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Measuring the Interactions between Air Traffic Control and Flow Management Using a Simulation-Based Framework*

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Abstract

Air traffic in Europe is predicted to increase considerably over the next decades. In this context, we present a study of the interactions between the costs due to ground-holding regulations and the costs due to en-route air traffic control. We describe a traffic simulator that considers the regulation delays, aircraft trajectories, and air conflict resolution. Through intensive simulations based on traffic forecasts extrapolated from French traffic data for 2012, we compute the regulation delays and avoidance maneuvers according to two scenarios: the current regulations and no regulations. The resulting cost analysis highlights the exponential growth in regulation costs that can be expected if the procedures and the airspace capacity do not change. Compared to the delay costs, the costs of the air traffic control are negligible with or without regulation. The analysis reveals the heavy controller workloads when there are no regulations, suggesting the need for regulations that are appropriate for large traffic volumes and an improved ATC system. These observations motivate the design of a third scenario that computes the sector capacities to find a compromise between the increase in the delay costs due to ground-holding regulations and the increase in the controller workload. The results reveal the sensitivity of the delay costs to the sector capacity; this information will be useful for further research into ATM sector capacity and ATC automated tool design. Finally, because of the growing interest in the free flight paradigm, we also perform a traffic and cost analysis for aircraft following direct routes. The results obtained highlight the fuel and time savings and the spatial restrictions that companies use to avoid congested areas.

Keywords: Air Traffic Control, Conflict Resolution, Air Traffic Management, Ground-Holding Regulation, Traffic Simulation, Traffic Forecasts

1 Introduction

1.1 Context and main concepts

Delays in air traffic can arise from many sources, including the regulations required to avoid congestion on the network. In Europe in 2012, the average delay due to regulations reached 1.15

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minutes per flight EUROCONTROL (2012). According to the latest long-term forecast issued by EUROCONTROL EUR (2013), traffic volumes are predicted to increase by 20% to 80% between 2012 and 2035, resulting in much higher congestion around and between airports and increased regulation delays. Joint European projects that are currently underway aim to remodel air traffic management (ATM) in Europe to adapt it to future traffic flow characteristics. Many of these projects are included in the SESAR (Single European Sky ATM Research) program SESAR Joint Undertaking (2012).

Currently, the European ATM system is composed of several layers with different time horizons, aiming to safely and efficiently handle the flow of aircraft. A few months in advance, the airspace management filter is triggered. It defines the structure of the route network and the navigation procedures. The airspace is divided into control sectors, which are three-dimensional regions that are each the responsibility of a pair of controllers.

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). Airspace capacity estimation methods have already been developed. A study estimating the airspace capacity in Europe as a combination of different types of air traffic movement in different sectors has been performed Majumdar et al. (2002). More recently, a simulation-based approach has been designed by Steiner and Krozel Steiner and Krozel (2009). They used ensemble-based weather forecasts to generate probability distributions of airspace capacities. Their model has been extended by Clarke et al. Clarke et al. (2013), who developed a more general model including an air traffic control (ATC) module and capturing traffic-related uncertainties. However, they did not analyze the costs incurred or the impact on the network.

From a few days to a few hours in advance, air traffic flow management (ATFM) regulates the traffic to enforce the sector capacities. This task is assigned to the Central Flow Management Unit (CFMU), whose work relies on traffic predictions based on pilots' flight plans. During peak periods, the CFMU issues ground-holding 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 in a greedy *first-planned, first-served* fashion. The ground-holding problem (GHP) was defined in 1994 by Vranas et al. Vranas et al. (1994b) and has been widely studied since. The techniques in the articles include stochastic models Mukherjee and Hansen (2007) and shortest path problems Vranas et al. (1994a). Since congestion in the United States is primarily related to important hubs whereas in Europe both airspace and airport capacities can cause congestion issues, most studies focus on European traffic. For instance, the difficulties and potential improvement points of European ATFM have been studied in Lulli and Odoni (2007).

ATC aims to manage air traffic on a short-term horizon. The main tasks of the controllers are to monitor the traffic and to keep the aircraft separated by at least 5NM horizontally or 1000 ft vertically, as depicted in Figure 1. To resolve conflict situations, i.e., to avoid predicted losses of separation between two or more aircraft, the controllers issue maneuvers to the pilots. These maneuvers involve changes in the speed, heading, or flight level, and they induce costs due to fuel consumption and delays.

A study of traffic complexity Kopardekar et al. (2008) states that if the traffic becomes twice as dense, no controller will be able to monitor and issue maneuvers without an automated tool, which indicates the need for optimization in this domain. Automated ATC has been thoroughly studied, and numerous algorithms have been developed. The literature on aircraft conflict detection and resolution is vast; the techniques applied include mixed integer linear programming Omer and Farges (2013); Vela et al. (2011), nonlinear programming Raghunathan et al. (2004); Alonso-Ayuso et al. (2012), metaheuristics Durand et al. (1996); Alonso-Ayuso et al. (2014), semidefinite programming Frazzoli et al. (1999), and force field models Hoekstra et al. (1998). See Martín-Campo (2010) for a comprehensive survey. Research has been conducted to

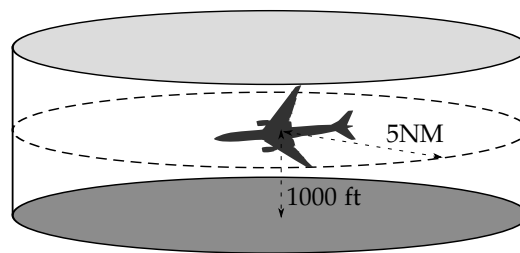


Figure 1: Vertical and horizontal separation. No other aircraft can be inside the cylinder at the same time.

test conflict resolution in a context of growing traffic. For instance, Farley and Erzberger Farley and Erzberger (2007) base their computational tests on future traffic.

In a second step, we aim at studying how quantified objectives could be set for a continuous improvement of ATM. Our main assumption in this study is that the delay costs due to ground holding regulations should not grow faster than linearly with the increase of traffic.

1.2 Contribution statement

Our literature review highlights that significant progress has been achieved at all levels of decision of ATM. To push the research further, more bridges between those levels have to be built. In other words, a better understanding of the interactions between the different decision levels would help the improvement of the ATM system as a whole. More specifically, a study focusing on these interactions in a context of extrapolated traffic would be of great value to the field, since it would be fundamental for a better understanding of future situations and their inherent difficulties. To find possible solutions to these upcoming challenges, the knowledge of the aforementioned interactions could highlight key features needed from future optimization tools, and could drive the research towards the main subjects of improvement. Despite the diversity of the literature, we have found few work aiming at filling these gaps.

