Concept of a Long-Range Air Traffic Flow Management

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***Abstract*—The air transportation system provides infrastructures and procedures to ensure the efficient utilization of given resources, such as airspace or airport capacity. The main principle of corresponding flow management is an appropriate demand-capacity balancing on local and global levels. We provide a concept of operations, which focused on long-range air traffic flow management in the Asia-Pacific region. Coordination of long-range international flights demands collaboration between different flight information regions and local regulations. To demonstrate our approach, we choose Singapore Changi International Airport and use aircraft-transmitted positional data and flight plan information. The data are cleaned, analyzed, filtered, and processed to provide expected arrival flows with a given distance around the airport. A regulation of long-range flights by speed advisories shows a significant relief from times of excessive demands at the airport.**

***Keywords*—flow management, long-range flights, optimization, LR-ATFM, ICAO, airport performance**

I. Introduction

The air transportation system provides infrastructures and procedures to ensure the efficient utilization of given resources, such as airspace or airport capacity. The main principle of the Air Traffic Flow Management (ATFM) is an appropriate demand-capacity balancing on both local and global levels [1]–[3]. Therefore, ATFM ensures that ”capacity is utilized to the maximum extent possible and that the traffic volume is compatible with the capacities declared” [4]. The demand is driven by scheduled flight plans and operational deviations on the day of operations. These deviations could result from expected, system immanent uncertainties (e.g. reactionary delay), disturbance from external factors (e.g. weather conditions at airports or wind changes during en-route flight phases), disruptions of aircraft (e.g. cancellations, use of alternate airports), or airspace operations (e.g. reduced sector capacity by activated temporary restricted area).

Even though air transport is an international and intercontinental mode of transport, regional service concepts and providers do not pursue a homogeneous ATFM approach. In Europe, the Network Manager (NM) is responsible to provide centralized ATFM related actions and information for airspace users [5]. With our focus on the Asia-Pacific Region (APAC) region, we see different approaches implemented. In Japan, for example, the Air Traffic Management Center controls the entire air traffic flow in the corresponding Fukuoka Flight Information Region (FIR). To provide efficient arrival traffic at the Tokyo International Airport (RJTT), the most congested airport in Japan, takeoff times are controlled at the departure airports. The release of Expected Departure Clearance Time (EDCT) at domestic airports (pre-flight, transmitted 40 minutes before Estimated Off-Block Time (EOBT)) and the in-flight control of arrival volumes (e.g. speed control) are key elements of this regional flow management. These efforts have improved the general air traffic flow in Fukuoka FIR, but further improvements in the different traffic phases are still needed even under the increasing requirements of air traffic. With a focus on Singapore, the management of air traffic flows into and out of the Singapore FIR is a task of the Singapore Air Traffic Flow Management Unit (ATFMU). ATFMU regulates the traffic flows by ATFM measures (such as ground delay program (GDP), minimum departure interval, or miles/minutes-in-trail), performs the demand-capacity balancing, and provides a Calculated Take-Off Time (CTOT) for the flights, which are affected by GDP before take-off from the departure airport. Based on Aeronautical Information Publication (AIP) Singapore 2020 under section ENR 1.9 Singapore can assign CTOTs to flights departing from 37 different airports in the APAC region. Within APAC region, the concept of Long-Range Air Traffic Management (LR-ATFM) was proposed to improve the demand-capacity management by an extension of the current time horizon of regional ATFM implementations. Thus, major traffic flows could be efficiently managed across ATM regions with a long-range situational awareness (more transparent traffic management) enabled by an early provision of target times over a waypoint. The LR-ATFM has been successfully tested and flight tests have demonstrated performance improvements [6].

The operational challenges in the aviation system are related to different time horizons (look ahead times), associated with different types of available data and control approaches. The Collaborative Decision-Making (CDM) process is a key enabler of ATFM [2] since stakeholders could reliable coordinate tasks to monitor and improve ATM system performance in their respective areas of responsibility before decisions are made in the ATFM process. This coordination is supported by a system-wide information management [7] and could reduce cost, increase environmental benefits, optimize airport and airspace capacity, and improve efficiency and effectiveness of air navigation services. This is achieved, for example, by shortening taxi times (-7%), decreasing fuel burn (-7.7%), and reducing ATFM delay (-10.3%) [8]. In Europe, CDM will be implemented as part of the European Air Traffic Management (ATM) Master Plan within the Single European Sky (SES) initiative [9]. The master plan serves as an ongoing roadmap for achieving the goals of the SES ATM research program (SESAR) and as such contains important building blocks for the future European air traffic system. In the APAC region, the Seamless Air Navigation Service (ANS) Plan [10] is developed to jointly meet the ANS challenges, such as providing a common performance framework or deployment plan with specific operational improvements and transition arrangements.

