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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Foreword - This paper describes a project that is part of SESAR Work Package E, which is addressing long-term and innovative research.

***Abstract*— SESAR WP-E STREAM project seeks to fill a currently existing gap between the strategic and the tactical planning in ATM, by designing innovative tools capable of detecting and solving conflicts among aircraft in a time-efficient manner, in order to deliver traffic to ATCOs with a diminished number of conflicts. In this paper, Clustering and Interaction Causal Solver (ICS) models are presented, being developed under the formalism of Colored Petri Nets for the generation of several feasible conflict free solutions. By clustering, the computational complexity is significantly reduced. The separation of trajectories according to their interactions is the key idea in high-density traffic scenarios, bringing several benefits such as a direct increase of processing capacity and troubleshooting. In the same direction, the ICS model makes an intelligent construction through the use of causal interactions, thus limiting the search exploration process only to those combinations supported within each cluster. Therefore, both tools offer significant advantages over the efficiency and effectiveness for the construction and evaluation of Air Traffic Management conflict-free scenarios. According to the STREAM concept, these models produce multiple combinations of feasible conflict free solutions, to be later weighted according to different metrics (for efficiency, safety, robustness, equity and fairness among others) and selected based on stakeholders' priorities.**

Considered as a whole, the decision support tool , once implemented, provides a new and efficient network-oriented conflict detection and resolution process, fitting into the overall performance framework currently implemented at European level.

Keywords-Strategic ATM; Causal Modeling; Decision Support Tools; Colored Petri Nets.

I. Introduction

SESAR WP-E project STREAM (Strategic Trajectory de-confliction to Enable seamless Aircraft conflict Management) [http://www.hala-sesar.net/stream] is currently being undertaken by a consortium composed of Advanced Logistics Group (ALG-Indra), Boeing Research & Technology Europe (BR&TE) and Universitat Autònoma de Barcelona (UAB). The project aims to fill the current existing gap between the strategic and the tactical planning in ATM, by designing Conflict Detection & Resolution (CD&R) tools that re-organize air traffic at strategic level (thus, diminishing the amount of conflicts to be solved at a tactical level), while generating useful network information in order to improve the decision making process [1].

For a thorough description of the concept and of the high level architecture of the STREAM solution, the reader is referred to [3]. Several results have been obtained under project activities during the course of 2012, within the different technical Work Packages: WP2 Strategic trajectory de-confliction tool development, WP3 Metrics & methodology development and WP4 Analysis & evaluation. This paper however focuses only on the algorithmic innovations related with the conflict resolution thread of the research. These innovations were achieved under WP2 and have been selected for publication due to their interest for scientific community and maturity for presentation. The work in WP3 and WP4 is underway and results should be available for presentation within the next few months.

The approach proposed by WP2 for conflict resolution is based on the generation of several resolution trajectories per conflict and on a post-processing activity based on the causal network interactions. This determines several conflict-free network solutions or network solutions with a diminished number of conflicts (*i.e.* several final states).

This paper presents the details of the Clustering and Interaction Causal Solver sub-models within the CD&R architectural framework, which are functional to the generation of several feasible conflict-free solutions.

II. PROBLEM DESCRIPTION

The architectural framework for CD&R developed under the STREAM project, is summarized in figure 1 and basically consists of:

- A Conflict Detection (CD) module which analyzes the different trajectories under study by means of a Spatial Data Structure.
- Resolution Trajectory Generator (RTG) module to solve the conflicts at trajectory level by implementing Heading Angle Change (HAC) procedures.
- Clustering (C) and Interaction Causal Solver (ICS) to detect network interactions between trial trajectories and propose conflict-free scenarios at network level.
- A communication interface to coordinate the CD, RTG and C/ICS modules.