Our motivation is two-fold. We first want to identify the main bottlenecks in terms of costs and security in ATFM and ATC. For this our approach is to apply a progressive increase in the traffic volume using the reference values of EUR (2010, 2013), and analyze the evolution of the ATFM and ATC costs, and that of the controllers' workload. For ATFM, we focus on the ground-holding and the delay costs, whereas for ATC we study the avoidance maneuver costs and the controller workload. In a second step, we aim at studying how quantified objectives could be set for a continuous improvement of ATM. Our main assumption in this study is that the delay costs due to ground holding regulations should not grow faster than linearly with the increase of traffic. For this, we design a scenario controlling the growth in ground-holding costs with an increase in sector capacities. The capacity values computed allow us to determine objectives for research on ATM improvement.

The paper is organized as follows. Section 2 describes the mechanics of the automated tools we used in our simulations. Section 3 describes the traffic data used, along with the ground-holding cost model and the controller's workload measures. In Section 4, we study the interactions between ATC and ATFM by simulating traffic with and without ground holding regulations. Section 5 provides a possible answer to observations made in Section 4, with a design of a scenario representing a trade-off between high ground-holding costs and heavy workloads.

2 Description of the simulation algorithms

The study of the interactions between ATFM and ATC requires several automated procedures: a trajectory simulator, a ground-holding algorithm, and a conflict solver. Figure 2 provides an overview, with references to the sections in which we discuss each component.

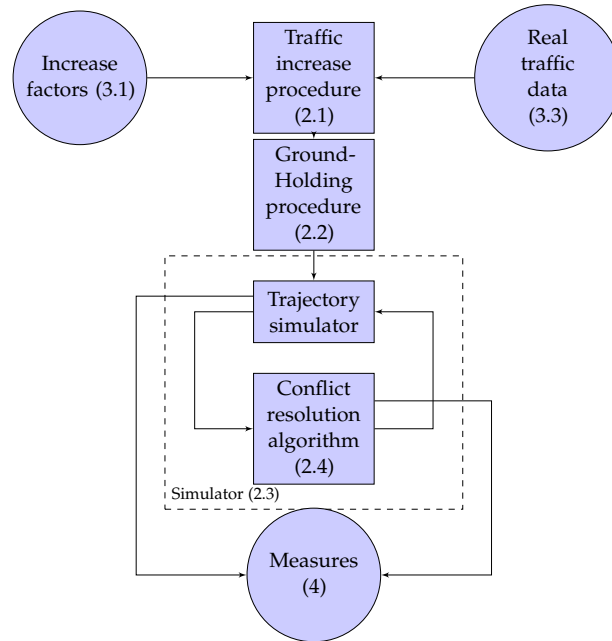


Figure 2: Simulation modules

2.1 Traffic increase

To increase the traffic to reflect the available forecasts, we used a procedure parametrized by a multiplying factor. Given an increase factor f (e.g., $f = 0.4$ for a 40% increase) and an initial set T of n flights, $n_+ = f \times n$ new flights are created. To create a new flight, we randomly choose a flight in T and create a copy with a small random modification to its departure time. The random shift typically lies in $[-15, -1] \cup [+1, +15]$ minutes to avoid the exact duplication of the flight. Excluding the interval $(-1, 1)$ ensures aircraft separation, since an offset of one minute for aircraft taking off at 150 kts ensures the separation.

The main advantage of this method is that it maintains a similar distribution of the departure times over a day of traffic. Indeed, the random shift tends to broaden and flatten the peaks of the distribution, hence giving a conservative lower bound on the actual distribution. A more realistic forecast would be based on a market study carried out on a global scale, but such information is not yet available.

A drawback of duplicating flights in this fashion is the creation of conflicts with pursuing aircraft. Depending on the random shift, the process may lead to flights that follow each other very closely. To overcome this, we apply a regulation at each airspace entry point to enforce the necessary separation between the flights. Typically, we impose at least two minutes between two flights entering the airspace at the same entry point.

2.2 Ground-Holding procedure

The regulations imposed by the CFMU affect the flights crossing regulated areas. These areas are determined on a daily basis by experts, depending mainly on the expected traffic. In a given regulated area, the departure slots are allocated with a ground-holding procedure following a *first planned, first served* scheme, meaning that the order in which aircraft enter the area is not modified.

Figure 3 gives a flowchart of the ground-holding algorithm described in EUR (2011) for a given regulated area. For each such 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 of 30 results in an allocation list with 60 two-minute slots. A flight crossing this area has a priority linked to its estimated time over (ETO) the point where it enters the area: the earlier the ETO, the higher the priority. It is important to notice the cascade effect of this mechanism. Reallocating slots to flights can have consequences for other flights that must also be reallocated, hence increasing the number of delays in the network. One limitation of this algorithm is the independent regulation of each area. If a given flight is regulated in two or more areas, its departure slot must satisfy the most restrictive regulation, which may violate constraints in the other areas. In other words, the ground holding effectively assigned to a flight will be the maximum over the ground-holding delays computed for each regulated area the flight will cross.

