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Title

D4.1 Results of Simulation Experiments: Comparative Analysis of Different Tactical Slot and Trajectory Allocation Mechanisms

Keywords

UDPP, flight prioritisation, agent-based model, network effects, flexibility, cost efficiency, equity, punctuality, robustness

Summary

The purpose of this document is to describe and discuss the results of the simulation experiments obtained using the agent-based model described in deliverable D3.1. The document provides a detailed analysis of the impact of different prioritisation mechanisms on the Key Performance Areas included in the performance assessment framework described in D1.1.

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1. Introduction

1.1 Scope and objectives

The work described in this document is framed within the project "Exploring Future UDPP Concepts through Computational Behavioural Economics". This report is intended to provide a detailed and exhaustive analysis of the simulation results obtained using the agent-based model described in deliverable D3.1. The rationale of the particular combination of variables defining the simulation scenarios is provided, as well as a table illustrating the final list of scenarios simulated. Results are presented and analysed according to the Key Performance Areas (KPAs) included in the performance assessment framework described in D1.1. The most relevant conclusions for each prioritisation mechanism are discussed, with special emphasis on their resilience and robustness in the presence of irrational or strategic behaviour.

1.2 Document structure

This document is structured as follows:

- Section 1 introduces the document explaining its aim and scope, includes a list of acronyms, and describes the structure of the report.
- Section 2 provides the definition of the simulation scenarios, corresponding to a particular combination of variables of the model, and shows the final list of simulation scenarios defined for the project.
- Section 3 presents the analysis of the simulation results organised by KPAs.
- Section 4 presents the main conclusions of the simulation experiments.
- Section 5 suggests a number of future research avenues.

1.3 List of acronyms

Acronym	Definition
ANS	Air Navigation Services
ATM	Air Traffic Management
AU	Airspace Users
CASA	Computer Assisted Slot Allocation
ETO	Estimated Time Over
E-SFP	Enhanced Selective Flight Protection
FPFS	First Planned First Served
FPL	Late Flight-Plan
KPA	Key Performance Area
KPI	Key Performance Indicator
OD	Origin - Destination

Acronym	Definition
SESAR	Single European Sky ATM Research
SFP	Selective Flight Protection
TMA	Terminal Manoeuvring Area
UDPP	User Driven Prioritisation Process

2. Definition of simulation scenarios

The definition of the simulation scenarios comprises three main aspects:

- The capacity configuration provides the congestion level and the characteristics of this congestion.
- The behavioural configuration determines the behavioural rules of the AU agents.
- The re-routing option adds the possibility of choosing whether to include or not the re-routing process in the simulations.

2.1 Capacity configuration

The evaluation of the prioritisation actions chosen by the airlines required the generation of a sufficient number of hotspots. To do so, a manual calibration process based on trial and error was carried out. The approach followed for the manual generation of capacity shortages sought to limit as much as possible the re-routing capacity of the airlines. It was found that on many occasions the airlines only used the re-routing option to the detriment of the activated prioritisation mechanism. This behaviour can be explained by the very advantageous situation created by the re-routing alternative, since it allows airlines to get rid of the delay associated with a certain trajectory at a low cost associated to the change to a sub-optimal route. This situation hinders the correct evaluation of the prioritisation mechanisms, so the reduction in capacity was carried out as follows:

- Simultaneously reduce (during the same time windows) the capacities of the sectors which have to be crossed by any of the three available routes connecting each OD pair.
- Reduce the capacity of the TMA sectors. These sectors surrounding the airport cannot be avoided with a change of route, and therefore the re-routing option loses all meaning in these situations.

In the end, the chosen capacity configuration generates a scenario where the congestion level oscillates between 10 and 15 hotspots, mostly due to network effects, depending largely on the prioritisation mechanism activated and the possibility or not of re-routing.

2.2 Behavioural configuration

One of the main objectives of the project is to evaluate several prioritisation mechanisms under certain behaviours that depart from the purely rational paradigm. We have studied the inclusion of behavioural economics within the decision-making logic of airlines in situations where they face ground delays due to demand-capacity imbalances in the airspace system. A suitable framework should take into account the main pillars of behavioural economics:

- **Prospect Theory** describes how people make decisions between several alternatives involving risks and uncertainty, including features such as:
    - Loss aversion: since individuals dislike losses more than equivalent gains, they are more willing to take risks to avoid a loss.
    - Endowment effect: cognitive bias to overvalue certain items already owned in relation to its objective (market) value. In the context of slot allocation, this may make AUs less likely to trade 'their' slots at a 'fair' value.

- **Bounded Rationality** reflects the idea that human rationality is limited when people make decisions. Rationality is bounded because there are limits to our thinking capacity, available information and feasible time to make the decision.
- **Hyperbolic Discounting** represents the fact that the expectation of when a reward is received is as critical as the amount of the reward. This effect is especially relevant for slot trading, as earlier rewards for letting a slot go may (sometimes only) be spent in the future, and not in the same regulation ('now'). Particularly, in the case where regulations are infrequent, the decision to have a lower flight priority now in order to get a better one in the future can be distorted by such an effect.

Table 1 shows the applicability to the model of each of the described biases followed by the chosen implementation within the simulation.

	Applicability to the model	Mechanism where it applies	Implementation
Prospect Theory	Due to loss aversion, an airline can outbid for a slot paying more money in order to avoid losing the slot	Auction	The airline will increase the value of the slot bids, which are generated from a calculated distribution of the cost of delay across all the slot options in the hotspot
Bounded Rationality	An airline can possibly underestimate or overestimate the value of a flight due to limited available information when taking the decision	SFP, E-SFP, Auction	Modify the final cost of delay of the delayed flights by applying an increase or decrease of 15% to the final cost value to some flights randomly selected
Hyperbolic Discounting	An airline can possibly underestimate the value of the credits due to the lack of immediacy in its use	E-SFP	A 20% decrease in the monetary value that each airline assigns to their own credits

Table 1. Behavioural economics implementation

2.3 Re-routing configuration

The option of making a change in the route is a possibility that airlines have when evaluating any of the prioritisation mechanisms framed within the FPFS paradigm. However, as described in deliverable D3.1, due to the limitation of resources within the project, the implementation that was carried out to simulate the prioritisation mechanism based on the auction of slots does not include the possibility of re-routing. Due to this fact, and with the intention of making a fair comparison between the performance of the different flight prioritisation mechanisms, the mechanisms based on the FPFS paradigm have also been tested without including the re-routing option.

