Coupling and Complexity of Interaction of STCA Networks

Fabrizio Lillo
Dip. di Fisica e Tecnologie Relative, Università di Palermo
Palermo, Italy.
Santa Fe Institute
Santa Fe, USA
lillo@unipa.it

Simone Pozzi,
Alessandra Tedeschi
Deep Blue Research and Consulting
Rome, Italy
[simone.pozzi ,
alessandra.tedeschi]
@dblue.it

Giancarlo Ferrara,
Giorgio Matrella
ENAV
Rome, Italy
[giancarlo.ferrara ,
giorgio.matrella]@enav.it

Frederic Lieutaud,
Bernard Lucat,
Antonio Licu
EUROCONTROL HQ
Brussels, Belgium
[frederic.lieutaud ,
bernard.lucat ,
antonio.licu]
@eurocontrol.int

***Abstract*—This paper provides an overview on the results of an ENAV feasibility study, where we exploited an automatic safety data gathering tool to analyze the ATM system performances. In particular, it addresses the use of the EUROCONTROL tool, ASMT (Automatic Safety Monitoring Tool), as a support to monitor STCA performance. The contribution of this study is to explore how analysis methods derived from complex systems theory (i.e. network analysis) can assist in the understanding, monitoring and management of the performance of ATM systems. Our data show that a large number of STCAs do not occur in isolation, but rather that in roughly half of the cases the aircraft involved in an STCA are subsequently involved in other STCAs with other aircraft in a sort of chain (or cascade) process. In the concluding section, we reflect on open issues and areas of future research that would need to be addressed for an optimal use of Automatic Safety Data Gathering tools.**

Keywords-ASMT; Safety; STCA; Network Analysis; complexity

I. INTRODUCTION

All the civil aviation policy making bodies – including EUROCONTROL, the European Commission and the International Civil Aviation Organisation (ICAO) - have recommended that Air Navigation Service providers (ANSPs) should allocate the necessary resources to safety management systems, including safety occurrence reporting and analysis [1]. The Commission Regulation (EC) No. 2096/2005 transposing ESARR3 into Common Requirements [2] defines the "Safety Monitoring principle": *methods should be in place to detect changes in systems or operations which may suggest any element is approaching a point at which acceptable standards of safety can no longer be met and corrective action should be taken.*

Then, questions are how to monitor large quantity of safety data and how to complement human reporting, that is currently the most widely and well understood method in ATM to monitor system performances. However, technological advances – especially the digitalization of large part of ATM data – has opened the opportunity to implement Automatic Safety Data Gathering (ASDG), with the unique goal of enhancing safety.

II. WHAT IS ASMT

The Automatic Safety Monitoring Tool (ASMT) has been developed by the EUROCONTROL Experimental Centre, in co-operation with and on the basis of the requirements of the Maastricht Upper Area Control Centre (MUAC). The design was initiated in the 1996 and the first ASMT version was installed in MUAC in the 1999. More than 10 years of successive development and successful validation have led to the current version of ASMT that EUROCONTROL HQ is currently supervising to reflect the requests and needs of a growing group of users. ASMT can now be considered as the most advanced tool for Automatic Safety Data Gathering (ASDG).

ASMT can be connected to the operational ATM system in an on line or off-line mode (it can be also connected to a simulation platform in the context of Real Time Simulation) to elaborate in quasi real-time data on radar tracks, flight plans and system alerts. It automatically detects operational and technical occurrences according to user defined parameters. ASMT detects events through the computation of the current air traffic situation, continuously updated from the track and flight plan inputs.

Currently ASMT gathers data on six types of safety events. ASMT own modules detect three of these types: Proximity (e.g. separation minima infringements), Airspace Penetration, Altitude Deviation (e.g. level busts). The recording of the three other types is triggered by system alerts, coming from the ATC system, e.g. the case of Safety Nets (STCA alert or Area Proximity Warning), or down-linked from aircraft, e.g. the case of ACAS-RA alert. For each detected occurrence, it stores the relevant data (shortly before, during and shortly after the event) into a database which can be later queried to extract the data or to review the occurrence in a dedicated replay window. More information on ASMT and on Automatic Safety Data Gathering can be found in [3-6] and at the EUROCONTROL ASMT website.

III. AIM OF THIS STUDY

This paper continues the work carried out in an ENAV study (the results of which can be found in [7]), where two feasibility studies were conducted to further our understanding on the use of Automatic Safety Data Gathering tool (the Automatic Safety Monitoring Tool - ASMT) as a support to (i) monitor radar tracking issues and (ii) STCA performance. The two feasibility studies were strongly oriented towards ASMT operational use, while the study we report in this paper was more research-oriented and explorative in nature. Using the STCA data, we explored how analysis methods derived from complex systems theory (i.e. network analysis) can assist in the understanding, monitoring and management of ATM systems. The application of complex system theory meant to address an issue we have identified in the previous research, that is the lack of structured methods to make sense of large sets of ATM data.

