Interactions between Operations and Planning in Air Traffic Control

Thibault Lehouillier, Jérémy Omer, François Soumis, Cyril Allignol

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Thibault Lehouillier, Jérémy Omer, François Soumis
Group for Research in Decision Analysis
Polytechnique Montréal, QC, Canada
{thibault.lehouillier,jeremy.omer,francois.soumis}@gerad.ca

Cyril Allignol
École Nationale de l'Aviation Civile
Toulouse, France
allignol@recherche.enac.fr

***Abstract*—Air traffic in Europe is predicted to largely increase over the next decades. In such a context, this paper presents a study of the interactions between costs due to ground holding regulation and costs due to en-route air traffic control. With that in mind, a traffic simulator including the computations of regulation delays, aircraft trajectories and air conflict resolution is described. Through intensive simulations based on traffic forecasts extrapolated from 2012 historical French traffic data, regulation delays and avoidance maneuvers are computed assuming the current regulation or no regulation at all. The resulting costs analysis highlights the exponential growth of regulation costs that should be expected if the airspace capacity and the involved procedure do not change. Compared to this, the costs of air traffic control remain negligible whether regulation is performed or not. The analysis of controllers' workloads however emphasizes the future need to combine automated tools assisting controllers with a regulation better adapted to bigger traffic volumes.**

***Index Terms*—Air Traffic Control, Conflict Resolution, Air Traffic Management, Ground Holding Regulation**

I. INTRODUCTION

Delays in air traffic can have many sources, among which the regulations required to avoid congestion on the network. In 2012, the average delay due to regulations in Europe reached 1.15 minutes per flight [1]. As stated by the latest long-term forecast issued by EUROCONTROL [2], between 2012 and 2035 the traffic volume is predicted to experience a 20 to 80% increase, resulting in a much higher congestion around and between airports, and increased regulation delays. European joint projects that are presently conducted aim at remodeling Air Traffic Management (ATM) in Europe for future decades, in order to adapt it to the future traffic flow characteristics. Among these projects, a large part is gathered under the SESAR (Single European Sky ATM Research) program [3]. One of SESAR's main objectives is to set up a trajectory-based management, where companies and regulation units negotiate a trajectory that would satisfy both their economic objectives and congestion constraints.

The ATM system that is currently implemented in Europe is composed of several layers with different time horizons, aiming at safely and efficiently handle the flow of aircraft. A few months in advance, the airspace management filter is triggered, defining the structure of the route network, as well as navigation procedures. Furthermore, the airspace is divided into control sectors, that is, three-dimensional regions, each one under the responsibility of a pair of controllers.

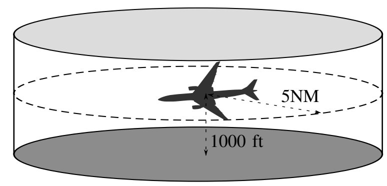


Fig. 1: Vertical and horizontal separation. Another aircraft cannot be inside the cylinder at the same time.

In order to maintain the workload of the controllers at an acceptable level, each control sector has a *capacity*, defined as the maximum number of aircraft entering the sector in one hour (typically, between 20 and 40 aircraft per hour for a control sector in Europe). A few days to a few hours in advance, Air Traffic Flow Management (ATFM) aims at regulating the traffic in order to enforce those sector capacities. This mission is assigned to the Central Flow Management Unit (CFMU), whose work relies on traffic predictions, built upon flight plans that pilots ought to submit. During peak hours, the CFMU issues regulations for flights over congested areas of the airspace by automatically assigning take-off slots via the Computer Assisted Slot Allocation (CASA) algorithm, which works according to a greedy *first-planned, first-served* fashion.

ATC aims at managing air traffic on a short-term horizon. The main missions of controllers are to monitor the traffic and keep aircraft separated from each other by at least 5 NM horizontally or 1000 ft vertically, as depicted in figure 1. In order to solve conflicting situations, i.e. avoid predicted losses of separation between two or more aircraft, controllers issue maneuvers to pilots. Those maneuvers consist in changes in speed, heading or flight level, and induce costs due to fuel consumption and delays.

A study on traffic complexity [4] states that, given a traffic twice denser, no controller will be able to monitor and issue maneuvers without an automated advisory tool, which proves the need of optimization in this domain. Automated ATC is a thoroughly studied subject and numerous algorithms were developed. The literature on aircraft conflict detection and resolution is vast, with a large variety of techniques used such as mixed integer linear programming [5], [6], nonlinear programming [7], [8], metaheuristics [9], semi-definite programming [10], force field models [11]. One can refer to [12] for a comprehensive survey covering these methods.

The performances of automated conflict solvers depend on the number and complexity of the conflicts, which also need to be correlated to sectors' capacities. Despite the diversity of the existing literature, we did not find any published work involving automated conflict resolution and real traffic data extrapolated to predict future traffic. The studies in [6], [13] base their computational tests on historical traffic data, but they do not allow for a thorough analysis of costs and interactions with the other layers of ATM. Nevertheless, a study involving an estimation of future traffic is fundamental to acquire a better understanding on future situations and anticipate difficulties inherent to them. There is also a strong need to study the nature of the relations between the costs incurred by airport and en-route regulations. The insight that one would get on the potential economical impacts would allow to take advantage of these interactions.