2.4 Simulation scenarios

The series of scenarios finally chosen to carry out the simulation of each mechanism is the result of the combination of all the aforementioned variables: capacity configuration, behavioural configuration and re-routing configuration. Table 2 illustrates the selected scenarios.

	Re-routing ON				Re-routing OFF			
	Rational	Bounded rationality	Hyperbolic discounting	Prospect theory	Rational	Bounded rationality	Hyperbolic discounting	Prospect theory
Baseline	✓				✓			
SFP	✓	✓			✓			
E-SFP	✓	✓	✓		✓			
Auction					✓	✓		✓

Table 2. Simulation scheme

The set of chosen scenarios is just a limited selection of all the possible combinations that can be simulated. This set of combinations could be extended in future research.

Due to the random components included within the model itself, n simulations have been performed for each scenario. Consequently, the results presented correspond to the average of the results obtained from the n runs of each scenario.

3. Analysis of the results

3.1 Punctuality and Predictability KPA

Predictability and punctuality are merged into one KPA in the SESAR Performance Framework 2018 due to the strong interdependencies between them. However, the chosen metrics for the project only reflect the punctuality performance. As explained in D1.1, the metrics derived to measure predictability are not included due to the limitations in the scope of the simulation model: for instance, neither the ability of the airlines to change the cost index (change the flight speed) nor the assignments of en-route delays (holding patterns) are modelled. These assumptions will drive measurements of perfect predictability, which is totally unrealistic.

The three selected metrics are: the percentage of flights 'on-time', meaning flights departing within +/- 3 minutes of the scheduled departure time, the flight departure delay, and the passenger arrival delay.

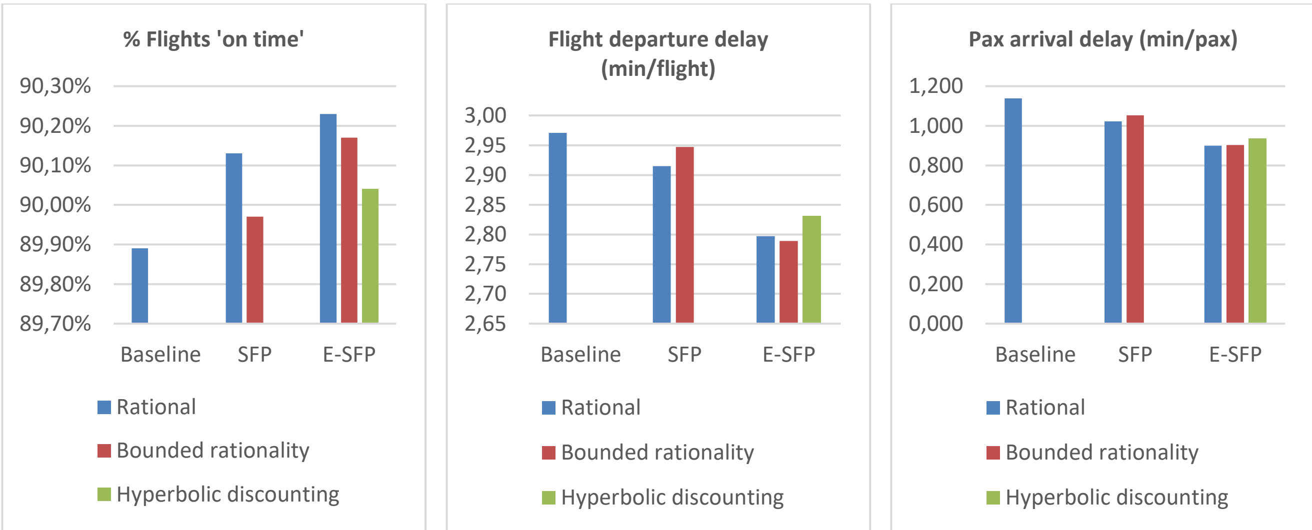

Figure 1. Punctuality metrics for scenarios with re-routing on

Figure 1 displays the results for the simulated scenarios with the ability to re-routing option activated. Firstly, it can be observed that the punctuality values offered by the SFP mechanism improve with respect to those offered by the baseline scenario, where only slot swapping is activated. Additionally, it is also noticeable that the credit-based E-SFP mechanism provides the best punctuality results of all the mechanisms simulated with the re-routing capacity available. Therefore, an interesting trend can be extracted between the level of flexibility offered by each mechanism and its performance in the area of punctuality, which may indicate that a high level of airline flexibility relates with a better optimisation of air traffic.

Figure 1 also offers a comparison of the results for each of the different selected airlines behaviours by mechanism. From there, it can be noticed that, as a general rule, the appearance of 'irrationalities' inside airline behaviour comes with a worsening in the punctuality levels measured by the indicators. However, despite this deterioration, the performance of both the SFP and the E-SFP still improves the results of the baseline mechanism.

Figure 2. Punctuality metrics for scenarios with re-routing off

Figure 2 displays the results for the simulated scenarios without the ability to change the route. In general, as expected, all the mechanisms experiment a deterioration in the punctuality levels. However, this series of simulations offers other insights that at first glance may seem counter-intuitive. Now, unlike in the previous case where the SFP mechanism provided better results than the baseline scenario, the punctuality values of the SFP mechanism are the worst of all the mechanisms. Despite offering more flexibility to airlines, the SFP mechanism ends up with worst results than the baseline configuration. The reason is that the extra level of flexibility allows airlines to make more optimal requests, compared with the baseline scenario, which in most cases involve larger alterations in the flight plans of the affected flights. This fact has a direct impact on other flights, which on certain occasions generates downstream network effects motivating the cancellation of several flights due to curfew. These cancellations explain the drastic deterioration in the punctuality levels for the SFP scenario.

