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VALIDATION AND SIMULATION STUDY OF THE ARRIVAL MERGING PROCEDURE MODEL

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Abstract

This paper describes a fast-time simulation model for the arrival merging procedure that is one of the important issues in Japanese Air Traffic Management (ATM). To improve ATM performance, the operational improvements are being implemented [1, 2]. The benefits of the operational improvements should be estimated in the pre-implementation phase. Fast-time simulation is a useful technique because the benefits can be estimated in an efficient way. Meanwhile, to obtain reliable estimations, the simulation model has to reproduce actual operations to a certain degree.

Current operation is modeled as a baseline and validated for the reproduction. In the validation, the simulated and actual trajectories are compared. Landing-count, flight-time and flight-distance are used as the comparison metrics. As an application instance of the baseline model, Point Merge is modeled and the benefits are estimated.

1 Modeling

1.1 Arrival Flow

Arrivals at Tokyo International Airport (RJTT) are modeled in this study. RJTT is the principle airport for Japanese domestic flights. Fig. 1 represents the arrival flows at RJTT. As shown in the figure, the flows are mainly comprised of two streams; northern (orange) and western (red).

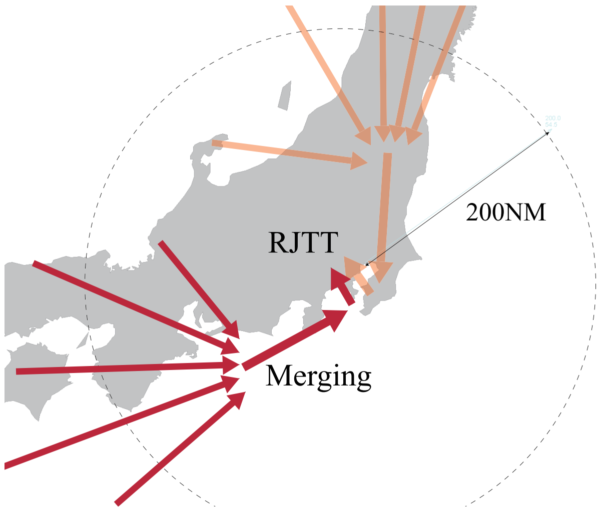

Fig. 1 The Arrival Flows at RJTT

Being vertically separated, two arrival streams can be operated independently. For each of the steams, the arrivals have to be merged with adequate separation.

More than 70% of the arrivals at this airport use the western stream. The arrival merging in this stream is therefore one of the main issues of the airport. This study focuses on the merging in the western stream.

The merging of arrival streams currently relies on the use of radar vectors. Although this procedure is efficient and flexible, under high traffic load conditions, it imposes rapid decisions for the air traffic controller and time-critical executions by the flight crew[3] .

The runway configuration for north wind alone is modeled. Because arrival merging is focused on, the model covers the surrounding areas of the airport (within a radius of 200NM).

1.2 Traffic Scenario

Traffic scenario defines the information for the arrivals in the simulation model. The information includes flight identification number, aircraft type, reference time (scenario-time at which the arrivals come into the simulation) , cruise altitude and planned-route.

Radar data recorded in the actual operation was used. The recorded time at which each arrival actually entered the area within a radius of 200NM from the airport was converted to the reference time. At the same time, the position and altitude recorded at the time were converted to the initial position and altitude.

A single day's worth of radar data was converted into one scenario. In total, 11 scenarios were made and the scenarios are respectively referred to as Scen 1 to Scen 11. In each of the scenarios, around 320 arrivals were modeled.

Radar data was also used to define planned-routes in the scenarios. Although STAR (Standard Terminal Arrival Route)s were defined as pre-defined routes, shortcut routes following radar vector were determined from the radar data and used as the standard routes. Passing altitudes on the defined routes were also determined based on the radar data.

1.3 Runways and Airspace

The coordinate data of the runways and the waypoints in the airspace were obtained from the published information[4]. Based on the coordinates, RW34L that was a dedicated arrival runway for the stream and the waypoints were modeled.

From the radar data, the area available for the radar vector was determined and modeled.

1.4 Separation Standards

The behavior of the arrival models is driven by required separation on the final approach [5]. Analyzing the actual data, the separation standard on the final approach was determined and defined as 5 NM in the model.

