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An optimisation framework for aircraft operators dealing with capacity-demand imbalances in SESAR

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***Abstract*—This paper presents a framework for the negotiation phase that is foreseen in the new operational concept proposed in the Single European Sky Research (SESAR) program. In particular, this paper describes a possible strategy for the airspace users in order to deal with the Collaborative Decision Making (CDM) process that is expected in this future scenario. The aim of this strategy is to improve the efficiency in the CDM process by computing the different operational costs associated to different solutions that may solve a particular demand-capacity imbalance in the airspace. This will allow them to optimise their operating costs while reducing fuel consumption and therefore being more environmentally friendly. In the SESAR scenario, airspace users will become owners of their trajectories and they will be responsible to solve possible mismatches between capacity and demand in a particular airspace sector. Some suggestions have already been done for the mechanism that might help on this negotiation process. However, the different options that aircraft operators might use have not yet been sufficiently investigated. In this paper, the authors propose an optimisation framework for aircraft operators aimed at computing 4D trajectories with time constraints and deal in this way, with possible airspace regulations. Once a nominal flight plan and a potential regulation is known, it is suggested to compute several possible alternative flight plans (including re-routing, but also altitude and speed profiles) that may solve the capacity-demand problem. If more than one regulation exists a tree of options is subsequently computed and the cost of all the options is also calculated in order to allow the airspace users to initiate the negotiation process with other airlines. A preliminary example is given at the end of this paper in order to better illustrate the proposed methodology.**

I. INTRODUCTION

As it is well known, the number of IFR flights is growing all around the world. The forecast of flight movements in the Eurocontrol Statistical Reference Area (ESRA) for 2030 is between 1.7 and 2.9 times the traffic of 2007 [1] and, according to [2], by 2030 the 11% of actual demand will not be accommodated, in the most-likely growth scenario. For example, during the period from 2003 to 2008, the European traffic has increased by 19.9% (average of 27818 flights per day in 2008), the total delay has increased by 60.7% (65138 minutes per day) and the total delay per flight has increased by 34% (2.3 minutes on average for all flights) [3]. This trend shows that capacity of the system is starting to get over-passed and, as traffic is expected to continue growing, new concepts of operation are starting to be developed with the SESAR project (in Europe) and NextGen (in the USA).

If the focus is given to Europe, two big changes arise from the SESAR guidelines: 4D trajectories should become a reality and the airspace users (i.e. the aircraft operators) will be the owners of their trajectories. That means that if an capacity-demand imbalance exists, a negotiation process among airlines should be done in order to solve the potential conflicts. In this way, the airspace users will be involved in the process of balancing demand and capacity and a collaborative Decision Making (CDM) will become mandatory at strategic level [4]. Moreover, aircraft operators should optimise their 4D trajectories according to the cost of time and fuel burned. This optimisation is essential if they want to reduce their operational costs and therefore, be more competitive in front of other operators. For example, during summer 2008, 14.1% of the traffic in Europe was delayed with an average delay of almost 20 minutes [5]. On the other hand, during 2008 the price of fuel reached prices over $100 per barrel and therefore, most airlines reported fuel costs to be between the 30 and 40 percent of their total expenses.

In the future SESAR scenario, it will be critical for them to know the associated cost of solving capacity-demand imbalances in the air transportation network. Therefore, if a negotiation process is established with concurrent airlines, those ones with more options, and with better information of the associated costs for each option, will be better placed. In this context, the negotiation process has already been analysed in [6], where a market based mechanism is suggested to be used. However, the different options that the aircraft operators would have when facing this negotiation process have not been yet assessed and this is the main motivation of the proposed research by the authors.

Thus, this paper suggests an optimisation framework for aircraft operators that have to negotiate with other airlines in order to solve a capacity-demand imbalance problem in the airspace. In this negotiation process, different slots might be traded among the negotiating airlines. In this case, it would be essential for the airline to compute the different vertical profiles and speeds to be used for each of the possible options, resulting in different final costs. Then, when a regulation is set, the affected airspace users will initiate this negotiation process but might act in different ways to deal with the possible delay according to their own interests and associated costs. Therefore, the proposed methodology is intended to assess the different options that a particular aircraft operator would have and to compute the associate cost for each of them in order to better perform in the negotiation process.