The study hereby presented highlights the existing relations between the costs of regulations and those of operations in a context of increased traffic. In particular, our main contribution is to derive an estimation of the potential savings resulting from the insertion of automated tools in ATC to assist the operators. For that purpose, a complete simulator embedding traffic increase, regulation, flight dynamics simulation and automated conflict resolution is developed. Computational tests are based on flight plans extracted from historical traffic, and realistic estimations of the costs incurred by regulation delays and avoidance maneuvers. The intensive simulations focus on different types of sectors and time horizons in order to derive conclusions on what to expect in 20 years. What challenges should be expected and where does the need for optimization reside?

The paper is organized as follows. Section II describes the mechanics of all the automated components and algorithms implemented for this study. Section III depicts the experimental design of the study. The results are presented and discussed in section IV. Conclusions and future work perspectives are shared in section V.

II. Description of simulation algorithms

The study of interactions between planning and control over real traffic requires several automated procedures, among which a trajectories simulator, a regulation algorithm and a conflict solver. Figure 2 displays the organization of our experimental setting, along with references to the corresponding sections providing details about each component.

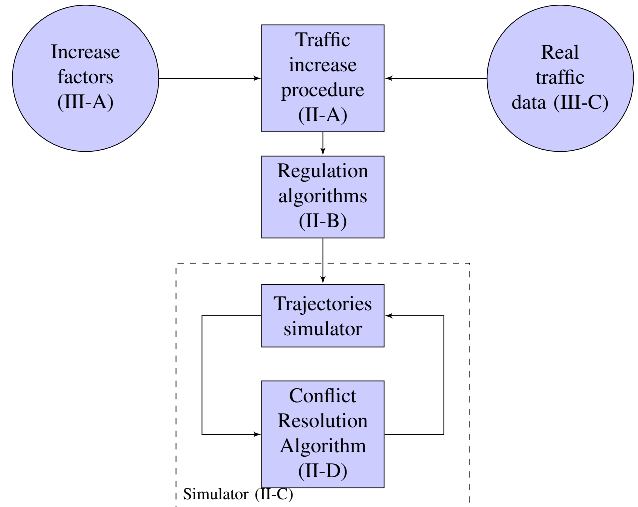


Fig. 2: Experimental design

A. *Traffic increase*

In order to increase traffic to reflect available forecasts, a procedure parametrized by a multiplying factor was designed. Given an increase factor f (e.g. $f = 0.4$ for a 40% increase) and an initial traffic consisting of a set T of n flights, $n_+ = f \times n$ new flights are created. To create a new flight, a flight is randomly chosen in T, and is then duplicated with a slight random modification on its departure time. The random shift typically lies in $[-15; -1] \cup [+1; +15]$ minutes in order to avoid the exact duplication of the flight.

The main advantage of such a method is to maintain a similar distribution of departure times over a day of traffic. Indeed, the random shift tends to broaden and flatten the peaks of the distribution, hence deriving a conservative lower bound of the actual distribution. A more realistic forecast would lie on a market study carried out at a global scale, but such material is not available yet.

Nevertheless, a drawback of duplicating flights in such a fashion is creating conflicts with pursuing aircraft. Depending on the random shift, the duplication may lead to flights following each other very closely. To overcome this issue, a regulation was set up at each airspace entry point in order to force the necessary separation between those flights.

B. *Regulation*

The regulations carried out by the CFMU affect flights crossing regulated areas. Those areas are designed on a daily basis by experts, depending mainly on the expected traffic. Over a given regulated area, departure slots are allocated following a *first planned, first served* scheme, meaning that aircraft are allowed to enter the area in the same order as if not regulated at all.

Figure 3 reflects the mechanism of the algorithm as described in [14] for a given regulated area. For each regulated area, CASA maintains a *slot allocation list*, which is a series of consecutive slots of equal length covering the regulation period. For instance, a two-hour period with a capacity equal to 30 results in an allocation list composed of 60 two minutes long slots. A flight crossing this area has a priority linked to the Estimated Time Over (ETO) the point where it enters the area: the sooner the ETO, the higher the priority. It is really important to notice the cascade effect incurred by this mechanism. Re-allocating slots to flights can indeed have consequences for other flights that would also be re-allocated in return, hence