In the modeled terminal area, the arrivals are radar vectored to meet the sedation standard. In addition, Air Traffic Flow management (ATFM) function is modeled to limit the arrival traffic volume in the terminal area for each time-bin. The upper limit of the volume is determined from the radar data.

1.5 Wind Data

Weather affects ground speed and each operational day has unique weather. Utilizing the unique characteristics of a specific day makes the results more realistic[6]. For that reason, wind data was incorporated into the model.

From the National Oceanic and Atmospheric Administration archive in the States[7], wind direction and speed in each area was obtained. Although the wind direction and speed could change in accordance with the recording hour, the data recorded at 0900 (local time) of each corresponding date was used in the scenarios.

1.6 Model Implementation

For the modeling and conducting simulation, the simulation software AirTOp by Airtopsoft SA is used. The software has features such as modeling of runways, STARs, holding stacks and approach sequencing via vectoring[8].

2 Validation

2.1 Comparison Metrics

Comparing the simulation results with the actual data, the model is validated. The purpose of the validation is to examine the validity of the data set including separation rules, aircraft performance data, and pre-defined routes.

The following items are used as the comparison metrics:

- Landing-count
- Flight-time
- Flight-distance

In addition, descent profiles are compared.

On each scenario, a simulation experiment is conducted and the result is compared with the corresponding radar data.

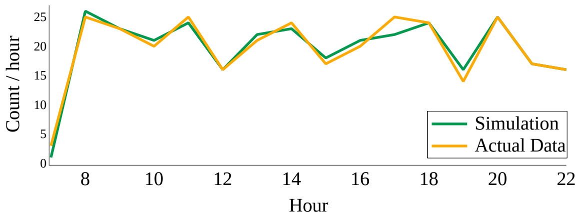

Fig. 2 A Comparison of Hourly Landing-counts

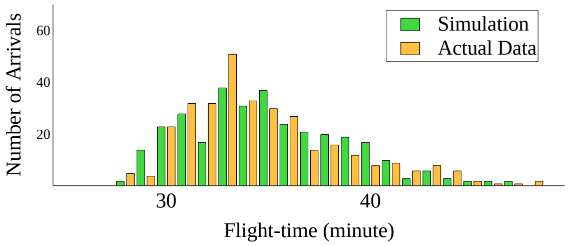

Fig. 3 A Comparison of Flight-time Distribution

Table 1 Correlation Coefficients

Scen	1	2	3	4	5	6
Coef.	0.98	0.98	0.97	0.96	0.98	0.95

Scen	7	8	9	10	11
Coef.	0.94	0.97	0.96	0.97	0.94

Table 2 Averages / SDs of ΔE_T

Scen	1	2	3	4	5	6
Ave.	4%	3%	7%	7%	0%	-2%
SD	21%	9%	13%	14%	13%	11%

Scen	7	8	9	10	11
Ave.	5%	8%	4%	7%	2%
SD	15%	15%	14%	10%	11%

2.2 Landing-count

Figure 2 represents a comparison of hourly landing-counts in one of the scenarios. Although some difference was observed, the two sets of landing-counts were virtually identical in the figure.

The correlation coefficients between the two sets are computed for all the scenarios. The correlation coefficient is the index of the degree to which two series of variable movements are correlated. The coefficients ranges -1 to 1. The values close to 1 means strong correlation between the movements.

Table 1 shows the computed coefficients between the simulation results and actual data. The computed coefficients took the values between 0.94 and 0.98. The values implied that the two sets of the landing-counts were strongly correlated. That is, the landing-counts were well reproduced in the simulation model.

2.3 Flight-time

Figure 3 shows a comparison of flight-time distribution in one of the scenarios. In the chart, similarities between the two distribution shapes were observed.

As mentioned in 1.4, ATFM was modeled and arrivals were delayed if necessary. To absorb the delay, the speed of the arrivals was adjusted. In case the speed adjustment could not absorb the entire delay, the arrivals were suspended at their starting points of the flight. In the simulation results, the suspended time period was added to the flight-time.

For each of the arrivals, flight-time difference between the simulation results and actual data is computed. Hereafter, the flight-time difference for arrival i is denoted as ΔE_{T_i}, that is computed as

$$\Delta E_{T_i} = (T_{M_i} - T_{A_i})/T_{A_i}$$

in which T_{A_i} and T_{M_i} represents the flight-time of arrival i in the actual data and simulation results, respectively. 0 value of ΔE_{T_i} means flight-time for the arrival i is completely reproduced.