This paper is organised as follows: in Section II the current framework of operations used in Europe is presented, regarding both the the network manager and the airlines. Section III presents the operational framework in the SESAR scenario while taking into account the proposal of the authors for the aircraft operators. Section IV is devoted to show a preliminary example of the proposed methodology, considering the computations that a given airspace user would perform for a hypothetical regulation. Finally, in Section V the main concepts are summarised and further work on this research is explained.

II. CURRENT OPERATIONAL FRAMEWORK

Nowadays, in the operational concept as implemented in Europe the Air Navigation Service Providers (ANSP) submit the capacity of their airspace sectors to the Control Flow Management Unit (CFMU). The CFMU acts as a network manager and has the responsibility of maintaining the demand below the capacity for each sector. In order to attain this objective, the airspace users must submit their intended flight plans to the CFMU well in advance. As can be seen in Figure 1, the CFMU will regulate the demand by imposing on-ground delays to some of the flights.

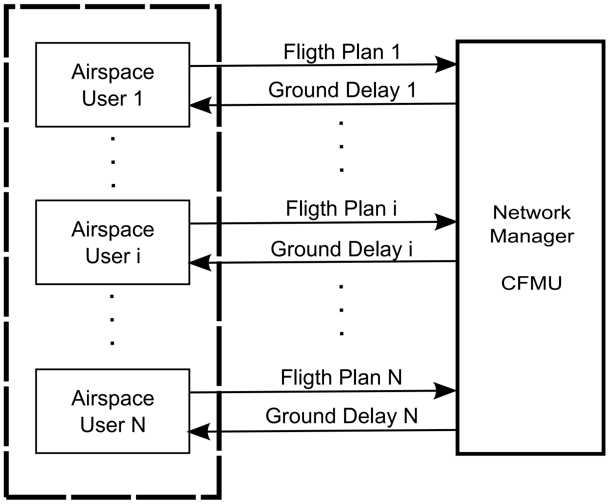

Fig. 1. Current concept of operations in Europe

On the other hand, airline operators optimise their flight plan with respect the cost of time and fuel. During this optimisation process different operational parameters are taken into consideration, such as crew and maintenance costs, number of transfer passengers, the type of the aircraft, weather conditions, available airspace routes, etc. However, airspace capacity information is hardly never taken into account. Next, current airspace network management and airline operation strategies are briefly described.

A. Network Manager

In Europe, the CFMU simulates flight plans in order to identify those sectors where the capacity might be exceeded by the foreseen demand. In this case, the Computer Assisted Slot Allocation (CASA) algorithm is used to mitigate this mismatching by imposing on-ground delays to some flights. CASA implements a First Planned First Served (FPFS) sequence to assign slots to flights while preserving fairness. Briefly, this slot allocation algorithm can be explained by the following simple example.

TABLE I
EXAMPLE FLIGHTS

Flight	ETO
F1	10:00
F2	10:06
F3	10:07
F4	10:10
F5	10:12
F6	10:18

Let us set a regulated area with one available slot every five minutes (10:00, 10:05, 10:10...), and six planes that want to cross this regulated airspace with the Estimated Time of Overfly (ETO), as shown in Table I. As it can be seen in Figure 2 the first plane (F1) will take slot number one while F2 will take slot number two. Without any regulation, the ETO of the third aircraft (F3) is 10:07, corresponding as well to slot number two (between 10:05 and 10:10). However, this slot has been already assigned to F2 that will keep it as its ETO is lower than the ETO of F3. Then, the third slot will be assigned to F3 and this flight will be delayed on ground by three minutes. In the event of having more than one regulation, the delay coming from the most penalising regulation will be imposed to the aircraft. Then, the over-flight time of the remaining regulations will be fixed to this most restrictive value [7].