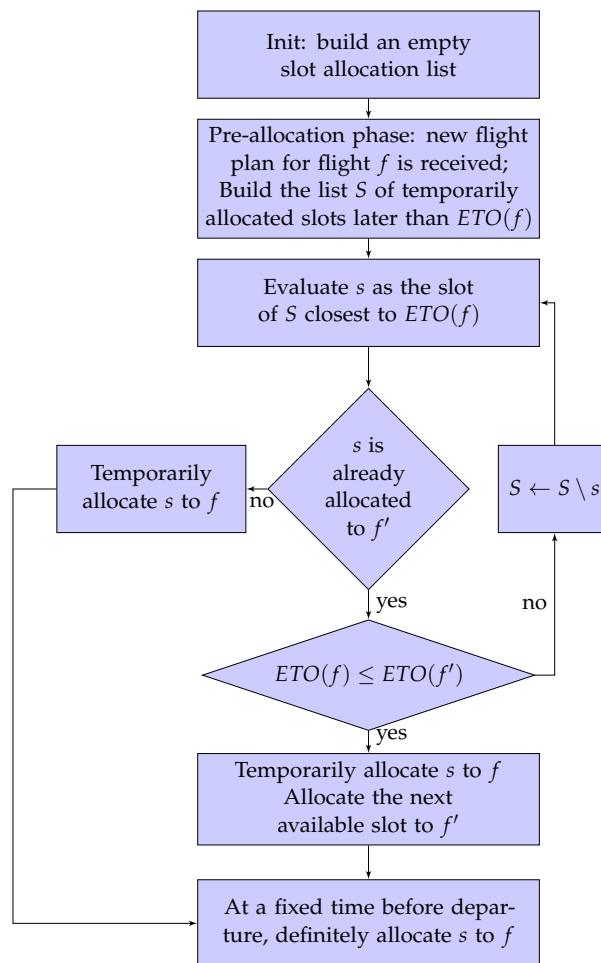


Figure 3: CASA procedure for a regulated area

We implement the CASA algorithm in our simulation engine. For this we use the 2012 French control sectors with their nominal capacities. In practice, the shape and the capacities of the control sectors can be modified dynamically to adapt to, e.g., bad weather conditions. Although this limitation could have an impact on the results, it does not jeopardize the whole process. Indeed, as stated in Section 1 the objective of this paper is to obtain an insight into a future need for optimization. As a consequence, we will be basing our interpretations on the trends indicated on the results, instead of the accuracy of the figures themselves.

2.3 Trajectory simulation

The flight simulations are performed by the Complete Air Traffic Simulator (CATS) Alliot et al. (1997). CATS is an en-route air traffic simulation engine based on a time-discretized execution model, i.e., the position and velocity vectors of every aircraft are computed at times separated by a period τ set by the user. The aircraft specifications and performance, such as the horizontal and vertical speeds and the fuel consumption, are extracted from the Base of Aircraft Data (BADA) summary tables based on the total energy model EUR (1998). 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 the conflicts: geometry, duration, and conflict-resolution statistics.

2.4 Conflict resolution

Our goal is not to study the performance of a particular algorithm or to prove that it is suitable for practical implementation. The conflict resolution module is used only to estimate the costs incurred by the maneuvers that are necessary to maintain the aircraft separation. It is impossible to precisely correlate the costs of the maneuvers designed by an automated conflict solver with those selected by a controller, but the order of magnitude is the same.

The conflict resolution algorithm designed by Durand et al. in Durand et al. (1996) is used in the simulations because it is already embedded in CATS. Moreover, the performed tests highlighted that the maneuvers computed by the model in Durand et al. (1996) are more conservative than the ones generated by the native solver in CATS. In the first step, conflicts are detected over a 20-minute horizon, and they are 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.

The genetic algorithm is based on the concepts described by Goldberg Goldberg (1989). The principle is to manipulate a *population* where each *individual* is a candidate solution to the problem. The population is composed of n possible trajectories, one per aircraft. For a given aircraft, the possible trajectories correspond to the discretized set of permissible maneuvers: 7 heading-change values between -30° and 30° , 5 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 step, the quantity to optimize, called the fitness, is computed for each individual, and the best individuals are selected according to their fitness. These individuals are used as inputs to the cross-over and mutation operators that aim to generate new individuals in the current population.

3 Simulation input

3.1 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 latest mid-term forecast provides predictions for 2013 to 2019 EUR (2010), while the long-term forecast extends the analysis to 2035 EUR (2013). Since the predictions depend on the evolution of the global economic situation, several scenarios are considered, and annual growth rates are estimated for each. Table 1 summarizes the long-term forecast EUR (2013).

Table 1: Summary of traffic forecast for Europe to 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%

The scenarios listed in Table 1 correspond to different assumptions about the future. Global Growth and Fragmented World depict two extremes situations in which the economic and political circumstances allow flourishing exchanges or cause a recession. In our computational tests, the increased traffic reflects the in-between Regulated Growth scenario, which is more likely. This scenario represents average economic growth along with regulations to address environmental and sustainability issues. Moreover, with this scenario it is assumed that the projected traffic growth will respect future airport departure and arrival capacities. A sufficient range of traffic-increase rates is then achieved by focusing on six specific years between 2014 and 2035. These years and the corresponding traffic rates are given in Table 2.

Table 2: Traffic predictions with regulated growth using 2012 as a starting point

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

3.2 Airspace capacity

CASA needs the capacity of each regulated area. We run the simulations with the following three scenarios:

- S_1 - the capacities remain constant;
- S_2 - the capacities are deleted: there is no ground-holding;
- S_3 - the capacities satisfy a condition corresponding to a controlled growth in the delay costs due to ground-holding.

The scenarios S_1 and S_2 correspond to two extreme situations: in S_1 nothing new is designed to handle greater traffic, and in S_2 the traffic flows freely without any constraint. Our study of S_1 will give a better understanding of the need to modify the current procedures. Focusing on S_2 will enable us to quantify the effect of a worst-case scenario from the ATC point of view. Indeed, S_2 should lead to the worst possible situation in terms of conflicts and the controller

workload. Since the design of S_3 is motivated by the results given in Section 4, we describe this scenario in Section 5.

3.3 Description of the reference historical data

The study focuses on French traffic, because we were able to get traffic data and information on the sector capacities and geometry. Moreover, the French airspace is dense because it is a crossroads of various European hubs. We use data for the 2012 traffic over France in our tests. Simulations focus on June, 8th, 2012, since it was a typical busy day.

3.4 Delay and maneuver costs

A study performed by EUROCONTROL EUROCONTROL (2012) estimates that in 2012, ATFM delays in Europe cost €0.85 billion. For a given flight, the costs depend on a variety of factors, such as the operational conditions, the phase of flight where the delay occurs, the type and size of the aircraft, and the load factor. As a consequence, we need a large quantity of data for a thorough study of the cost model.

Our study focuses on two types of costs. First, we consider delays induced by maneuvers issued by the ATC. These costs depend on the maneuver model and on the air conflict solver used, since its performance will impact the commands issued. We observe again that if the traffic becomes twice as dense, no controller will be able to monitor and issue maneuvers without an automated tool Kopardekar et al. (2008). Thus, a conflict solver is a valid tool for addressing the ATC costs. The planned maneuvers lead to extra fuel consumption. We use the model described in the BADA user manual BAD (2011) to compute the consumption, which depends mostly on the type, speed, and altitude of the aircraft. It is computed for three maneuvers: speed, heading, and altitude changes. Second, delay costs are introduced when the ground-holding leads to allocated slots that differ from the airlines' preferred slots. Modeling these costs properly is a complex task; the passenger, crew, and maintenance costs must be taken into account. It is also important to study the consequences of a delay on the whole network: one delay will lead to further delays in the rotation that includes the delayed flight.

