

Dynamic Approaches from Complexity to Manage the Air Transport Network

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Foreword – This paper describes a project that is part of SESAR Workpackage E, which is addressing long-term and innovative research. The project was started early 2011 so this description is limited to an outline of the project objectives augmented by some early findings.

Abstract – Much recent research activity has been devoted to the study and the development of theoretical models of complex networks. The SESAR WP-E project NEWO (emerging NEtwork-Wide Effects of inventive Operational approaches in ATM) explores the emergence of propagation phenomena in the air transport complex network by means of a mesoscopic modelling framework for analysing multi-component systems with complex interactions. The project studies the link between specific prioritisation rules applied to flights in cases of capacity shortfalls at nodes, and the network behaviour and stability, both locally and at network-wide scales. This paper outlines the modelling framework chosen, as well as the current regulatory framework in air transport and some preliminary ideas for prioritisation coming from complexity related literature and applications in other complex networks.

Keywords–air transport; complexity; network management; emerging behaviour; delay propagation.

I. INTRODUCTION

The last decades have witnessed the birth of a new movement of interest and research in the study of complex networks, i.e. networks whose structure is irregular, complex and dynamically evolving in time, with a renewed attention to the properties of networks of dynamical units. This flurry of activity has been certainly induced by the increased computing powers and by the possibility to study the properties of a plenty of large databases of real networks. These include transportation networks, phone call networks, the Internet and the World Wide Web, the actors' collaboration network in movie databases, scientific co-authorship and citation networks from the Science Citation Index, but also systems of interest in biology and medicine, as neural networks or genetic, metabolic and protein networks.

The existing literature and research results range from purely theoretical network studies to models and simulations of real-world networks. A matter of much study is the relation between specific network properties, either static/structural or

dynamic/diffusive, and their consequences in terms of network local and global behaviour. The SESAR WP-E project NEWO (emerging NEtwork-Wide Effects of inventive Operational approaches in ATM) explores the potential applicability of concepts and results of these studies to the management of the air transport network. In particular, NEWO project is focussed on how certain routing rules, if applied to the air transport network, could potentially improve the network stability and help constraining the propagation of delays. Ideas are sought in theoretical studies and in other real complex networks. The exploration requires the use of techniques able to capture how local scale changes are translated into network scale effects, modelling and simulating a number of scenarios to cover as much as possible all potential situations and network configurations.

A. Modelling the Air Transport Network

Air Traffic Management (ATM) modelling is a discipline almost as old as ATM itself. The catalogue of existing models and modelling approaches is ample. Looking at the level of detail the model accounts for, classical ATM models are either microscopic, meaning that they consider the dynamics and detailed routing of every individual vehicle, or macroscopic, focussing on system properties as a result of integrating the state of the ATM elements. Most simulation effort in ATM has been devoted to microscopic models.

Mesoscopic models are the intermediate and most recent approach being under study. These models exploit probabilistic methods to account for the microscopic details without losing the macroscopic and strategic view of the system. Results are expressed as probability distributions, linked, for instance, to the probability of having aircraft A at time t in position x. These models simulate individual vehicles, but describe their activities and interactions based on aggregate (macroscopic) relationships. A mesoscopic approach is in NEWO the preferred option for the assessment of the potential impact of general (non-vehicle specific) routing rules on the delay and overloads propagation patterns, geographical stability and global performance degradation.

B. Characteristics of Air Transport as a Complex Network

The air transport network presents non-linear coupling of local dynamics, queuing generation and congestion propagation phenomena, all characteristics of complex networks.

For the study of the air transport properties in this context, the chosen approach is to consider airports as nodes or vertices with symmetric relationships (undirected networks), with minor asymmetries arising from a small number of flights following a “circular” path. The capacity or intensity of the relationship between nodes is heterogeneous (weighted networks). Elements travelling between two nodes are flights or aircraft. The weights of the links are given by the number of flights connecting two airports.

The U.S. airline system, as studied by [2], is a scale-free network, which contains hubs — nodes with a very high number of links. Small-world and scale-free properties of the U.S. and the world-wide air transportation network are confirmed in different datasets and analysis ([1], [18], [19]). In [20] it is included a summary of other studies focussing on diverse airport network such as China, India or Brazil. In scale-free networks, the distribution of node linkages or node degrees follows a power law, with most nodes having just a few connections and some having a great number of links. In that sense, the system has no “scale.” The defining characteristic of such networks is that the distribution of links, if plotted on a double-logarithmic scale, results in a straight line.

Moreover, in the air transport system nodes are dynamical systems whose dynamics are both influenced by and influencing other nodes dynamics through the matrix of connections.

The community structures are evident in the Air Transport. Using network theory terminology, communities are sub graphs whose nodes are tightly connected, or at least more connected than in a random equivalent network. As it could be predicted, the vertices connecting different communities are usually hubs in their own community [1]. This strong hub structure manifests itself through a great tolerance of the Air Transport network to errors and random attacks (attacks targeting nodes at random), but extreme vulnerability to a target attack to hubs [3].