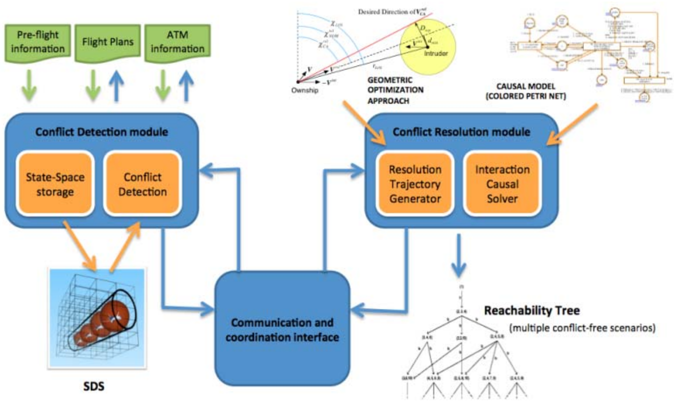

Figure 1. STREAM solution architecture.

Spatial Data Structures (SDS) permit the conflict detection problem to be reduced to a linear complexity O(n) and at the same time they provide a very natural representation of the status of the Air Traffic Management (ATM) system and of its evolution over time. The state-space information stored in the SDS by the conflict detection module can be used by the conflict resolution algorithm to calculate the trajectory amendments; a detailed explanation of SDS is presented in [1] and details of the conceptual and technological framework in [2].

To provide air traffic controllers with conflict free traffic scenarios, several trajectories must be generated in the resolution of each conflict detected at local level, but a global analysis considering the interactions of the proposed amendments at network level is required to determine the feasible solutions. This conclusion is one of the preliminary results obtained in the STREAM project [3]. Figure 2 illustrates a couple of scenarios with different conflicts between 4-Dimensional Trajectories (4DT's) and two alternative new trajectories to solve the conflicts at local level.

At the left hand side of the figure, a conflict (nc1) between two trajectories (Tr1 and Tr2) together with alternative HAC trajectory resolution (Tr11 and Tr12) is represented. Thus, considering at local level conflict nc1, the Conflict Resolution (CR) would provide as feasible solutions the combinations Tr1 and Tr21 or Tr11 and Tr2. By considering also the conflict nc2 between trajectories Tr3 and Tr4 together with their local resolution trajectories (ie. Tr31 and Tr41) the new set of feasible solutions is extended to:

Tr1,Tr21,Tr3,Tr41

Tr1,Tr21,Tr31,Tr4

Tr11,Tr2,Tr3,Tr41

Tr11,Tr2,Tr31,Tr4.

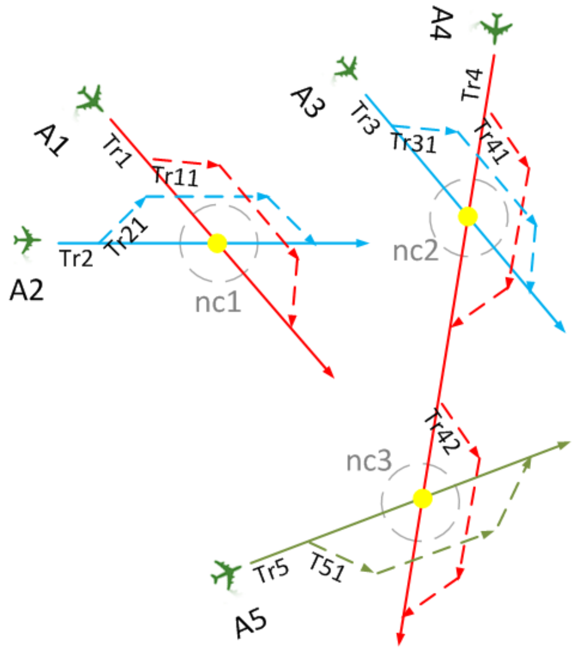

Figure 2. Example of an air traffic scenario

However, by considering the existence of two conflicts (nc2 and nc3) between aircraft A4 with A3 and A5, a new dynamic behavior must be considered in the computation of feasible solutions since conflict nc3 appears only if conflict nc2 is solved by implementing trajectory Tr31 without requiring the computation of resolution trajectories Tr42 and Tr51. It should be noted that the existence of conflict nc3 depends on upstream decisions (i.e. earlier events within the system) since the implementation of trajectory Tr41 introduces a downstream time modification that can incur new conflicts or remove original ones. At a network level, conflict nc3 can be resolved without the need to implement Tr42 or Tr51, just by implementing a combination considered in trajectory Tr41.

