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# Implementation of a Long-Range Air Traffic Flow Management for the Asia-Pacific Region

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**ABSTRACT** We provide a concept of operations and a corresponding implementation of a long-range air traffic flow management in the Asia-Pacific region. This management will provide an appropriate demand-capacity balancing considering both aircraft sequencing by local arrival management procedures and flow optimization to prevent over-demand in the approach area around the airport. Thus, coordination of long-range international flights demands collaboration between different flight information regions and local regulations. As Singapore Changi Airport is a central element of the Asia-Pacific flow management high share of long-haul air traffic, we use this airport to demonstrate our approach. To derive the operational conditions and actual traffic patterns at the airport, ADS-B messages and flight plan information are processed. The data are cleaned, analyzed, and filtered to provide information about arrival flows within given distances to the airport. We provide an efficacy analysis of the long-range air traffic flow management using two approaches. First, we applied a mixed-integer optimization of time shifts of normal distributed flight times. Here, the regulation of long-range flights by time shifts (e.g., achieved by speed advisories) shows a significant relief from periods of over-demand at the airport approach sector. Second, we implement a reference and a test case scenario in an agent-based simulation environment including the local arrival management procedures. Here, the number of holdings and the associated holding time could be reduced by at least 26%.

**INDEX TERMS** Agent-based simulation, airport performance, flight optimization, flow management, long-range flight regulations.

## 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], [2]. Therefore, flow management ensures that current airport and airspace capacity is used efficiently so that air traffic demand can be met (in a regulated manner) [3]. The demand is driven by scheduled flight plans and operational deviations on the day of operations [4]. These deviations could result from several sources [5], [6], such as system immanent uncertainties (e.g., reactionary delay [7],

[8]), disturbance from external factors (e.g., weather conditions at airports [9] or effects of changing wind conditions during flight [10], [11]), disruptions of flights (e.g., cancellations [12], use of alternate airports [13]), or airspace operations (e.g., reduced sector capacity by activated temporary restricted areas [14]).

Even though aviation takes place in an international and intercontinental transportation network, regional service concepts and providers do not follow a homogeneous ATFM approach. In Europe, for example, the Network Manager (NM) is responsible to provide centralized ATFM related actions and information for airspace users [15]. In contrast to this centralized concept, in the Asia-Pacific (APAC) region we focus on, different approaches exist in a heterogeneous environment. In Japan, for example, the Air Traffic Management Center controls the entire air traffic flow

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in the corresponding Fukuoka Flight Information Region (FIR) [16]. To provide efficient arrival traffic at Tokyo International Airport (RJTT), the most congested airport in Japan, takeoff times are controlled at the departure airports [17]. 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. With a focus on Singapore, the management of air traffic flows in the Singapore FIR is a task of the Singapore Air Traffic Flow Management Unit (ATFMU) [18]. This unit regulates the traffic flows by ATFM measures (e.g., 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 the Aeronautical Information Publication (AIP), Singapore can assign CTOTs to flights departing from 38 different airports in the APAC region (same airports used in Multi-Nodal ATFM, but without Langkawi airport) [18], [19]. In the APAC region, the Long-Range Air Traffic Management (LR-ATFM) concept was tested in 2018 to improve demand capacity management by extending the current time horizon to complement regional ATFM implementations [20].

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 [4]. Collaboration is a key enabler of Air Traffic Management (ATM) since stakeholders could reliably coordinate tasks to monitor and improve aviation system performance in their respective areas of responsibility before decisions are made [21]. This coordination is supported by a system-wide information management [22]. Improved performance is achieved, for example, by shortening taxi times ( $-7\%$ ), decreasing fuel burn ( $-7.7\%$ ), and reducing ATFM delay ( $-10.3\%$ ) [23]. In Europe, the ATM Master Plan within the Single European Sky (SES) initiative [24] 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 [25] 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. FOCUS AND STRUCTURE OF DOCUMENT

In our paper, we develop for the first time a mathematical model for the LR-ATFM approach and implement it in a simulation environment with operational constraints. From this tactical traffic flow management concept, regulation solutions for the long-haul air traffic are derived while optimizing the airport capacity utilization. Since ATFM has already been shown to contribute to flight efficiency, cost-effectiveness, and environmental sustainability of the air transportation sys-

tem, we demonstrate the substantial improvements associated with the LR-ATFM approach. The cost of ATFM-related delays is more than 2 B€ per year in Europe (2019), considering reported ATFM delays with an average delay per flight of 2.18 min (en-route 1.57 min, airport 0.61 min) [26] and delay costs of 100 €/min [27]. Delays can be significantly reduced through improved planning at both the strategic (before the day of operations) and tactical (on the day of operations) ATFM levels. Strategic approaches might reduce the number of delayed flights by 10% [28] and tactical arrival management could reduce delays by 20%-40% [29].