In the literature, passenger costs are usually divided into "hard" costs representing compensation costs such as the cost of rebooking passengers, and "soft" costs such as the cost of passengers switching to another airline because of recurring delays. Joint work on this topic between the University of Westminster and EUROCONTROL resulted in a series of articles published between 2004 and 2011. The cost per minute per passenger of ground and airborne delays due to ATFM is derived in Cook et al. (2004). In Cook and Tanner (2009), Cook and Tanner estimate the airline delay costs as a function of the delay magnitude. This function is combined with fuel consumption and future emission charges to derive a cost-benefit trade-off during the ground and airborne phases. In Cook and Tanner (2011a), 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) or nonrotational. Using values extracted from Beatty et al. (1999), the authors derive cost values that depend on the rotation structure, the aircraft involved, and the magnitude of the delay. The results from the earlier articles are collected in Cook and Tanner (2011b), which gives reference values for the delay costs incurred at both the strategic and tactical levels. The report presents cost values for all the phases of a flight: at-gate, taxi, cruise extension, and arrival. The values are assigned under different scenarios (low, base, and high), for twelve different aircraft types. Sample costs are given in Table 3 for the at-gate base scenario.

We use the costs that were computed under the base-case hypotheses in Cook and Tanner (2011b). We also assume that companies ask for their preferred take-off slots. Thus, the slots allocated by CASA provide a valid estimate of the ground-holding-related delays.

Table 3: Tactical costs (euros, total) of ground-holding delay for different aircraft types.

Aircraft type	Delay (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

4 Impact of the ground-holding regulation

In this section, we focus on the potential impact ground-holding regulations have from an economical and operational point of view. More specifically, we study the evolution of delay costs due to ground-holding regulations, along with the costs of ATC maneuvers. We also quantify the effects on controllers' workload. The air traffic controllers' workload primarily consists of four tasks: monitoring the sector, coordinating the traffic with adjacent sectors, communicating with pilots, and maintaining separation. These tasks are demanding, and it is crucial to determine the impact of increased traffic on the controller workload. We define several performance indicators for the scenarios described in Section 3.2:

- the entering flow per hour for a sector, which is correlated with the monitoring and coordination;
- the number of conflicts, which is related to the complexity of maintaining separation;
- the number of conflict-resolution maneuvers, which affects both the monitoring and communications.

We chose this set of measures because they are easy to compute and give a good indicator of the cognitive charge of the controller and the safety risks that could arise in the airspace.

4.1 Impact on the entering flow per hour

The airspace surrounding Reims is particularly challenging in terms of traffic complexity: the control sectors are quite small, and they include routes that connect important European hubs such as London, Milan, Zurich, and Frankfurt. We focus on the KR sector, which is a busy sector in the Reims control zone. The motivation behind this choice is to study a zone as challenging as possible, to identify possible bottlenecks in ATC or ATFM. Figure 4 displays the flow entering KR per hour for different volumes of traffic, i.e., the current traffic and the traffic increased by 32%, 42%, and 50%. For each traffic volume, statistics are extracted for scenarios S_1 and S_2 ; in S_1 the ground-holding scheme is based on the nominal sector capacities of 2012, and in S_2 there is no ground-holding regulation.

Figure 4 clearly indicates that the flow depends on the presence or absence of ground-holding regulation. Without it, the entering flow distribution tends to aggregate into a peak over the period from 10 a.m. to 12 a.m., leading to a large overcapacity. A threshold on the controller workload may thus be distinguished. Indeed, for traffic volumes greater than +32%, the entering flow per hour may exceed the capacity by more than 12 flights without ground-holding. This would require a tremendous monitoring effort. This suggests that increased traffic needs to be handled with modified regulations or with automated tools that decrease the controller workload. On the other hand, if ground-holding is present, it controls the entering flow to prevent overcapacity. However, the capacity is still exceeded in several cases; this is