A. *Status quo*

Accommodating arrival traffic flow at highly-frequented airports, strategic arrival management is the key to reduce arrival delay time and to mitigate traffic congestion around and at the airport. The flexible use of airspace [11] and high utilization of the runway system are key elements to ensure efficient use of the (declared) airport capacity, even under different weather constraints [12]. Aircraft arrival processes are mainly distinguished by two parts; flow-based control and time-based tactical control. The former is termed ATFM, which controls aircraft arrival time by balancing traffic demands and airspace/airport capacity. The latter is arrival management, which controls time-spacing among arrival aircraft (establishing a safe arrival sequence per runway) [13,14]. In the past, several studies have analyzed the aircraft arrival process at airports using queuing theory. For example, the aircraft arrival delay was analyzed by employing queuing models focused especially on runway-related delay and capacity constraints [15]–[18]. Using operational data from Tokyo International Airport, a data-driven and queue-based modeling approach was proposed to estimate a bottleneck of current arrival traffic and to suggest even better arrival strategies [19]–[21]. Furthermore, intentions of airspace users to optimize their en-route and on-ground operations [22,23], the effect of airspace constraints to the performance of the ATM system [24], or the impact of free routes on airspace demand [25] are associated research topics.

One of the most difficult tasks is the management of long-range traffic flows, as a globally harmonized ATM operational concept must be available. This concept should provide a ”holistic, cooperative and collaborative decision-making environment, where the expectations of the members of the ATM community would be balanced” [26].

The control of air traffic by network interventions can lead to congestion at specific nodes, in particular, when (increased) Arrival Manager (AMAN) activities are not taken into consideration [27]. This can be avoided with an integrated and balanced consideration of both arrival and flow management, aiming at a cost reduction by moving delay into a more efficient phase of flight [6]. For this purpose, the authors' past work analyzed characteristics of aircraft arrival traffic considering different time horizons and traffic mix [28].

For the successful implementation of the LR-ATFM concept, several conditions must be met. The most important of these is the speed advisories required during the flight. Flight tests have shown that advice should only be given if the recommended speed significantly deviates from the current speed, e.g. only for changes greater than 0.01 Mach [29]. This also prevents an increasing workload and leads to a higher acceptance by the operators. The aircraft speed could be set between optimal cruise speed and minimum fuel consumption speed to mitigate delays [30]. Besides, speed control affects the fuel consumption of the aircraft, which means that the airline's cost index must also be included in the decision process [31,32] as well as regulations applied within a ground delay program [33] or in a holistic turnaround management [34,35]. The speed control provides only a limited ability to influence the target arrival time and also depends on the remaining flight time [36]. Furthermore, the flight should arrive at the terminal area and land at the airport with little or no trajectory adjustment [37].

B. *Focus and structure of the document*

In our contribution, we seize the idea of long-range flow management and set-up a demonstration case to emphasize the potentials of this concept. Besides the common ground delay approaches, en-route regulations in a heterogeneous, cross-national ATFM environment could raise additional benefits for aviation stakeholders. Thus, we change our perspective from a location-based trajectory description to a time-based process view. We gain flight time and aircraft position-related information from an ex-post analysis of Automatic Dependent Surveillance — Broadcast (ADS-B) messages from incoming flights into Singapore Changi International Airport (WSSS). The derived statistical information is used as input to shift time-distributed, long-range flights to mitigate the effect of local congestion at the airport terminal area.

The paper is structured as follows. After the introduction, we provide a brief overview of air traffic flow management with a focus on cross-border and long-range approaches and the WSSS environment as our field of application (Section II). A data analysis on WSSS arrival traffic is given in Section III. This analysis is based on aircraft position data derived from ADS-B messages. In Section IV, we implement the LR-ATFM concept and show in a demonstration case that regulation of long-range flights will lead to an improved flow and capacity management at the airport. Finally, the paper closes with a discussion and conclusions (Section V).

II. Air Traffic Flow and Capacity Management

The number of delayed ATFM flights in 2019 has increased to 9.9% of all flights in Europe, resulting in 17.2 million minutes of delay due to en-route ATFM regulations [38]. The main delay causes are restrictions due to ATC capacity (43.9%), ATC personnel (24.3%), and weather events (21.2%). Considering an average value of 100€ for one minute of ATFM delay [39], ATFM delay will results in costs of 1.7 bill. €. This value clearly indicates an improvement (innovation) pressure on current aviation infrastructure and procedures.

In this context, the flow management has to be separated from the arrival management. The primary task of the arrival management at airports is to establish an aircraft-specific sequence per active runway preventing separation infringements and high capacity utilization. In the flow management, individual aircraft are combined to incoming traffic streams into the airport terminal area and regulated by aggregated measures at larger time scales (e.g. movements per hour). With a specific focus on WSSS, we briefly introduce the concept of air traffic flow management in the following.

A. Cross-Border ATFM

Cross-border ATFM concepts control national and international flights [40]. The challenge of such a system is the compatibility of ATFM procedures between all participating countries considering trans-regional features. For example, unified standards and procedures are necessary for airlines, Air Navigation Service Provider (ANSP)s, and airports in the region. Advantages of cross-border ATFM (especially in the APAC) are [41]:

- trans-regional balancing of capacity and demand,
- optimized airport performance and airspace usage,
- simplification of traffic flows, lower controller workload,
- increased situational awareness of ATFM partners, and
- emission and fuel savings, reduction of delays.