II. PROPOSED MODELLING FRAMEWORK OF AIR TRANSPORT NETWORK

A. Model Structure

The model proposed in NEWO is a mesoscopic approach to the ATM network in terms of graphs, analytical equations and statistical parameters.

The model network is composed of heterogeneous nodes (saturated areas and airports) linked by air routes aggregations:

- Nodes are ATM elements with capacity restrictions: airports and high density airspace areas.

- Network topology includes geodesic coordinates of airports, distance layer and design capacities of each node, regardless of the specific capacity limiting factor.
- Local rules determine how traffic flows diffuse across the network by modelling the internal dynamics of the nodes behaviour, and they are the mean of simulating airport operations from a macroscopic point of view.
- Global and local variables are defined to obtain performance indicators and to depict the network behaviour.

The type of input traffic managed by the tool consists of a list of scheduled flights with at least the following basic information for each flight: Estimated Take-Off Time, Callsign, departure airport, destination airport, and flight duration. For each particular flight a set of customisable milestones are considered to mark the transition between phases of flight (e.g. Off-Block Time, Take-Off Time, Arrival Time and In-Block Time).

Free routing is assumed to be in place for most connections between airports, and thus airports are linked by the shortest routes. Highly congested areas are considered as additional nodes of the network with capacity restrictions. These areas are defined based on the assumption that the airspace structure will, in most cases, be able to deliver the required capacity for the area, i.e. that most capacity limitations lie within the nodes, typically airports. Congested airspace areas are simulated by introducing additional nodes. Ad-hoc or user defined airspace areas with capacity restrictions can be set, for instance to analyse the impact of a meteorological event affecting part of the network (airports and airspace). These ad-hoc airspace areas are set to infinite capacity in nominal conditions and their capacity is reduced according to the temporal occurrence of the disturbance in abnormal conditions.

An airspace density map can be built from the traffic demand, in order to identify the trajectories (links between airport nodes) crossing each area.

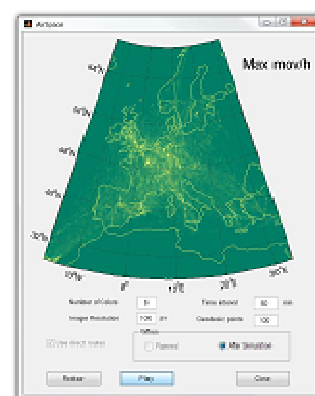


Figure 1. Airspace density map.

B. Operation of the Model and implementation of Routing Rules

The model confronts, for the day of operations, the planned demand (input traffic sample) and available capacity at nodes. Demand and capacity balance is observed by dynamically adapting traffic to capacity constraints, according to the defined rules for traffic diffusion. Departures and arrivals are aligned with actual network conditions: when capacity at departure airport and/or destination airport is insufficient to accommodate demand, departures and arrivals are managed according to prioritisation rules on flights. Main parameters used are:

- Time interval T : used to check capacity availability in an interval smaller than one hour (typically 15 min).
- Real capacity of a node at T_i : it is coincident with declared capacity unless there is a capacity shortfall.
- Estimated capacity of a node at T_i : it depends on the information about the capacity of the node that is available for the rest of the network.
- Ratio Arrival/ Departure of airport A at T_i : it can be a given proportion or calculated for each T_i from the planned demand.

A dynamic graph is generated from the traffic demand. Distances between nodes are modelled in terms of time units (each time unit representing a time interval). Planned traffic is thus grouped into flows, according to the defined time interval, generating a dynamic graph.

In air transport, two flights can be linked because both are using the same aircraft. These links are the main cause of the appearance of reactionary delays in the system [4]. The model applies on the traffic sample an algorithm for linking flights. For two consecutive, linked flights, a minimum rotation time is defined (considered as the minimum turnaround time required), so that there is a start-to-end link between the $n+1$ rotation and the precedent flight. The algorithm used is the following:

- 1) In order to clean the traffic sample, for every flight, origin and destination are checked to note if they are the same (circuit flights). These flights are not linked with any other flight (as they are typically test flights, training, etc.)
- 2) For each flight F, a search is done between all flights with take-off time later than the estimated time of arrival of F, checking if there is a coincidence of the tail number: if this is the case, the link is established.
- 3) For each flight G of the flights not previously linked, a search is performed at the destination aerodrome for the next flight with estimated take-off time later than the estimated time of arrival of G plus a defined minimum rotation time, checking if there is a coincidence of aircraft type and operator: if this is the case, the link is established.