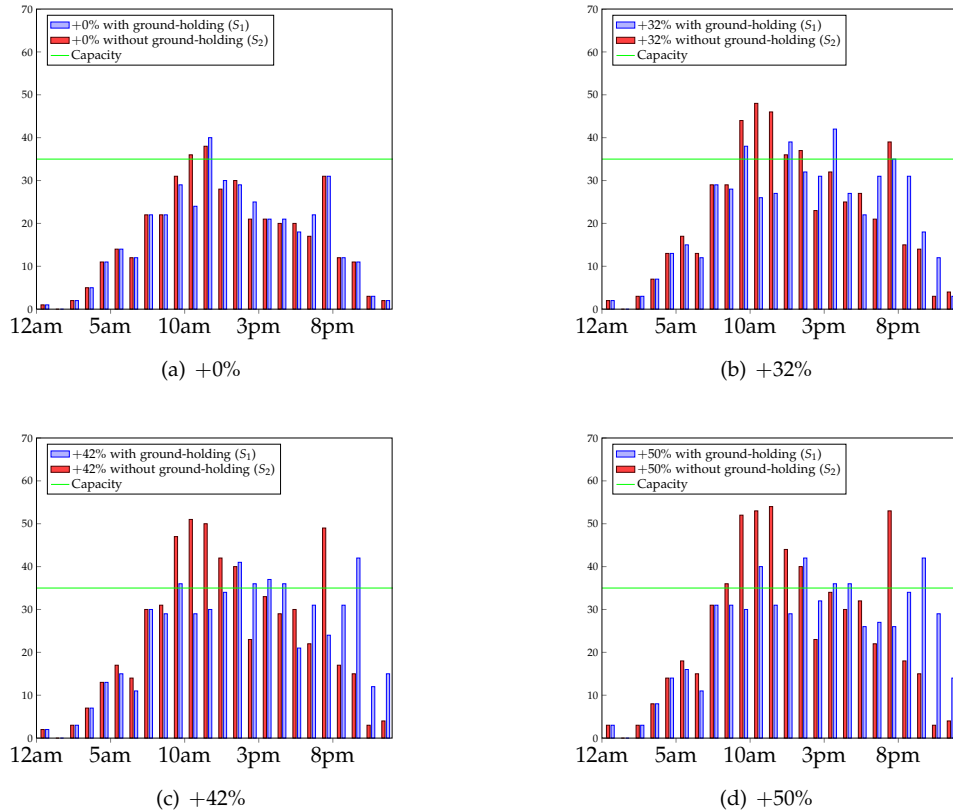


Figure 4: Entering flow per hour for different traffic volumes in KR sector

because of the difficulties the CASA algorithm encounters when a flight is regulated in several sectors. A saturated capacity plateau can be seen, and increasing the traffic volume enlarges the plateau. Moreover, it is important to recall that CASA regulates the traffic by postponing flights. A drawback of this approach can be seen in the last blue column in Figure 4(d): many flights are delayed between 9 p.m. and 10 p.m., leading to an entering flow of 40 flights, which is 5 flights over the declared capacity of 35 flights per hour.

4.2 Impact on the number of conflicts

In addition to the effects on the flow distribution, ground-holding has an impact on the conflicts. Figure 5 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 ground-holding. The sectors represent different types of flow density: two dense sectors, three average sectors, and two sparse sectors.

Surprisingly, Figure 5(a) shows that the removal of the ground-holding does not imply a greater number of conflicts until a traffic volume of +20%. Beyond this approximate threshold, the number of conflicts without ground-holding increases faster than when ground-holding is maintained, leading to a 15% difference for a +50% traffic volume. This observation at the global scale can be paired with an observation at the sector level. The evolution of the number of conflicts with increasing traffic depends on the type of sector, as highlighted by Figures 5(b) and 5(c). Results suggest that the ground-holding has an impact only on sectors where capacities are already saturated. One of the regulation's main benefits can be highlighted: to prevent overcapacity in different sectors, the ground-holding scheme smoothes the flow,

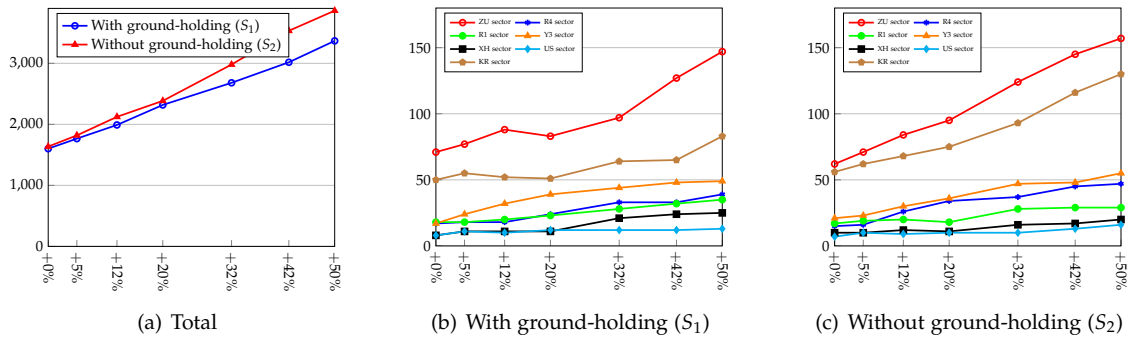


Figure 5: Comparison of the number of conflicts observed with and without ground-holding

spreading the number of conflicts over the day, as shown in Figure 6. This also reduces the workload of the controllers, especially in monitoring and communications. Indeed, as depicted by Figure 6(d) the number of conflicts per hour explodes when no ground-holding regulation is performed, with up to 27 conflicts within an hour.

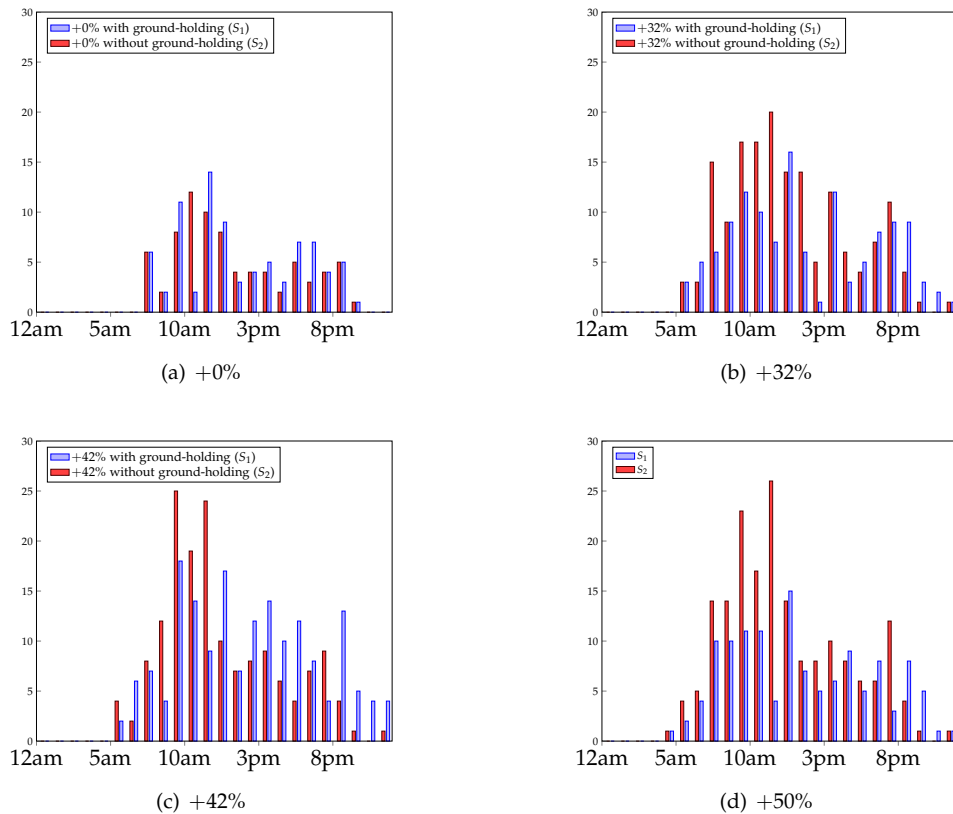


Figure 6: Number of conflicts per hour in KR for different traffic volumes

4.3 Cost analysis

Ground-holding and conflict-resolution induce delays whose costs are important aggregate indicators of the overall traffic complexity. These costs are computed as described in Section 3.4 and are displayed in Figures 7(a) and 7(b) for scenarios S_1 and S_2 . Clearly, there is no regulation cost in S_2 .