The basis of an ATFM system is the control of flights which are carried out within the area of responsibility of the coordinating authority [42]. For ATFM to be effective and generate the desired benefits, at least 70%-75% of the flights at an airport should be controllable [40,42,43]. WSSS and Hong Kong airports are not served by domestic flights as they are located in city states. At other major airports (e.g. Bangkok, Tokyo-Narita, or Kuala Lumpur) in the APAC, the national air traffic share is below 30%, which is well below the necessary traffic share for effective ATFM. For this reason, the implementation of a multi-nodal ATFM concept in the APAC was initiated in 2014 [43]. The basic framework of this trans-regional ATFM program is based on an IATA project with the ANSPs in the APAC, which led to the conclusion that centralized ATFM (as implemented in Europe) is not feasible. Fig. 1 exhibits the basic idea of the multi-nodal ATFM principle [44].

The ANSPs of the respective regions coordinate a virtual node within their area of responsibility, which is operated independently from the other nodes. They are connected via a web-based platform for information exchange. With the help of standardized procedures and the exchange of important data, the traffic flows between the nodes are effectively managed following the principles of joint decision-making [2]. As of May 2019, a total of 39 airports in eleven different ANSP regions are organized in the Multi-Nodal ATFM.

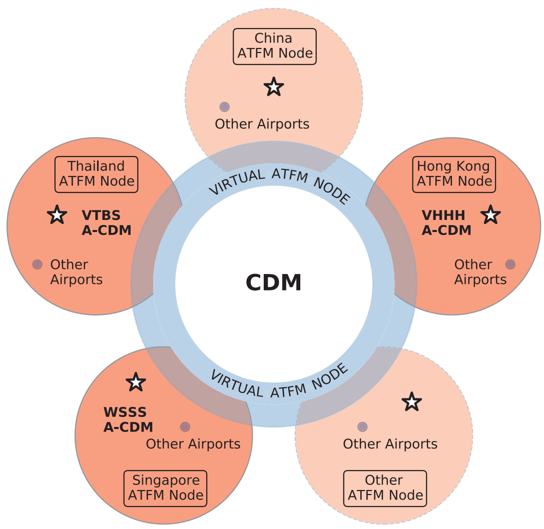

Figure 1. Multi-Nodal ATFM concept in APAC region [40].

B. Longe-Range ATFM

The general concept of LR-ATFM is that the flow into an airport is regulated by direct communication with the Airline Operator Center (AOC) of the airlines instead of indirect information exchange between adjacent ATFM units of the states. With a focus on the APAC region, the ATFMU in Singapore could manage not only traffic flows from airports in that region, but also long-range flows to Singapore in the airspace from the member states with which there is a consensus for ATFM cooperation (Asia-Pacific Distributed Multi-Nodal ATFM Network Collaboration Group). Thus, ATFMU calculates and issues the Target Time Over (TTO) to the flights over a waypoint (TTO-fix) along their routes. The LR-ATFM concept is envisaged to be most applicable in the cruise phase of flight share of aircraft from a point where estimate/advisory time (Estimated Time Over (ETO), TTO) is most accurate and the flight is least subject to subsequent operational variabilities and Air Traffic Control (ATC) intervention. Fig. 2 depicts the overall concept and steps involved with it.

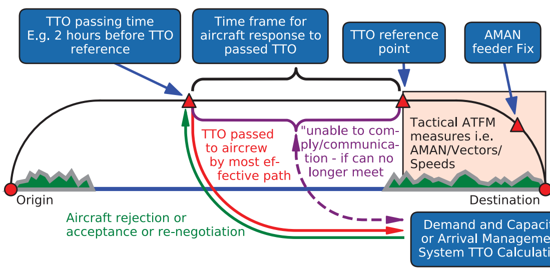

Figure 2. General Concept of Long-Range ATFM [6].

According to the ICAO information paper ”Long Range ATFM concept trials”, the workflow of the LR-ATFM consists of the following five steps [6]. (1) ANSPs and airspace users establish a timeframe before a TTO metering fix within which LR-ATFM can be applied, considering the operational environment, accuracy/stability of estimates, communication, and aircraft capacity to comply. (2) An ETO at the TTO-fix is established for each flight and a TTO is calculated (inclusive of any ATFM measures). (3) At the TTO passing time, it is passed to the aircraft via an agreed communication path. (4) Aircrew confirms their ability/inability to comply and advise the appropriate authority. (5) The crew manages the flight to reach the TTO-fix at the TTO time or advise if they are subsequently unable to do so, with a revised ETO.

The two main problems that are associated with LR-ATFM are the location of TTO-fix and from where onwards ATFMU should regulate the flow. The location of TTO-fix affects the ability of the flight to meet the passed TTO time. If flights are unable to comply with passed TTO time, the flow might be distorted, and flights might go into holdings. How much delay can be absorbed by the flights depends on where onwards the flow control started. Control of flights farther from Changi Airport allows flights to reduce more delay or gain more time.