Table 2 shows the averages and standard deviation (SD)s of ΔE_T. From the table, it was observed that the averages are close to 0 in all the scenarios. Compared to the averages, SDs took larger values.

It should be noted that the difference in the arrival sequence order affects the flight-time for each aircraft: Difference in the arrival sequencing order increases the distribution of ΔE_T. To reduce the SD, it is required to study sequencing of the arrivals.

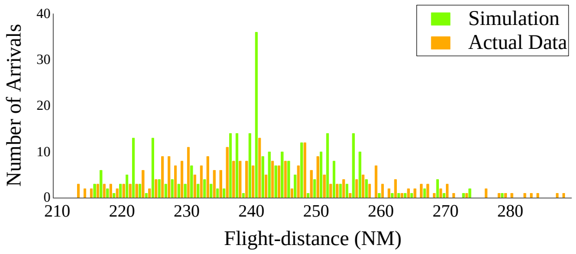

Fig. 4 A Comparison of Flight-distance Distribution

Table 3 Averages / SDs of ΔE_D

Scen	1	2	3	4	5	6
Ave.	3%	-1%	-1%	0%	-1%	0%
SD	25%	4%	4%	4%	19%	13%

Scen	7	8	9	10	11
Ave.	0%	-1%	0%	-1%	0%
SD	18%	5%	14%	14%	12%

2.4 Flight-distance

Figure 4 shows a comparison example of flight-distance distribution in one of the scenarios. From the figure, it was observed that the distance in the simulation results tended to concentrate on particular values. It was due to the difference in the vectoring methodology. This observation was common throughout all the scenarios.

In the same manner as the flight-time, flight-distance difference for arrival i is denoted as ΔE_{D_i} that is computed as

$$\Delta E_{D_i} = (D_{M_i} - D_{A_i})/D_{A_i}$$

in which D_{A_i} and D_{M_i} represents the flight distance of arrival i in the actual data and simulation results, respectively. Table 3 shows the averages and the SDs of ΔE_D. In the table, ΔE_D tends to be smaller than ΔE_T. It could be because of the fact that flight-distance did not reflect the ATFM delay absorbed by the suspension at the starting points.

2.5 Descent Profiles

The model focuses on arrival procedure in which the passing altitude can be a meaningful item. Hence, descent profiles play an important role.

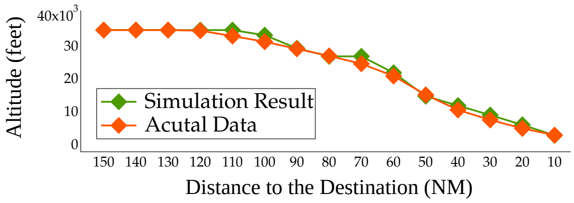

Fig. 5 A Comparison of Descent Profiles (Median)

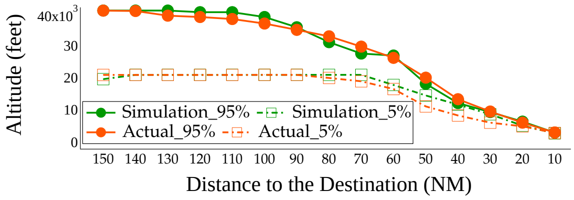

Fig. 6 A Comparison of Descent Profiles (95 Percentile and 5 Percentile)

For the purpose of validation, descent-profiles are compared based on the passing altitude on the points in the descending path. The points are defined based on the distance from the reference point of the destination airport.

Figure 5 shows a comparison example of the median of the passing altitude. Figure 6 shows a comparison example of the passing altitude range based on the 95 percentile and 5 percentile. In the figures, the passing altitude and range were compared for the same scenario.

In the figures, the green lines (simulation results) are nearly equal to the orange lines (actual data). It was confirmed that the simulation model reproduced descent profile with high accuracy. This observation was common throughout all the scenarios.

3 Point Merge

3.1 Modeling

In the previous section, it was confirmed that the simulation model of the current procedure (the baseline model) reproduced the traffic flow with high accuracy. As an application instance of the model, Point Merge is modeled and the benefits from the procedure are studied.