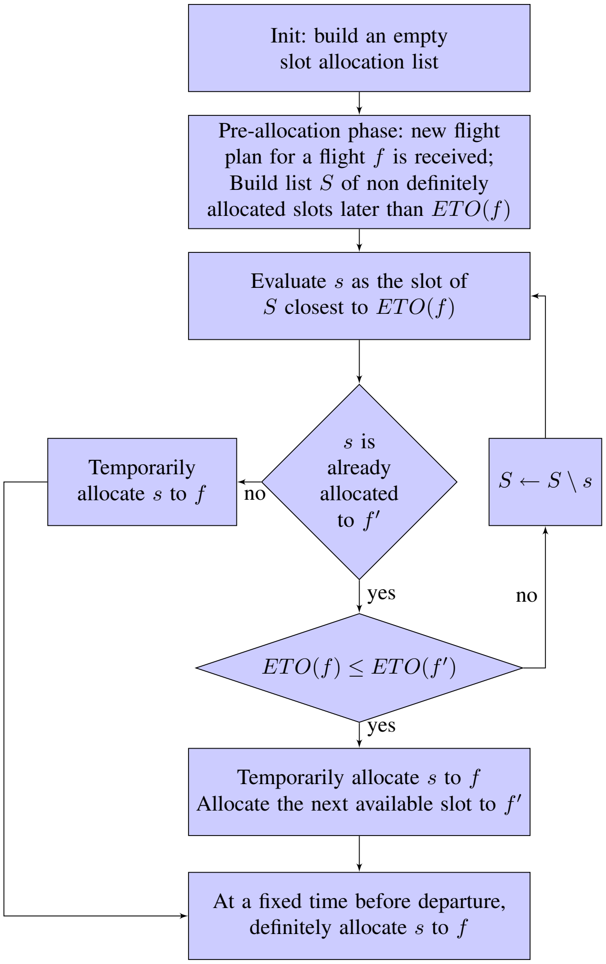


Fig. 3: Mechanics of CASA over a regulated area

increasing the number of delays on the network. One limitation of this algorithm relies in the independent regulation of each area. If a given flight is regulated in two or more areas, its departure slot is chosen as the biggest regulation, which may violate the constraints in the other areas.

The CASA algorithm was implemented in the simulation engine, but the exact regulation areas being unavailable they were assumed to coincide with the 2012 control sectors. This assumption differs from the CFMU's procedure because the actual areas are specifically designed depending on several factors such as changing weather conditions. Also, the capacities input in CASA were chosen as 2012 nominal sectors capacities as no more accurate data could be found.

C. Trajectories simulation

The flights simulations were performed by the Complete Air Traffic Simulator (CATS) [15]. CATS is an en-route air traffic simulation engine based on a time-discretized execution model, i.e both position and velocity vectors of every aircraft are computed at steps separated by a period τ set by the user. Aircraft specifications and performances, such as horizontal and vertical speeds, or fuel consumption are extracted from the Base of Aircraft Data (BADA) summary tables deriving from the total energy model [16]. The simulation engine processes data corresponding to real flight plans and gives detailed outputs including traffic statistics, sector occupation at any time and a thorough examination of conflicts: geometry, duration and conflict resolution statistics.

D. Conflict resolution

The aim is not to study the performances of a particular algorithm nor to prove that it is fit for a practical implementation. The conflict resolution module is only used to estimate the costs incurred by the maneuvers that are necessary to maintain the aircraft separated. Although it is impossible to precisely correlate the costs of maneuvers designed by an automated conflict solver with the ones that would be decided by a controller, those costs necessarily have the same orders of magnitude.

The conflict resolution algorithm designed by Durand et al. in [9] was used in the simulations because it is already embedded in CATS. In a first step, conflicts are detected over a 20 minutes horizon, and aggregated into independent *clusters*. For instance, if aircraft A conflicts with aircraft B and aircraft B conflicts with aircraft C, then aircraft A, B and C are aggregated into the same cluster. Each cluster is then deconflicted independently, using a genetic algorithm (GA).

The genetic algorithm is based on the concepts described in the reference handbook by Goldberg [17]. The principle is to manipulate a *population* where each *individual* is a candidate solution to the problem. The population is thus composed of n possible trajectories, one per aircraft. For a given aircraft, the possible trajectories correspond to the set of allowed maneuvers: heading changes between $-30°$ and $30°$, speed changes between -6% and $+3\%$ and, incidentally, altitude maneuvers corresponding to climb interruptions and descent anticipations.

The population is initialized with randomly generated maneuvers for each aircraft. At each resolution step, the quantity to optimize, called fitness, is computed for each individual, and the best individuals are selected according to their fitness. These individuals are used as input to cross-over and mutation operators aiming at generating new individuals in the current population, before applying again the iterative process.

III. Experimental design

A. Traffic predictions

Medium and long term traffic forecasts are regularly issued by EUROCONTROL. Based on a thorough study of current traffic trends and statistics and recent air industry-related events, the last mid-term forecast provides predictions for the period ranging from 2013 to 2019 [18], while the long term extends the analysis until 2035 [2]. The predictions depending on the evolution of the global economical context, several scenarios are considered, and annual growth rates are estimated for each one of them. The rates in table I summarize the long-term forecast that may be found in [2].

Scenarios displayed in table I correspond to different assumptions made on the future. Global Growth and Fragmented

TABLE I: SUMMARY OF FLIGHT FORECAST FOR EUROPE UNTIL 2035

Scenario	Annual growth			
	Global Growth	Regulated Growth	Happy Localism	Fragmented World
2012-2019	3.4%	2.3%	2.3%	0.9%
2019-2020	3.7%	2.2%	1.5%	0.6%
2021-2025	2.5%	1.9%	1.5%	0.8%
2026-2030	2.2%	1.5%	1.2%	0.4%
2031-2035	1.9%	1.2%	1.1%	0.7%

World depict two extremes situations in which both economical and political circumstances allow flourishing exchanges or cause a recession. In our computational tests, the increase traffic reflects the in-between Regulated Growth scenario, which is most likely happen. This scenario represents an average economic growth along with regulations to address environmental and sustainability issues. A sufficient range of traffic increase rates is then achieved by focusing on six horizons spread between 2014 and 2035. The particular chosen years and the corresponding traffic rates are given in table II.