C. *Changi airport environment*

Singapore Changi airport (WSSS) is the aviation hub of Southeast Asia and one of the largest airports in the world with over 350,000 aircraft movements and 65 million passengers in 2019. More than 100 airlines are operating at the airport and connect Singapore to 380 cities worldwide. There are three parallel runways, with 02R/20L still under construction and intended for military use only. Both runways are equipped for precision approaches and are operated 24 hours a day. Between 0:00 and 15:00 UTC a parallel use is possible. Fig. 3 emphasizes the central location of WSSS in the APAC region, surrounded by several FIRs.

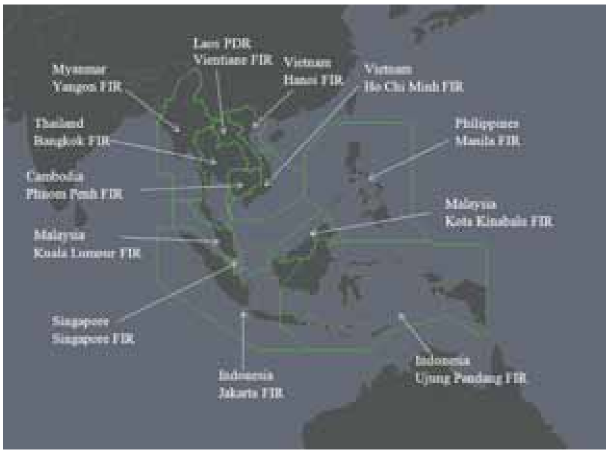

Figure 3. Flight information region around Singapore airport.

Regional flights from the APAC region to WSSS are controlled by the Multi-Nodal ATFM concept [45]. With the help of LR-ATFM and related concepts such as ASIST, long-haul flights will be integrated into the approach sequence generation. This will lead to fewer flight distances in Singapore FIR and fewer flights with holdings. Effective classical ATFM approaches must be able to influence at least 70-75% of flights. According to a simulation for WSSS, flights in a radius of 2,400 NM must be controllable [43]. In this case, the delay for both controlled flights and flights exempted from ATFM measures can be significantly reduced. With the help of LR-ATFM it is possible to integrate flights outside the APAC region into the process of air traffic flow control.

The flight times of important routes from WSSS to North-East Asia, the Middle East, Europe, North America, and Australia are at least 3 hours. Every third flight reaches WSSS from these regions. These form the group with a high potential for network interventions to control traffic flow. Fig. 4 depicts the delay situation of flights connected to WSSS. In addition to the management of short- and medium-haul flights, delayed long-haul flights have an increased forecast, which allows for appropriate impact mitigation strategies to be taken on the day of operations.

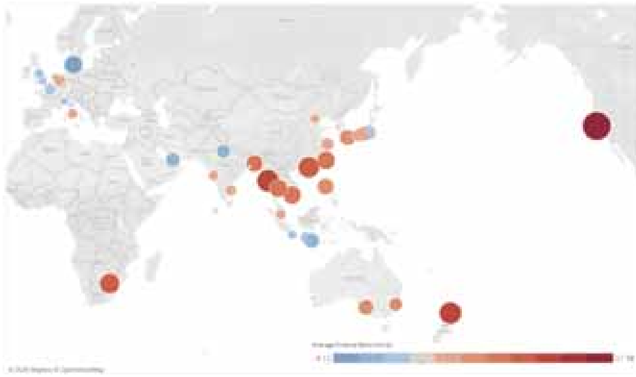

Figure 4. Airborne delay of flights connected to WSSS [46].

III. Data analysis

To model the incoming traffic of WSSS we use aircraft-broadcasted data (ADS-B) and flight plan data from the airport. Within the context of LR-ATFM, we are particularly interested in a time- and flow-based view of flights to enable speed advisories to which indicates a necessary speed reduction or increase. Before the analysis starts, we cleaned and filtered the data, created and simplified trajectories from location information, and assigned flights by merging location-based trajectories with flight plan data.

A. *ADS-B data*

It is expected, that current surveillance systems will be extended by ADS-B capabilities of aircraft. Today air traffic surveillance is ensured by primary and secondary surveillance radar (PSR, SSR) including Mode-S [47], to provide situational awareness to air traffic management systems. The Mode-S transponders broadcast aircraft position and states (e.g. ground speed, rate of climb/descent, heading) on 1090 MHz SSR-Mode-S downlink frequency (ADS-B Out): a decent ADS-B receiver antenna can receive messages from cruising aircraft located up to 400 km far away, while the range is much lower for aircraft flying in low altitude or on the ground. Aircraft determine their position via satellite, inertial, and radio navigation and periodically emit it (roughly one sample per second) with other relevant parameters to ground stations and other equipped aircraft. Flights worldwide must increasingly be equipped with Mode-S transponders [48]–[50]. To the simple requirements on the receivers, ADS-B has contributed to the development of online services that display the current air traffic in real-time with worldwide receiver networks (depending on the local coverage), such as OpenSky Network (opensky-network.org), Flightradar24 (flightradar24.com), or FlightAware (flightaware.com). This technology also offers a solution for monitoring remote areas and flights over the oceans with space-based ADS-B [51]. The data sent by aircraft could be used to monitor, evaluate, and predict airport performance and airspace utilization. Besides, this data would enable a new area for cooperative management by creating a deeper situational awareness for local and network-wide operations.