In our conceptual implementation, we focus on Singapore Changi International Airport (WSSS), which is a major hub and key element of air traffic flow management in the Asia-Pacific region. In this heterogeneous, transnational ATFM environment, the overarching management of long-range flights can bring benefits to several stakeholders in the air transportation system. Major traffic flows could be efficiently managed across ATFM regions with a long-range situational awareness (more transparent traffic management), enabled by the early provision of target times over specific waypoints along flight routes. We change the perspective from a location-based trajectory description to a time-based flight progress view. Through an ex-post analysis of the continuously updated aircraft positions of arriving flights, the remaining flight time is determined in correlation to the respective aircraft location. The derived statistical information is then used as input to reschedule time-distributed, long-range flights to mitigate the effect of local congestion in the approach sector of WSSS. In this context, we do not consider rare events (e.g., severe weather conditions or flight diversion), but only regularly observed deviations in daily operations. These deviations are taken into account in our model as statistical variances in arrival times.

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 (Section II). Since we use WSSS as our application domain for the LR-ATFM approach, details about the operating environment are provided in Section III. A deeper data analysis on actual WSSS arrival traffic is given in Section IV. This analysis is based on regular aircraft positions updates and leads to a clustered network for the arrival flows. This network allows transferring aircraft locations into a time-to-fly view, which is input for a mathematical model to optimize the utilization of the approach area at WSSS. In Section V, we develop and implement the LR-ATFM concept and use a demonstration case to show that regulation of long-range flights leads to improved traffic flow and capacity utilization at the airport. Finally, the paper closes with a discussion and conclusions (Section VI).

#### B. LITERATURE REVIEW

Accommodating arrival traffic flow at highly-frequented airports, strategic arrival management is the key to reduce arrival delay time and mitigating traffic congestion around and at

the airport. Current and future ATFM-related research activities will provide the foundation for a further improved air transportation system. Various general principles and operational concepts are used in different areas of the world. The central element for controlling air traffic in Europe is the allocation of departure slots and the definition of CTOT [15], [30]. Traffic management initiatives like ground delay programs or rerouting are used predominantly in the USA [31], [32]. In Asia, there are regional associations of ATFMUs to improve the coordination of traffic flows, such as Multi-Nodal ATFM concept in APAC region [33] or the Northeast Asia Regional ATFM Harmonization Group (NARAHG) [34]. To handle the traffic volumes more efficiently, new concepts for traffic control are necessary, such as trajectory-based operations [35], dynamic demand capacity balancing [36], or improved data transfer between responsible authorities [37].

The flexible use of airspace [38], [39] and high utilization of the runway system [40]–[42] are key elements to ensure efficient use of the (declared) airport capacity, even under different weather constraints [9], [43]. Aircraft arrival processes are mainly distinguished by two parts; flow-based control (management of a group of flights) and time-based tactical control (individual sequencing) [4], [44]. Part of the former is the ATFM, which calculates and issues the take-off time of arrivals at their departure airports to balance traffic demands and airspace/airport capacity per time window (e.g., one hour). The latter is the Arrival Manager (AMAN), which controls time-spacing among arriving aircraft to establish safe management of the synchronized arrival traffic [45], [46]. In this context, the concept of the extended AMAN tries to shift the area of responsibility for the aircraft sequencing from the terminal area to the neighboring en-route airspace [47]. Considering a 500 NM radius around an airport, 20% of delay can be shifted from the Terminal Manoeuvring Area (TMA) airspace around the airport to the aircraft cruise phase and could be efficiently managed by speed adjustments [48]. But, flights should arrive at the terminal area and land at the airport with little or no trajectory adjustments. The positive effect of shifting delays from the vicinity of the airport to the route sections through speed adjustments has already been demonstrated [49], [50]. The advanced prediction of arrival times at predefined waypoints along the flight path and the associated remaining flight times can lead to a further improved capacity utilization [51].