TABLE II: TRAFFIC PREDICTIONS WITH REGULATED GROWTH

Year	2014	2017	2020	2025	2030	2035
Increase	+5%	+12%	+20%	+32%	+42%	+50%

B. Airspace capacity

CASA needs the capacity of each regulated area. As previously mentioned, it was only possible to obtain the nominal capacities of sectors covering the French territory. No complete study providing an estimation of the evolution of those capacities was found either. Moreover, the intent of our work being to estimate the impact of automated conflict resolution, the capacities forecast should not account for the inclusion of such decision aid in the tools available by the controllers. Out of simplicity, the simulations are thus run according to the two following scenarios:

- S_1 - capacities values remain unchanged in the future;
- S_2 - capacities are deleted: no regulation is performed.

S_1 and S_2 correspond to two extreme situations where, on one hand, nothing new is designed to handle greater traffic, and on the other hand, traffic flows freely without any constraints. The study of S_1 will lead to a better insight on the necessity to modify current procedures. Focusing on S_2 will enable to quantify the effect of a worst case-scenario from the ATC point of view. Indeed, if no regulation is performed, S_2 should lead to the worst situations that could be expected in terms of conflicts and controllers' workload.

C. Choice of the reference historical data

Historical data describing the 2012 traffic over France are used in experimental tests. The simulations focused on Friday, June 8^{th} as it happens to be a busy day for which the delays actually affected by CASA are close to the delays that we computed with the nominal sectors capacities. For illustration, number of flights, computed delays, and delays actually affected by the CFMU for the week going from June, 6^{th} to June, 12^{th} are given in table III. Although numbers can differ by a large margin, the computed data remains valid as no absurd behavior arises. Indeed, flight volumes per day follow a similar distribution. It also appears that June, 8^{th} is simultaneously the day with the greatest number of flight and of delay minutes. For this reason, the choice of this day should allow for the emergence of the difficulties related to the management of a very dense traffic.

TABLE III: TRAFFIC STATISTICS FROM 2012/6/6 TO 2012/6/12

Date	Number of flights	Computed delays (min)	CFMU delays (min)
6/6	8656	1835	4503
6/7	8723	1875	8845
6/8	9053	16086	15505
6/9	8469	5708	13215
6/10	8786	11075	10924
6/11	8817	5507	11449
6/12	8618	4739	8006
Average	8731.7	6689.3	10349.5

D. Delay and maneuvers costs

A study performed by EUROCONTROL [1] estimates that in 2012, ATFM delays cost €0.85 billion in Europe. For a given flight, the costs depend on a variety of factors, such as the operational conditions, the phase of flight where the delay happens, the type and size of the aircraft, and the load factor. As a consequence, a thorough study of costs modeling and a large quantity of data is necessary for the present work.

The study presented in this paper focuses on two main types of costs. On the one hand, the maneuvers returned by the automated conflict resolution result in extra fuel consumption. We referred to the model described in the BADA user manual [19] to compute the consumption, which depends mostly on the type, speed and altitude of the aircraft.Fuel consumptions are computed for three different maneuvers: speed, heading or altitude changes. On the other hand, delay costs are caused by the regulation when it results in allocated slots that differ from the preference of the airline. Modeling properly these costs is a complex task for which several components are to be considered. Among those components, costs of passenger delays, along with crew and maintenance, need to be taken into account. It is also important to study the consequences of a delay on the whole network. Indeed, a delay induces reactions among the rotation in which the concerned flight was included.

In the existing literature, passenger costs are usually divided between "hard" costs representing compensation costs like accommodating passengers or rebooking, and "soft" costs accounting for passengers defecting from an airline because of recurring delays, or passengers owning a flexible ticket deciding to choose one company over another one for punctuality

TABLE IV: TACTICAL COSTS (EUROS, TOTAL) OF GROUND HOLDING DELAY FOR DIFFERENT AIRCRAFT TYPES.

Delays (min)	15	60	120	240
B733	360	5780	29730	53720
B752	520	8780	45610	81610
B763	880	14510	84200	149510
B744	1230	20760	120940	213950
A320	410	6800	35280	63530
A321	470	8150	42460	76140

reasons. A joint work between the University of Westminster and EUROCONTROL resulted in a series of articles published between 2004 and 2011. A cost per minute per passenger of ground and airborne delays due to ATC is derived in [20]. In [21], Cook et al. estimate airline delay costs as a function of delay magnitude. This function is combined with fuel consumption and future emissions charges to derive a cost-benefit trade-off during ground and airborne phases. In [22], the authors focus on the costs related to delay propagation in the network. Those delays can be either rotational (i.e related to flights within the rotation involved) or non-rotational. Using values extracted from [23], the authors derive costs values depending on the rotation structure, the aircraft involved and the magnitude of the delay. Results from those articles are gathered in [24], providing reference values for delay costs incurred both at strategic and tactical levels. The report presents costs values for all phases of a flight: at-gate, taxi, cruise extension and arrival management. Those values are assigned under different scenarios (low, base and high case), for twelve different types of aircrafts. Sample costs are given in table IV for the at-gate base scenario.

The costs that were computed under the base case hypotheses in [24] are used in this study. Additionally, the simplifying assumption that companies ask for take-off slots they want is made. As a consequence, the slots attributed by CASA lead to a valid estimation of the regulations-related delays.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

Simulations were run for the entire French traffic of Friday, June, 8$^{\text{th}}$. A first set of tests were performed without any conflict resolution, in order to derive conclusions on the intrinseque nature of an increased traffic. Tests with conflict resolution are described in the following subsection.