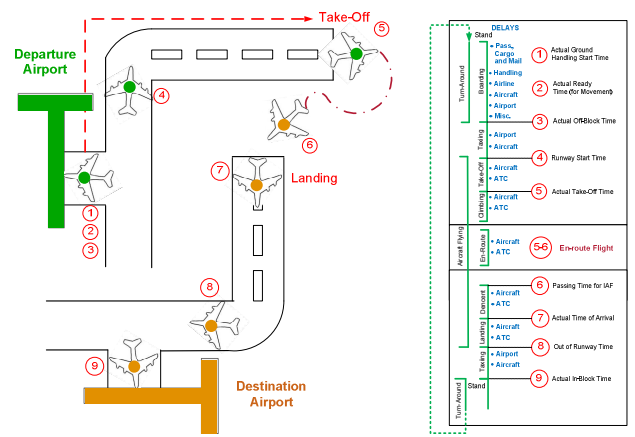


Figure 2. Example of customisable flight milestones and possible primary delays at each flight step.

The routing rules define how flights are handled at airports and airspace high density areas. They define which criteria must be fulfilled for a flight to go from a milestone of the set of customisable milestones to the next one (see Fig. 2 for an example of flight milestones). At airports, usually these criteria are a minimum time elapsed and, if a flight is linked to a previous one, the completion of the precedent flight, meaning the availability of the aircraft. The model checks in real-time or within a pre-defined time interval if the estimated capacity at nodes is exceeded for any T_i . In case a capacity problem is detected, regulation is applied in the form of ground delays, holdings and flight speed adjustments. Prioritisation criteria are applied to flights for imposing delays.

The level of granularity of such rules can be customised, from traffic flows to individual flights. Traffic flows can be defined in terms of departure airport, arrival airport, airline, type of aircraft, etc.

Internal disturbances account for all the potential sources of uncertainty related to the air transport system: turnaround process of aircraft at airports, taxi and flight duration variability, etc. They are modelled as aggregated parameters which values are obtained from a statistical analysis of delay data. In the case of the turnaround, for instance, a fixed rotation time can be defined (considered as the minimum turnaround time required for each type of aircraft being modelled) and variability is included as a stochastic variable added to the fixed rotation time. This variable follows a probability distribution defined in line with available statistics of actual variability (or primary delays) of turn-around time at airports.

The occurrence of diverse events can be simulated (uncertainty of demand, capacity shortfalls at nodes, etc.), in order to study questions as follows:

- How local unexpected events and uncertainty affect the dynamics of the whole network?
- How local rules affect the behaviour of the network?

The modelling framework developed is highly flexible and allows the introduction of new rules or modification of existing ones with low computational effort, as well as the consideration of new stochastic parameters impacting the performance at different phases of flight.

C. Type of Modelling Outcomes

Given the same initial conditions, deterministic models obtain identical results over repeated simulations. Proposed modelling framework, ATM-NEMMO¹, produces different results at each simulation run, for the same given set of network static conditions (topology, capacities and planned traffic). This is related to the existence of the stochastic parameters permeating the performance of all elements and processes and producing different variability values in each simulation run.

Monte Carlo simulation is performed, repeating each simulation run a significant number of times. Features studied are local (at airport level) and global (at network-wide level) indicators, which serve to characterise the network state and behaviour. Examples are classical ATM performance indicators, such as delays or overloads, as well as ad-hoc defined indicators. Results are obtained as empirical probability distributions built over repeated simulation runs. Statistical analysis allows obtaining the probability density, or the likelihood that the indicator being analysed displays a certain value.

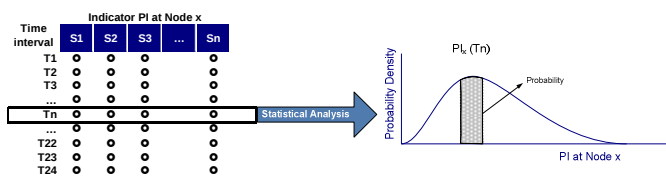


Figure 3. Indicator PI at node x - Probability distribution obtained through Monte Carlo simulation.

The interest of these results is, more than producing average values for each indicator, the characterisation, given certain initial conditions, of worst and best scenarios.

Besides, the results can also answer the question of how predictable the value of an indicator is from the set of simulation responses produced:

- A scattered set of results (high standard deviation) indicates that, under the specific conditions imposed by the scenario, quite different responses of the network are possible, and that even the most likely response is not highly probable. The network behaviour is highly unpredictable.
- A concentrated set of results (low standard deviation) indicates that all possible responses of the network are close to the average response, which is a good

prediction of the most likely response. The network behaviour is quite predictable.

The results obtained do not only characterise the network performance and behaviour, but also deepen in how predictable this performance is. A clear distinction must be made between network behaviour predictability – in the sense on how forecastable is the response of the network to certain conditions – and network predictability – which is a Key Performance Area dealing with performance indicators such as arrival delay.

To measure the propagation across the network of the delay caused by external disturbances, ATM-NEMMO provides a framework for the application of the methodology depicted in Fig. 4.