The above network logics can and should be exploited in the analysis and resolution of traffic scenarios to generate conflict-free feasible solutions, by exploring the interactions between possible local conflict free solutions: The implementation of an alternative trajectory can avoid a local conflict and also inhibit a downstream conflict.

Other examples of emergent dynamics (cascade effects) [4] for such systems are the secondary conflicts between planned trajectories and resolution paths as illustrated in Figure 3, or even tertiary conflicts, that are artificially incurred by the local resolution trajectories between different conflicts [5]. From this point of view it is important to analyze and process resolution scenarios at network level, considering the interactions between the original and the generated resolution trajectories.

Cascade effects are not a minor issue, considering the volume of traffic and possible conflicts between planned trajectories. For simplicity, in this paper only one alternative resolution trajectory is considered for each aircraft involved in a conflict, however, for practical purposes usually more than one alternative trajectory is generated, which increases the complexity of the resolution trajectory interaction effect analysis.

Under a causal approach, considering the interactions (conflicts and emergent dynamics) between aircraft and their trajectories, it is possible to analyze the resolution trajectory interaction effects at network level and generate a set of efficient feasible conflict free solutions.

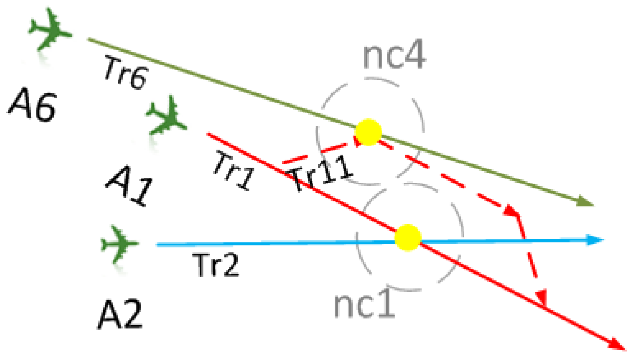

Figure 3. Examples of a cascade effect.

III. Causal Modeling Framework

Colored Petri Net (CPN) approach is a high level modeling formalism for complex systems that has been widely used to model and verify systems, allowing representation of not only the system dynamics and static behavior but also the information flow.

The main CPN components that fulfill the modeling requirements are:

- Places: These are very useful to specify both queues and logical conditions, represented by circles.
- Transitions: These represent the events of the system, depicted by rectangles.
- Input arc expressions and guards: These are used to indicate which type of tokens can be used to fire a transition.
- Output arc expressions: These are used to indicate the system state change that appears as a result of firing a transition.
- Color sets: Determine the types, operations and functions that can be used by the elements of the CPN model. Token colors can be seen as entity attributes of commercial simulation software packages.
- State vector: The smallest piece of information needed to predict the events that can appear. The state vector represents the number of tokens in each place, and the colors of each token.

The color sets will allow the modeler to specify the entity attributes. The output arc expressions make it possible to define which actions should be coded in the event routines associated with each event (transition). The input arc expressions, in turn, make it possible to see when and why an event can appear, and consequently introduce new pre-conditions (or removing them) in the model, or alternatively change some variable or attribute values in the event routines to disable active events.

From the Operational Research (OR) point of view, the CPN model provides the following mathematical structures:

- Variables: A variable can be identified for each color specified in every place node.
- Domains: The domains of the variables can be easily determined by enumerating all the tokens specified in the initial state.
- Constraints: Can be obtained straightforwardly from the arc and guard expressions. Arc expressions can contain constant values, color variables or mathematical expressions.

From the Artificial Intelligence (AI) point of view, the coverability tree of a CPN model makes it possible to determine:

- All the events that could appear according to a particular system state.
- All the events that can set off the firing of a particular event.
- All the system states (markings) that can be reached starting from a certain set of initial system operating conditions M0.
- The transition sequence to be fired to drive the system from a certain initial state to a desired end-state.

Different approaches have been developed to combine the high description capabilities of simulation models with the benefits of analytical techniques of optimization models that have been proposed in several simulation–optimization approaches. One of the most classical and widely accepted has been the parameterization of the decision variables of the simulation model in such a way that an optimization algorithm can efficiently check the results of the most promising decision variable values. At the end of the procedure it compares the different system outputs and keeps the best of the solutions obtained [6].