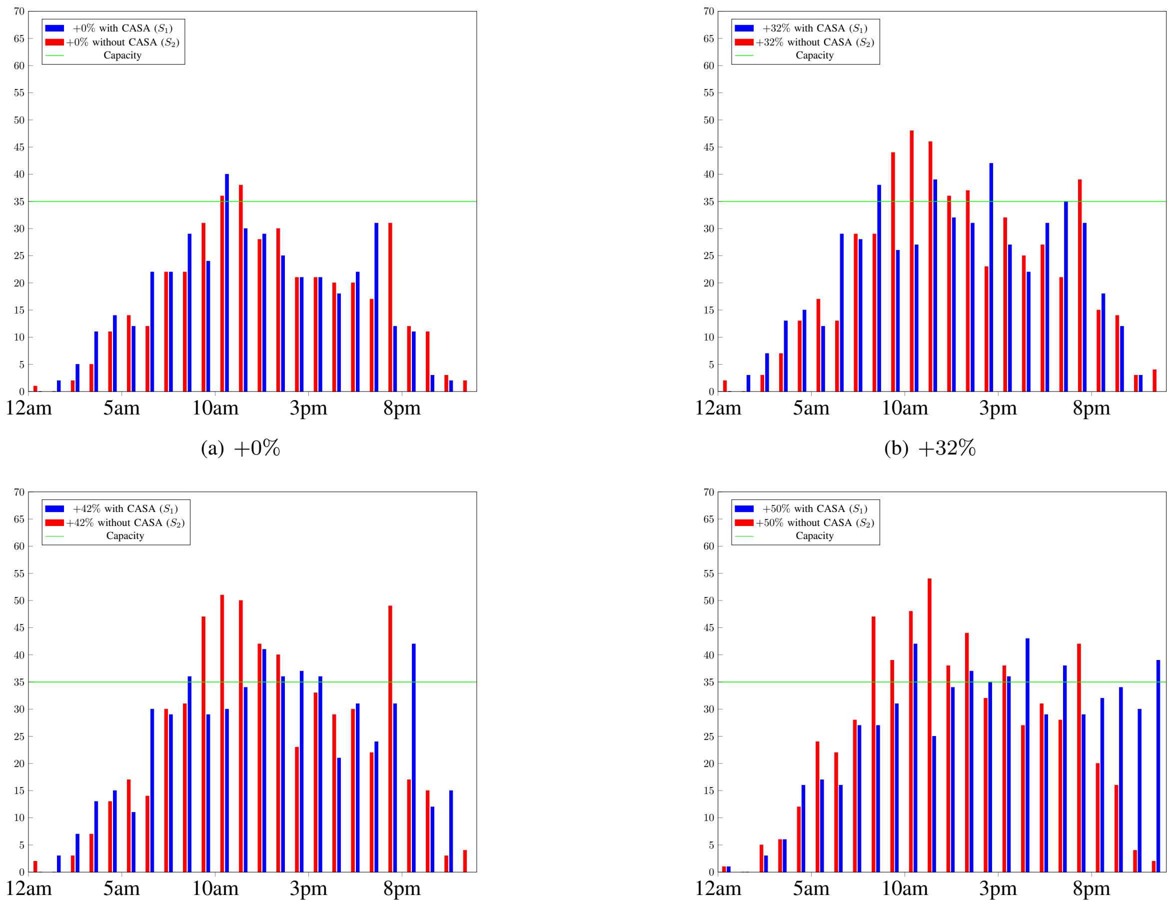
A. Simulations without conflict resolution

The first results are devoted to simulations focused on a dense sector. The airspace surrounding Reims is particularly challenging in terms of traffic complexity: control sectors are quite small and include routes joining important European hubs such as London to others including Milan, Zurich or Frankfurt. As a consequence, we focused on the KR sector, which is a busy sector belonging to Reims control zone. The entering flow was studied as a congestion measure of KR. Figure 4 displays this measure for different volumes of traffic, respectively actual traffic and traffic increased by 32%, 42% and 50%. For each traffic volume, statistics were extracted for both scenarios S_1 and S_2 in which, respectively, the CASA regulation refers to the 2012 nominal sector capacities, and no regulation is performed.

Charts' trends clearly distinguish the nature of the flow depending on the presence or absence of the regulation. Without any regulation, the entering flow distribution tends to aggregate into a peak over the period ranging from 10AM to 12AM, thus inducing a large overcapacity. A first threshold regarding controllers' workload may thus be distinguished. Indeed, for traffic volumes greater than $+32\%$, the entering flow per hour may overcome the capacity by more than 12 flights if no regulation is performed. As a consequence, a tremendous effort in monitoring would be required. This suggests that future traffic needs to be handled with an adapted regulation or with highly-automated tools decreasing controllers' workload. On the other hand, the regulation controls the entering flow to prevent the overcapacity. A saturated capacity plateau is noticeable, and increasing the traffic volume enlarges the plateau. The fact that even with CASA, the capacity is overcome in several cases results from the already mentioned difficulties the algorithm encounters when a flight is regulated on several areas.