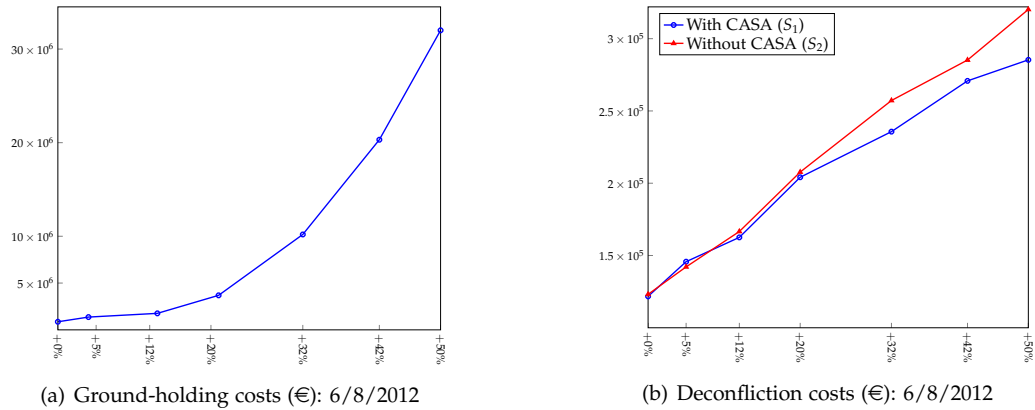


Figure 7: Ground-holding and ATC costs for 6/8/2012

Figure 7(a) suggests that the global costs resulting from ground-holding vary exponentially with the traffic volume. This is a logical trend considering that the intensification of the traffic mainly affects the congested areas during peak periods. Moreover, the plateau effect highlighted in Figure 4 shows that the peak periods tend to be flattened and widened, which leads to larger and more expensive delays. This indicates that significant savings could be made by improving the regulation procedure, and it also emphasizes that this improvement is necessary to handle larger traffic volumes.

The expected disadvantage of suppressing ground-holding is that it would result in extra conflict-resolution costs. Without ground-holding, a larger traffic flow must be handled, which increases the number of conflicts and the resolution maneuvers issued in response. Figure 7(b) shows the deconfliction costs for scenarios S_1 and S_2 . These global costs are the sum of the costs of the different types of maneuvers described in Section 3.4. Of these maneuvers, speed changes, which are seldom performed and relatively cheap, represent around 1% of the total cost. The remaining costs are equally divided between heading changes and altitude changes, which are more numerous and more expensive. The total costs are similar until the +32% traffic volume, where the conflict-resolution costs increase faster in S_2 than in S_1 . This results in 15% larger costs in S_2 for a traffic volume of +50%. Although this is an important increase, the conflict-resolution costs are much smaller than the ground-holding costs: around €250 000 for conflict resolution versus €32 000 000 for ground-holding costs. Thus, the extra costs necessary to handle the traffic are negligible compared to the potential savings made by removing the ground-holding policies.

4.4 Impact on the number of maneuvers

Section 4.3 shows that removing the ground-holding regulations induces small additional costs for ATC compared to the potential savings, but the impact on the number of maneuvers is major. Indeed, as shown in Figure 8, the number of maneuvers issued per hour in dense areas becomes much higher than the current value: up to 27 maneuvers are performed within one hour for a traffic volume of +50%, which represents approximately one command every 2.5 minutes. This

corresponds to a considerable workload in addition to the monitoring workload, making the controllers' task even more intensive. Moreover, it represents 27 opportunities where a dramatic incident could occur if mistakes were to be done during the execution of maneuvers.

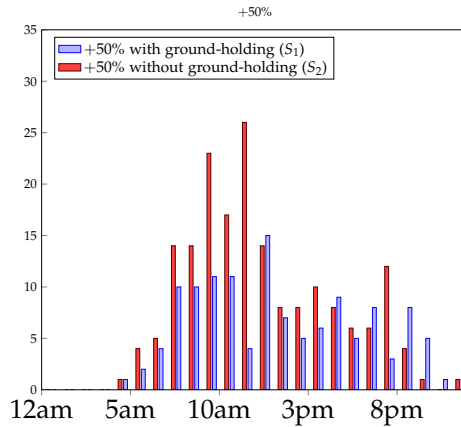


Figure 8: Maneuvers per hour for +50% traffic volume in KR sector

5 Finding a compromise between costs and workload

5.1 Motivation

The previous section presented a traffic and cost analysis for scenarios S_1 and S_2 , which correspond to two extreme situations. The results show that retaining the current sector capacities induces an exponential growth in the ground-holding costs. However, suppressing ground-holding leads to a large increase in the controller workload that is unrealistic with today's tools.

In this section, we make the reasonable assumption that air transportation companies could not handle a growth in the costs of delays due to ground-holding that is linear with the traffic volume. It therefore seems worth investigating a scenario that yields such a growth while keeping the controllers' workload manageable. Such a scenario would set sector capacity values controlling the growth in ground-holding costs. This would be of great value to the field, since it would quantify objectives for the continuous improvement of the ATM system.

5.2 Design of the scenario

Figure 7(a) indicates that the ground-holding costs grow exponentially with the traffic volume. The function linking these quantities can be described by a sequence of positive slopes denoted $(s_i)_{i=1,\dots,6}$, with each slope indicating the magnitude of the increase in the delay costs between two consecutive traffic volumes. In other words, a steep slope emphasizes that retaining the current capacities between two traffic volumes leads to a large increase in the regulation costs.

Scenario S_3 represents a trade-off situation where the growth in the ground-holding costs is controlled with an increase in the sector capacity. Figure 7(a) is used to determine the average slope s^* for the next five years; this represents an indicator for short-term trends in the cost increase. This value is used as a ceiling growth rate for the future traffic, hence yielding a bounded increase in the ground-holding costs. To enforce this constraint, we determine the new capacity values for each traffic increase iteratively via Algorithm 1. Basically, the algorithm increases the sector capacities until the rate of the cost increase drops below s^* .