The main advantage of tools like ASMT is that they make it feasible to conduct extensive data gathering with a reasonable amount of resources. However, currently safety analysis and performance analysis is mostly based on a reductionist approach, that isolates single events/features to draw conclusions and intervention recommendations [8]. ASDG data enable system performance monitoring by gathering large amount of data and compiling statistics, and it does not appear to be neither viable nor methodologically correct to return to the single-event level and analyze case by case, as this might fail to appreciate emergent system properties or to highlight macro-level patterns. Emerging properties and patterns often do not have an unique interpretation and it is hardly the case that a clear cut indication can obtained. If resilience has to be a system property [9, 10], then we would need disciplined ways of conducting system level analyses.

Current analysis approaches we found in the ATM literature for the analysis of large sets of data either restrain to the descriptive level without actually moving to the intervention phase, or develop *ad hoc* categorizations based on (sometimes controversial) assumptions like “every STCA alert that lasts less than 20 seconds can be considered as a nuisance alert because controllers do not have enough time to react” [11]. The approach we exploited in [7] was based on the iteration of descriptive statistics and interviews with operational experts, in order to profit of their knowledge in making sense of the data. In practical terms, the results of statistical analyses were shown to operational experts to have their interpretation, comments, or questions. On the basis of their input, further analyses were performed to gain new insights, or to validate their interpretations, or to focus on specific sub-sets of data (e.g. only occurrences above FL280, or with leveled a/c, etc.).

Even though these approaches have all yielded some good results, we still lack a structured method to analyze large amount of dynamic data and to produce results that can be interpreted by operational experts.

IV. STUDY APPROACH

ASMT may be a very sensitive issue in an ANSP, especially as far as legal recording and human reporting are concerned (at least at the current state). Before starting implementing ASMT, fundamentals principles shall be put in place. These are, as a minimum, the policy to use ASMT, to analyze Safety Events with provisions principles for Operational & Technical usage. And according to the policy, the communication to Air Traffic Controller and Technical staff of the use of ASMT.

It is easily considered as a “big brother” tool, spying over the controller’s shoulder and supporting a blame culture of punishment. The approach we adopted in this project tried to avoid this pitfall by designing ASMT use around already existing ENAV process, instead of creating new processes because of ASMT. This activity involved interviews and focus groups with ENAV people to identify potential ASMT uses and how it could support the existing activities.

At the beginning of the project ASMT ENAV, it was quite clear what the instrument could have and should have done at a technical level (the functional requirements), but on the other hand it was not clear which were the aims and objectives the system would be used for (requirements which we could call organizational, i.e. the ASMT role in the organisation). The focus groups and interviews were thus aimed to obtain information on the ASTM role. A first session was conducted during the kick-off meeting, where we presented the tool and some potential uses, in order to gather immediate feedback and expressions of interested from ENAV attendees. This session resulted in four potential uses being identified as more relevant: (i) support to analysis of loss of separation, (ii) support to Multi Radar Tracking tuning, (iii) SID and STAR monitoring, (iv) support to STCA performance monitoring. These four areas were then further explored via dedicated interviews with relevant stakeholders. The objectives of these interviews were to understand what ENAV was currently doing on each area, to identify the ASMT potential contribution to these processes, to discuss potential negative impact. At the end of this phase, the role of ASMT was better understood and we could select two of the above areas for a deeper study. The two feasibility studies were related to (i) Multi Radar Tracking tuning and (ii) STCA performance monitoring.

A follow-up study was later set up to assess the use of more advanced analysis techniques, in particular those related to complex systems study. The use of network analysis to study STCA events was selected among different analyses. Network theory [12-14] has recently proven to be extremely effective in modeling the dynamics of a large number of complex systems, including the internet, ecosystems, social interactions, and economic exchanges. Networks are composed by elements (nodes) that can be connected one with each other with edges (links), representing some form of interaction or similarity between the two nodes. Networks are therefore used to represent in a schematic yet rich way the complexity of interactions among the elements of a system and sometimes its temporal dynamics. Moreover one of the striking results of network theory is that very different systems often share similar characteristics when investigated at a network level, suggesting the possible existence of universal mechanisms of organization. The main goal of the present work was to analyze networks of STCA (i.e. alerts linked by the co-presence of at least one a/c) to identify their topological characteristics, their geographical distribution, and to compare these results with those typical of "single-event STCA".

STCA networks may be engendered by a variety of factors, related to specific a/c (e.g. transponder issues), STCA algorithm configuration, airspace structure, controller's style, traffic load, etc.. Not all of the above factors could be explored, due to the characteristics of the data set. For instance, there were no data available for traffic load, controller on duty, transponder type. Given those limitations, our analysis mainly tried to analyze the geographical distribution of the different networks (and of the different network types, like for instance star-shaped networks *versus* tree-shaped networks), in order to: (i) identify airspace areas where a higher density of STCA networks could be found, (ii) identify areas with a higher density of networks of a specific type. The end goal was to provide a characterization of the different airspace areas in terms of degree of coupling and complexity of interactions:

- Degree of coupling: areas can be differentiated along different degrees of coupling on the basis of the density of STCA networks therein. An area is highly coupled if one STCA triggers other STCA events. It is loosely coupled if the STCA is "solved locally", i.e. it is not linked to other STCA events.
- Complexity of interaction: different network types can be differentiated on the basis of the complexity of their topological structure. Complexity of interaction can result from different aspects, including: number of nodes, number of links, topological structure. In this study we considered the maximum degree (i.e. the maximum number of links connected to one of the network nodes) and the number of edges, as indications of complexity.