Additionally, it is very interesting to observe how the auction scenario provides the best punctuality results among all the flight prioritisation mechanisms tested. As explained in D3.1, the auction does not order the flights by ETO of the specific congested sector but according to how much the airline is willing to pay to win the slot. This paradigm ends up with fewer empty slots because the FPFS order does not have to be enforced and consequently the usability of the network is increased. It will be very interesting to see, as a future step, if the good results offered by the auction refer exclusively to the most efficient way of ordering the traffic or if it is the market mechanism itself that offers the advantages.

Finally, Figure 2 also shows how the level of the punctuality is not affected by the ‘irrationalities’ introduced inside the airlines behaviour. No extreme behaviour has been introduced so the overall performance of punctuality is not affected. It would be interesting to analyse, however, the effect of these ‘irrationalities’ at the level of the airlines, in a disaggregated way.

3.2 Cost Efficiency KPA

The Cost Efficiency KPA is highly related to the delay airlines face in their operations and how they manage it. The SESAR Performance Framework distinguishes two main focus areas inside this KPA. The first cost impact considered is the direct gate-to-gate ANS cost, and the second cost impact area is the Airspace User (AU) costs. Following the objectives of the project, we will restrict our vision to AUs cost. The two selected metrics are the per-flight direct cost and the tactical per-flight cost of delay.

Figure 3. Cost Efficiency metrics for scenarios with re-routing on

Figure 3 displays the results for the simulated scenarios with the re-routing option activated. The first conclusion that we can draw is that there is practically no difference in the direct cost per flight between the different mechanisms tested. Following the definition of the direct cost described in D3.1, the value of the direct cost per flight from one simulation to another is only modified if the flight performs a re-routing to fly a different trajectory, since the fuel cost and cost index values remain constant for all scenarios. Given that the direct cost difference between flying each one of the available OD routes is not extraordinary large, the final direct cost per flight calculated for each scenario is almost equal.

In contrast, as expected, the results of the cost of delay do present a significant difference in the performance of each prioritisation mechanism. Figure 3 shows that the E-SFP mechanism provides the lowest cost of delay per flight, outperforming the values for the SFP mechanism and for the baseline. From these data it is possible to derive that the cost of delay is directly related to the flexibility provided by the mechanisms, as expected.

Figure 3 also offers a comparison of the results for each of the different selected airlines behaviours by mechanism. Particularly for the cost of delay indicator, it can be noticed that, as a general rule, the appearance of 'irrationalities' inside airline behaviour comes with a small cost increase. However, an unexpected exception is found for the E-SFP mechanism with bounded rationality biases included. This can be explained again by the appearance of network effects. For this particular scenario, the factor included to alter the calculation of the cost of delay affects the decisions of the airlines and, on average, the simulation ends up with slightly lower average congestion compared to other scenarios with the same mechanism. This fact is directly related with the flight delay and consequently it slightly reduces the cost of delay per flight.

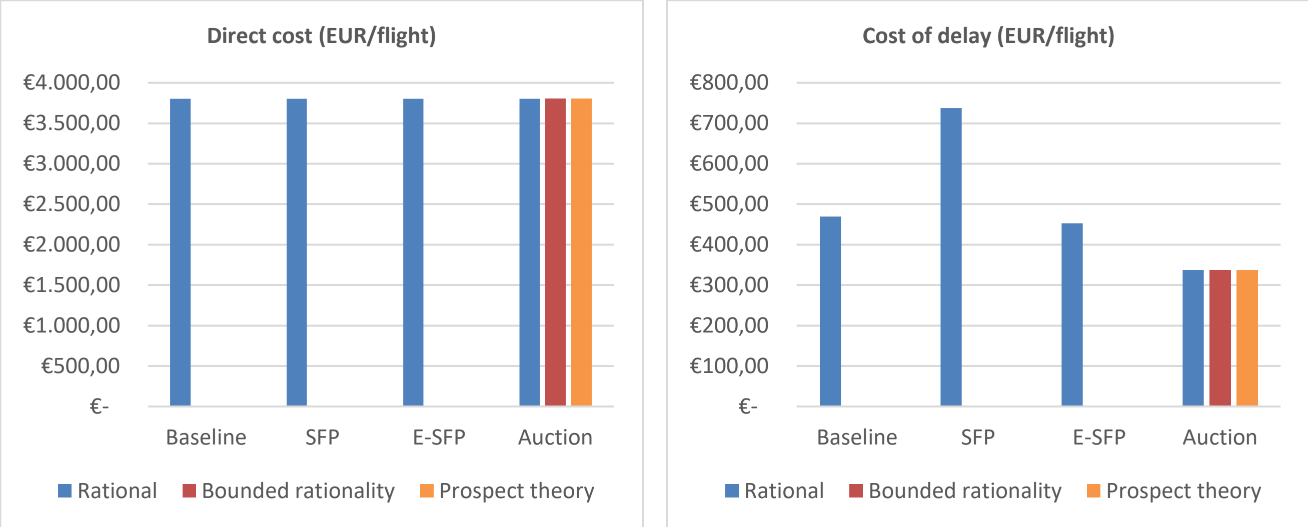

Figure 4. Cost Efficiency metrics for scenarios with re-routing off

Figure 4 displays the results for the simulated scenarios without the ability to change the route. Firstly, it can be noticed that the direct cost per flight is marginally affected by the suppression of the re-routing capability. Additionally, it is relevant to highlight that its value is now exactly the same for all the scenarios because all flight trajectories remain constant now.

From the point of view of cost of delay, in general, as expected, all the mechanisms experiment a deterioration in the cost levels. The detected trend is similar to that observed in section 3.1 for the punctuality indicators. Due to the dramatic increase in the flight delay as a result to the cancellations that appear in some simulations of the scenario with the SFP mechanism, the cost of delay per flight increases considerably and exceeds the values for the baseline scenario.

In the same way, consistently with punctuality results, the auction-based mechanism presents the best performance levels and it's not affected by the 'irrationalities' introduced inside airlines' behaviour. Again, it will be very interesting to check if the good results are only due to the better usability of the network.