Algorithm 1 Determining sector capacities for traffic volume increased by $\alpha\%$

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1:  $\mathcal{C}$ : set of current sector capacities
2:  $D$ : cost of delays due to the ground-holding for the current traffic
3:  $\mathcal{C}_\alpha$ : set of sector capacities for a traffic volume increased by  $\alpha\%$ 
4:  $R_\alpha$ : cost of delays due to the ground-holding for a traffic volume increased by  $\alpha\%$ 
5:  $\mathcal{C}_\alpha \leftarrow \mathcal{C}$ 
6: while  $\frac{R_\alpha - D}{\alpha} > s^*$  do
7:   for  $c \in \mathcal{C}_\alpha$  do
8:      $c \leftarrow c + \frac{1}{100}c$ 
9:   end for
10: end while

```

Applying Algorithm 1 leads to the capacity-increase percentages listed in Table 4. The sector capacities are obtained by rounding down to the nearest integer. These new capacity values represent an interesting indicator for future objectives in terms of continuous improvement of ATC with a fixed growth rate in ATFM costs.

Table 4: Increased capacities for scenario S_3

Traffic volume	Capacity increase
+5%	+4%
+12%	+5%
+20%	+8%
+32%	+16%
+42%	+24%
+50%	+32%

Since the new sector capacities are determined iteratively, it is interesting to plot the ground-holding costs computed at each step of the algorithm; see Figure 9.

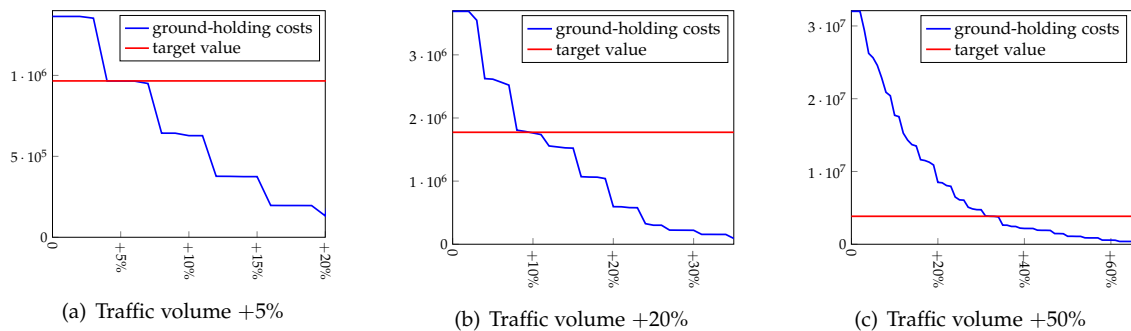


Figure 9: Ground-holding costs for increasing capacities

Figure 9 shows that the ground-holding costs are an approximately stepwise decreasing function of the increase in capacity. The increased capacities yielding similar ground-holding costs can be gathered into clusters. Two capacity sets with a difference of 1% are separated by a gap, indicating a large difference in the ground-holding costs. For instance, for a +20% traffic volume, €700000 could be saved daily by increasing the sector capacities by 7% instead of 6%. This difference can be explained by observing the distribution of the magnitude of the delays assigned by the ground-holding regulation. Some capacity values, especially for dense

sectors, can trigger a bottleneck effect on the traffic flow, inducing long and costly delays. This observation is supported by the expanding plateau effect seen in Figure 4, where the flights are more and more delayed during peak periods. It is therefore possible to identify threshold capacity values that are critical with respect to the issued delays. Moreover, the shape of the curves indicates that one can expect stepwise improvements in the ground-holding costs.

5.3 Cost analysis

Figure 10 shows the ground-holding and conflict-resolution costs for the three scenarios. The results for the ground-holding costs suggest an almost linear growth for S_3 , as imposed by the constraints of Algorithm 1, hence indicating considerable potential savings. The results provide evidence that S_3 represents a compromise situation for ATC. It appears that S_3 is closer to S_2 than to S_1 for high traffic volumes. This is because the constraint on the controlled ground-holding costs imposed in the design of S_3 is strict. More precisely, since the maximum increase rate allowed in the ground-holding costs in S_3 is small compared to the natural rate, the constraint is closer to S_2 than S_1 for high traffic volumes.

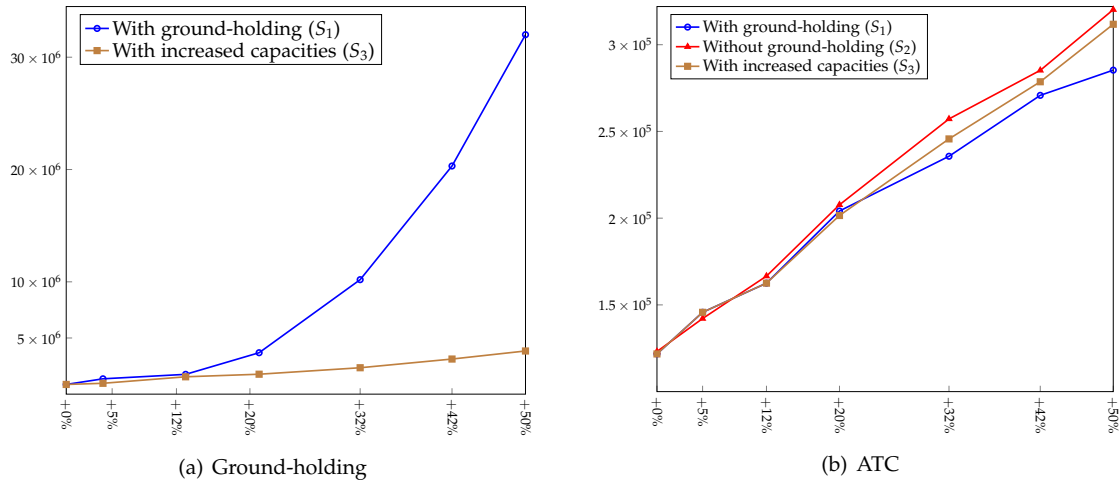


Figure 10: Ground-holding and ATC costs for the three scenarios on 08/06/2012

5.4 Workload analysis

To evaluate how S_3 compares to S_1 and S_2 in terms of the workload, we introduce the metric $OC(\cdot)$ defined as

$$OC(s) = \sum_{h=1}^{24} \max\{0; f_s(h) - c_s\}^2 \quad (1)$$

where c_s is a reference capacity value for sector s , and $f_s(h)$ is the entering flow of aircraft for sector s in a given hour h . The measure $OC(s)$ represents aggregated information on the overcapacity for sector s for a given regulation scenario. The greater the value of $OC(s)$, the more effort required from the controller. Moreover, $OC(s)$ tends to penalize situations with high peaks over a short period of time more than situations with lower peaks that last longer. This is consistent for a measure of the controller workload, because a short, high peak is much harder to handle than a lower, broad peak. Figure 11 depicts $OC(KR)$ for the traffic simulated under the scenarios S_1 , S_2 and S_3 with nominal sector capacities. More specifically:

- the blue curve with circles shows $OC(KR)$ for S_1 ;
- the red curve with squares shows $OC(KR)$ for S_2 ;
- the green curve with triangles shows $OC(KR)$ for S_3 .

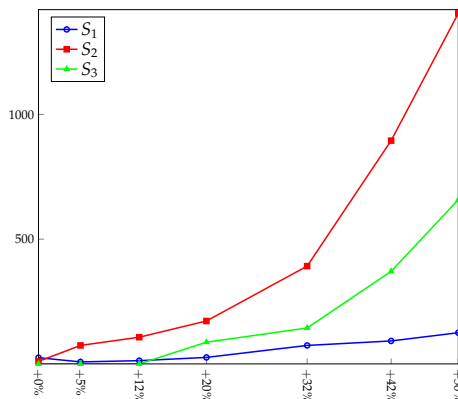


Figure 11: $OC(KR)$ for different traffic volumes and ground-holding scenarios

Figure 11 shows that $OC(KR)$ grows exponentially for S_2 whereas it increases slowly for S_1 . This observation corroborates our observations in Section 4.1: localized high peaks appear in the entering flow distribution for S_2 , whereas broader but smaller overcapacity plateaus emerge for S_1 . S_3 appears to be a compromise scenario for OC . The curve tends to grow exponentially, but with a much gentler slope than that of S_2 , indicating that the traffic simulated with S_3 would require less monitoring and management by the controllers.