The choice of these two characteristics was informed by the comparison of aspects typically studied by network analysis with theories of system safety. In particular, degree of coupling and complexity of interaction are the two features along which Perrow built his famous map of "normal-accident" organizations [15]. According to Perrow, the likelihood of one organization facing a major accident can be described by measuring it along these two structural (i.e. non domain dependent) characteristics.

In summary, our study tried to analyze the different areas of the Italian airspace in terms of degree of coupling and complexity of interactions, by using the STCA networks as a proxy measure (in the sense that we measure the outcome, whilst we would need to measure the process).

V. DATA GATHERING

The data gathering phase of this study was structured in the following steps:

1) Collection of a significant amount of STCA events: the stop rule was defined on a purely statistical basis, by setting the minimum amount of events to be collected to at least 1.000.

2) Validation of collected data. Events were manually searched to find potential false positives and to verify that parameters and filters already in place were working as expected.

STCA was monitored on the whole FIR for approximately four weeks (mid of June '07 to second week of July '07). The connection between ASMT and the operational LAN was subject to frequent interruptions, so it was decided to base our analysis only on consecutive recording periods of at least 24 hours, i.e. with no gaps or interruptions. Only one recording period satisfied our minimum data set requirement, with 1.340 events recorded.

The STCA monitoring is performed by ASMT as a passive receiver of STCA alerts going off on the Shadow Mode platform of Rome ACC. In other words, ASMT does not calculate STCA with its own logic, but it only records traffic data whenever a STCA alert goes off on the shadow mode platform. ASMT filters were set as to filter out all the Double Tracks events (same SSR code for the two tracks) and all the events involving military aircraft (filtered out by referring to military SSR codes).

Manual validation was also conducted on the recorded data, by inspecting most of the recorded events. Additional double tracks or garbling events (i.e. transponder issues) were identified and discarded, as well as airport traffic and a few VFR flights.

VI. DATA ANALYSIS METHOD

The main purpose of this article is to investigate (i) the number of STCAs generated by a pair of aircraft and (ii) the network of aircraft involved in a STCA. For both types of analysis it is necessary to identify uniquely each aircraft. The collected data contain this information coded in the transponder codes of the two aircraft involved in a STCA. Unfortunately the same transponder code can be associated to different aircraft in different times of the day or in different days. In order to identify uniquely aircraft, we decided to put a temporal threshold such that if the same code appears in two STCAs separated by a time lag longer than the threshold, we consider the two aircraft as different. We do not choose the threshold arbitrarily but we derive it from the data. Specifically, we consider all the 222 pairs of codes that generated more than one STCA. We assume that it is very unlikely that both codes involved in an STCA are reassigned to two new aircraft in a short time period and that these two new aircraft also generate an STCA. The analysis of the time interval elapsed between the first and the last STCA of a given pair of codes shows that in one case it is equal to 417 minutes, while in the other 221 cases it is shorter than 70 minutes. We therefore decided to put our threshold equal to 70 minutes. In other words, in our analysis we will assume that if the same code appears in two STCAs separated by more than 70 minutes, the code is associated to two different aircraft. This threshold was also discussed with ENAV ATM experts, who confirmed its soundness from an operational perspective (different criteria might be applicable, depending on the available data; see the Discussion Section for a list of alternative threshold criteria). This procedure leads to interpret the 912 distinct codes in our database as generated from 1513 distinct aircraft.

We construct a network of aircraft involved in a STCA in the following way. The nodes of the network are the aircraft, which have been involved in at least one STCA. Two nodes (aircraft) are linked if they were involved together in at least one STCA. The meaning of this network is the following. If each STCA were an isolated event involving two aircraft and if, once the STCA is resolved, the two aircraft did not generate other STCAs, the network of aircraft would be composed of many connected components[1] made of two nodes and one link between them. The presence of connected components with more than two nodes is an indication that the scenario is not so simple and that, once a STCA is resolved, the aircraft generate new STCAs with other aircraft, which in turn can generate other STCAs and so on in a sort of chain reaction. In other words the presence of connected components with more than two nodes may be an indication that resolving a problem at a local level is not the same as resolving the problem at a global level and that the resolution of a STCA should take into account the other STCA it may generate in the future.