It remains worth noting that an effect of the CASA regulation is to postpone flights. A drawback of such a way to proceed is displayed as the last blue column in chart 4(d): an important amount of flights were delayed between 11 pm and 12 pm, inducing an entering flow of 40 flights, i.e 5 flights over the declared capacity of 35 flights per hour. In this case, the 35 first flights get a slot between 11pm and 12pm, while the 5 remaining others are postponed to the following day.

In addition to the effects on the flow distribution, it is necessary to determine whether regulation has an impact on the conflicts. Figure 6 displays for each traffic volume previously described the total number of conflicts per day, along with the number of conflicts per day for different sectors, with and without applying CASA. Chosen sectors represent different types of flow density: two dense sectors, along with three average sectors and two sparse sectors. Surprisingly, chart 6(a) shows that the removal of regulation does not imply a greater number of conflicts until a +20% traffic. Beyond this approximate threshold, the number of conflicts without CASA increases faster than when CASA is applied, leading to a 15% difference for a $+50\%$ traffic volume. This observation made at the global scale can be paired with an observation at the sector level. Indeed, the evolution of the number of conflicts with an increase of traffic depends on the type of sector, as highlighted by charts 6(b) and 6(c). On the one hand, the magnitude of the number of conflicts remains similar, whether or not CASA is applied. This observation suggests that the regulation has little effect on small or average sectors, except slightly reducing the minimum and maximum number of conflicts per day. This can be explained by the fact that for small traffic densities, nominal capacities are seldom saturated, hence preventing CASA to have an actual effect on the flow distribution. On the other hand, for highly loaded sectors, the margin by which the number of conflicts



(a) $+0\%$ (b) $+32\%$

(c) $+42\%$ (d) $+50\%$

Fig. 4: Entering flow per hour for different traffic volumes on KR control sector

without CASA exceeds the number of conflicts with CASA grows with traffic density. This difference is a consequence of nominal capacities being more than saturated for high traffic densities. As a consequence, one of this regulation's main benefits can be highlighted. Indeed, in order to prevent an over-capacity on different sectors, CASA smoothes the flow, equally spreading over the day the number of conflicts, as evidenced on figure 5. Besides, operating according to such a fashion eases the tasks of air traffic controllers, such as monitoring and communications with pilots and other controllers.

B. Simulations with conflict resolution

The first interpretation of the simulations focuses on regulation delay and conflict resolution costs as they are valuable aggregated indicators of the overall traffic complexity. These costs were computed as described as in section III-D and are displayed on figures 7 and 8 for both scenarios S_1 and S_2. Clearly, there is no regulation cost in scenario S_2.

The curve represented on figure 7 suggests that the global costs resulting from the regulation algorithm vary exponentially with the traffic volume. This is a logical trend considering that the intensification of the traffic affects mostly the congested areas during peak hours. Moreover, the plateau

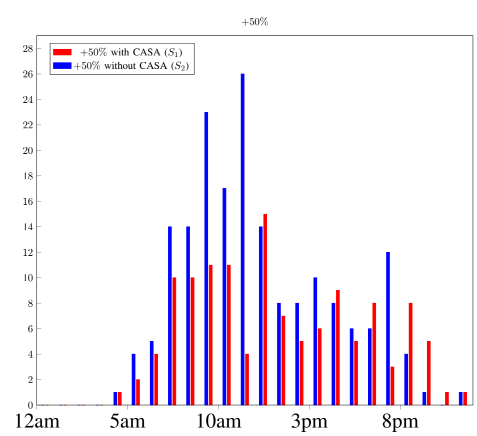
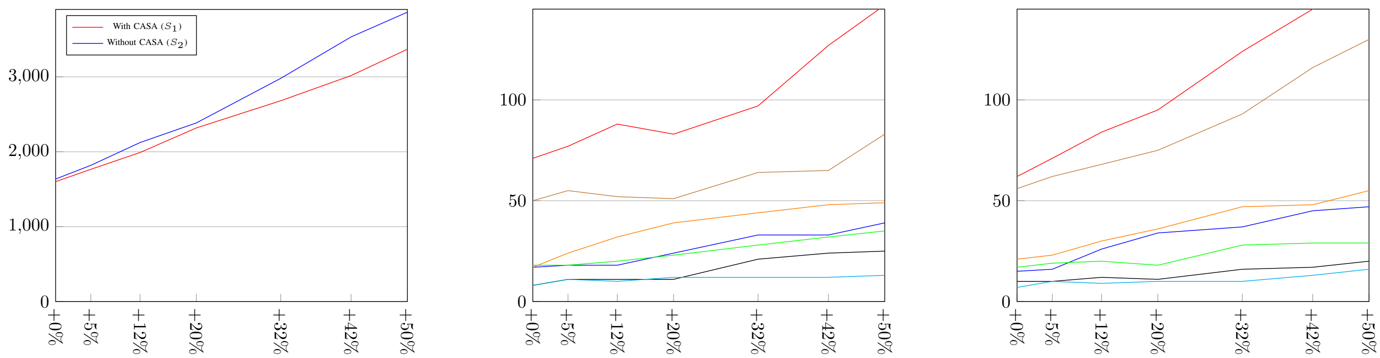


Fig. 5: Conflicts per hour for a $+50\%$ traffic on KR control sector

effect highlighted in charts 4 emphasizes that peak periods tend to be flattened and widened, hence inducing larger and costly delays. Not only does it show that a tremendous amount of money could be saved in the near future by improving the regulation procedure, but it also emphasizes that this