3.3 Flexibility KPA

The SESAR Performance Framework defines the Flexibility KPA as the ability of the ATM System and airports to respond to changes in planned flights and late FPL request (non-scheduled traffic). Accordingly, the indicators and metrics used and derived to measure the system flexibility in our simulation model will point to that direction and will evaluate how the system is capable of absorbing late FPL requests in the presence of different prioritisation mechanisms. The two selected metrics are: the average delay for flights with late FPL request and the % of late FPL requests successful. A successful FPL request is understood as an accepted prioritisation request affecting a late FPL flight which enables the flight to depart within a specific defined time margin.

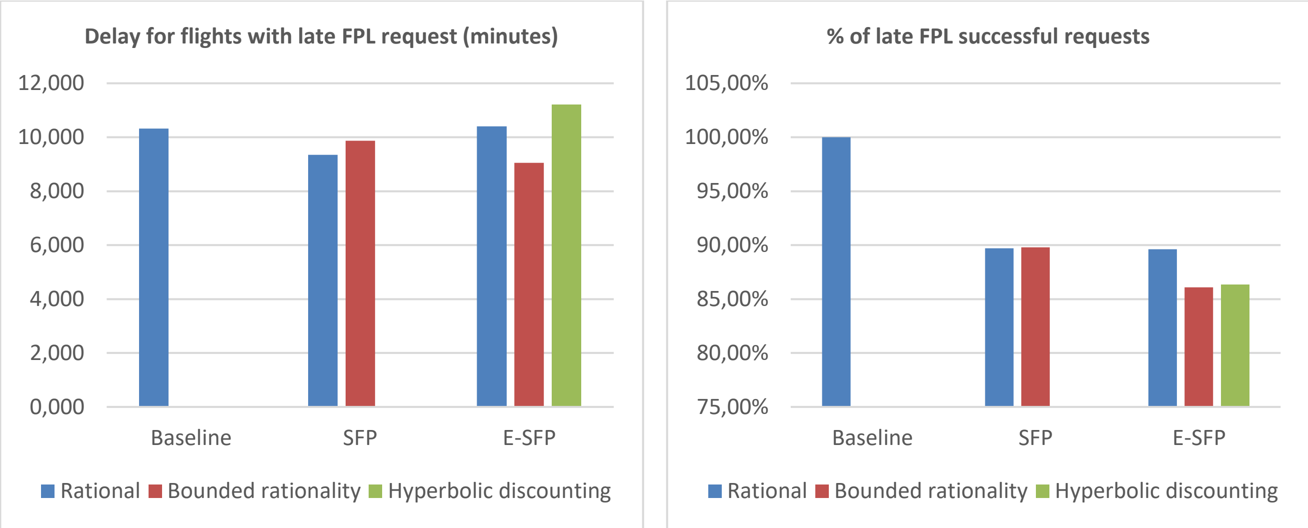

Figure 5. Flexibility metrics for scenarios with re-routing on

Figure 5 displays the results for the simulated scenarios with the re-routing option activated. The values of average delay for flights with late FPL requests are extremely similar for the different mechanisms' scenarios and no trend or conclusion can be clearly drawn. Furthermore, the inclusion of irrational behaviours does not offer any further insight: in some cases the delay worsens, while in others it is reduced.

On the other hand, the % of late FPL successful request shows an interesting trend. The higher percentage of successful requests belongs to the baseline scenario, where all FPL requests are successful. The SFP and the E-SFP present almost the same percentage, which is surprisingly lower than in the baseline scenario. This can be explained by the fact that greater mechanism flexibility level when proposing a prioritisation influences in many cases the position of other flights belonging to other airlines and due to the restrictions imposed on the model it is more common that this type of request can be rejected. For that reason, and taking into account that the airlines only have three possible prioritisation requests, the % of late FPL successful requests is lower for the SFP and the E-SFP mechanisms scenarios.

Additionally, it is important to remark that this last metric is very dependent on the definition of what is a 'successful request'. The values change considerably when the flight time margin for departure is changed.

Figure 6 displays the results for the simulated scenarios without the ability to change the route. In general, as expected and consistently with the punctuality and the cost efficiency indicators, all the previous mechanisms experiment a performance deterioration in the flexibility metrics.

The auction-based mechanism provides again the best performance, reflecting the best network ability at absorbing non-schedule traffic or late modifications. However, this is mainly due to the inherent differences between the auction approach and the FPFS paradigm: here, no order is enforced so the late FPL flight cannot be sent at the end of the hotspot and it is treated in the same way as the rest of the flights.