The final result that is obtained with this assignation is shown in Figure 2. As it can be seen, flight F3 has been delayed for three minutes, and will arrive at the regulated area at the slot R1S3, flight F4 will be delayed for five minutes and will use slot R1S4. Finally, F5 would have arrived at the regulated area to take slot R1S3, but being the CASA algorithm FPFS, it must be delayed DGF5 minutes in order to arrive at the regulated area with slot R1S5. In Figure 2, the slot that F5 would have taken is presented along with the finally assigned one and the ground delay (GDF5) that consequently has been imposed to this flight. It is worth mentioning that besides the departure time, the flight plans of the delayed flights are not changed. This means that once the delay has been absorbed on ground, the flight will operate at its initially planned cruise speed.

The main advantages of this solution are that it is simple to find a robust solution, the algorithm can easily deal with real-time modifications and cancellations of flight plans and, being a FPFS algorithm, a minimisation of the total delay is achieved [6]. However, it does not take into account the cost for the operators that the imposed delay may lead to. In other words, the economical impact of the regulation is not minimised because the same amount of delay can indeed be much more expensive for a given operator than for another

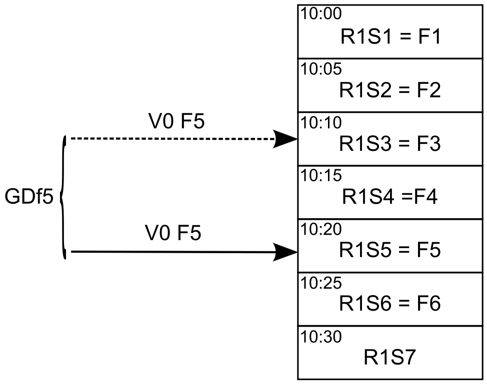

Fig. 2. Example of a regulation area with 5 slots every five minutes

one [6], [8].

Some effort has been done to try to improve this CASA algorithm with new techniques as constraint programming (see for instance [9]) or extend the ground delay to deal with conflict and not only with capacity-demand imbalances [10]. Moreover, other criteria rather than the FPFS algorithm have been analysed like for instance distance based criteria [11]. Nevertheless, this modifications of CASA algorithm present some issues that stop their practical implementation. Even if the computation time has been significantly reduced, they still have difficulties to deal with real time modifications and cancellations of flight plans. Moreover, some of them have problems with equity and fairness.

B. Airspace Users

The main objective of aircraft operators is to minimise their operating costs. Therefore they will try to compute and fly an efficient flight plan. In Figure 3 it is presented the optimisation process that the airline should do for each of its flights. Before this optimisation, the airline will have to compute the route planning and the fleet and crew assignment. The reader is referred to [12] and [13] for more details on these processes, which are out of the scope of this paper.

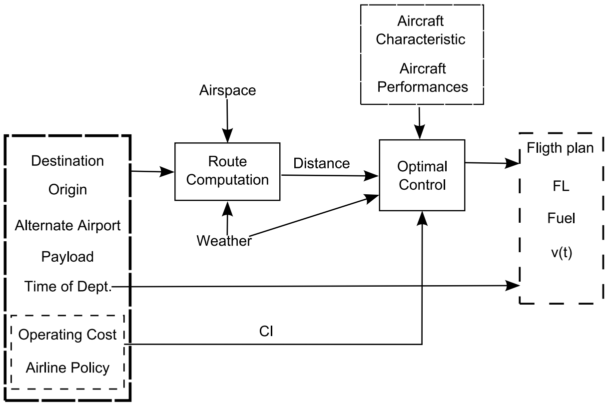

Fig. 3. Flight optimisation applied nowadays

In the flight plan optimisation, the input values are the route that the airline will fly (origin, destination and alternative airports), the intended payload and the time of departure. With the information of the airports and using the airspace configuration and the weather data, the route will be computed [14]. After this process, the distance to be flown will be obtained. A main aspect to take into account in this process is the airline policy related with its operating costs. This will result on a given CI (Cost Index) for the intended flight. The Cost Index will be part of the optimisation function which will weight the cost of time against the cost of the fuel. Therefore, the optimisation function would be $J = Fuel + CI \cdot Time$. As expected, changes on CI will impact on the profile of the flight, on the speeds and, as a result, on the fuel consumed and on the final take off weight [15]. It has been demonstrated how variations on CI might have an small impact on time but a great repercussion on fuel consumed [16].