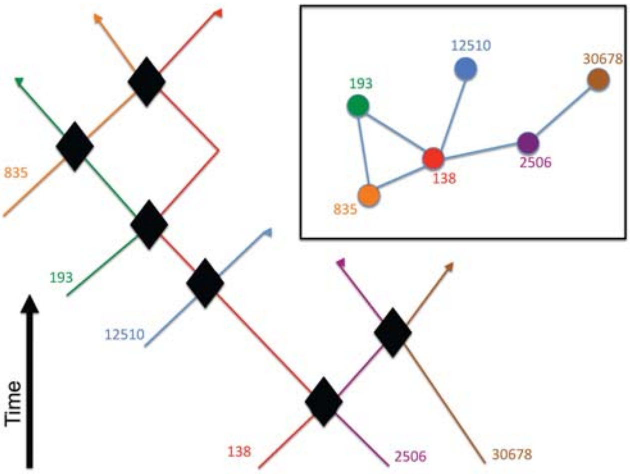

Figure 1.Example of a group of 6 aircraft generating 6 STCAs. The inset shows the corresponding network investigated in our study. For a detailed description of the figure see the text.

Figure 1 shows an example of one of the connected components detected in our data. The case study describes a group of 6 aircraft, which generated 6 STCAs among themselves. In the main panel we indicate with a black circle a STCA between a pair of aircraft, while we represent the aircraft with lines (the colour of the line and the number identifies the aircraft). Time goes from bottom to top of the figure. We represent this set of aircraft/STCAs with the network shown in the inset of figure 1. Here the nodes are the aircraft and a link between two nodes indicates that (at least) one STCA involved the two corresponding aircraft. Note that even if more than one STCA existed between two aircraft, we represented it as a simple edge (i.e. we considered the unweighted network).

The present analysis focuses on the topological properties of the connected components of the network of aircraft. We will compare the connected components to three types of topology namely a tree, a star, and a path graph. A tree is a graph in which any two vertices are connected by exactly one path, i.e. it is a connected graph without loops. A star is a specific type of tree in which one node is connected to all the other nodes that are not directly linked one with each other. Finally, a path graph is another type of tree with two nodes of degree[2] 1 and the other nodes of degree 2. In other words a path graph is a chain (or a thread) of nodes. The relevance and meaning of these topologies is the following. A prevalence of tree structures indicates that if aircraft A and B generated an STCA and aircraft B and C generated an STCA, it is unlikely that A and C generate an STCA. A prevalence of star structures indicates that it is common that one aircraft generates many STCAs with other aircraft, which do not interact one with each other. Finally, a path graph structure indicates that A generated an STCA with B, B generated an STCA with C, and so on. In order to assess the degree of treeness of a connected component we simply count the number of edges in each connected component. If there are N nodes (aircraft) in the component, there must be at least N-1 edges. If there are exactly N-1, the component is a tree. If we know that a component is a tree we can test for its “starness” by measuring its maximum degree. If it is N-1, the tree is a star, if it is 2 it is a path graph. A star structure with 5 nodes is depicted below, in Figure 2.

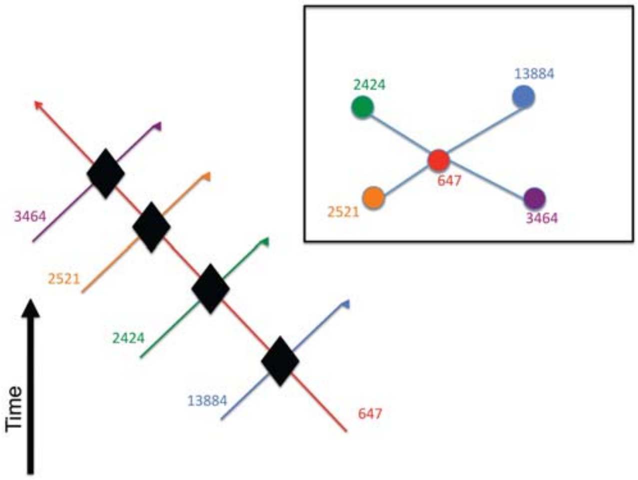

Figure 2. Pure star structure with 5 nodes.

Network analysis was complemented by descriptive statistics, to analyse the distribution of STCA in relation to geography (latitude, longitude and FL bands), time, and duration. These analyses were performed on the network of aircraft and compared with the results of the same analyses on the complete data set (i.e. STCA generated by the network of

---

[1] A connected component is a subgraph in which any two vertices are connected to each other by paths, and to which no more vertices or edges can be added while preserving its connectivity.

[2] The degree of a node is the number of edges incident to the node.

aircraft and all the STCAs). The latter analyses are described in [7].

Results were discussed with ATM experts to have their support in the interpretation of results, to understand the operational relevance of results (if any), to identify additional analyses to be performed.

VII. RESULTS

We first investigate the frequency of the number of STCAs generated by a pair of aircraft. This number gives a rough measure of how rapidly an STCA is resolved. Ideally, one would expect that when a pair of aircraft generates an STCA a countermeasure is taken to solve the problem and these two aircraft do not generate (together) other STCAs. The analysis shows that this is not the case. The following table shows the frequency of number of STCAs generated by a pair of aircraft.