Point Merge is a systemized method for sequencing arrival flows developed by the Euro-

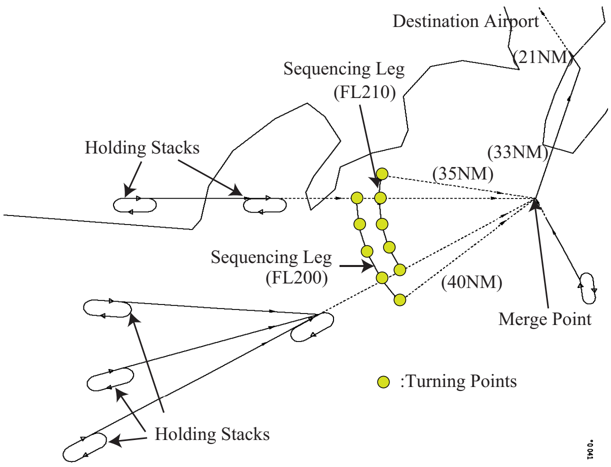

Fig. 7 Design of Point Merge

control Experimental Centre in 2006. Point Merge has been implemented in Oslo(2011), Dublin(2012), Seoul(2012) and Paris(2013) [9].

Since the data set that contributed to the excellent reproduction is used, the Point Merge model is expected to yield trustworthy estimations.

The arrival routes in the Point Merge model are designed based on one of the author's own ideas and the design does not always reflect actual operational requirements. Figure 7 shows the design of the model.

Two arrival flows come into the arcs (Sequencing Legs) via two major flows and they merge at Merge Point. Two Sequencing Legs are vertically and laterally separated. On Sequencing Legs, Turning Points are defined at 10 degree intervals of the central angle. On each arc, five Turning Points are defined.

Sequencing Legs are dedicated to path stretching/shortening. The operating method is comprised of two steps [10]:

- Create the spacing by "direct-to" instructions to the Merge Point issued for each aircraft on the appropriate Turning Point.
- Maintaining the spacing by speed control after leaving Sequencing Legs.

Descent instructions may be given when leaving Sequencing Legs. It should be a continuous descent as the distance is known by the FMS (Flight Management System) [10].

Since the flows are mainly merged within an arrival ACC (Area Control Centre) sector in the baseline model, Sequencing Legs and the Merge Point are set in the arrival ACC sector. In view of the range of cruise altitude in the scenarios, the passing altitudes (FL200 / 210) on Sequencing Legs are determined.

Because the arrivals are merged outside the terminal area, ATFM is not modeled in the Point Merge Model. Instead of ATFM, the Holding Stacks are introduced to absorb the required delay. Prior to the Sequence Legs, the Holding Stacks are designated. For each aircraft type, speed envelope (the maximum and minimum feasible speed) is defined. To ensure the separation, the speed is reduced within the envelope and flight distance is extended within the defined vector area. In case required adjustment is more than the value these two measures can handle, the arrivals are put into the Holding Stacks.

Simulation experiments are conducted on the same 11 scenarios set and the benefits are estimated based on the comparison of the simulation results.

This study aims at estimating the effects from the arrival procedure change. For the purpose, landing-count, flight-time, flight-distance and fuel-burn are compared.

For the Point Merge operations, simulation studies have been conducted[3, 5]. The studies showed that Point Merge decreased the number of maneuver instructions. However, since the number of instructions in the baseline model is not validated, the number of instructions is not compared in this application study.

3.2 Flight-time

Fligure 8 shows a comparison example of flight-time. It was observed that the Point Merge model increased flight-time. Figure 9 shows a comparison of the flight-time averages and SDs for each scenario. For all the scenarios, the Point Merge model increased the averages and SDs. The averages was increased by a range of 3% to 24%.