(a) Total (b) With CASA (S_1) (c) Without CASA (S_2)

Fig. 6: Comparison of the number of conflicts observed with and without CASA

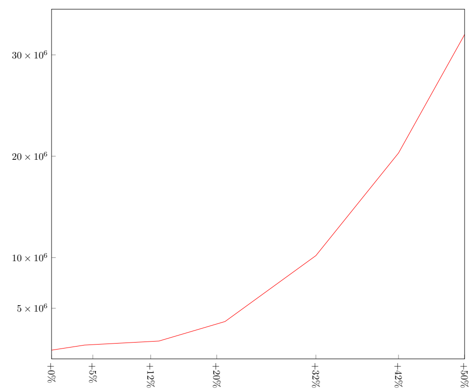


Fig. 7: Ground-holding regulation costs(€), 2012/6/8

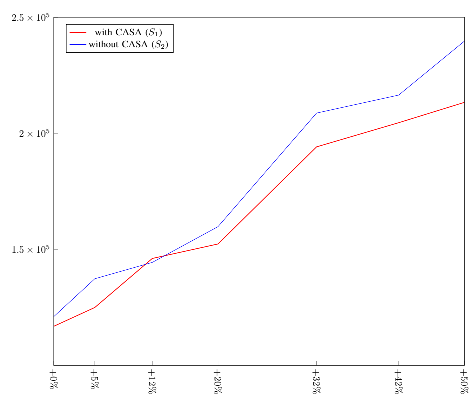


Fig. 8: Deconfliction costs(€) - 2012/6/8

improvement is necessary to handle larger traffic volumes.

The expected disadvantage of suppressing ground-holding regulations is that it should result in extra conflict resolution costs. Indeed, without any regulation, a larger traffic flow has to be handled, hence increasing the number of conflicts and resolution maneuvers issued in response. Figure 8 displays conflict regulation costs for scenario S_1 and S_2. These global costs are the sum of costs for the different types of maneuvers described in subsection III-D. Among these maneuvers, speed changes, seldom performed and less costly represent around 1% of the total cost. The remainder of the costs is equally divided between heading changes and altitude changes, which are more numerous and more costly. The total costs remain very similar until the +20% traffic where conflict resolution costs increase faster in S_2 than in S_1. This results in 17% larger costs in S_2 for a traffic volume of +50%. Although it is an important increase, the magnitude of the conflict resolution costs is largely lower than the one of regulation-related costs: around €250 000 for conflict resolution versus €32 000 000 for ground-holding regulation. As a consequence, the extra costs necessary to handle traffic are negligible compared to the possible savings obtained through removing ground-holding policies.

Nevertheless, as depicted in figure 9, the number of maneuvers issued per hour on dense areas becomes far greater than what controllers presently perform: up to 27 maneuvers are performed within one hour for a traffic volume of +50%, which represents almost a command every two minutes. This corresponds to a considerable workload that adds up to the monitoring workload, making controllers' task all the more heavier.

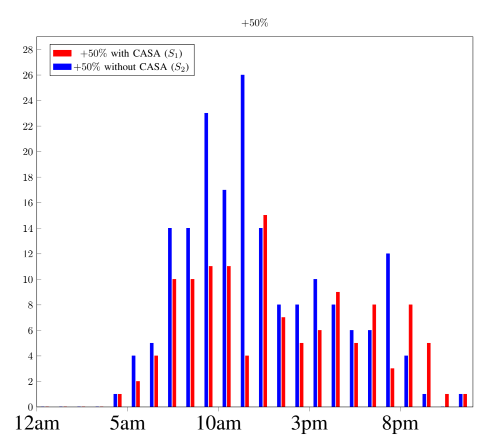


Fig. 9: Maneuvers per hour for a +50% traffic on KR control sector

V. Conclusion

In this paper, we analyzed the interactions between two consecutive layers of the ATM ; the aim being to evaluate the impacts of the current ground holding regulation scheme on delays costs, sector loads, and conflict resolution costs. The study is based on a fast-time traffic simulator relying on three modules respectively in charge of computing the regulation delays, simulating the trajectories, and solving conflicts. The French traffic data of a particularly busy day of 2012 was chosen as an input for the simulator, and a traffic increase procedure was described in order to generate meaningful predictions up to 2035.

The tests focused on two different scenarios respectively reflecting the current regulation procedure and no regulation at all. The first analysis does not include conflict resolution in order to highlight the sole effect of regulation on the traffic. As expected, for a busy sector, it reduces the amplitude of the peaks and spread the entering flow over the day. However, the impact on the total number of conflicts is not as important as one would think, and only for a traffic increased by 30% does it really prove to improve the situation on this aspect.

Including the conflict resolution leads to the the main conclusions of our work. We estimated that for a traffic increase by 50%, the delay costs would amount to millions of euros if the current regulation procedure is let unchanged. In the same time, the additional conflict resolution effort required to treat a traffic without regulation would raise the associated cost by 15%, but the corresponding amount would still remain negligible when compared to delay costs. Despite the few extra cost involved in terms of fuel consumption, the workload resulting from the new distribution of conflicts would become hardly manageable for controllers working in the current framework. Indeed, on top of monitoring very dense areas, they would have to issue a maneuver instruction every two minutes in some congested areas. Our opinion is thus that a great amount of money could be saved in the future by developing a regulation algorithm more adapted to very dense traffics. Such a procedure would certainly benefit from the introduction of automated tools assisting controllers in every task – namely monitoring, communication, and conflict detection and resolution–, as it would allow for the successful management of much more complex situations with a comparable effort. Finally, we showed that one of the main motivation for the development of efficient automated tools should be the massive indirect savings they could generate if an adapted regulation procedure was simultaneously implemented.