The complete data set comprises data points with 21 different pieces of information. These include flight plan data, flight parameters, position, and time information. The following types are important for our research: (a) actual and scheduled times at WSSS arrivals and origin departures; (b) timestamps; (c) transponder unique identifiers (to be related to the tail number and aircraft type), (d) positional information about latitude and longitude (°, 6 digits), altitude (ft, with steps of 25ft); (e) velocity information - ground speed (kts), track angle (°) and vertical speed (ft/min).

Of the 96,097 flights to Singapore Changi Airport contained in the complete data set, 13,551 flights are sorted out due to poor data quality. The data set contains a total of more than 24 million data points describing 82,546 flights. With 13,459 tracked flights to WSSS, May is the busiest month in the used data set. Since not every aircraft is equipped with an ADS-B transponder, not all of the active flights are included in the overall data set. Further sorting based on data quality will further reduce the number of flights. The following assumptions and determining values for capacities and demand refer to a limited data set and thus lead to an underestimation in comparison to the actual values.

B. Analysis of flight position data and flight plans

If the average delay reaches a maximum acceptable value, the corresponding capacity value corresponds to the practical capacity. The throughput capacity corresponds to the maximum demand that a system can handle in a certain period. This is a theoretical value that cannot be reached during operation to describe the maximum performance. To derive the capacity of the approach sector, we count the hourly numbers of flights in the sector and chose the 90% quantile value of all observed values.

Fig. 5 exhibits the number of movements between 02 April to 27 October 2019 related to the time of day. The curves show gliding hour values for different quantiles. In the first half of the day (until about 11:00 a.m.) the continuous capacity is not exceeded. During the night hours, the capacity utilization at WSSS is at its lowest. These periods are not suitable for the application of LR-ATFM, as it is only used when the approach sector is overloaded. From 6:00 a.m. onwards the number of movements increases significantly for all quantiles. The curves fluctuate in the second half of the day, resulting in isolated peaks.

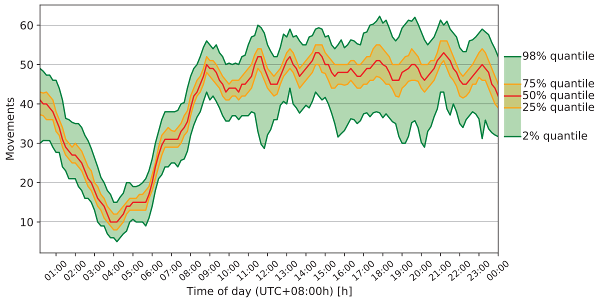

Figure 5. Flightplan data used to derive aircraft flows over the time of the day.

The flights arriving at WSSS are shown in Fig. 6 and depict the mix of traffic with regards to the actual flight time. More than 50% of the flights possess a flight time longer than 3 hours. CAAS and Airways define flights with a total distance of over 2.200 NM as long-haul flights [6]. Within the data set, this corresponds to around 25% of the overall flights.

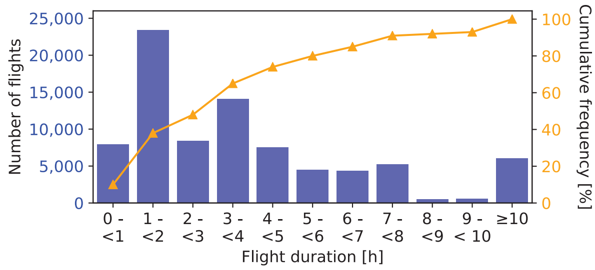

Figure 6. Histogram of distances from flights to Singapore airport.

WSSS is a central Asian hub, which is connected to 175 airports from 5 different continents. Fig. 7 shows the air transportation network derived from the data set (flight movements).

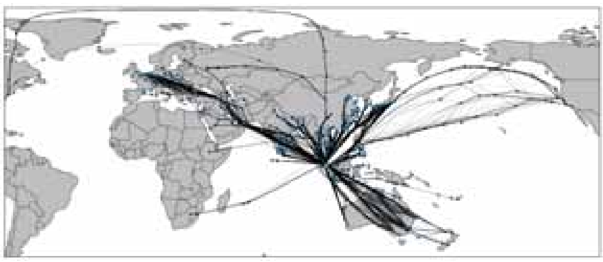

Figure 7. WSSS is a world-wide connected air transportation hub.

Large main traffic routes run from Europe via the Middle East and India to Singapore. Flights from the west coast of the USA and Australia mainly cross the Pacific Ocean. Approaches from South Africa reach WSSS from the southwest coming from the Indian Ocean. The flight from Newark is of particular interest because this flight mainly uses a connection over the Arctic.

C. Arrival flows and network

Long-range flights from different regions of the world arrive at WSSS (see Fig. 8). These flows are getting merged with a decreasing distance to the airport.