Table 4 shows the ratio of the arrivals that are put into the Holding Stacks and Table 5 shows the

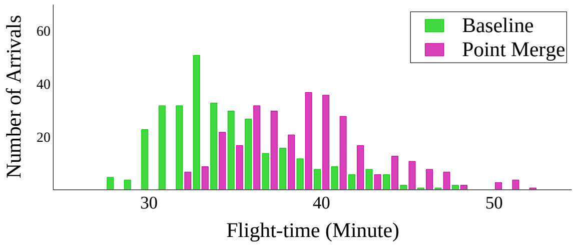

Fig. 8 A Comparison of Flight-time Distribution

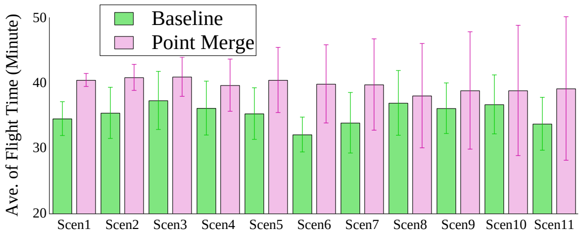

Fig. 9 A Comparison of Flight-time Averages (Bars Represent SDs)

Table 4 Ratio of Arrivals in the Holding Stacks

Scen	1	2	3	4	5	6
Ratio	51%	52%	53%	47%	57%	51%

Scen	7	8	9	10	11
Ratio	52%	28%	51%	50%	50%

averages of the durations in the Holding Stacks. Although the durations were not long, in almost all the scenarios, no less than half of the arrivals were put in the Holding Stacks.

Table 4 and Table 5 implied that under the route design, the Holding Stacks are indispensable to handle the traffic volume.

Table 5 Averages of Holding Durations (Unit: Minutes)

Scen	1	2	3	4	5	6
Ave.	3.9	4.0	4.3	4.0	4.4	4.1

Scen	7	8	9	10	11
Ave.	3.6	2.5	4.0	4.7	4.3

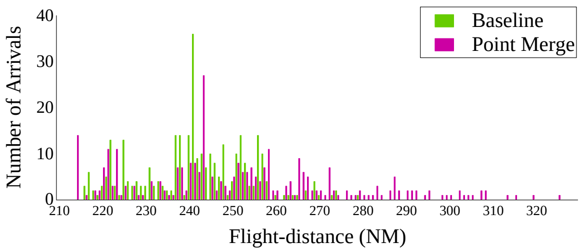

Fig. 10 A Comparison of Flight-distance Distributions

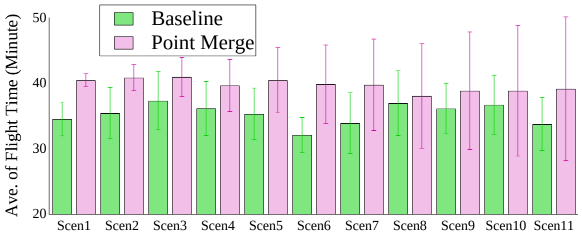

Fig. 11 Comparisons of Flight-distance Averages (Bars Represent SDs)

3.3 Flight-distance

Figure 10 shows a comparison example of the flight-distance distributions in one scenario. The chart demonstrated that, in the Point Merge model, some arrivals took long flight-distance and this observation is common among all the scenarios. The ratio of arrivals put into the Holding Stacks in Table 4 confirms this observation.

Figure 11 shows comparisons of the averages and SDs of flight-distance for each of the scenarios. For all the scenarios, the Point Merge model increased the averages and SDs.

3.4 Landing-separation

Figure 12 represents a comparison example of landing separation. In both of the models, the same landing separation minima (5NM) were applied. The chart showed that although the baseline model provided more arrival routes options and the model could vector the arrivals until just before the final approach course, the difference of the landing-count was small.

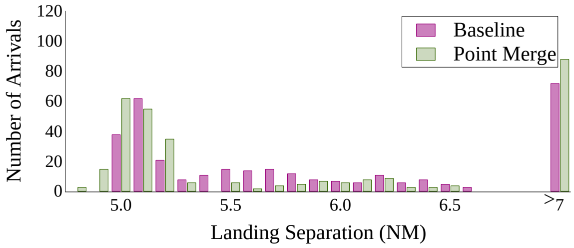

Fig. 12 A Comparison of Landing Separation Distribution

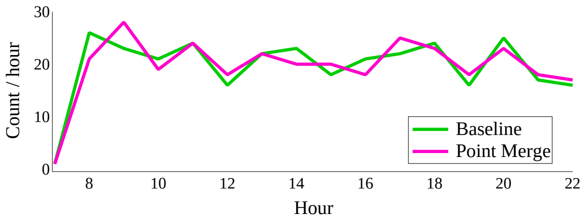

Fig. 13 A Comparison of Hourly Landing-counts

3.5 Landing-count

Figure 13 represents a comparison example of the landing-count. In the figure, it was observed that the Point Merge model delayed the peaks of the landing-count slightly. The increased flight-time shown in 3.2 could have delayed the peaks of the landing count. This tendency was observed throughout all the scenarios.