In the past, studies have analyzed the aircraft arrival process at airports using queuing theory, such as scheduling methods for one or multiple runways [52], [53] or the ability of different queue systems to describe arrival flows [54], [55]. 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 [56] and to suggest more appropriate arrival strategies [57], [58].

Furthermore, intentions of airspace users to optimize their en-route and on-ground operations [10], [59], the effect of airspace constraints to the performance of the ATM

system [60], or the impact of free routes on airspace demand [61] are associated research topics.

However, the advantage of dynamic flight planning has been widely researched and recommended because of benefits in fuel flow between 3 % [62] and 8 % [63]. Operators and flight planning tools are continuously implementing a function to dynamically react to changes in the boundary conditions of flight planning [64], [65]. These dynamic adjustments of aircraft routes enable us to appropriately react to actual environmental and traffic conditions [66]. Thereby, the main focus either lays on the uncertainty of the significant parameter for efficient flight planning, which could be wind [67], [68], or on safety issues for the prediction of turbulence cells [69]. Operators could be further assisted in creating, rescheduling, testing, and evaluating dynamic flight plans as implemented in interactive flight plan management and rehearsal systems [70].

The control of air traffic by network interventions can lead to congestion at specific nodes, in particular when (increased) AMAN activities are not taken into consideration [71]. This can be avoided with integrated and balanced consideration of both local arrival and flow management, aiming at a cost reduction by moving delay into a more efficient phase of flight. For this purpose, the authors' past work analyzed characteristics of aircraft arrival traffic considering different time horizons and traffic mix [72]. The concept of adjusting the aircraft speed to reduce congestion is proofed to be an appropriate solution. Thus, speed reductions up to 12% are feasible without additional fuel cost compared to the initially planned cruise speed [73]. When speed adjustments take place, time shifts up to 2-3 minutes per 30 minutes flight time are observed [74]. Aircraft speed could be set between optimal cruise speed and minimum fuel consumption, and speed control may affect the fuel consumption of the aircraft (maximum speed reduction during cruise phase is around the 7% [75]). Thus airline's cost index must be included in delay mitigation strategies [66]. But even in-flight trajectory optimization could already lead to fuel savings of about 0.5%-7% [8] and thus may also improve delay situations if efficiently integrated into ATFM [73]. In holistic airport management, tactical airline prioritization processes for schedule recovery [76] should also be considered as changes to standard aircraft ground handling processes [77].

For the successful implementation of the LR-ATFM concept, several conditions must be met (cf. [78]). For example, it is essential to be able to determine, transmit and implement speed recommendations during the entire 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 [79].

## 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 [5]. In this context, (network) flow management must be separated from (local)

arrival management. The primary task of the arrival management at airports is to establish an aircraft-specific sequence per (active) runway to avoid separation violations and high utilization of the local capacities [44]. In flow management, individual aircraft are grouped into arriving traffic flows and regulated by aggregated measures on larger time scales (e.g., movements per hour) [4]. With a special focus on WSSS, we briefly introduce the concepts of traffic flow management in the following sections.

### A. CROSS-BORDER AIR TRAFFIC FLOW MANAGEMENT

Cross-border ATFM concepts control national and international flights [80]. 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 region) are (see [81]):

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

The basis of an ATFM system is the control of flights that are carried out within the area of responsibility of the coordinating authority [82]. For ATFM to be effective and generate the desired benefits, at least 70%-75% of the flights at an airport should be controllable [33], [80], [82]. Singapore 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 region, 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 region was initiated in 2014 [33]. The basic framework of this trans-regional ATFM program is based on an IATA project with the ANSPs in the APAC region, 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 [19].

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 [4]. As of May 2019, a total of 39 airports and eleven ANSP regions are organized in the Multi-Nodal ATFM [19].