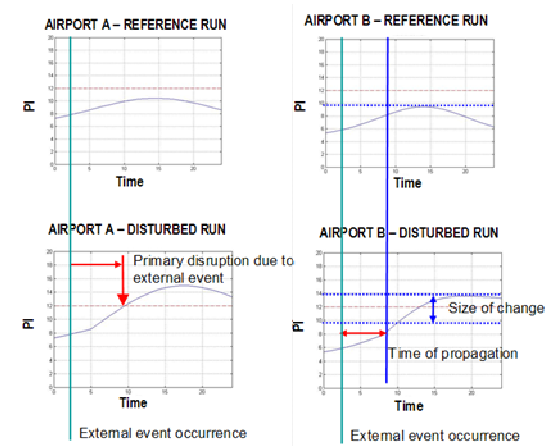


Figure 4. Capturing delay propagation patterns: time of propagation.

A reference simulation run not disturbed by any external event is performed and performance indicators are monitored at airports of the network. From the reference simulation run, the values for the stochastic parameters representing internal disturbances are stored. Keeping internal disturbances constant (equal to the values stored during the reference run), an external event is reproduced and several simulation runs are performed. The parameters stored and in use ensure that the simulation runs display the exact same results until the external event is reproduced. From that moment onwards, stochasticity is again allowed. The performance degradation observed between the reference run and the various simulation runs is due to the introduction of the external event and its impact on the dynamics of the network.

Fig. 4 shows graphically the method described: the external event takes place at airport A and its propagation is monitored at airport B. The green line indicates the start of the external event occurrence. The red arrow in left side (airport A) shows the appearance of local disruptions at that airport due to the external event. Horizontal dotted red lines in the four graphs indicate the disruption threshold. On the right side, the vertical blue line marks the time where local performance indicator (PI) starts showing degradation with respect to the reference run. Horizontal dotted blue lines indicate the maximum PI degradation in the reference run and the maximum PI

¹ ATM-NEMMO (NETwork Macro Model) modelling tool framework has been developed from 2008 onwards by Isdefe R&D Department, Modelling and Simulation Group (M. Sánchez Cidoncha, E. Ochovo and R. García Lasheras).

degradation due to propagation of disruptions: the difference between both values is the size of change in performance due to the external event. The critical time is the time at which the average performance degradation obtained from several disturbed runs reaches its maximum.

III. PROBLEM DESCRIPTION AND CURRENT STRATEGIES

A. *The Congested Scene.*

Over the 2009-2028 period, world passenger traffic is expected to increase by 4.7% per annum, and the numbers of frequencies offered on passenger routes will more than double (according to the Airbus 2009-2028 Global Market Forecast [6]). Hence, traffic demand will nearly triple, and airlines will more than double their fleets of passenger aircraft (with over 100 seats) from 14,016 at the beginning of 2009 to 28,111 in 2028 [5]. At the same time, air transport is highly exposed to socio-economic fluctuations. In future, airlines will seek to further develop business models with reactivity and flexibility (evolution of Low-Cost Carriers (LCCs) and major carriers, alliances, market segmentation, and so on) in response to volatile market conditions. Airlines will look to manufacturers and other actors in support of this in-built reactivity.

The air transportation system both in Europe and in the U.S. is highly capacity constrained due to the limited availability of resources on the ground and en-route. The capacity of an airport is dependent on the combined availability of its limiting components, such as runways, aircraft parking positions, gates, passenger terminal throughput. A good management of these areas determines the extent to which the airport can reach its full capacity potential. En-route sectors of airspace also have a limited capacity determined by the maximum workload acceptable for the Air Traffic Controllers (ATCOs). When occasional events occur, either unexpected such as meteorological phenomena and technical failures or predicted in advance such as ATCOs strikes, resource capacity is further reduced.

The challenge for Air Traffic Management and airports is illustrated by the EUROCONTROL Long-Term Forecast: IFR Flight Movements 2008-2030 [7]. This forecasts between 16.5 and 22.1 million IFR flight movements in the EUROCONTROL Statistical Reference Area in 2030 - this is between 1.7 and 2.2 times the traffic in 2007 and represents an annual average growth of 2.3%-3.5%. The growth will be distributed unevenly in time and across regions.

The EUROCONTROL forecast also indicates that required capacity at 138 reviewed European airports will increase by 41% in total by 2030, but the demand will exceed the capacity of the airport system by as many as 7.0 million flights. Airport congestion will be a challenge for the quality of service provided by the air transport system. Almost no new airports will be built in Europe, the only expansion possible being with the development of secondary airports. If large airports become saturated, traffic will spread to non-saturated regional airports, unless economic and environmental regulations limit such development. In future, long-haul demand is likely to grow at

the expense of short-haul. With the shortage of EU runway capacity, this means more slot substitution than growth. Passenger numbers will rise but the number of aircraft movements will not increase as fast (higher load factors, less frequency, and bigger aircraft).