This study also opens several perspectives for future work. Among them, this analysis would certainly benefit from the inclusion of several conflict solvers and a comparison of their performances. This way we would be able to address the possibility to keep aircraft safe in any situation and within a practical computational time. Different regulation procedures including realistic predictions for the sectors' capacities should also be considered, keeping in mind that regulation and conflict resolution algorithms should be developed with the intent to optimize their interactions. Finally we did not investigate radical changes in the flow management. For instance, using direct routes between origins and destinations of the different flights could be studied.

References

[1] "Performance review report for 2012," EUROCONTROL, Tech. Rep., 2012.

[2] "Eurocontrol long-term forecast: IFR flight movements 2013-2035," Eurocontrol - STATFOR, Tech. Rep., 2013.

[3] SESAR Joint Undertaking, "European ATM master plan, edition 2," Tech. Rep., 2012.

[4] P. Kopardekar, T. Prevot, and M. Jastrzebski, "Traffic complexity measurement under higher levels of automation and higher traffic densities," in *Proceedings of the Guidance, Navigation, and Control Conference and Exhibit*, 2008.

[5] J. Omer and J.-L. Farges, "Hybridization of nonlinear and mixed-integer linear programming for aircraft separation with trajectory recovery," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 3, pp. 1218–1230, 2013.

[6] A. Vela, S. Solak, J.-P. Clarke, W. E. Singhose, E. R. Barnes, and E. L. Johnson, "Near real-time fuel-optimal en route conflict resolution," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 1, pp. 47–57, 2011.

[7] A. U. Raghunathan, V. Gopal, D. Subramanian, L. T. Biegler, and T. Samad, "Dynamic optimization strategies for three-dimensional conflict resolution of multiple aircraft," *Journal of guidance, control, and dynamics*, vol. 27, no. 4, pp. 586–594, 2004.

[8] A. Alonso-Ayuso, L. F. Escudero, and F. J. Martin-Campo, "A mixed 01 nonlinear optimization model and algorithmic approach for the collision avoidance in ATM: Velocity changes through a time horizon," *IEEE Transactions on Intelligent Transportation Systems*, vol. 39, pp. 3136–3146, 2012.

[9] N. Durand, J.-M. Alliot, and J. Noailles, "Automatic aircraft conflict resolution using genetic algorithms," *Proceedings of the Symposium Applied Computing, Philadelphia*, 1996.

[10] E. Frazzoli, Z.-H. Mao, J.-H. Oh, and E. Feron, "Resolution of conflicts involving many aircraft via semidefinite programming," *AIAA Journal of Guidance, Control and Dynamics*, vol. 24, no. 1, pp. 79–86, 1999.

[11] J. Hoekstra, R. V. Gent, and R. Ruigrok, "Conceptual design of free flight with airborne separation assurance," *AIAA Guidance, Navigation, Control Conference, Boston, MA, USA*, vol. 4239, pp. 807–817, 1998.

[12] M. Campo and F. Javier, "The collision avoidance problem: methods and algorithms," Ph.D. dissertation, 2010.

[13] J. Omer and T. Chaboud, "Automated conflict-free planning: Experiments on real air traffic data," *International Council of the Aeronautical Sciences (ICAS)*, 2012.

[14] *Basic CFMU handbook, General & CFMU systems*, Eurocontrol Std., Rev. v15.0, 2011.

[15] J.-M. Alliot, J.-F. Bosc, N. Durand, and L. Maugis, "Cats: A complete air traffic simulator," *16th Digital Avionics System Conference*, 1997.

[16] "Aircraft performance summary tables for the base of aircraft data (bada) revision 3.0," EUROCONTROL, Tech. Rep., 1998.

[17] D. Goldberg, *Genetic Algorithms*. Addison Wesley, 1989.

[18] "Eurocontrol seven year forecast: Flight movements and service units 2013 - 2019," Eurocontrol - STATFOR, Tech. Rep., 2010.

[19] "User manual for the Base of Aircraft Data (BADA)," Eurocontrol, Tech. Rep. 11/03/08-08, 2011.

[20] A. J. Cook, G. Tanner, and S. Anderson, "Evaluating the true cost to airlines of one minute of airborne or ground delay: final report," 2004.

[21] A. Cook and G. Tanner, "The challenge of managing airline delay costs," in *Conference on Air Traffic Management (ATM) Economics*, vol. 1, 2009.

[22] ——, "Modelling the airline costs of delay propagation," *AGIFORS Airline Operations Conference, London, UK*, 2011.

[23] R. Beatty, R. Hsu, L. Berry, and J. Rome, "Preliminary evaluation of flight delay propagation through an airline schedule," *Air Traffic Control Quarterly*, vol. 7, no. 4, pp. 259–270, 1999.

[24] A. J. Cook and G. Tanner, "European airline delay cost reference values," 2011.