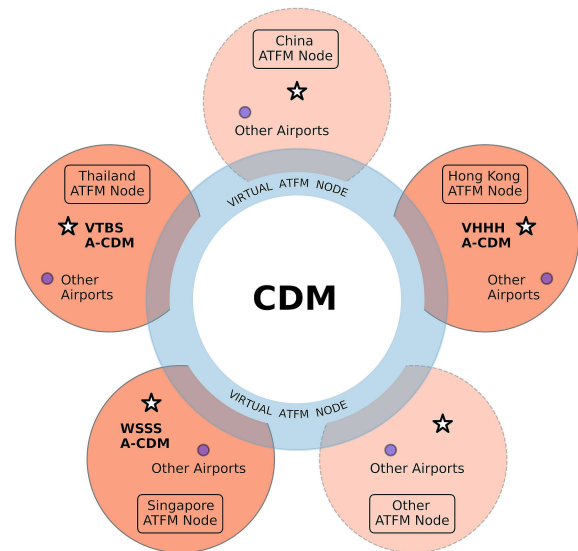


FIGURE 1. Multi-nodal ATFM concept in APAC region [80].

### B. LONG-RANGE AIR TRAFFIC FLOW MANAGEMENT

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. [83]). 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 [20]. 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) over a waypoint at which a flight will be regulated to arrive at the TTO reference point. The LR-ATFM concept is most applicable in the cruise phase from the point where the flight is independent of local operational variations and Air Traffic Control (ATC) interventions, and thus the time estimate for reaching the TTO reference point is most accurate. Fig. 2 depicts the overall concept and steps involved with it.

The workflow of the LR-ATFM consists of the following five steps [20].

- (1) ANSPs and airspace users establish a timeframe before a TTO reference point within which LR-ATFM can be applied. Consideration will be given to the operational environment, accuracy/stability of estimates, communications, and aircraft capability to comply.
- (2) An Estimated Time Over (ETO) at the TTO reference point is established for each flight and a TTO is calculated (inclusive of any ATFM measures).

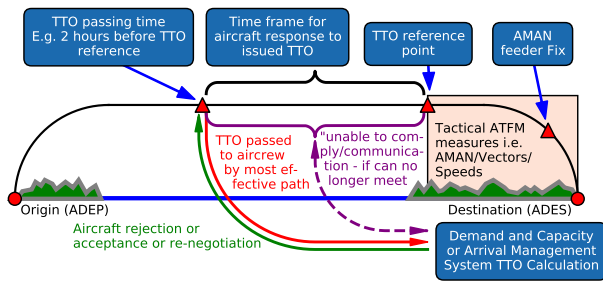


FIGURE 2. General concept of long-range ATFM [20].

- (3) At the TTO passing time (Time at which TTO is issued to the flight), it is transmitted to the aircraft via an agreed communication path.
- (4) The flight crew confirms their ability/inability to comply and notifies the appropriate authority.
- (5) The crew manages the flight to reach the TTO reference point at the TTO 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 reference point and from where onwards ATFMU should regulate the flow. The location of TTO reference point affects the ability of the flight to meet the issued TTO. If flights are unable to comply with issued TTO, the flow might be distorted, and flights might go into holdings. The second problem arises from the questions of how much time can be absorbed by flights depends on where onwards the regulations start. By managing flights farther away from Singapore Changi Airport, flights can reduce or gain more time. Trials in 2017/2018 on selected flights between New Zealand and Singapore show that flights to New Zealand can absorb about 2 to 3 minutes per flight hour, whereas flights to Singapore only achieve one minute per hour [20]. This results from different infrastructural conditions (FIR structure) and the traffic load in the respective regions. A simulation of international arrival flights from westward (East Asia and Southeast Asia) to Tokyo Haneda indicates a possible time shift of up to 8 minutes during the cruise phase due to speed adjustments [74].

### III. OPERATIONAL ENVIRONMENT

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. To model the incoming traffic of WSSS we use data from regular aircraft position updates and flight plan data from the airport. 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. SINGAPORE CHANGI AIRPORT ENVIRONMENT

Singapore Changi Airport (WSSS) is one important aviation hub of Southeast Asia and one of the largest airports in the