IV. CLUSTERING (C) AND INTERACTION CAUSAL SOLVER (ICS) MODELS

The complexity (*i.e.* state space size) of the interaction causal analysis between original and resolution trajectories increases considerably with the amount of trajectories to be analyzed. Thus, it is proposed to identify a set of independent groups of trajectories which do not share any conflict and analyze each subset from the causal point of view by avoiding the combinatorial explosion problem. It is easy to realize that a set of trajectories distributed physically in 2 non coupled areas would lead to 2 different clusters. However, it should be noted that the fact that trajectories share a physical area does not imply that they all belong to the same subset. An efficient clustering causal model has been developed under the formalism of Colored Petri Nets and it is represented in figures 4 and 5a and 5b. Tables I to VI describe the place nodes, transitions and color of each token.

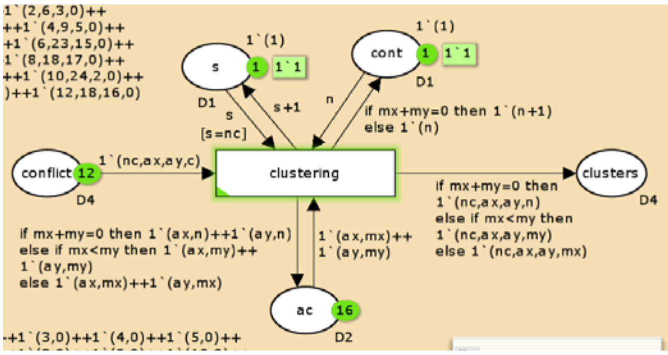

Figure 4. Clustering model in CPN formalism.

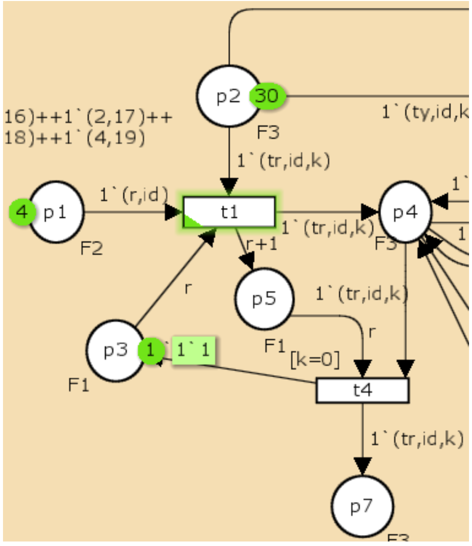

Figure 5a. Interaction Causal Solver (ICS) in CPN formalism (Trajectory picking section).

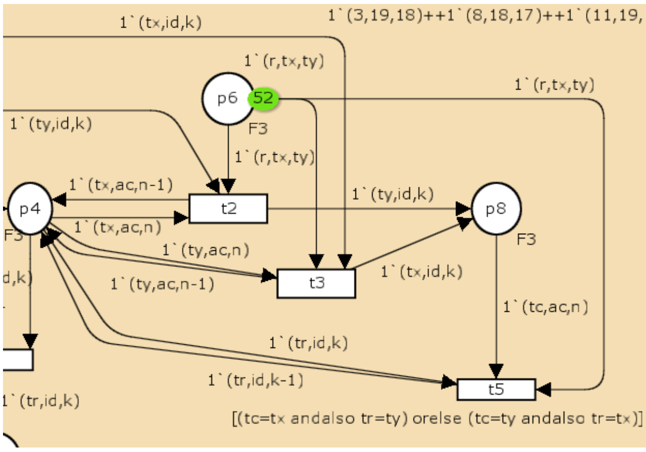

Figure 5b. Interaction Causal Solver (ICS) in CPN formalism (Trajectory interaction analysis section).

A. *Clustering model*

List of place nodes in the model:

- Conflict: set of conflicts (nc) between two aircraft (ax and ay).
- Ac: set of aircraft (ax and ay) with original conflicts (nc).
- S: switch for the sequence of analysis (starts in 1).
- Cont: cluster (n) to be assigned to each conflict (c) together with the aircraft (mx and my) involved.
- Clusters: conflicts processed with a cluster number.

The *clustering* transition evaluates for each conflict and the related aircraft the cluster where trajectories should be assigned.