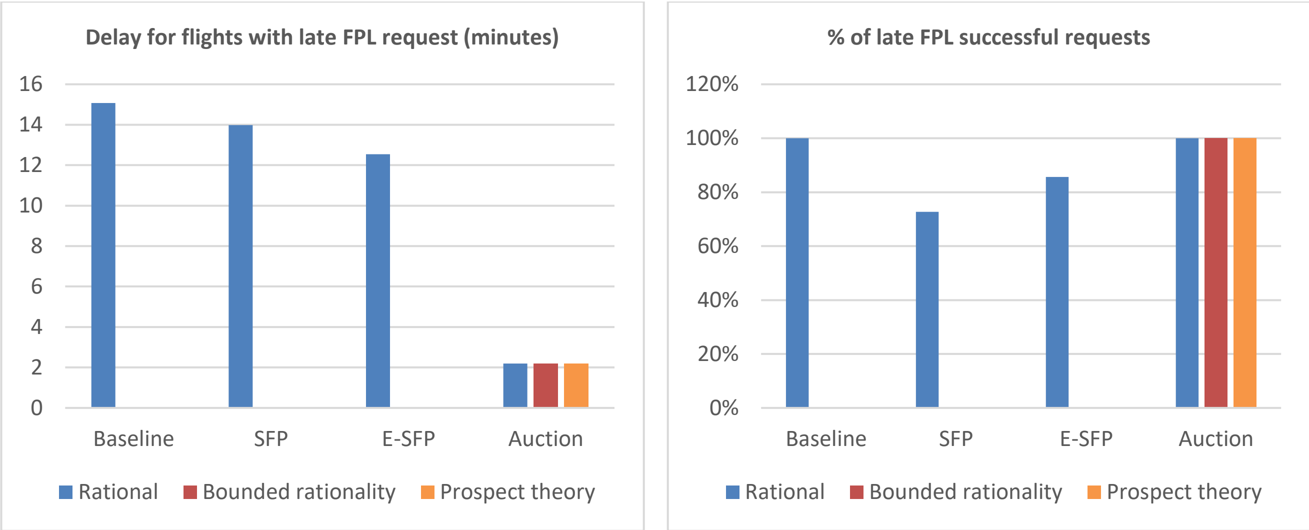

Figure 6. Flexibility metrics for scenarios with re-routing off

3.4 Equity and Access KPA

Within SESAR's UDPP programme, Equity is considered as a mandatory constraint. A lack of Equity can arise, for example, when one AU receives an advantage or net gain relative to others. This is an essential requirement from AUs' perspective and is closely related with Access, which refers to the need to offer the same prioritisation possibilities to all involved AUs.

The majority of the selected metrics to measure equity are calculated in relation to a baseline scenario which is understood as equitable. This baseline scenario corresponds to the simulation of the current concept of operations, the FPFS mechanism plus the swapping capability. The subset of chosen metrics are: the change in AU's delay or cost compared with the total change in delay or cost of all the AUs; the change in AU's delay or cost per flight compared with the total change in delay or cost per flight of all the AUs; the AU total delay or cost relative to the baseline total delay or cost; the number of flights advantaged and disadvantaged; and the number of AUs that use the prioritisation mechanism in a hotspot.

Due to the disaggregated nature of the first three indicators (data per AU), the equity metrics are analysed by mechanism. The results indicate how the different airlines within the model change with respect to the baseline situation and therefore give an idea of the equity levels regarding each of the mechanism tested. However, some precautions must be taken when analysing the results and drawing strong conclusions about the level of equity of each mechanism. A simulation time of one day is not enough to accurately characterise the behaviour of the airlines and especially their learning abilities. Results are thus very sensitive to the reduced simulation time window and the rigidity of the behaviours imposed on the airlines together with the specific traffic and the network used in the simulation.

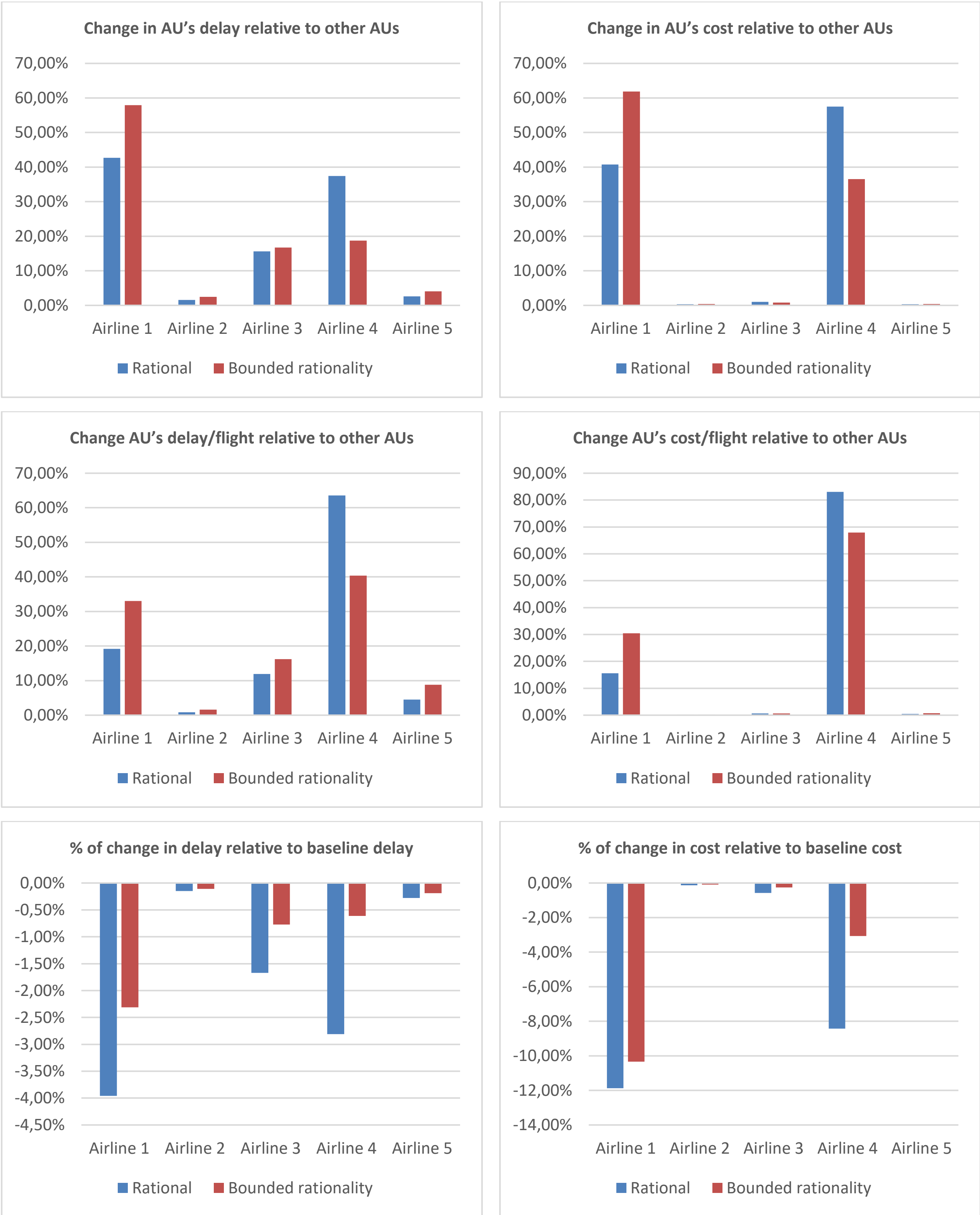

Figure 7. Equity metrics for the Selective Flight Protection mechanism

Figure 7 displays the results obtained for the scenarios with the SFP mechanism and with the re-routing capability available. Results for both behavioural levels affecting the SFP mechanism, rational and bounded rationality, are presented.