Summing up, by using the aircraft characteristics and aerodynamic data, the payload, the distance, the weather and the CI, the optimiser will compute the operational flight plan that will be composed of speed and vertical profiles as well as the fuel needed for that flight [17], [18]. During the flight, the CI is introduced in the Flight Management System (FMS) by the pilot. The management of the flight will be done by changes on the CI. This is the reason why it is not surprising that extensive research has been conducted to help airlines to optimise the value of their CIs. If a flight is delayed, but time is critical, which means that the cost of time is high, some time might be recovered during the flight. Nevertheless, as it has been analysed in [8], there is a compromise between the time recovered and the fuel burned. Therefore, to optimise the new value of CI becomes crucial [8], [19].

III. PROPOSED FRAMEWORK FOR SESAR

As mentioned before, the main change that SESAR introduces is that the airspace users become owners of their trajectories [4]. It means that in this new operational scenario, the network manager should not modify the intended flight plans of the aircraft, unless it is strictly necessary. In SESAR, as in NextGen too, the trajectories will be based on the 4D concept. A 4D trajectory is a precise description of the flight path of an aircraft as a 4 dimensional continuum, from its current position to the point at which it touches down at its destination. Thus, every point on a 4D Trajectory is precisely associated with a time [20]. Obviously, this will help on the predictability of the flights and some gain in efficiency is also expected. Then, the airspace users will create their trajectories that in turn, will be shared using the network manager. With this information, along with the airspace related data, the airlines will have to negotiate among them to solve possible capacity-demand imbalances. In this case, the network manager will only act as a supervisor of the negotiation process that airspace users will do in case the demand excess the capacity (see Figure 4).

A. Network Manager

The task assigned to the network manager in the new operational context is the coordination of the different airspace users. As previously mentioned, in [6] a market mechanism

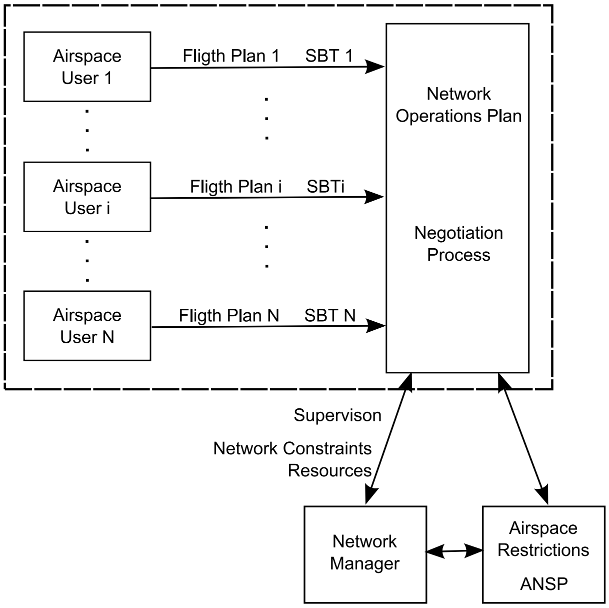

Fig. 4. SESAR concept of operations

aimed at assigning the air traffic flow management slots is proposed. In this case, after an initial First Planned First Served (FPFS) assignation (done by the network manager), an auction process is subsequently initiated. The airlines are owners of their initially assigned slots by the FPFS algorithm, but during the auction process they might keep or sell them according to their own interests.