In the context of ATM when an imbalance between forecasted traffic and available capacity is detected, it is usually the ATM authority that imposes a regulation, which aims at protecting the potentially overloaded node by imposing delay on some flights. The flights are usually prioritized on a First Planned First Served (FPFS) basis, meaning that the flight which planned to use the resource earlier receives priority on another flight which planned to use it later. In this way delay is imposed without regarding users-preferences, but just on the base of a generally accepted concept of equity among users. The per-minute cost of delay experienced by a flight can vary within a wide range of values depending on several factors. In the case of a single capacitated resource, the FPFS criterion produces an optimal allocation in the case of identical cost of delay values. As soon as we introduce different cost weights for the delayed flights, the FPFS solution is no longer optimal and another system must be employed to guarantee an efficient allocation that minimizes the aggregated cost of delay.

B. *The Current European Resource Allocation System*

In the context of European ATM when an imbalance between demand and availability of air transport infrastructure is detected, the EUROCONTROL Central Flow Management Unit (CFMU) in close collaboration with the regional Flow Management Positions (FMPs) may employ a number of measures at the pre-tactical stage to avoid congestion. These measures can vary from different Air Traffic Control (ATC) sector configurations to enhance capacity, to the activation of mandatory routes for certain trajectories, to the creation of slot allocation regulations. In this latter case an Air Traffic Flow Management (ATFM) regulation (also simply referred as regulation) aims at protecting a certain element of the system by limiting the maximum number of flights which can enter it, during an established period of time; thus on the day of operations all flights affected by regulations can either decide to re-route, in order to avoid the affected areas, or to be issued a controlled take-off time, represented by an ATFM departure slot. This measure is based on the principle that delays on the ground are safer and less costly than those in the air, thus it is preferred to anticipate any delay forecasted somewhere in the system, at the departure airport prior to the take-off.

The ATFM slots are calculated by the Computer Assisted Slot Allocation (CASA) system at CFMU on a FPFS basis. To do so CASA creates for each regulated point, area or airport a Slot Allocation List (SAL) composed by a number of slots depending on the rate of acceptance and the duration of the regulation and assigns consecutively slots to flights as close to their Estimated Time Over (ETO) as available. If two flights require the same slot, it is assigned to the one with the lower ETO. If a flight is affected by several regulations, the delay caused by the most penalizing one is forced in all the others.

Delays caused by ATFM measures in 2007 amounted to 21.5M minutes, causing an estimated cost of €1,300M to the users [8].

C. User Driven Prioritisation Process (UDPP)

Nowadays in real-time operations, Air Traffic Management provides services on a “First come, first served” basis without real reference to maintaining airline schedules. This minimizes the possibilities to help airspace users and airport operators managing punctuality performance. This contrasts with the commercial airline sector which is very competitive. It is therefore essential for airlines to construct their individual schedules to satisfy their selected market, resulting in their competing needs not necessarily being aligned with some notion of overall network optimisation.

Airspace users among themselves can recommend to the Network Management a priority order for flights affected by delays caused by an unexpected reduction of capacity, and more generally any kind of measures such as cancellation or re-routing. The airspace users will respond in a collaborative manner to the Network Management with a demand that best matches the available capacity. UDPP requires the cooperative action of a group of actors with diverse objectives and incentives determining their behaviour.

1) Constraints for UDPP.

In the future, airspace should have sufficient capacity to cope with demand in normal circumstances. Nevertheless, there will be more airports which will be working at maximum capacity for significant periods of the day. Most delay allocation will be the result of scheduling such airports close to their capacity limits and delay management at such airports will be a daily activity.

The key aspects of UDPP are to achieve an effective balance between the overall Network efficiency/stability and the diversity of user requirements and to assure an impartial perspective, balancing the various and potentially conflicting requirements and keeping the overall performance requirements and access right as a guiding principle.

2) Degrees of Freedom Left.

Prioritisation will be needed in case of disruptions of the network and at congested airports. The airspace users will be able to trade slots, if they individually agree to do so, based on agreements and rules that are transparent to the other actors. The process will be monitored by the Network Management function in order to make sure that an acceptable solution is available in due time and that all concerned parties are aware of any adverse network wide effects that may develop.

A delay management function will be implemented at network level to assist airspace users in the UDPP process. Consequently, the users will make their prioritisation according to the UDPP process. The Network Management function will assess the impact of the UDPP proposal on network stability or will also call a Collaborative Decision Making (CDM) process to agree an alternative solution in order to minimise the impact of the users' proposal on the network stability.

When runway slots are known, delay will be allocated by users working collaboratively according to their own priorities (UDPP). The network management function is independent and will assure the overall efficiency of the system and may act as decider of last resort if parties fail to agree.