To form clusters, the model uses the interactions between aircraft and conflicts, and theses clusters can be analyzed separately more efficiently as subsystems in the ICS (Interaction Causal Solver) model.

TABLE I. COLOR DEFINITION IN CLUSTERING MODEL

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

TABLE II. PLACES IN CLUSTERING MODEL

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.

TABLE III. TRANSITIONS IN CLUSTERING MODEL

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

B. *Interaction Causal Solver (ICS) model*

List of place nodes in the model:

- P1: set of aircraft (id) with a sequence number for being processed (r).
- P2: set of trajectories to avoid original conflicts (tr), for each aircraft (id) and with the number of interactions in the system (k).
- P3: switch for the sequence of analysis (starts in 1).
- P4: trajectory to be analyzed once it has been picked.
- P5: the next aircraft to be processed.
- P6: set of interactions between the set of trajectories.
- P7: set of selected trajectories for the conflict free solution
- p8: set of non-compatible trajectories, after the analysis of interactions against a picked trajectory.

TABLE IV. COLOR DEFINITION IN INTERACTION CASUAL SOLVER (ICS) MODEL

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

TABLE V. PLACES IN INTERACTION CAUSAL SOLVER (ICS) MODEL

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.

TABLE VI. TRANSITIONS IN INTERACTION CAUSAL SOLVER (ICS) MODEL

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

The core idea of the ICS model developed is to assign one conflict-free trajectory per aircraft in each feasible solution.

Since there will be different alternative trajectories for each aircraft in conflict there will also be many combinations among them that lead to several feasible conflict free solutions. To find these feasible solutions, the algorithm uses the information on the interactions and the information on the alternative and original generated trajectories.

At the end of the process, several combinations of feasible conflict-free solutions are delivered. By applying different metrics to measure efficiency, safety, robustness, equity and fairness, among other criteria, it would be possible to determine which of the feasible conflict-free solutions is the most preferred, for both the airlines and the Network Manager [4].

V. CASE STUDY, SIMULATION AND RESULTS

In order to show the performance of Clustering and ICS models, a synthetic scenario is presented, featuring 16 aircraft with 12 primary conflicts, and 91 secondary and tertiary conflicts.

Table VII presents the data and figure 6 shows the results for the clustering analysis, and the resultant clusters are listed in table VIII.

TABLE VII. SYNTHETIC SCENARIO

Aircraft	***Trajectories Tr1, Tr2, Tr3…TrN***	***Primary Conflicts (nc, tx, ty)***
2	2	(1,9,8)
3	3,289,315,1589,1615,1641,1667	(2,6,3)
4	4,1590,1616	(3,19,18)
5	5,811,837	(4,9,15)
6	6,292,318,1072,1098	(5,10,6)
8	8,34,60	(6,23,15)
9	9,35,61,815,841,867,893	(7,4,3)
10	10,1076,1102	(8,18,17)
15	15,1341,1367,2121,2147,2173,2199	(9,20,15)
16	16,2902,2928	(10,24,2)
17	17,1863,1889,2643,2669,2695,2721	(11,19,17)
18	18,564,590,1864,1890,1916,1942,2904, 2930,2956,2982,3008,3034	(12,18,16)
19	19,565,591,2645,2671,2697,2723	
20	20,2126,2152	
23	23,1349,1375,1401,1427	
24	24,2390,2416	

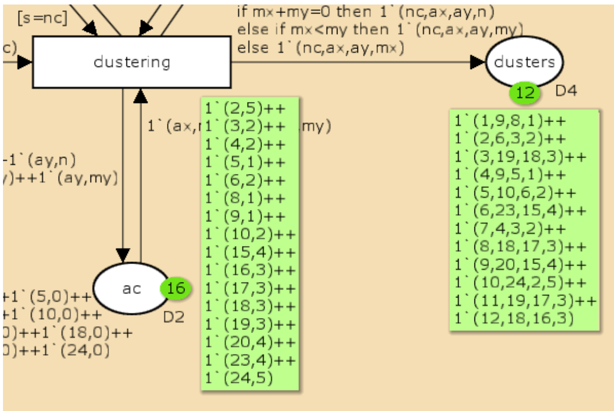

Figure 6. Clustering results in the Colored Petri Net.