In order to achieve an optimum from an economical point of view, the airspace users must have a good knowledge of the cost associated with a particular slot. This would help them to choose a particular slot, and eventually sell their initial one, with regards to the other slots. In the work done by [6] and [8] a fixed cost is chosen for each minute of delay. In these works, if the aircraft operator chooses a slot later that the initial one an extra on-ground delay must be performed (as shown in Figure 2) and no other options are left to the airlines. Moreover, in [6] the delay that the airline suffers at the take-off is supposed to be the same delay that the flight will experiment at the arrival airport, with respect to the initially planned arrival time. This means that the airline is not allowed to change the original flight plan that was proposed before the regulation was known. In addition, the possibility of speeding up the flight before the regulation is also not considered and therefore only the slots that come after the slot that the aircraft would have with no delay are taken into account. However, as it will be shown in next section, the authors propose that airlines might be more active during this negotiation process. Then, we propose that the aircraft operator could change the initial flight plan (i.e. vertical and speed profiles, or even re-routing) in function of the chosen slot.

B. Airspace Users

In a complete 4D environment, where airspace users can fully optimise their trajectories, many options arise to deal with capacity-demand imbalance problems. First, a re-routing may be possible in order to avoid the regulated area.

In the case that the original route is kept, the aircraft might take off later (as it is done nowadays with the on-ground delay methodology) but it would be also possible to take off on time and fly slower. In this way the aircraft would be airborne earlier and if for some reason the regulation is cancelled it would be easier for the operator to recover the initial delay. Moreover, by flying slower, the cost of arriving to a later slot is also optimised [19]. Finally, the aircraft could increase the cruise speed in order to arrive to a previous slot. In fact, the optimisation algorithm that the airspace user should use might compute different solutions for each possible slot by using a combination of all above strategies.

Once the regulation has been passed, some time might be recovered if the aircraft speeds up. Due to the fact that recovering time would have an impact on fuel consumption, in [8] an analysis has been done showing the amount of optimal time that should be recovered. As it could be expected, optimised solutions often do not recover all the possible delay due to the involved fuel consumption. On the other hand, even with high cost indexes, the time that is possible to be recovered is quite limited for short-haul routes. Thus, this technique may become more interesting for longer flights [8], [19].

The optimisation process that airspace users have to do will be enhanced to include time constraints, as shown in Figure 5. The authors propose the computation of the whole trajectory using an optimal control approach while meeting all possible constraints. Thus, the input of the optimiser will be the distance computed as in Figure 3, the weather conditions, the aircraft characteristics, but also the way-point time windows constraints for each slot and regulation.

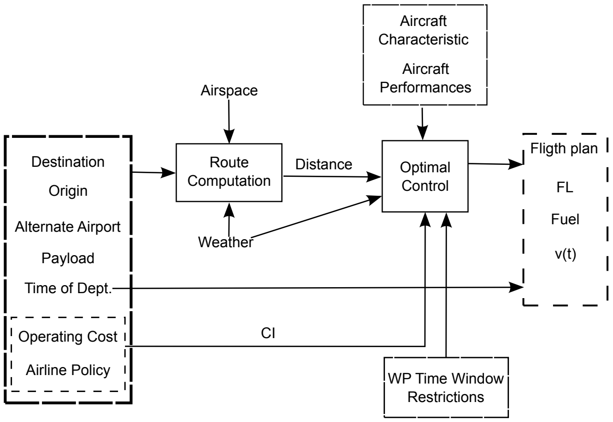

Fig. 5. Proposed flight optimisation

Therefore, for a given regulation set of achievable slots will be computed for each airline. These sets will be bigger than other proposed approaches, such as [6], where all the delay is supposed to be absorbed on ground. The first valid slot will be determined by the aircraft taking off as soon as possible and flying to the regulated area at the maximum operational speed (or VMO). On the other hand, the last slot will be reached when flying at an optimal speed before the regulation to arrive at the slot ($VoptBR_jS_i$) and eventually doing some on-ground delay of GD_i. The last useful slot will be determined when the cost of the delay produced at the arrival airport due to the fact of using that slot becomes bigger than the economical profit that can be attained by using that slot.

After the regulation it will exist an optimal speed ($VoptAR_jS_i$) that will allow to eventually recover some time in order to minimise the cost of the delay at the destination airport. This optimal speed will take also into account the increase in fuel consumption (due to the fact that the aircraft is flying faster than the initial intended speed) [8]. The authors also suggest that the variable that should be taken into account in this optimisation process is the total delay at the destination airport instead of the on-ground delay before take-off as it is usually done nowadays. In fact, the real cost for a minute of delay is because the flight arrives late at the destination airport rather than because it departed later.

