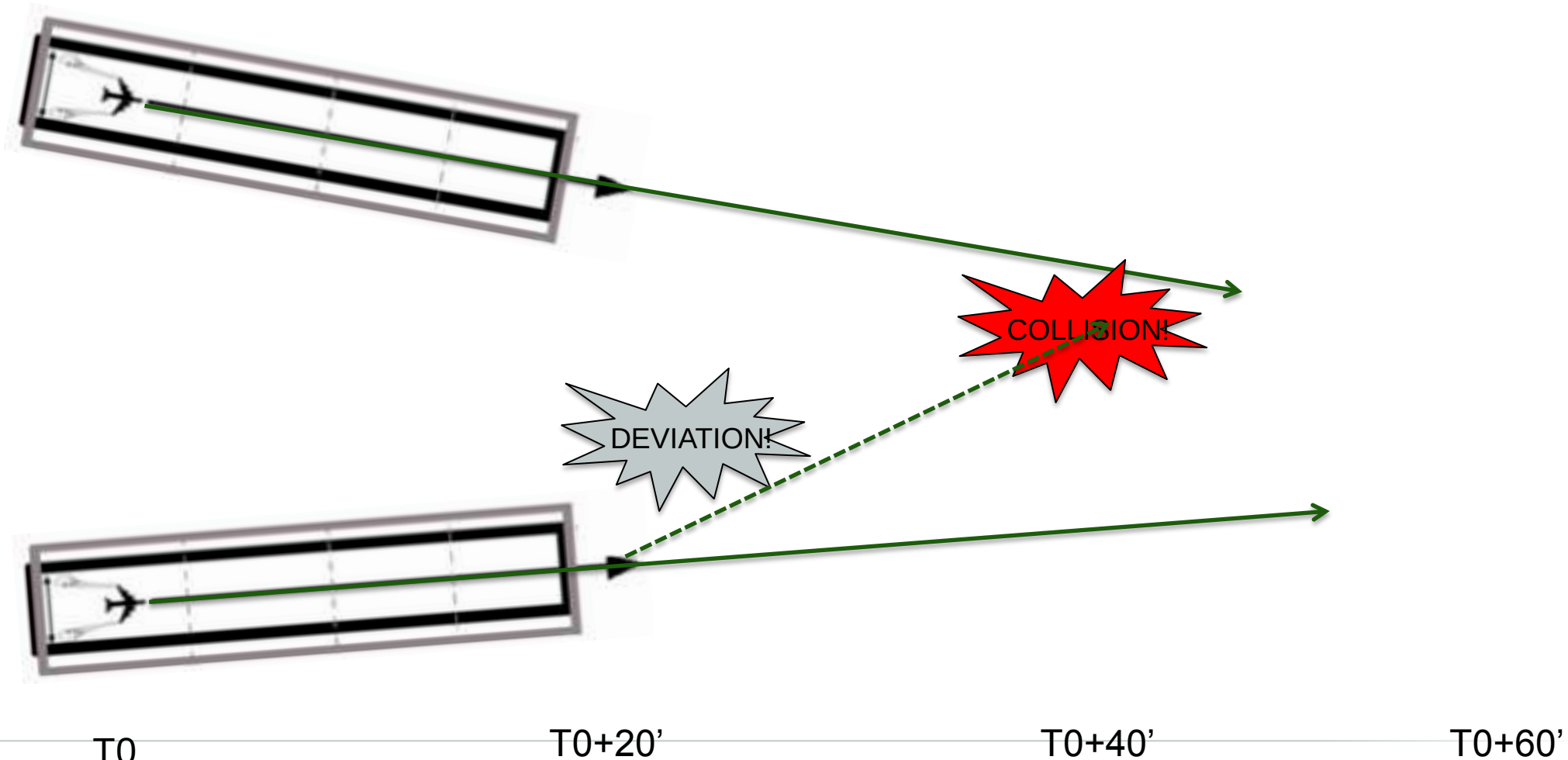




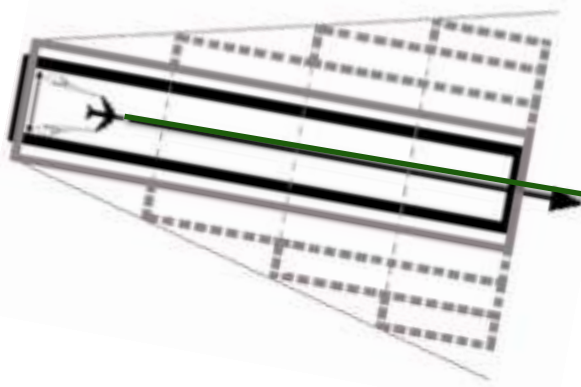




TP uncertainty

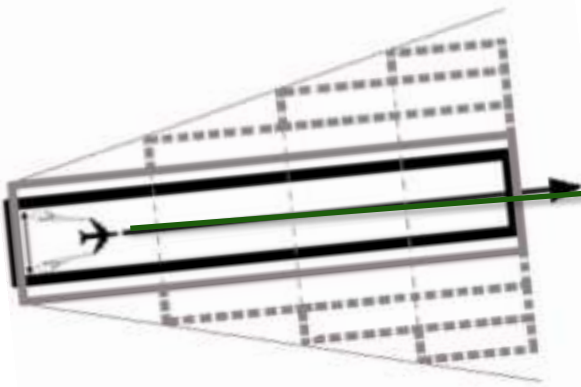


TP uncertainty



Nominal trajectories are **not really in conflict**, but the **risk of collision** in case of deviation is too high (i.e. tactical ATC will consider it as a conflict)

Consider a risk-of-deviation model



T0

T0+20'

T0+40'

T0+60'

TP uncertainty

Now the route is sub-optimal but it is more robust and will reduce the workload of tactical controllers