#STCA	1	2	3	4	5	6	7	8	9	≥10
#events	724	144	47	12	5	6	2	1	2	3

The table shows that in 222 of the 1340 STCAs (23%) the same pair appears, i.e. the same pair generates more than one STCA. The following table shows the frequency of the number of minutes elapsed between the first and the last STCA of a given pair of aircraft.

Minutes	0	1	2	3-4	5-10	11-20	>20
#events	51	93	31	13	15	11	8

The table shows that while most of the STCAs are short lived a significant fraction of them last for many minutes, showing either a difficulty in resolving the conflict between two aircraft, or STCA alerts engendered by technical issues. ATM experts suggested issues related to the Multi-Radar Tracking system or transponder transmission as two possible causes.

We now turn to the investigation of the network of aircraft. The number of nodes is of course 1513, i.e. the number of distinct aircraft involved in at least one STCA and obtained with the filtering procedure described in the previous section. The number of edges is 947. The network is partitioned in 572 connected components. Note that in the ideal case in which each aircraft has a STCA with only another aircraft the number of connected components would be 1513/2=756.2. The fact that the real number of connected components is significantly smaller than this number indicates the presence of many components with more than two aircraft. We find that 404 components have exactly two nodes, while the remaining ones have more than 2 nodes. This means than 808 aircraft of the 1513 (53%) are involved in an STCA, which involves only two aircraft, and 705 aircraft (47%) are involved in subnetworks of STCAs with more than only another aircraft. This result is quite surprising because it indicates that in roughly half of the cases STCAs do not occur in isolation but rather they are clustered. This also indicates that the resolution of an STCA very often triggers other STCA. This may be the result of the typical time frame of the controller's work. Controllers can ensure a local optimization (i.e. they address STCA alerts), but they have limited means (and competence) to provide a conflict-free trajectory for a longer time frame.

More quantitatively, the distribution of the size of the connected components of more than two nodes is

Size	3	4	5	6	7	8	9	10	11	13	15	17
Freq.	94	32	17	8	4	4	4	1	1	1	1	1

The table shows that even if most of the components have 3 or 4 nodes, relatively large components with more than 10 nodes are present. The largest component describes a network of STCAs involving 17 aircraft.

The network of aircraft was also analysed with descriptive statistics, to obtain the distribution of STCA in relation to geography (latitude, longitude and FL bands), time, and duration. The comparison with the initial data set of STCA did not provide any useful insight, in the sense that no highly specific differences could be appreciated in the results. For brevity's sake, these results are not reported in this paper and only a 3D map of the STCA alerts is depicted below (Figure 3). A straightforward interpretation of this result is that "networked STCAs" (STCAs generated by aircraft part of the network) do not show any relevant difference from single STCAs, at least as far as geographical distribution (including FL bands), time distribution and duration are concerned. In other words, these results suggest that, at the present state of knowledge and with further more refined analyses pending, we can rule out the possibility that only specific types of STCAs give rise to network of STCAs.

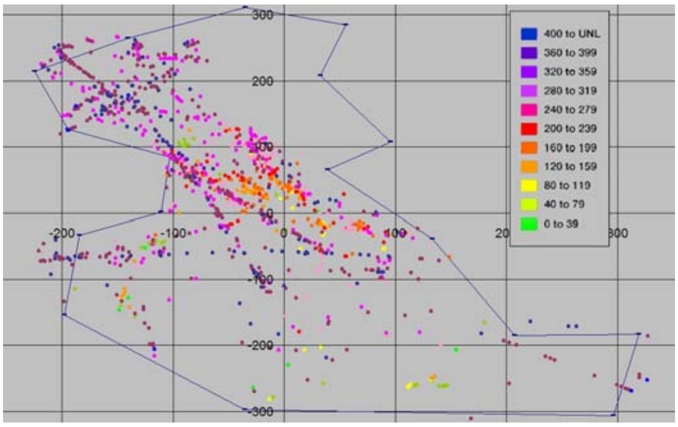

Figure 3. Geographical distribution of STCA events caused by the network of aircraft, colour coded for FL bands. N.B.: plots represent STCA events.

We now investigate the topological properties of the connected components. Figure 4 shows the mean number of edges in the components with a given number of nodes (aircraft). Remember that the connected nature of the components sets a lower limit of N-1 edges for a component of N nodes. We observe that the mean number of edges is very close to the value for a tree. A closer inspection confirms that only 6 of the 168 components with more than 2 nodes are not trees. Also in these cases the topology is not very different from a tree. The components are well described by trees, as reported in Figure 5, which shows the mean of the maximum degree as a function of the number of nodes in the component.