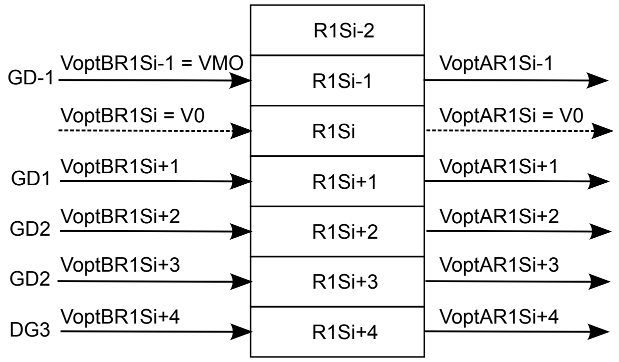

Fig. 6. One regulation with changes on flight plan

In Figure 6, it can be seen that for each available slot, the airspace user will have a certain amount of ground delay (GD_i), an optimum speed to arrive to that particular slot ($VoptAR1S_j$) and another optimum speed after the slot to eventually recover or loose some time if necessary ($VoptAR1S_j$). These speeds should be computed with the optimisation mechanism proposed in Figure 5 by changing the time window associated to the way-point that define the entry of the regulated airspace. In Figure 6 it is shown that if the aircraft flies as initially planed, it will over-fly the regulated area at the slot achieved at V_0. However, the aircraft operator has a set of alternative options, by using other slots with different associated costs on fuel and total delay. For each path (i.e. each different slot), the whole trajectory should be optimised by the aircraft operator and the optimal cost for each path will be computed in order to start the slot auction process described above.

It is not surprising that the aircraft has to go through more than one regulated area. Actually in Europe 21% of the flights had two regulations in the AIRAC 311: 21^{st} July 2008 to 27^{th} August 2008 [6]. In this case, as can be seen in Figure 7, from one slot of the first regulation a set of slots on the second regulation can be reached flying from VMO to Vmin.

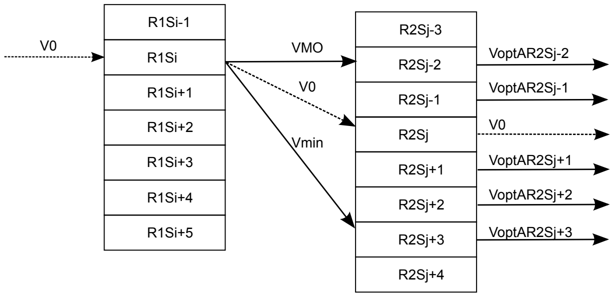

Fig. 7. Slots reachable form one slot of the first regulation

After the second regulation an optimum speed ($VoptAR2S_i$) can be used to recover the optimal amount of time. Then, the optimiser has to be extended to include the possibility of having more than one restriction. This should not be difficult due to the fact that a narrower set of slots at the second regulation might be reached from one slot of the first one (see Figure 7).

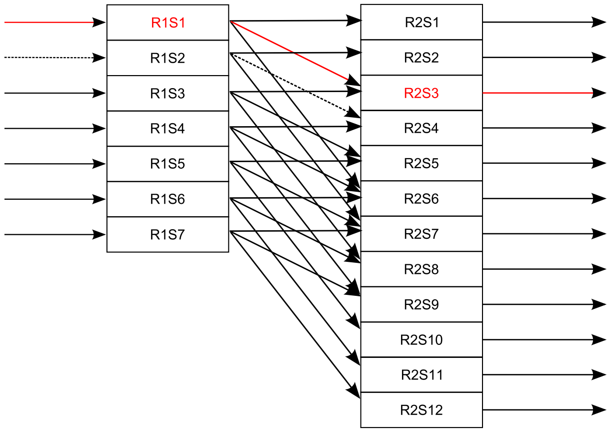

Fig. 8. Tree of reachable slots with two regulations in place

Therefore, for each slot of the first regulation the airspace user have a set of slots of the second regulation that can be reached. With this definition a tree can be created (see Figure 8), and for each path different speeds will be used to minimise the operational cost (fuel and time). It is expected that this tree will not be too large, and therefore become computationally feasible. In this context, it has been presented in [8], [15] and [19] how time that can be saved or lost by changing cruise speed is quite reduced.