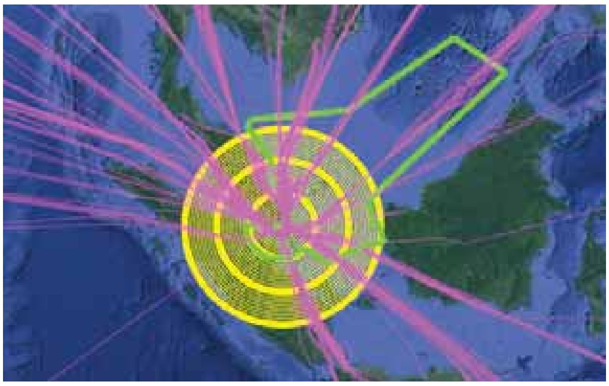

Figure 8. Arrival flows into WSSS with 100, 200 and 300 NM distance.

In Fig. 9, the corresponding bearings of the incoming traffic flows are depicted with more narrow positions around WSSS. Here we chose the TTO reference point defined in the LR-ATFM concept (Fig. 2) as a separation point between ATFM and arrival management (top of descent). This point is located at a distance from 170 NM around the airport. A more detailed figure is given by using the true bearing from the north (QTE) and the share of aircraft entering from the corresponding directions. Thus nine major arrival directions could be identified, marked in Fig. 9 with red lines (left) and red dots (right).

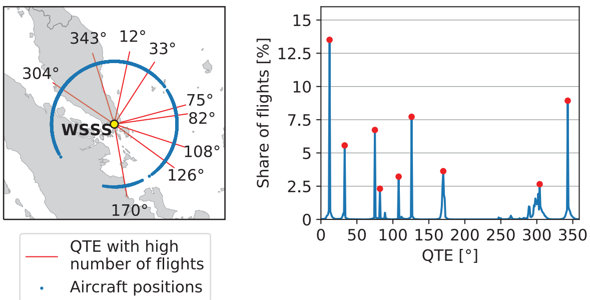

Figure 9. Bearing of arrival flows into WSSS measured at a distance of 170 NM out (TTO reference point, transition from LR-ATFM to Arrival Management).

Approximately 40% of the flights enter the approach sector of WSSS airport from the north, from east and west it is about 24%, and 12% from the south. Flows from the eastern direction consists of aggregated arrival streams (4 streams from 75-126°), from 304° a high variety of smaller flows reach the approach sector. Fig. 10 (left) exhibits clustered aircraft positions applying both kernel density estimation [52,53] and mean-shift clustering [54] (mode-seeking) on the circular area (cf. Fig. 9 (right)) with an average of 2h distance before landing considering 51,163 flights. The yellow points represent the determined 27 cluster centers and the red lines the corresponding cluster borders. The grey area covers 98% of the flights, excluding outliers from the statistical analysis. When the aircraft starts descending in the vicinity of the airport, the arrival flows are step-wise merged for the final arrival sequence provided by the local arrival management. Fig. 10 (right) emphasized this flow aggregation using k-Means clustering [55] with 6 clusters for aircraft positions 30 minutes before landing at WSSS.

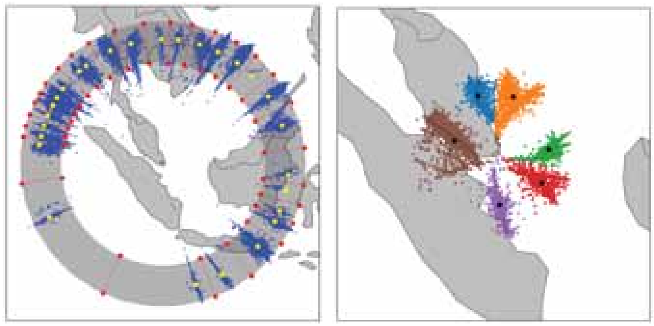

Figure 10. Arrival flows into WSSS considering aircraft positions at two hours before landing (left) and the top of decent (right).

IV. Concept Demonstration

Considering the average position in an hourly-stepped distance representation and the observed flight movements, a simplified network of the arrival flow could be derived. In Fig. 11, each circular sector represents a time to fly from 7 to 1 hour before landing at WSSS, where the inner and outer restrictions are defined by the 1% and 99% quantile of observed movements. The yellow dots are the cluster centers that represent an increased number of flight positions (from the outer to the inner ring).

These cluster centers are located at the average distance per circle (in the direction of flight) and possess a minimized lateral deviation from the corresponding traffic flow per sector. The black lines show the connections between the clusters, which are based on observed aircraft movements. From this time-based network, three main traffic directions to the airport WSSS can be derived. From the northwest, the traffic flows from Europe are connected with those from the Middle East and India. From the northeast, flights from Northeast Asia and North America reach WSSS airport. From the southeast, flights from Australia and New Zealand arrive.