There is another aspect to be considered when prioritizing: the degrees of freedom left. This means that although the main objective of UDPP is to assist airspace users' needs, there will be some predominant ATM measures that will not allow the prioritization of some of these airspace user preferences.

3) Future Implementation of UDPP concept.

Within SESAR JU framework, the possible implementations of UDPP will be analysed and validated under Project 7.6.4 scope, along three main steps:

a) Step 1: Time based operations.

The main change introduced with regards to today's

departure slot based process is the shift to the management of arrival times at the congested point/area. UDPP will be first used to address reduced airports capacity, with a primary focus on departure congestion (local demand management). The collaborative decision making process will mainly rely on the existing system using current techniques adapted to System Wide Information Management (SWIM) compliant information sharing.

b) Step 2: Trajectory based operations.

The scope of UDPP is progressively extended to the full 4D management and prioritisation of business/mission trajectories. However the collaborative process remains limited to important mismatch between the network capacity and the demand to ensure that procedures are available to maintain safe operations, to minimize the impact on the demand and to allow for a smooth recovery. This intermediate step will use ground-ground limited SWIM services enabling a mixed mode of information sharing both current techniques and SWIM capabilities.

c) Step 3: Performance based operations

The third step addresses the final UDPP implementation. The scope of the collaborative process is progressively extended to operations in nominal conditions giving airspace users the ability to manage any demand/capacity imbalance according to their business objectives and performance requirements. The Regional Network Manager is the last resort broker ensuring the stability of the whole network. The process is supported by full SWIM-enabled information sharing for the collaborative planning services.

Live trials experiments will be used to assess operational requirements related to Step 1 and Fast time simulation and modelling tools will be used to validate the concept in Step 2 and Step3.

IV. COMPLEXITY METRICS AND INDICATORS: A LITERATURE REVIEW

A. *How does the Network Affects Behaviour?*

It might sound obvious that there is a connection between topology and transport function in complex networks. The intricacy of unveiling it relies on discerning between which functionalities or behaviours in a complex network are linked to the network structural properties and which ones are due to the routing rules. The attempts to investigate this issue are focussed on relatively simple networks, from which conclusions can be identified more easily. Once these patterns are captured, similar behaviours in more intricate networks can be sought.

In [9] and [1] the congestion at node level (presence of queue) is correlated with the betweenness centrality. This is a topological property of a node i defined as the average number of times that a random walk between any pair of nodes of the network passes through i . The strong correlation links this random betweenness and the average of particles received by a node in case of random diffusion taking place.

In [9] the global structure of the air transport network is analysed, finding that is a scale-free, small-world network, but with anomalous values of centrality. These anomalies arise because of the multi-community structure of the network. The communities cannot be explained solely based on geographical constraints, but also geopolitical considerations have to be taken into account.

The “systems” analysis of the structure of the worldwide air transportation network carried out in [1] unveils that the network is a small-world network in which the number of nonstop connections from a given city and the number of shortest paths going through a given city have distributions that are scale-free. The nodes with more connections are not always the most central in the network. The work hypothesizes that the origin of such behaviour is the multi-community structure of the network. The analysis of the community structure allows identifying the most efficient ways to engineer the structure of the nodes, by detecting which ones are poorly connected. Cities that connect different communities play a disproportionate role in important dynamic processes such as propagation. While most of the nodes (95%) are peripheral; that is, the vast majority of their connections are within their own communities, nodes that connect different communities are typically hubs within their own community, although not necessarily global hubs. The existence of network-specific roles points to the more general question of what evolutionary constraints and pressures determine the topology of complex networks and of how the presence or absence of specific roles affects the performance of these networks.

The scale-free feature is key for improving the network functional robustness from a macroscopic point of view. Statistically, the probability that a hub node is impacted by random perturbations is the same that for a non-hub one, for which external perturbations or unexpected events impacting the performance of the node's elements do not imply that the

network structure is affected so severely [15] and [16]. However, the error tolerance comes at the expense of attack survivability. The topological weaknesses are linked to the inhomogeneous connectivity of these networks, a feature that could be exploited by those seeking to damage these systems.

Reference [17] establishes correlation between reliability and topology for electricity networks. Some topological features that are found to increase with the fragility of the network are the deviation from a random graph null model degree distribution, the increased preponderance of star and triangle motifs in spite of linear ones and the inhomogeneous patch size distribution. Evidences analysed show an increased fragility when the topology of the network deviates from a random one, maybe in search of a higher interconnectedness. On a topological basis, favouring the connectivity and interconnectedness, though originally intended to avoid interruptions in power service, would difficult, at the same time, the islanding of disturbances.

B. *Dynamic Indicators for Managing Complex Networks*

The behaviour of a complex network is very hard to predict, even if it stick to rigid local rules and no disturbances (noise) are in place, since very often the outcomes of ruling depends on the dynamics/ history of previous decisions. How to avoid the triggering of global cascades of “contaminations” (being epidemic diseases or overloads at nodes) is a matter of much study.