With this computation, the airspace user is able to determine which is the direct cost that it will have if a set of slots is chosen. If it is not possible to change the assigned slots, like in the current operational concept, the optimum speeds and vertical profiles to minimise the cost will be determined. If a negotiation process is possible with the network manager, the airspace user will be in a better position to choose between the options. Finally, if a market mechanism is established as the one described in [6] the airspace user that implements this solution will know the cost of each of the paths. Each path will be a set of slots, for example R1S1 and R2S3 which are shown in red in Figure 8. With the optimisation process, for each path the vertical profile and the optimum speeds will be computed. Therefore the airline that performs this optimisation has more information to decide at which price is worth for them to sell the original assigned slots and to buy a different path.

One advantage of this optimisation is that the objective functions for the airline can be easily modeled while the negotiation process supervised by the network manager ensures that the capacity is not exceeded. Moreover, the suggested model allows to include different types of airlines, with different objectives and even airlines that do not optimise their trajectories with time constraints. The difference will be that those who did will have more information and therefore, will be in a better situation to perform the negotiation.

Then, the mechanism described in [6] might be easily extended to include re-routing. In this case, the airspace user will monitor the cost of different paths through different sectors while performing the negotiation.

IV. PRELIMINARY EXAMPLE

In this section, an illustrative example of the concept proposed above will be shown. The following preliminary results are based on a hypothetical situation where an Airbus A320 is scheduled to fly a route of 2000 NM with a payload of 15 tons. Let us suppose that the aircraft operator chooses a cost index (CI) of 40. For this aircraft and payload, this CI represents a cruise speed of M 0.789 with a total flight time of 250 minutes (the climb and descent phases are neglected in this preliminary example) [21], [22]. On the other hand, let us have a regulation located at 800 NM ahead from the departing airport and where airspace slots are available at six minutes intervals. For the sake of simplicity, the time references are set to zero at the original intended take-off time.

Figure 9 shows the initial intended flight plan, where the CI is set to 40. In this case, the aircraft will enter the regulated area after flying 107 minutes and therefore, it will use the third available slot (R1S3) that spans from minute 106 to minute 112. Let us assume that another flight with a lower ETO has already been assigned to this slot R1S3. This means, that our aircraft will be delayed for five minutes on-ground in order to enter the regulated area by using the slot R1S4. If the flight plan is not changed, as it is done nowadays, the aircraft will always fly at CI 40 and therefore will arrive to the destination airport with a delay of five minutes.

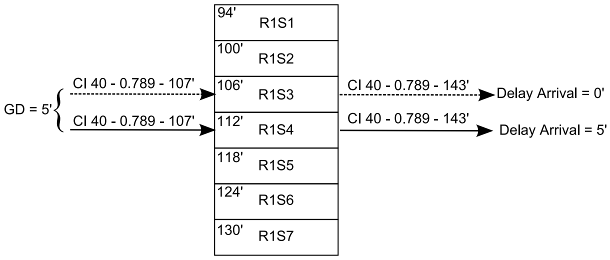

Fig. 9. Example of one regulated area without changes on the original flight plan

With the mechanism proposed in this paper, the aircraft operator can compute the cost of all available slots. For each slot a flight plan optimisation is performed in order to minimise their own policy of time and fuel consumption. Figure 10 shows the different available slots for this particular example. Even if the aircraft takes off at the original intended take-off time it is not possible to reach the regulation after 94 to 100 of flight minutes (corresponding to R1S1) due to the limitation on the maximum cruise speed. It turns that the first available slot for this example is the second one (R1S2), spanning from minute 100 to 106. To achieve this slot, no ground delay will be done and a CI of 150 will be used. For the studied aircraft this corresponds to a cruise speed of M 0.80 from the take-off to the regulated area. After the regulation it is possible to fly slower to save some fuel since the aircraft is two minutes ahead of the original schedule. In this case, the CI is changed to 25 and the flight will continue at M 0.78 during 145 minutes to the destination airport, where the plane will arrive on time.