3.6 Fuel-burn

AirTOp has a built-in function of fuel-burn estimation. The estimation is based on BADA (Base of Aircraft DAta) that is the data set developed by Eurcontrol Experimental Center[11]. Using the function, fuel-burn is compared.

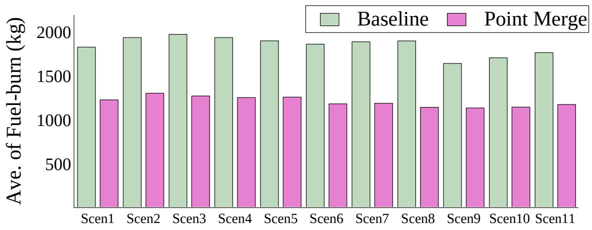

Fig. 14 Comparisons of Fuel-burn Averages

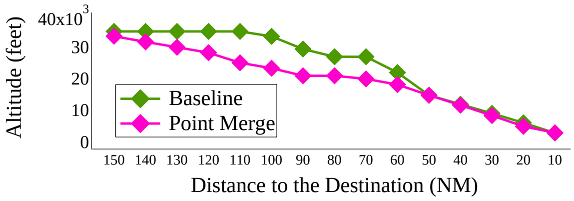

Fig. 15 A Comparison of Descent Profile (Median)

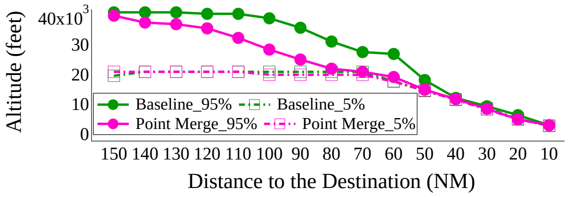

Fig. 16 A Comparison of Descent Profile (95 Percentile and 5 Percentile)

Figure 14 shows the comparison results. As shown in the chart, the Point Merge model reduced fuel-burn. The fuel-burn reduction range was 31% to 40%. In the chart, fuel-burn amount corresponding to the suspension at the starting points is not considered. That is, fuel-burn in the baseline model is underestimated and fuel-burn reduction amount should be bigger than in the chart.

To study the factors of the fuel-burn reduction, descent profiles are compared. Figure 15 and Figure 16 respectively show a comparison example of the median and the range of the passing altitude in the same scenario. The figures demonstrated that, in the Point Merge model, the arrivals tended to commence descent earlier and keep descending until touch-down without leveling. On the other hand, in the baseline model, arrivals tended to level their altitude.

The previous studies showed that, with Point Merge, arrivals remained higher [3, 5]. The figures conflict with the previous studies.

This was because of the design of the Point Merge arrival routes design in this instance. As shown in Figure 7, arrivals were required to descend to the altitude of FL200 / 210 above Sequence Legs located far from the destination airport. To comply with the constraints, arrivals commenced descending in early stages.

As mentioned in 3.2, the Point Merge model increased flight-time. It was due to the early commencement of descending.

4 Conclusions

A fast-time simulation model for the arrival merging procedure was described. The model was validated for the reproduction of the actual operations and the results demonstrated the high-fidelity of the model.

As an application instance of the validated model, Point Merge was modeled. For the modeling, the data set that contributed to the excellent reproductions was utilized to yield trustworthy estimations.

The simulation results implied that the Point Merge model stretched out the flight-time and consequently put more arrivals into the Holding Stacks. On the other hand, fuel-burn was reduced. These results were because of the routes design in which arrivals commenced descending in early stages.

It should be emphasized that the comparison metrics profoundly depend on the routes design. To fully benefit from Point Merge procedure, the routes design should be studied in detail.

At the same time, as mentioned earlier, workload reduction is assumed to be the benefit from Point Merge procedure. To study the benefit in the simulation, workload has to be incorporated.

On the other hand, as this application study demonstrated, the benefits can be estimated in a relatively simple manner. It is without doubt that the baseline model provides reliable simulation results and the model is the platform for the arrival merging procedure study.

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