Aircraft positions and time to fly are connected to provide a comparison of isochrone-position and aircraft location (latitude, longitude). Here environmental conditions (e.g. wind) and airspace restriction could significantly impact the flight time, as well as the actual use of runways and corresponding arrival procedures. These different impacts are emphasized in Fig. 12, where the color-coded (green to red) line represents the average position of the isochrone with a flight time of

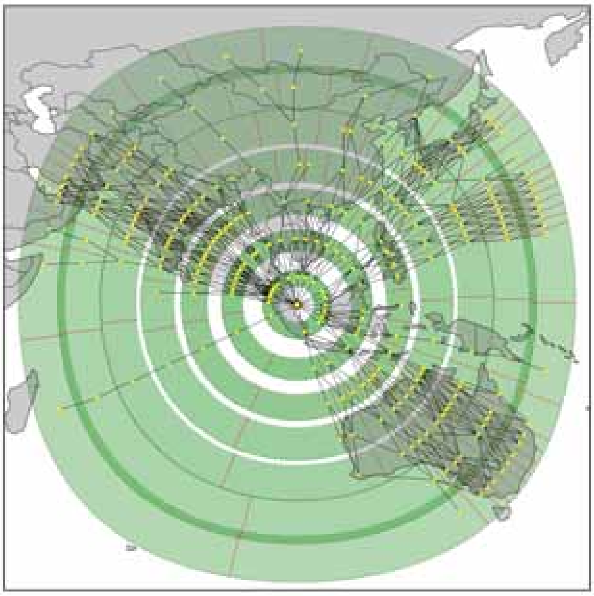

Figure 11. Network of clustered positions and deviation of positions with hourly-based distance circles around WSSS.

Figure 12. Isochrone with flight time of 7 hours to Singapore airport (green = data available, red = interpolation).

7 hours. The green sections of the isochrone indicate existing arrival flows passing through and on the red sections no aircraft approaching WSSS. The yellow circular area corresponds to the outer area in Fig. 11.

As an example, Fig. 13 depicts the deviation of aircraft locations per average flight time of the corresponding circle (see Fig. 11). All flight numbers are aggregated to city pairs and show a location statistic, where flight numbers with the lowest standard deviation in the location are depicted at the top and with the highest standard deviation below in Fig. 13. Only flight connections with at least 50 flights are considered. Furthermore, the standard deviation of the flight position decreases with the remaining time until landing, which gives a first indication of the regulation potential of long-range flights. The average position converges also with decreasing distance.

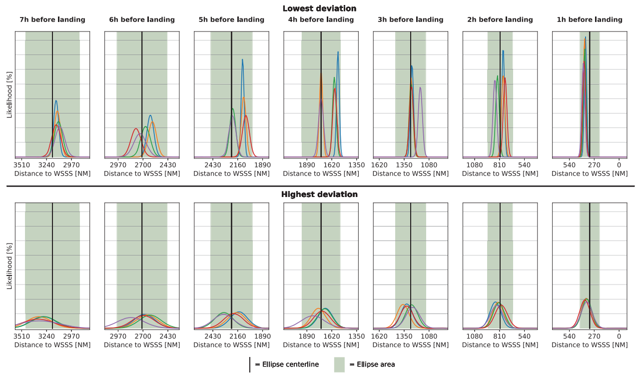

Figure 13. Distance related deviations in the hourly-based circles around WSSS.

Since we are aiming for a regulation based on speed advisories, the distances to the airport have to be defined as a time to fly as depicted in Fig. 14. This picture confirms the variation of flight times and also shows a significant difference in the standard deviation of flights by time to fly and city pair.

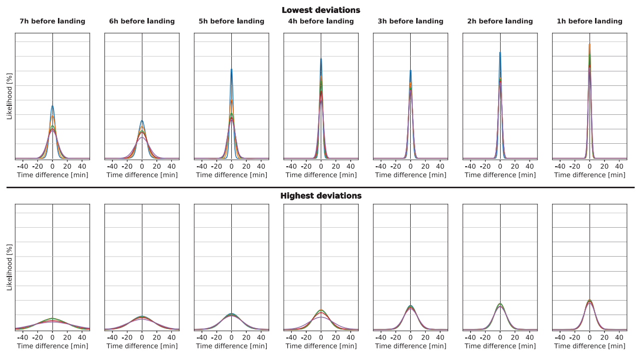

Figure 14. Time related deviations in the hourly-based circles around WSSS.

In the following, we assume the temporal distribution of the arrival of each flight depending on the remaining flight time. The initial view on the expected arrival situation at WSSS, see Fig. 15, is valid at 11:20 and indicates three arrival peaks. The peak between 16:00 and 17:30 is caused by the fact that the long-haul arrivals coincide with short-/medium-haul arrivals.

The prior observed deviations in flight times could be used to shift long-haul flights to mitigate this over demand. Flights before 16:00 lead to no exceeding of the capacity and the peak at 12:00 is not caused by long-haul operations. At this stage, we use a capacity value of 20 to demonstrate our concept. This value is derived from the 90% value of hourly counted aircraft entries (rolling horizon) into the approach sector.

Every actual flight is influenced by a multitude of parameters, which affect flight time differently. In contrast to a complex flight control system, we assume that on average each flight could be accelerated or decelerated by an appropriate

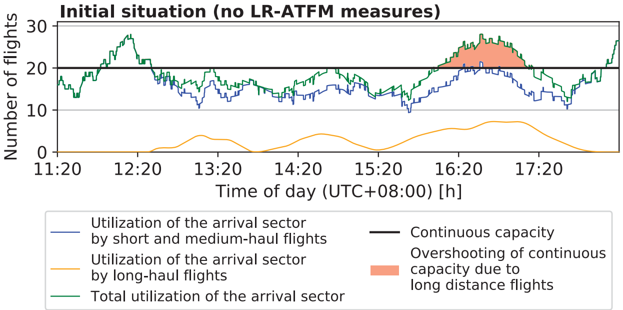

Figure 15. Arrival peaks at the TTO reference point of WSSS.

amount of time from ±1 minute to ±6 minutes per flight hour. This allows us to control the arrival flows of long-range flights and prevent congestion of WSSS airspace and airport. In future research, we will extend this simplified approach to more realistic flight profiles on the day of operation considering actual constraints, such as weather and wind conditions, specific take-off mass, airspace regulations, or runways in use.