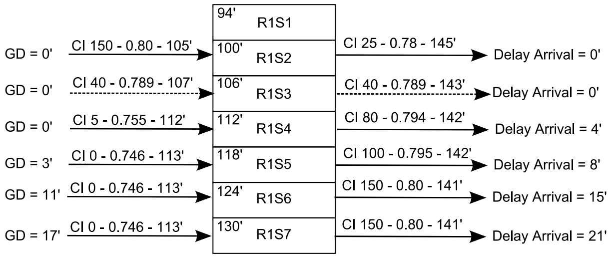

Fig. 10. Example of one regulated area allowing changes on the original flight plan

Obviously, for the third slot (R1S3) the flight is performed at the intended CI of 40 and any delay is experienced. If the slot R1S4 were to be used, it is worth mentioning that on the current operational scenario the aircraft would be delayed five minutes on ground (see Figure 9). However, with the proposed mechanism slot R1S4 can be reached with no delay on ground if flying at a lower airspeed before reaching the regulation. In this case a CI of 5 would be used, corresponding to a cruise speed of M 0.755. Using this cost index, the plane will arrive to R1S4 consuming less fuel than initially planed, but with five minutes of delay. Moreover, once the regulation is passed, a speed up might be done by increasing the CI to 80. This will represent arriving with four minutes of delay instead of the initial five minutes expected with the current operational concept of operations. Finally, for the last three slots (R1S5, R1S6 and R1S7), the best that can be done is to fly at CI=0 to minimise the fuel consumption during the segment before the regulation while adding the needed ground delay in order to arrive to the regulated area at the appropriate slot. As it was done with slot R1S4, once the regulation is passed some time may be recovered speeding up the flight. In this case, the authors refer to the work presented in [8] where it is shown in which conditions it is worth to increase the airspeed by trading off fuel consumption and time recovered.

After this optimisation process, the aircraft operator knows exactly the cost associated to each slot, how much delay the flight would experience at the destination airport, how much fuel would be used and therefore the best sequence of CI depending of the flight segment. In this way, if a marked based mechanism is used, as described in [6], the airline will be on a better position to decide if it is worth to sell their initially assigned slot (in this example slot R1S4) and to buy another one.

V. CONCLUSION AND FURTHER WORK

This paper explains a framework for the optimisation of aircraft trajectories in the SESAR operational scenario. In the current operational concept, airlines have to optimise their flight plans and some effort has to be done to minimise the effect of delays. However, airlines act almost passively because when the network manager imposes them a delay the only optimisation that they might try is to recover some time after the regulation is passed. On the other hand, in the new concept of operations, airlines can be more active. Once a congested airspace is delcared, airspace users will have to agree with the solution facing this demand-capacity imbalance. As airlines will have to negotiate the delay, a game from an economical point of view is set. As it is well known from game theory, the agent with most information is most likely to have advantage with respect to the others.

In this paper, the authors, suggest the idea of compute the cost of different paths that arise through the use of different slot combinations. Once one or several regulations are set, the airspace user might compute the cost of using different slots, but having in mind that an optimisation of every single path will be done. This optimisation will compute the optimal speed and altitude profiles for each alternative leading in consequence to different fuel consumptions and different delays at the destination airport. Summing up, the aircraft operator will have a clear picture of the cost associated to each alternative. With this solution, we expect that they will be in a better position to negotiate with other users the assigned slots.

As further work, the optimiser that deals with time constraints windows should be improved and some studies to analyse the benefits of this solution with more than one restrictions might be also implemented. The results might be compared with some practical cases. Also, some simulations with the market mechanism should be done with and without the optimiser to analyse the benefit for an airline of having this data available. Finally, as airlines work with the CI parameter, a complete translation from this optimisation process to the CI values might be also interesting.

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