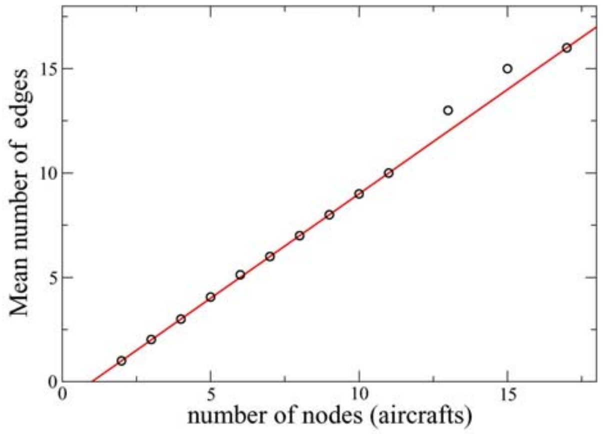

Figure 4. Mean number of edges as a function of the number of nodes in the connected component. The straight line is described by the equation y=x-1 which is expected for a tree structure.

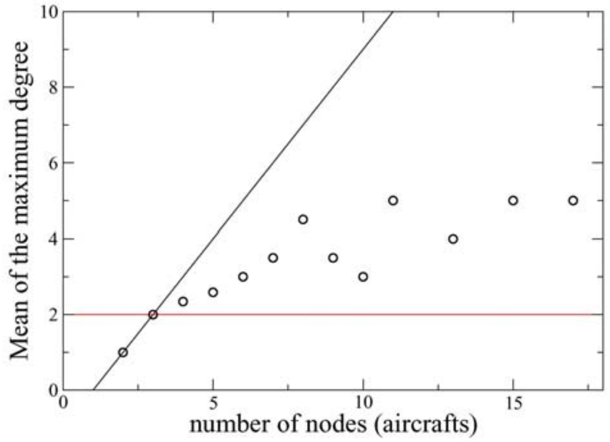

Figure 5. Mean of the maximum degree as a function of the number of nodes in the connected component. The black line is described by the equation y=x-1 which is expected for a star structure, while the red line is described by the equation y=2, which is expected for a path graph (i.e. a chain).

The figure above shows that for large subnetworks the topology is more similar to a path structure than to a star structure. However there is a large dispersion indicating that the simple star and path topologies do not capture the typical topology of the subnetworks. In fact, in the figure above, we only show the mean values, however there are no "pure" star structures with more than 5 nodes, nor "pure" path structures with more than nodes. Two conclusions can be drawn from this graph:

- our subnetworks can often be described as trees, which cannot be described as simple "pure stars" or "pure paths"
- highly coupled structures (with many nodes) tend to become more similar to path structures

The vertical dimension of connected components (subnetworks of aircraft) was also analysed. For each subnetwork, we calculated the following statistics: average FL, median FL, max FL, min FL, Delta FL (max minus min), standard deviation. These figures represent the vertical distribution of aircraft in the subnetwork, e.g. STCAs that all occurred on the same FL would result in delta equal to zero, while STCAs widely distributed on many FL would give a high delta. The average FL shows no correlation with the number of nodes, while correlation exists between Delta FL and number of nodes (see Figure 6).

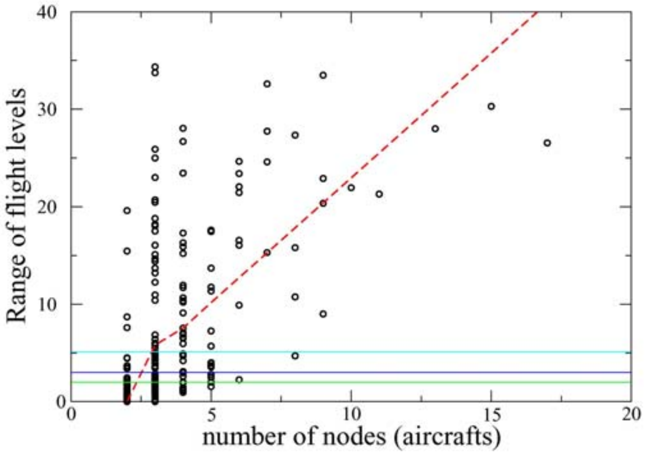

Figure 6. Delta FL for each subnetwork of aircraft. The red line shows the average Delta FL (smoother LOWESS) as a function of the number of nodes. The green line is the median Delta FL value for the whole data set, the blue one is the 75th percentile, the light blue one the 95th percentile.

In the above figure small subnetworks consistently show a small Delta FL, while big subnetworks (i.e. those with more than 5 aircraft) span across a much larger FL band. Even if this might have been anticipated, the magnitude is quite a remarkable one: above 9 aircraft the average Delta FL is 20 or 30 times bigger than the average for the whole data set.

This can be taken as an indication that networks of aircraft are not constrained only in specific FL bands, nor they tend to propagate only in the same flight phase (i.e. en-route STCAs only trigger other en-route STCAs). A Delta of more than 20 flight levels means that aircraft in the corresponding network are likely to be in markedly different flight phases, from post-departure or pre-arrival sections to en-route ones (the STCA is not in use in departure and arrival sectors in Italy). Figure 7 shows how one big network (11 nodes, only STCAs plotted in figure) spans a wide FL band (from FL160 to higher than

FL400).