One of pioneering books on complex networks approaches the discussion of the appearance of cascades [10]. The propagation of undesired disruptions is linked to the existence of percolating clusters. Taking as example a network of individuals of two types (vulnerable and stable) and the transmission of information, Watts describes how an innovation can only spread if the initial innovator is connected to at least one early adopter. If the innovation hits a vulnerable cluster (one containing potential adopters) and this cluster happens to percolate throughout the network, then the innovation will trigger a global cascade. The potential occurrence of global cascades can be predicted from the existence in the network of percolating vulnerable clusters. As one of the conclusions included in the book, Watts highlights that real-world complex systems are both robust and fragile at the same time. They are robust because they have to survive in the real world and, if not able to withstand shocks, they would have either to be re-designed or evolved. But the cascade model shows also that every complex system has a weak point, which if struck can provoke even collapse of the system. Usually the weakness is quickly fixed once identified, but as it is demonstrated, that does not remove the fundamental fragility of a complex system, and the weakness will most probably only be moved to another part of the system.

Dynamic robustness is monitored in [11] to provide indications on the actions that can be performed in a network in order to decrease undesired effects. Robustness, as defined for the study of the impact of structure on the network behaviour, is defined as the ability of a network to avoid cascading of

overloads failures when a fraction of its constituents is damaged. The dynamic robustness is then introduced to study the impact of dynamics on the behaviour. The damage or malfunction (degraded capacity) of a single node can trigger a cascade. The question discussed in [11] is the identification of the possible operational strategies to prevent the cascade from propagating through the entire network. In [12] the “strategy of defence” is based on the selective further removal of nodes having small load and edges having large excess of load, right after the initial attack or failure and before the propagation of the cascade. In [13], instead of permanently removing the overloaded nodes to prevent propagation of overloads, the diffusion through these nodes is degraded.

The network critical load, defined as the particle density beyond which jamming at the nodes appears, is used in [9] as an indicator of the influence of network routing rules on behaviour. Congestion awareness is introduced in the diffusion rules of the particles in the network: particles are randomly assigned origin and destination nodes, and the routing rule for the particle to be moved to the next location in its way from origin to destination is based on the local information about congestion degree of neighbours, i.e. the queue lengths of the neighbouring nodes. The routing rules are varied between random diffusion and rigid congestion-gradient driven flows. The main result shown with the theoretical models used, is the existence of an optimum value of the congestion awareness parameter, both for random and for scale-free networks: the network critical load increases when a small amount of local congestion awareness is present in the routing rules, but it decreases as the routing rules become too rigid. The result reveals the existence of “stubs” acting as traps for the particles: low degree nodes connected to hubs with long queues.

For the correct reading of these conclusions, it must be highlighted that the routing rules used a purely local congestion-awareness parameter. In this line, other significant result shown by the authors of the model is that, regardless of the network topology, the critical load decreases as the number of nodes increases: in large networks with routing based on local information jamming at nodes appears unavoidable.

Within the air transport domain, the reorganisation of the airlines route networks is another field of study for improving the performance of the network. Reference [14] proposes a complex network approach to the matter. The work is based on the premise that the two main categories of airline route networks, point-to-point and hub-and-spoke, are examples of small-world and scale-free networks respectively, and so the related studies from complex networks domain are applicable for the study of airline route networks. The paper focuses therefore on measuring airline route related indicators such as the average shortest flight distance of an airline route network and the airline network robustness against closure of airport(s) and/or route segment(s).

V. PRELIMINARY SET OF SCENARIOS

With a view on the challenge of improving the efficiency of the European air transport system, and trying to anticipate the

impact at network level, a list of criteria is included here as potentially beneficial in the context of European ATM. Implementation and simulation of the resulting routing rules and combinations of them in the network will provide feedback on the possible consequences in terms of network stability and performance.

Criteria should take into account the following scenarios:

- Giving priority to flights with higher number of passengers with connecting flights, or with higher ratio “number of passengers with connecting flights” / “total number of passengers”. When using this criterion, a number of sub-criteria can be also applied:
 - For those passengers with connecting flights, the time buffer for transfer at the transfer airport must be maximised, therefore trying to give priority to flights with passengers for whom a minimum delay would imply the consumption of the transfer buffer and, ultimately, missing the connecting flight;
 - In the same line, looking upstream could unveil that final destination (that of the connecting flight) is a poorly connected airport. This would imply that those passengers missing the connecting flight will probably have to wait until the day after to find another option for reaching final destination.
- Criteria for passengers with connecting flights are also applicable to cargo connections for cargo flights. Here, besides, another factor is called into play: perishable cargo, for which a delay in delivery will mean a dramatic loss of value. An example are daily newspapers;
- Service quality commitments of airlines depend on the particular business model of each aircraft operator. Diverse models can be implemented, assigning higher priorities to flights with certain characteristics pre-defined by the company. An example is the number of business passengers on board;
- The previous criterion links with the establishment of global scoring criteria for flights, where prioritised lists issued within each company are further filtered taking into account the cost that delay would imply for each type of operator;
- Looking at limiting the propagation of delays, flights going to less congested airports should be given priority. Otherwise, overloads will follow and stacks will give raise to the appearance of delays yet at new network locations;
- Dependencies between flights through the use of the same aircraft are source of much reactionary delays.