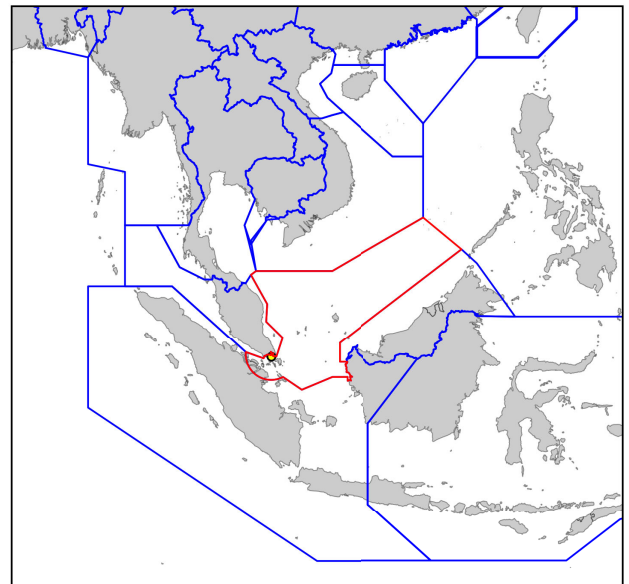


FIGURE 3. Flight information region of Singapore Changi Airport (red area) and adjacent regions [87].

world with over 380,000 aircraft movements and 68 million passengers in 2019 [84]. More than 100 airlines are operating at the airport and connect Singapore to over 300 cities worldwide in more than 80 different countries [85]. Due to its central geographical location, the airport serves as a transfer airport for travel from Australia to Europe and vice versa (Kangaroo route) [86]. Additional flights to North America, Africa, and the Middle East result in a high proportion of long-haul flights at WSSS. There are three parallel runways, with 02R/20L still under construction. Both runways are equipped for precision approaches and are operated 24 hours a day [18]. Between 0:00 and 15:00 UTC a parallel use is possible. Fig. 3 emphasizes the central location of WSSS in the APAC region.

Regional flights from the APAC region to WSSS are controlled by the Multi-Nodal ATFM concept [88]. Using LR-ATFM and related concepts, long-haul flights can be integrated pre-tactically into the approach sequence generation. This results in fewer flight distances in the Singapore FIR and fewer holdings. Effective classical ATFM approaches must be able to affect at least 70-75% of flights [33], [80]. For WSSS, this relates to flights within a 2,400 NM radius [33]. In this case, delay can be significantly reduced for both controlled flights and flights exempt from ATFM measures. When applying LR-ATFM, it is even possible to integrate flights outside the APAC region into the air traffic flow management.

The flight times of important routes to WSSS from North-East Asia, the Middle East, Europe, North America, and Australia are at least 3 hours. These routes nearly cover one-third of the inbound traffic flow with a high potential for network regulations to efficiently manage the air traffic system. Fig. 4

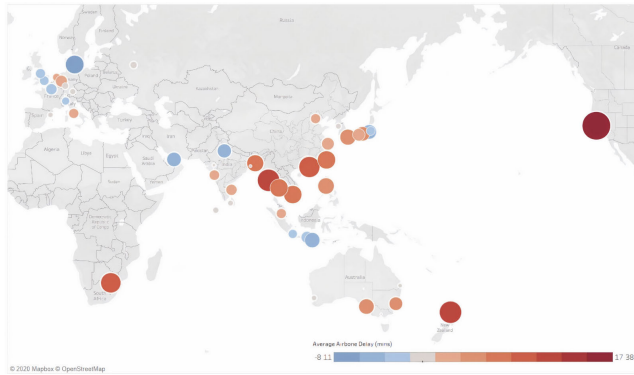


FIGURE 4. Airborne delay of flights connected to WSSS [89].

depicts the delay situation of flights connected to WSSS [89]. Due to the large forecast period and in addition to active regulation of short- and medium-haul flights, the impact of delayed long-haul flights can be sustainably mitigated by appropriate management strategies.