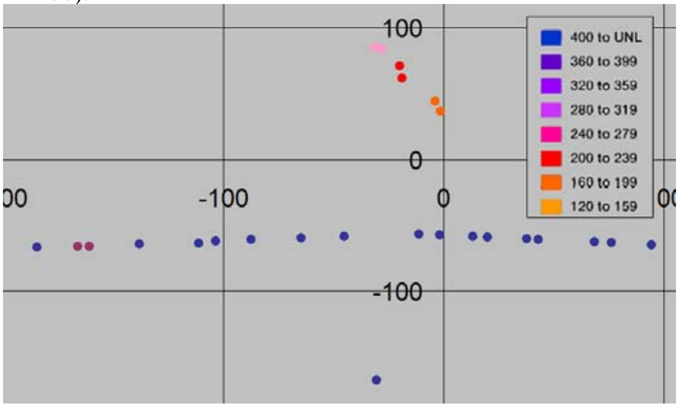

Figure 7. The STCAs caused by one network of aircraft with 11 nodes.

VIII. DISCUSSION

The main point we would like to elaborate on in this section is related to the benefits of applying network analysis to ATM data. Even if our data sample cannot be considered as representative of the rest of the European airspace (and not even as representative of the rest of the Italian airspace and/or of other year periods), we cannot disregard how nearly 50% of the aircraft was involved in the network of aircraft. This indicates a good capability of local optimisation, however at the cost of a less efficient strategic optimisation. One out of two STCAs is likely to be linked with other STCAs.

This exploratory study mainly aimed to deepen our knowledge on methodological issues, i.e. on how to study ATM as a complex system. However, some results can also be mentioned:

- compared to ATM experts' expectations, the system is highly coupled:
    - 50% of the STCAs are linked with another STCA,
    - 23% of the STCAs are multiple STCAs, i.e. the same pair of aircraft has already generated another STCA
- almost all the subnetworks can be described as trees (low number of nodes, low maximum degree). This means that if aircraft A and B have been involved in a STCA, then aircraft B is involved in one with aircraft C, then it is very unlikely that a STCA link aircraft C and A. In general the topology of the subnetworks cannot be described by pure star structures or path (i.e. linear) structures. However, by using topological measures we conclude that the subnetwork topology is more similar to a path structure than to a star structure (even if there is large dispersion)
- there is a significant correlation between the Delta FL and the number of nodes. This indicates that STCAs do not propagate only in specific FL bands, rather they may propagate between different flight phases, from departure/arrival to en-route
- "Network STCAs" do not show highly specific characteristics compared to "single STCAs". This is the result of our preliminary data set. A more extensive data set and more focused analysis techniques would be needed to quantitatively compare "network STCAs" with "single STCAs" characteristics

The last bullet brings into the light one key benefit of network analysis. If we want to focus on system properties, these cannot be appreciated by focusing on STCAs as single events. You would not be able to distinguish a "network STCA" from a "single STCA" just by analysing its characteristics. System features can only emerge by directly studying the ATM system with appropriate techniques, different than current reductionist approaches typically used in the domain of system safety [8].

IX. OPEN ISSUES

This study was carried out to tentatively outline an analysis method for big ATM data sets, collected by means of ASDG tools. Rather than achieving specific results, we are now in a better position to plan further (and more extensive) data gathering campaigns, and to define other analysis approaches that might be worth pursuing. Additional data fields, presently not collected by ASMT, are also among our desiderata: use of aircraft callsigns instead of SSR codes to build the networks, vicinity traffic to construct "second-order" networks, sector ID to obtain the sector taxonomy we aimed for.

The next objective we would like to tackle is to draft a taxonomy of sectors (or airspace portions) along the two dimensions of *degree of coupling* and *complexity of interactions*. For such a study, we would need to complement our data set with the geographical coordinates of Rome FIR sectors, to be able to couple networks with concerned sector(s). A study on the relative frequency of networks in the various sectors would then yield the expected result, possibly including recurring correlations between some sectors (e.g. the boundary between two sectors may result more "permeable" by networks than other boundaries). Such a study would also entail the definition of a normalisation factor, to make sure that network frequencies take into account the different traffic load of each sector. Other possible sector categorizations, according to different complexity metrics for air traffic, as defined in [16][17][18], would be object of further investigations.

The application of different thresholds to identify and define networks is also a likely area of future research. Identification-wise, we may want to directly use callsigns, or distance travelled as a function of time elapsed (this is going to be FL dependent). The network definition can be based on the following criteria:

- operationally-informed thresholds could be applied (e.g. 15 minutes, or even shorter ones). Such a threshold would be primarily based on operational considerations on how long it takes for a "STCA perturbation" to vanish. In practical terms, this means that an aircraft involved in two STCAs would not be considered as part of the same network if 15 minutes have passed between the two STCA

- duration of STCA can be used to discard too short STCA as operationally non-relevant (see [11])
- consecutive alerts can be discarded, or simply put in a different data set to be studied on its own
- multiple STCA aircraft can be identified to analyse potential transponder issues

A shorter threshold may be compensated by the inclusion in the network of "second-order" aircraft, i.e. aircraft not directly involved in a STCA event, but close enough to be impacted by it. These aircraft can be recorded by the vicinity traffic function of ASMT. It also might be useful to complement the analysis we have performed in this paper with other analyses of the STCA performances, e.g. whether the STCA alerts are provided sufficiently in advance to allow controller's to avoid potential losses of separations, whether STCA misses some detection, the impact of STCA parameters change on the number of STCA alerts and their characteristics.