We set up a linear integer program to derive an optimal ATFM regulation for long-haul flights using speed restrictions, considering WSSS airport capacity and expected demand. The objective function minimizes the integral over demand over time. Fig. 16 shows the influence of long-range flight regulations at an example time (11:20).

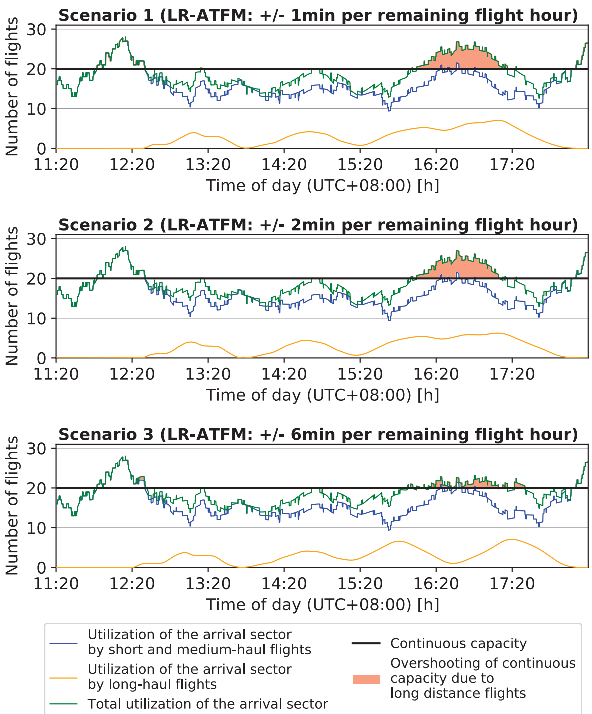

Figure 16. Arrival peaks at WSSS and optimized regulation of long-range flights by individual speed advisories of stochastically distributed flight times.

The blue curve shows the capacity utilization in the vicinity of the airport WSSS by short- and medium-haul flights. We assume these flights as fixed and not under the control of the ATFM regulation. The orange line corresponds to the expected demand due to long-haul flights, based on the derived stochastic time distribution of flights. Individual speed adjustments can be used to control the arrival flows so that the capacity (black line) is not exceeded. The orange area corresponds to the congestion resulting from the presence of long-haul flights around WSSS.

The application of scenarios with different LR-ATFM rules leads to a less severe phase of excessive demand. A shift of ±1 minute per remaining flight hour results in a reduction of 14% of the orange area, shifting flights by ±2 and ±6 minutes reduces this area by 20% and 80% in comparison to the original scenario, respectively. The shift of ±1 minute is a moderate speed regulation for arrivals at WSSS and was already applied at flight trials [6]. We expect that changes with more than 3 minutes per flight hour will be associated with a more complex trajectory management (e.g. re-routing).

V. Discussion and Conclusion

The implementation of a long-haul flight regulation is a complex and multifaceted challenge. The moderate speed control offers the opportunity to generate additional benefits for aviation stakeholders. During the day of operations, specific flight routes are active, as well as actual weather constraints, and airspace and airport restrictions. This may reduce the uncertainties of actual flights and results will differ from statistical approaches. Here, both machine learning and model-based flight performance approaches will significantly contribute to an improved prediction of expected trajectories and arrival times. The current concept is based on the regulation of ground speeds but has to be extended to the consideration of true airspeed. LR-ATFM is an additional part of flight regulation during an active flight and provides a link between en-route flight operations, regional ATFM regulations along the flight path, and local arrival management (cf. [56]). Key elements for a successful implementation are the cross-border collaboration between ATFM units and a system-wide information management.

In our contribution, we briefly describe the general concept of long-range air traffic management. With a focus on Singapore Changi International airport an analysis of the operational environment was done (arrival flows) to exhibit potentials of the regulation of long-range flights during the en-route phase. We implemented a mixed-integer method using a simplified approach for speed advisories considering both stochastic distributions of flight times and specific values for time to gain/ to lose. Our results indicate that the LR-ATFM holds the potential to improve the aviation system performance by mitigating periods of excess demand. In the following research, we will gradually remove the simplified assumptions. In a simulation environment, different operational scenarios will be tested to more precisely quantify the actual influence of regulation by individual speed advisories.

ACKNOWLEDGMENT

The authors would like to thank the research teams in Dresden, Tokyo, and Singapore for supporting our contribution. This research is supported by the Civil Aviation Authority of Singapore and Nanyang Technological University, Singapore under their collaboration in the Air Traffic Management Research Institute. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not reflect the views of the Civil Aviation Authority of Singapore.

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