TABLE VIII. LIST OF CLUSTERED CONFLICTS

Cluster	***Conflicts***
1	1,4
2	2,5,7
3	3,8,11,12
4	6,9
5	10

With the complete information (aircraft, trajectories and interactions), each cluster is introduced in the ICS to generate feasible conflict free solutions. Figure 7 presents the initial state for cluster number 3, including: 4 aircraft 16, 17, 18 y 19, and 30 trajectories and 52 interactions (primary, secondary and tertiary conflicts).

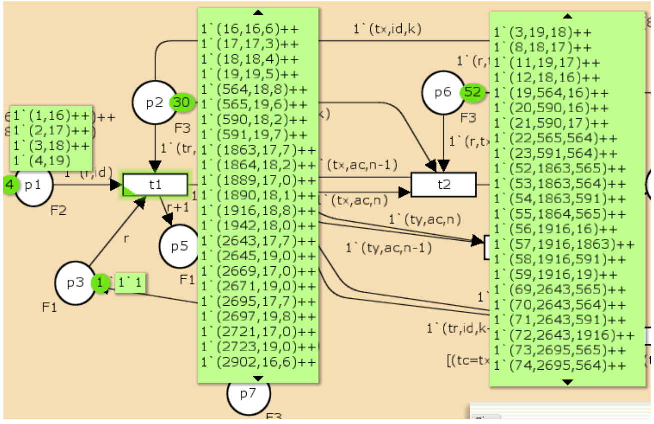

Figure 7. Initial conditions for the ICS Colored Petri Net

Figures 8 and 9 show the two conflict-free solutions (final states) which have been obtained through the state space analysis tool. Place 7 holds the final repository of conflict-free trajectories obtained, wherein the first color is the trajectory id, the second is the aircraft id, and the third is the number of interactions after the process. A feasible solution is obtained when the amount of tokens in place 7 is equal to the amount of aircraft.

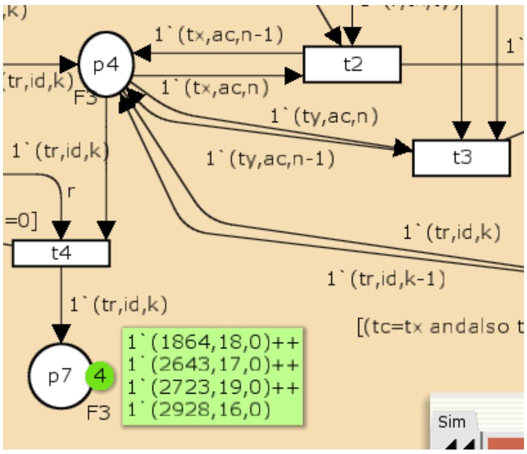

Figure 8. One Feasible conflict free solution for cluster 3.

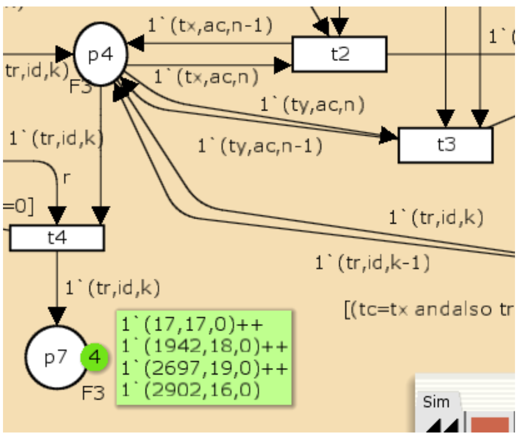

Figure 9. Another Feasible conflict free solution for cluster 3.

Despite the fact that the entire set of feasible solutions (final states) can be explored in the coverability tree, not all the feasible solutions may be of ATM interest, meaning that an efficient and effective search is necessary.

The causal framework and the formalism explained is capable of including some individual metrics (as an additional color) that provide intelligence for the process.

For example, it is possible, by ranking each alternative trajectory (under considerations of fuel consumption, or additional time, etc.) to reflect the preference for certain solutions. Figure 10 presents transition T4 l, with three additional places (*kpi*, *kpi value per trajectory*, *acum kpi*), connected to the transition, which are used to perform a metric assessment.