Different thresholds may also be defined to partition large networks into smaller subnetworks. These thresholds may be defined on a time-basis, or on other criteria such as number of links (i.e. strength of connection). The aim of such a study would be to identify subnetwork specific characteristics (different than those exhibited by the parent network), to be either blocked (if negative) or exploited and possibly replicated (if positive).

Further works might also research the applicability of additional metrics for the network analysis (e.g. centrality, spatial complexity, communities), or model how STCA networks are generated, in order to compare real and simulated results through multivariate analysis.

X. CONCLUSIONS

In conclusion, the implementation of ASDG tool like ASMT aims at reducing the safety risk by identifying potential difficulties and problems. The absence of such a tool or the refusal to implement it, despite its availability and the recommendations by the ATM authorities to use it, could go against the obligation of due diligence that ANSPs have to try and reduce safety risks, and could ultimately increase their potential liability.

This study has demonstrated the usefulness of ASMT in the technical aspects of the operations, with the ultimate aim of improving performance of technical systems (which may or may not require technical modifications). ASMT increases the visibility ANSPs have on safety occurrences, thus bringing about better opportunities for safety improvement initiatives. Supporting good SMS practices by providing factual evidences of e.g. high reporting levels, or providing evidences of proactive safety management, is also the role of such a tool.

EUROCONTROL is currently deploying ASMT ECAC-wide and also over ECAC.

ACKNOWLEDGMENT

The authors would like to express their gratitude to all the ENAV people that devoted part of their time for our study, to Paola Lanzi, Giulia Lotti, Alberto Pasquini and Luca Save (Deep Blue); to Gaetano Vito and Fernando Patrizi (SICTA) for their work on the technical part of the ASMT installation and configuration. We thank Mete Celiktin and Gilles Le Galo (EUROCONTROL) for their support to our work.

REFERENCES

[1] EUROCONTROL, A Strategic Safety Action Plan for Enhanced ATM Safety in a Single Pan-European Sky, 2003.

[2] Commission Regulation (EC) No 2096/2005, Laying down Common Requirements for the provision of air navigation services, 2005.

[3] EUROCONTROL, ASMT Introduction, 2006.

[4] EUROCONTROL, ASMT Data Analysis Guidance, 2007.

[5] EUROCONTROL, Guidance Material for Automatic Safety Data Gathering, 2004.

[6] EUROCONTROL, Operational Requirements for Automatic Safety Data Gathering Tools, 2004.

[7] Pozzi, S., et al. Turning information into knowledge. The case of Automatic Safety Data Gathering, in EUROCONTROL Annual Safety R&D Seminar, Southampton, UK, 2008.

[8] Leveson, N.G., "A New Accident Model for Engineering Safer Systems," Safety Science, **42**(4), p. 237-270, 2004.

[9] Hollnagel, E., Resilience-The challenge of the unstable, Resilience engineering: concepts and precepts. Aldershot, UK: Ashgate Publishing Limited, 2006.

[10] Hollnagel, E., D.D. Woods, and N. Leveson, Resilience engineering : concepts and precepts. Aldershot, UK; Burlington, VT: Ashgate Publishing Limited, 2006, p. xii, 397 p.

[11] Piccione, D. Air Traffic Control Safety Alerts: reducing the Nuisance, in EUROCONTROL Annual Safety R&D Seminar, Rome, Italy, 2007.

[12] Albert, R. and A.L. Barabasi, "Statistical mechanics of complex networks," Reviews of modern physics, **74**(1), p. 47-97, 2002.

[13] Newman, M.E.J., "The structure and function of complex networks," SIAM Rev., **45**(2), p. 167-256, 2003.

[14] Newman, M.E.J., A.L. Barabasi, and D.J. Watts, The structure and dynamics of networks, ed. . Princeton, N.J.: Princeton University Press, 2006.

[15] Perrow, C., Normal Accidents: Living with High-Risk Technologies, 1999, 2nd ed. New York, NY: Basic Books (2nd ed. Princeton, NJ: Princeton University Press), 1984.

[16] Complexity Algorithm Development: Literature Survey and Parameter Identification. EUROCONTROL, DAS/ATS, Edition 1.0, February 2004.

[17] Complexity Algorithm Development: The Algorithm. EUROCONTROL DAS/ATS, Edition 1.0, April 2004.

[18] Complexity Algorithm Development: Validation Exercise. EUROCONTROL DAS/ATS, Edition 0.3, September 2004.