It is clearly visible that not all the airlines are affected in the same way by the addition of the SFP mechanism. The first indicator, which estimates the percentage of change of one airline relative to the total change of all airlines together, evidences that Airline 1 and Airline 4 take most of the reduction in both delay and cost between the baseline and the SFP scenario. It also demonstrates again the non-linear relation between the delay and cost of delay. The rational scenario is paradigmatic: while the higher delay improvement corresponds to Airline 1, the higher cost improvement is found for Airline 4.

The reason why Airline 1 and Airline 4 are the only airlines that experience a considerable change with respect to the baseline scenario lies in the fact that due to the traffic conditions and capacity of the model, they are the only airlines that make use of the SFP mechanism. The variations experimented by the other airlines are only the result of the network effects generated by the use of the mechanism by former airlines.

As expected, the same trend noticed for the first metric is also observable for the second one. However, in this case, Airline 4 ends up being much more benefited than Airline 1. The rationale behind this difference has to do with the different model representation of the airlines. Unlike Airline 1, which is a flag carrier in the model, Airline 4 is represented as a low-cost carrier implying among other things that it has fewer flights. Consequently, the change per flight is higher for Airline 4.

Figure 7 also shows the delay and cost change of the airlines relative to their baseline delay or cost. The results reaffirm what we have seen with the first two metrics: the improvement is uneven among all the airlines; Airline 1 and Airline 4 are again the most advantaged airlines. It is interesting to analyse how Airline 1 is now the most benefited, experiencing a reduction of delay of almost 4% and a reduction in cost of almost 12%. Although Airline 4 takes most of the improvement from the introduction of the SFP mechanisms, as we observed in the first two equity metrics, it also has a higher cost of the delay in the baseline scenario which explains why its relative improvement is lower than that of Airline 1.

Figure 7 also offers a comparison of the results for each of the different behaviours tested. It is remarkable to see how the introduction of the bounded rationality bias results in an increment in the percentage of change of Airline 1 compared with the rational scenario. And, at the same time, a general reduction in the cost and delay improvement relative to the baseline is observed for all the airlines. Due to the bounded rationality bias, the airlines do not make optimal decisions and end up with a lower improvement in terms of both delay and cost.

One last important thing to point out from these results is that, although Airline 1 and Airline 4 are the only airlines benefited from the SFP mechanism for the reasons commented before, the rest of the airlines are not negatively affected by this fact.

Figure 8. Equity metrics for the Extended - Selective Flight Protection mechanism

Figure 8 displays the results for the scenarios with the E-SFP mechanism and with the re-routing capability available. Results for the three behaviours affecting the E-SFP mechanism, rational, bounded rationality and hyperbolic discounting, are presented.

The difference between the changes of the airlines is indeed more evident with the E-SFP mechanism, including even the worsening of some airlines (Airline 1, Airline 2 and Airline 5). However, this lack of equity should be treated with precaution. Here the results are extremely affected by the tendency of each airline to use or collect credits and the reduced picture of this behaviour (one day).

Both the first and the second equity metric evidence that pattern. Airline 1, Airline 2 and Airline 5, whose credit value is greater and therefore manifest a slight trend to collect credits for using them afterwards in more important flights, show negative percentages of delay change, meaning that they experiment a total delay increase due to the absorption of credits. This trend should not appear when analysing the cost, because the value of the credits absorbed is included in the cost calculation, however the pattern persists. After a detailed analysis, it was found that due to network effects caused by the larger modifications on the traffic as a result of the higher level of flexibility provided by the E-SFP, for some cases, several airlines ended up with an increase in delay higher than the expected increase corresponding only to the collection of those credits. This is an extremely interesting outcome of the simulation and explains why the Airline 1, Airline 2 and Airline 5 still show negative cost percentages although the monetary value of the collected credits is included in the calculation. This fact is extremely evident for Airline 1.

Additionally, it is interesting to see how Airline 3, despite being the second airline taking the most percentage of the total delay reduction, does not experiment any relevant reduction in the cost. In fact, it is Airline 4 the one that takes practically all the cost reduction compared to the baseline scenario.

The last indicator shows the percentage of increase or reduction in delay and cost for each airline. The results are very consistent with the trends observed previously, with a cost reduction of almost 50% for Airline 4 and a cost increase of 25% for Airline 1 within the rational scenario.

Finally, Figure 8 also offers a comparison of the results for each of the different behaviours tested. The scenario where the hyperbolic discounting bias is applied to the airlines behaviour seems to generate a more unbalanced situation regarding the proportion in which each airline changes its total delay with respect to the total delay change of airlines. However, due to the non-linearity between the delay and the cost of delay, this situation is not repeated for the cost. Another surprising conclusion is found in the scenario where the bounded rationality is included. It shows a tendency to balance the values of the indicators reducing the inequality between airlines. In fact, for this scenario, the vast majority of airlines, with the exception of Airline 2, reduce their cost with respect to the baseline, the most obvious case being that of Airline 1.

Figure 9. Equity metrics for the Auction-based mechanism

Figure 9 displays the results for the scenarios with the Auction-based mechanism without the re-routing capability available, meaning that the baseline scenario without re-routing is used for comparison. Results for the three behaviours affecting the Auction-based mechanism, rational, bounded rationality and prospect theory, are presented.

The results for the three equity metrics describe a relatively more balanced situation between most of the airlines, with the exception of Airline 3. The reduction in the total delay experimented for all airlines together is distributed almost evenly between Airline 1, Airline 2 and Airline 4. However, the reduction in cost shows a situation where, again, Airline 4 accounts for the highest percentage of cost reduction, followed by Airline 1 and then Airline 2. On the other hand, Airline 3 suffers a large increase in delay and a considerable increase in cost compared with the baseline scenario, while Airline 5 is barely affected by the implementation of the auction-based mechanisms and presents very similar delay and cost results to those of the baseline scenario. It is also interesting to remark the sudden improvement of Airline 1, which experiments a reduction of 80% in the cost of delay.