According to the value of the KPI, the models keep or discard the scenarios that do not match the expected performance.

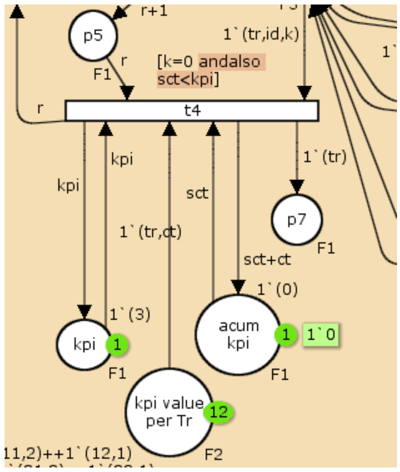

Figure 10. Metric assessment addition.

This structure can be replicated to other metrics and the assessment can be performed by the model simultaneously during the construction of the state space.

The construction of supported combinations of paths is a problem that grows in an expansive way (quadratic and sometimes exponential). To mitigate this problem, the clustered approach, prior to the construction of conflict free scenarios and as described above, allows a significant minimization of the State space size, by grouping the trajectories which have some kind of conflict relationship. As a first step, it is proposed to determine the number of possible trajectory combinations and, in a second step, to assess the compatibility of each local conflict-free trajectory.

By considering an equal amount of alternative trajectories per aircraft for all cases, the number of combinations to render, without clustering, would be K^N, where N corresponds to the number of aircraft and K the number of trajectories of each aircraft. In the proposed example, K is different for various aircraft. Therefore, the number of combinations would be: $(K_{Ac1})(K_{Ac2})(K_{Ac3})...(K_{Ac16})$.

Taking the values in Table VII, the amount of possible combinations is:

$(1)(7)(3)(3)(5)(3)(7)(3)(7)(3)(7)(13)(7)(3)(5)(3) = 1.19 \cdot 10^{10}$

On the other hand, considering each cluster separately, the number of total combinations is reduced considerably as a combination of the solutions provided in each cluster:

$(1)(3)+(3)(7)(13)(7)+(7)(3)(5)(3)+(3)(3)(7)+(7)(5)(3)$

$= 3+1911+315+63+105 = 2.397 \cdot 10^3$ possible combinations.

It is important to mention that not all possible combinations represent compatible conflict-free solutions.

The computational complexity is significantly reduced by clustering. The separation of trajectories according to their interactions is a key idea in high-density traffic scenarios and it deals with several benefits such as a direct increase of processing capacity and troubleshooting.

In the same direction, the ICS model, through the use of causal interactions, makes an intelligent construction by limiting the search exploration process only to those combinations supported within each cluster. Therefore, both tools offer significant advantages in terms of efficiency and effectiveness for the construction and evaluation of conflict-free scenarios in Air Traffic Management problems.

The discrete event-modeling approach—which reflects the dynamic and adaptive behavior of the system and, in turn, provides intelligence on the exploration of their evolution (this capacity is intrinsic in Colored Petri Net models)—plays an important role and draws significant advantages with respect to other tools and analytical techniques such as PL or MIP, methods that have traditionally been used to develop models for decision making in ATM.

For the synthetic example in general, as well as for each cluster separately, the ICS is able to obtain feasible solutions. Additionally, it ensures the existence of feasible combinations by generating as many alternative paths as there are conflicts detected and builds a path to avoid the conflict. In the event that such a trajectory is involved in a new conflict, another path is generated.

The two models presented have the capacity to generate feasible solutions in a reduced computational time either via simulation or by exploring the space of states. STREAM considers further evaluation of the complete platform with scenarios related to the full extent of pan European air traffic during a time window of 3 hours, with the aim to assess the performance and validation of different models (efficiency and effectiveness), including the calculation of KPIs for each scenario in such a way that it can find optimal or near-optimal values for a better strategic decision.