The countermeasure could be giving priority to flights with the higher number of rotations upstream;

- An airline at its hub airport usually has at its disposal aircraft for replacement in case the arrival of the previous rotation of a departing aircraft is delayed for any reason. Therefore, penalising flights heading to their airline hub might not be so critical in terms of delay propagation;
- The possibility of using secondary airports in combination with surface transport should be taken into account when congestion is also affecting destination airport, as a way to restrain delay propagation and to timely deliver cargo or passengers to their destination.

VI. EXPECTED OUTCOMES AND SESAR RESEARCH QUESTIONS ADDRESSED

The research proposed by NEWO project within SESAR WP-E scope will identify and evaluate new operational solutions for flight prioritization rules in case of severe capacity shortfalls affecting departures at airports.

This main objective responds to the interest of the airspace users in applying their own priorities, based upon a CDM approach, during periods of capacity shortfall. In the absence of any external event affecting the capacity of the Air Transport elements, flights are usually handled on a first come first served basis. In case of severe capacity shortfalls affecting departures, departure flights can be prioritised according to pre-defined rules/ criteria. The criteria for building the departure queue (either first come first served or prioritisation) might be necessary in case of disruptions in the network and at congested airports within the context of a congested network. It will be the responsibility of the airspace users (mainly airlines) to respond in a collaborative manner with a demand that best matches the available capacity. This is known as the User Driven Prioritisation (UDPP) Process. It is also foreseen that the UDPP process is supported by a catalogue of pre-defined strategies.

The success of this operative is linked to the evaluation of the set of airline operational strategies and potential solutions in support of the UDPP. A pre-assessment of the potential impact that diverse prioritisation rules would have on the network performance and stability is needed, capturing any adverse network-wide effects that their application may develop.

Expected outcome of the study are the probabilities and consequences in terms of operational performance (predictability, capacity, and efficiency), of the introduction of innovative and business preferred local operational approaches. In the ATM system, all players are concerned with minimising the impact in terms of potential operational, economic or environmental penalties derived from the implementation of local strategies with negative global consequences. Even if a certain local solution seems optimal for the individual operator applying it, the reactionary effects can mean, at the end of the

day, performance degradation in the network that revert in cost-inefficiencies for the operator. Moreover, today's strategies might not be optimal for tomorrow's network. The behaviour of a congested air traffic network is still an open issue within the field of air traffic management. In highly congested networks, sub-optimal behaviours may emerge, such as bunching, deadlocks, delays, or too long recovery times, which may spread across the network and hinder its performance. The assessment, previous to SESAR implementation phase, of the impact of these strategies, allows setting additional measures that enable tackling in the most beneficial way with the possible emerging behaviours generated by the congestion of the network at the horizon 2020+.

The NEWO project is part of the SESAR WP-E, dedicated to long term innovative research of air transport. Research included in WP-E is focussed on investigating promising ideas that could bring improvements to the air transport system beyond the SESAR timeframe. As a catalyst of European research capability, WP-E addressed the unveiling of system interrelations and dependencies by looking at the air transport from innovative perspectives. NEWO contributes to two of the four research themes proposed within WP-E:

- **Mastering Complex Systems safely.** Complexity science can help understanding the behaviour of the ATM complex system. The air traffic system contains a huge number of elements and agents that interact, in many situations nonlinearly, giving rise to degraded behaviours of parts of the network or of the whole network. NEWO applies the complexity prism to air transport network modelling, further developing and exploring the potential of the ATM-NEMMO modelling framework which incorporates schemes from the complexity science. The approach puts effort on global modelling to capture the nonlinear coupling effects and emergent behaviour.
- **Economics and Performance.** As it is stated in the Economics and Performance Theme, users will increasingly require that charges are based on quality of service provision, measured by such elements as capacity and delay, and therefore costs. The impact of certain prioritisation rules on departure delays and capacity are some of the issues that will be deeply addressed in the project.

Within the main addressed WP-E theme Mastering Complex Systems safely, NEWO project cover the following topics:

- **Intelligent modelling:** Investigate the modelling of the ATM system of systems using methods and tools from the science of complexity, with models able to capture its changing, dynamic and evolutionary behaviour.
- **Emergent behaviour:** Use any results to better understand emergent properties such as delay, predictability and safety.

- Non-determinism: Investigate the impact of uncertainty on overall system behaviour.

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