The results are strongly dependent on the bidding behaviour level implemented for each airline. However, the case of Airline 3 and Airline 4 is noticeable. Although they are both at an 'optimistic' bid level, meaning they bid below the worst possible delay cost for their flight, their results are completely opposite. Airline 3 ends up with a 20% increase in its delay cost, while Airline 4 ends up with an almost 60% reduction in its delay cost. This situation can only be explained by the traffic and network characteristics of the model. This situation involuntarily helps Airline 4 to win many more bids than Airline 3, placing its flights earlier in the sequence.

Finally, Figure 9 also offers a comparison of the metrics for each of the different behaviours tested. As it was also noticed with the previous key performance indicators, the equity results are barely influenced by the behavioural biases applied. As no extreme situations have been introduced, the operation of the market mechanism remains optimal. Impact of more extreme and varied behaviours should be further investigated.

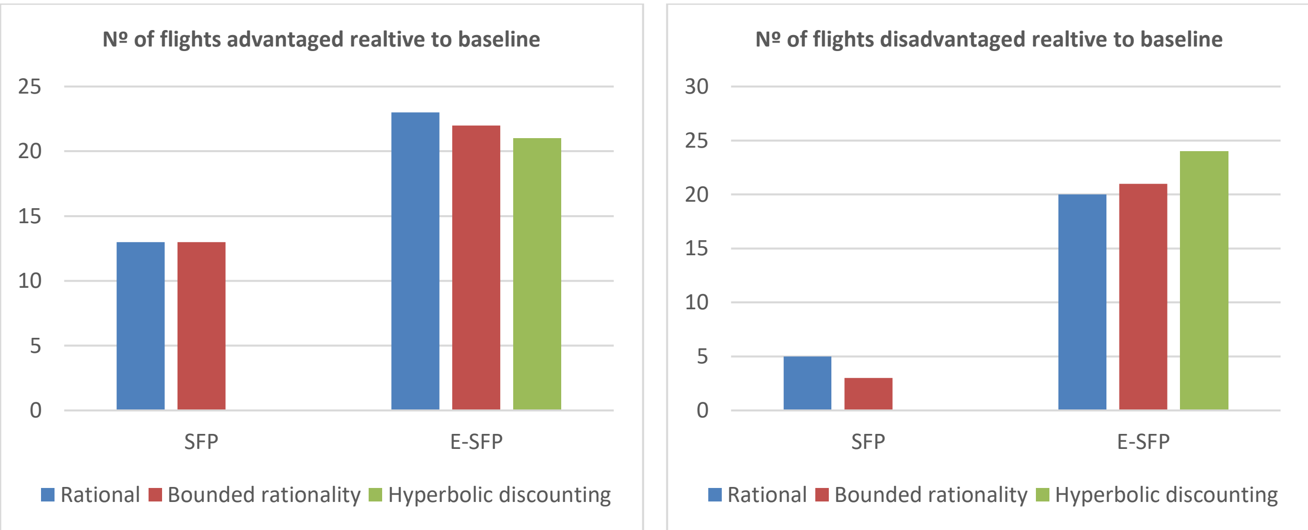

Figure 10. Number of flights advantaged/disadvantaged for scenarios with re-routing on

Figure 10 displays the number of advantaged and disadvantaged flights, in terms of delay, with respect to the baseline for the simulated scenarios with the ability to change the route activated. As expected, the number of advantaged flights is higher for the mechanism providing more flexibility to the airline, the E-SFP mechanism. However, due to that same flexibility and the corresponding ability of absorbing some delay to collect some credits, the E-SFP presents a very similar level of advantaged and disadvantaged flights.

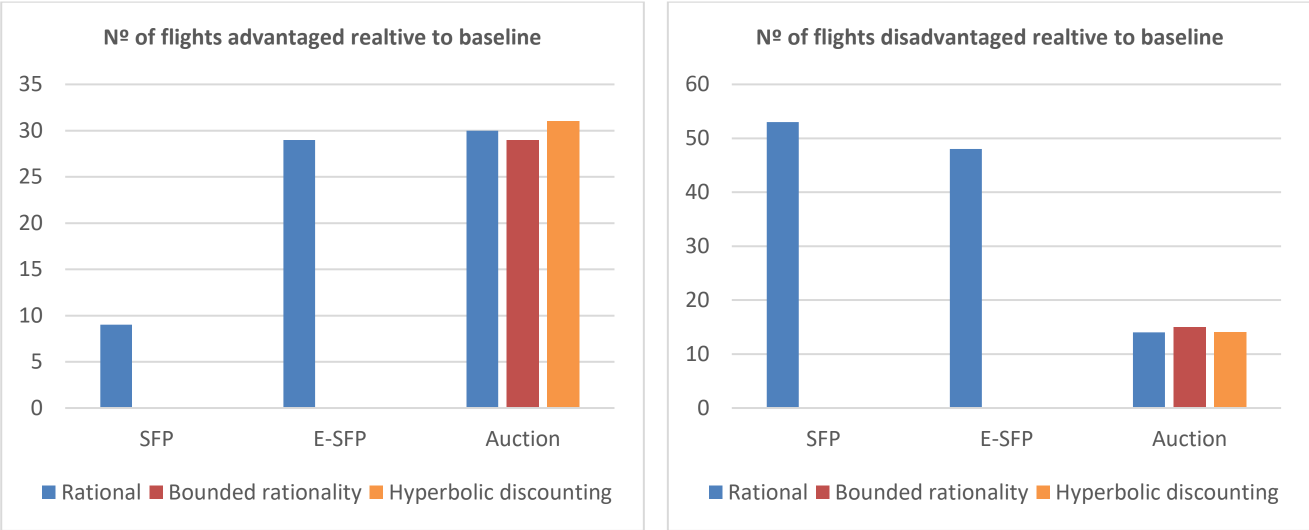

Figure 11. Number of flights advantaged/disadvantaged for scenarios with re-routing off

Figure 11 offers the same information than Figure 10 but for scenarios with the ability to change the route deactivated. The trend detected for the E-SFP mechanisms persists. However, the SFP mechanism displays a huge increment in the disadvantaged flights as a result of the network effects, as described in the previous KPAs. On the other side, the Auction-based mechanism presents a number of advantaged flights similar to the credit mechanism and a number of disadvantaged flights much lower than the rest of the mechanisms.