The primal application of the resulting tool is the strategic or pre-tactical de-confliction of trajectories, which could be triggered either by the Network Manager, due to the centrality of its role or directly by the ANSP in close coordination with the NM. The Airspace Users could be involved either directly into the process to ensure maximum visibility of its evolution or off-line through the initial definition of priorities. The use of a dedicated SWIM-based application constitutes the best candidate technology for implementation, since this is going to be established as a standard in ATM and some preliminary tests for flight data retrieving have shown excellent performances in terms of response times and stability. The Human actor, being the traffic manager or the ATCO, will be supported by the tool in identifying the best solutions in terms of conflict-free trajectories but will remain the ultimate responsible for selecting and activating the ones retained as valid. The agreement process should occur exactly as the one engineered by SESAR for the transition from SBT to RBT.

VI. CONCLUSIONS

Some of the emergent dynamics of an air traffic scenario have been shown through the presentation of causal modeling approach, clustering and Interaction Causal Solver (ICS) models. The construction of conflict free scenarios, as described above allows a significant minimization of the State space size, by grouping those trajectories which have some kind of conflict relationship.

This framework appears to be an effective approach for dealing with the emergent dynamics of an air traffic management scenario.

Not only has it been shown that a feasible conflict-free solution can be obtained for a particular synthetic European scenario, but it has been implicitly shown how this approach is extensible to the search of local or global, optimal and feasible conflict-free solutions.

In a scenario over the European ATM, with more than 4500 real trajectories of 1 hour average-length (sampled every 1 second), approximately 400 conflicts were detected in less than 10 seconds, and ICS responded by porposing conflict-free scenarios in less than 30 seconds. The hardware used in the simulations was a medium-range computer (10,000 MIPS) with 64GB RAM (around 40GB were used during the simulation).

The next steps to be undertaken are the development and implementation of metrics calculation; generation of criteria for selection of optimal solutions; development of performance analyses with more complex and denser scenarios; and, finally, the assessment of the advanced STREAM solution integrating latest innovations implemented.

STREAM outcomes fit into a V0 validation level within E-OCVM, extracting the specific needs for a trajectory de-confliction tool at strategic level. However, it also has traces of V1 validation step since it integrates assessments and tests of specific modules that solve some specific needs.

Stemming from this initial validation provided by STREAM (between V0 and V1), further steps towards the generation of a real decision support tool might be taken in more than one direction. The future developments can be derived in two main threads that can be combined. On one hand, it can focus on the specific development and refinement of the conflict detection and resolution with the aim of validating and producing an actual specific tool or application. Alternatively, on the other hand, the future developments can capitalize STREAM valuable outcomes and extrapolate their benefits to be used as a base for decision support tools addressing problems other than only de-confliction, such as demand/capacity balancing and complexity management.

The concepts used in STREAM algorithms can, therefore, be the input to generate new algorithms that focus on the optimization of trajectory design accounting for multiple KPAs and factors affecting the network. This approach would lead to a more thorough integration within a real and more ATM-extended decision support tool that could be used by different stakeholders (e.g. traffic manager, ANSPs, Airspace Users…).

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REFERENCES

[1] Ruiz, S., Piera, M., Zúñiga, C., 2011. “Relational Time-Space Data Structure To Speed Up Conflict Detection Under Heavy Traffic Conditions”. Presented at the SESAR Innovation Days (SID) 2011 EUROCONTROL, ENAC (Toulouse).

[2] Sergio Ruiz, Jenaro Nosedal, Miquel A. Piera, and Andrea Ranieri. “Strategic Conflict Detection and Resolution for Network Manager through Spatial Data Structures and Colored Petri Nets”, unpublished.

[3] Ranieri, A., Martinez, R., Piera, M.A., Lopez, J., Vilaplana, M., 2011. “Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (WP-E project STREAM)”. Presented at the SESAR Innovation Days, ENAC (Toulouse).

[4] Krozel, Bilimoria, Lee, 2001. System performance characteristics of centralized and decentralized air traffic separation strategies. ATM Seminar.

[5] Ruiz, S., Piera, M., Ranieri, A., 2012. Computational Efficient Conflict Detection and Resolution through Spatial Data Structures, in: Proc. of International Conferences on Research in Air Transportation 2012 (ICRAT). Berkley, CA, USA.

[6] Mújica, A., Piera, M., 2011. A compact timed state space approach for the analysis of manufacturing systems: key algorithmic improvements. Int. J. Comput. Integ. Manuf. 24, 135–156.