The differences between the three scenarios in terms of number of conflict avoidance maneuvers are shown in Figure 12. The maximum number of maneuvers computed by the solver in sector KR is reduced from 27 to 20 during the busiest hour, leading to a less challenging situation. The number of maneuvers can be greater for S_3 than for S_2 for several hours after the high peak of S_2 . This can be explained by the ground-holding that is applied for S_3 : the flights are delayed after the busy peak period, which leads to a greater flow entering the sector and more numerous conflict situations. However, this does not represent an unmanageable task for the controller. Indeed, the high peaks for the conflict-resolution maneuvers are the main challenge for the controllers. Therefore, S_3 represents a situation with a relatively high workload but where the peaks are more manageable than in S_2 .

5.5 Summary

The cost analysis provides insights into possible future ATM network-design objectives: the capacities should find a trade-off between the costs and the workload. The sensitivity of the ground-holding costs to the sector capacity suggests that the ground-holding should be more robust to capacity variations in terms of the costs incurred.

6 Conclusion

We have analyzed the interactions between two layers of the ATM, namely the ATFM and the ATC. More specifically, we evaluated the impacts of the current ground-holding regulation scheme on the delay costs, sector loads, and conflict-resolution costs. We used a traffic simulator with modules to compute the regulation delays, to simulate the trajectories, and to resolve the conflicts. We chose French traffic data for a particularly busy day in 2012 as the input for the

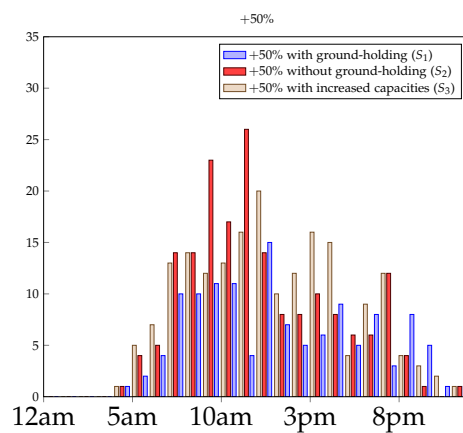


Figure 12: Maneuvers per hour for a +50% traffic volume in KR sector for the three scenarios

simulator, and we developed a traffic increase procedure to generate meaningful predictions to 2035.

The analysis of the impact of a traffic increase on ATFM and ATC leads to two major results. First, it shows that the costs due to ground-holding delays are several orders of magnitude larger than those due to conflict resolution maneuvers. Moreover, the ATFM costs should grow exponentially with traffic volume if the capacity of control sectors remain unchanged. Second, it is apparent that ground-holding regulations are necessary from a safety point of view. Without this regulation, the largest number of conflicts to handle in one hour could be multiplied by two. One important consequence of these results is that the improvement of ATC is necessary for the efficiency of the overall ATM system. The air transportation industry will not be able to support an exponential growth in ground-holding delay costs, so there is an absolute need to increase the capacities of the densest control sectors.

The second part of our study aims at setting quantified objectives for these improvements. We thus make the reasonable assumption that ATFM costs should grow at most linearly with traffic volume. A simulation-based iterative procedure then allows us to determine the increase in capacity that will provide such growth in ATFM costs. With these increased capacities, the maximum number of conflicts that a controller has to handle in one hour stays more reasonable than without ground-holding regulation. Nevertheless, the resulting overcapacity with respect to the current capacities suggests that the required increase in workload will be achieved only through a major shift in ATC procedures. This is a fundamental motivation for the development of automated tools for ATC including, for instance, automated conflict solvers that would provide an efficient operation and decision aid to controllers.

Finally, we have developed a simulation-based framework that could be used for evaluating any automated tool of air conflict resolution or ground-holding delay assignment. This framework will enable to study the performance of such tools independently or jointly under various scenarios.

Future work could develop more sophisticated traffic-increase procedures, based on more detailed local forecasts extracted from the STATFOR reports EUR (2013). This would lead to a geographically heterogeneous increase in the traffic, which is more realistic. It would also be interesting to compare several conflict solvers, and in particular their performance on direct routes. Different regulation procedures that include realistic predictions for the sector capacities should also be considered, keeping in mind that the interaction of regulation procedures and conflict-resolution algorithms should be optimized. Future work could also explore traffic scenarios that include the ability of companies to adapt their schedule according to the regulations applied; this would give more meaningful simulation results. Indeed, whatever the

future ATM framework, companies will adapt their schedule to avoid unnecessary delays.

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