Both Figure 10 and Figure 11 show that this indicator is scarcely affected by the different behaviour biases applied to the airlines.

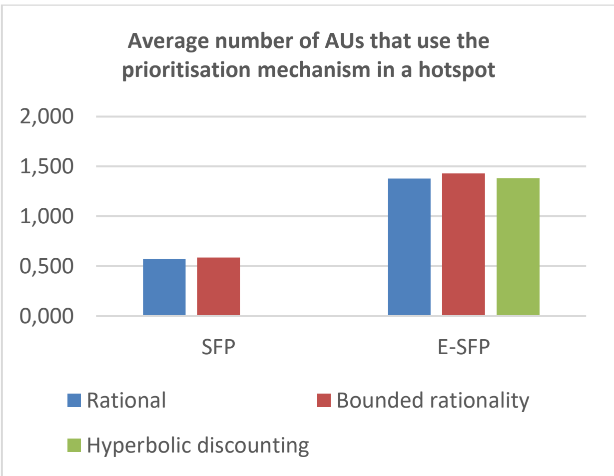

Figure 12. Number of AUs that use the prioritisation mechanism in a hotspot

The last equity metric included in the framework is more related to access. It measures the number of AUs that use the prioritisation mechanism in a hotspot. The results are displayed in Figure 12. Only the scenarios with the re-routing on and including the mechanisms SFP and E-SFP are represented. The Auction-based mechanism is not included because it is considered that all airlines make use of the auction mechanism in each hotspot and therefore this calculation does not make sense.

As expected, the E-SFP mechanism has a higher rate of utilisation than the SFP mechanism. The low number of airlines that use the SFP mechanism in a hotspot is explained by the rigidity of the conditions to be met for using that type of flight prioritisation.

3.5 Robustness KPA

Measuring the robustness of the different flight prioritisation mechanisms is a key ambition of the project. Here, the robustness is understood as the ability of a flight prioritisation mechanism to maintain the same performance regardless of the degree of irrationality in the behavior of the decision-making agents.

As presented in all the figures above, the robustness of each mechanism is determined by the comparison between the results of all the selected KPIs in a rational scenario and the results of the same KPIs for other scenarios with certain behavioural biases included. This robustness has already been briefly commented previously for each metric studied. Now, considering all this data together, we can assess it in a global way.

The robustness of the SFP mechanism is only evaluated against the results coming from the introduction of the bounded rationality bias inside the airlines behaviour for scenarios with the re-routing on. It is clear from the figures that the bounded rationality worsens the general performance of the mechanism: the punctuality level drops; the cost of delay increases and the equity metrics show a more unbalanced scenario between the airlines. However, despite this worsening, the SFP performance levels are still above those shown by the baseline scenario.

The E-SFP mechanism has been analysed under two different behavioural biases: bounded rationality and hyperbolic discounting. Results show that the mechanism is considerably sensitive to the ‘irrationalities’. Surprisingly, the scenario with the bounded rationality bias included show a slight improvement in the performance of the mechanism: the flight delay and the cost of delay drops a little and the equity levels tend to be slightly more balanced. In contrast, the hyperbolic discounting bias worsens all the selected performance metrics. It seems that the underestimation of the real value of the credit exchanges prevents airlines from realising the full potential of the mechanism.

Finally, the Auction-based mechanism is also evaluated against two different behavioural biases; bounded rationality and prospect theory. From all the figures presented, as previously commented, it is clearly visible that performance of the mechanism is hardly affected by the inclusion of the ‘irrationalities’ defined. As no extreme situations have been introduced, the operation of the market mechanism remains optimal. Therefore, it appears that the Auction-based mechanism is the most robust of all the mechanisms tested for the defined scenarios. However, it would be very interesting to test how this conclusion may vary by including more extreme airline behaviours inside the auction.

4. Conclusions

4.1 Conclusions about the experiments

From the detailed analysis of the experiment results, the following main conclusions can be drawn:

- The re-routing option has a big impact on the simulation and specifically on the selected KPIs.
- It is interesting and unexpected to see how the performance of the SFP mechanism, despite offering more flexibility to airlines, worsens the performance of the baseline situation when the re-routing option is disabled.
- The auction mechanism results are not significantly affected by the behavioural biases applied to the airlines.
- The auction mechanism has the most cost-efficient results.
- Cost of delay is directly related to the flexibility provided by the mechanisms.
- The flexibility KPIs, which intends to reflect the network ability to absorb non-scheduled traffic or late modifications, have turned out to be not very relevant and need further elaboration.
- No mechanism offers a high degree of equity: some airlines are much benefited while others are, on some occasions, even harmed with respect to their baseline situation. However, this is highly conditioned by the modelling assumptions and requires further investigation.
- A consolidated equity metric is missing to easily compare some mechanisms with others.

4.2 Conclusions about the model

Regarding the modelling approach and the key assumptions, the following conclusions can be drawn:

- The added value of ABM as a tool to measure the performance of flight prioritisation mechanism has been demonstrated: emergent and contra intuitive phenomena which would have been ignored otherwise have been identified for some scenarios.
- Network effects have a strong influence on the results and therefore are very relevant for the proper evaluation of the prioritisation mechanisms: the use of a network model is required
- The results seem to be very sensitive to some modelling assumptions (e.g., re-routings, airline strategies and behaviours, implementation of the CASA algorithm, traffic and network definition). The level of sensitivity of the model towards each of these factors needs a further and deeper study.

5. Future steps

The following future research lines are suggested:

- Explore a wider range of auction designs, coupled with the re-routing option.
- Explore more complex airlines strategies and 'irrational' behaviour.
- Use a more realistic and complex representation of the European network.
- Explore the impact of less rigid modelling assumptions (e.g., some hotspots solved at FMP level).
- Increase the time frame to be simulated to more than one day in order to allow the implementation of airlines' learning capabilities and adaptive behaviour.