### B. AIRCRAFT POSITION UPDATES AND FLIGHT SCHEDULES

Today, air traffic surveillance is provided by primary and secondary surveillance radars (PSRs, SSRs), including Mode-S [90], to provide a comprehensive situational awareness to air traffic management systems. These systems are augmented with information updates provided by aircraft (e.g., Automatic Dependent Surveillance – Broadcast (ADS-B) messages). For example, The Mode-S transponders transmit aircraft position and status (e.g., ground speed, rate of climb/descent, heading) on the 1090-MHz SSR-Mode-S downlink frequency (ADS-B Out) [91], and signals can be received up to a distance of 400 km. In this context, aircraft determine their positions via satellite, inertial, and radio navigation. Flights increasingly need to be equipped with Mode-S transponders [92]–[94]. Because of its simple receiver requirements, ADS-B has contributed significantly to the development of online services, such as OpenSky Network (opensky-network.org), Flightradar24 (flightradar24.com), or FlightAware (flightaware.com). Through these organized networks of receivers, current air traffic can be displayed worldwide (depending on the local coverage) in real-time. An example of the structure and content of a crowdsourced dataset is provided by the OpenSky Network [95]. ADS-B also allows monitoring remote areas and flights over the oceans with space-based solutions [96]. The data sent by aircraft could be used to monitor, evaluate, and predict airspace utilization and airport performance. Besides, this data would enable a new area for cooperative management by creating a deeper situational awareness for local and network-wide operations. In our LR-ATFM approach, we consider the following data from the ADS-B messages.

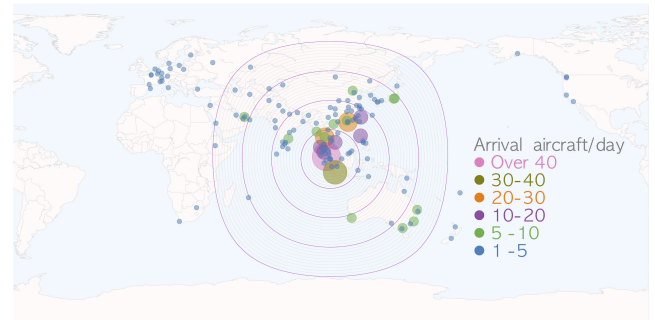


FIGURE 5. Departure airport distribution and average flight numbers in a day with concentric circles (1000 NM) in a less than 4000 NM radius.

- 1) time reference: timestamps of received messages (set from the receiver)
- 2) aircraft identity: transponder code and aircraft call sign
- 3) aircraft position: latitude, longitude, and altitude

Information on the flight connections (origins and destinations), arrival/departure times, and delays are extracted from flight schedule data. The data were linked by flight times and aircraft callsign. In addition, airport locations were derived from aeronautical information publications. The resulting great circle distance between airports was used to categorize the type of connections (e.g., long-range flights).

Since not every aircraft was equipped with an ADS-B transponder in 2019 (or does not always have it activated), not all active inbound flights are included in our dataset. A data validity check further reduces the number of flights available for the following analysis. Consequently, the assumptions made and as well as the determined values for capacities and demand refer to a limited data set. Therefore, we expect that our analyses tend to underestimate the actual arrival capacity values (conservative estimate). Of the 96,097 inbound flights to Singapore Changi Airport (from April 02 to October 27, 2019) contained in the initial data set, 13,551 flights are rejected due to poor data quality (e.g., missing information or inconsistent timestamps). The final, filtered dataset contains more than 24 million data points describing a total of 82,546 inbound flights (May 2019 is the busiest month with 13,459 recorded flights).

### C. ANALYSIS OF FLIGHT POSITION DATA AND FLIGHT PLANS

Flights arriving at WSSS start from several global destinations. Fig. 5 provides a brief overview of the locations and the connections, based on the dataset (April 02 to October 27, 2019).

The shares of traffic with regards to the actual flight times are shown in Fig. 6. More than 50% of the flights possess a flight time longer than 3 hours. The ANSPs of Singapore and New Zealand (CAAS and Airways New Zealand) define flights with a total distance of over 2.200 NM as long-haul flights [20]. Within our dataset, this definition corresponds to about 25% of the total flights.

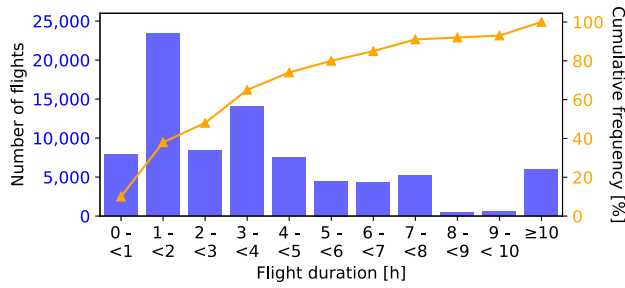


FIGURE 6. Histogram of distances from flights to Singapore airport.

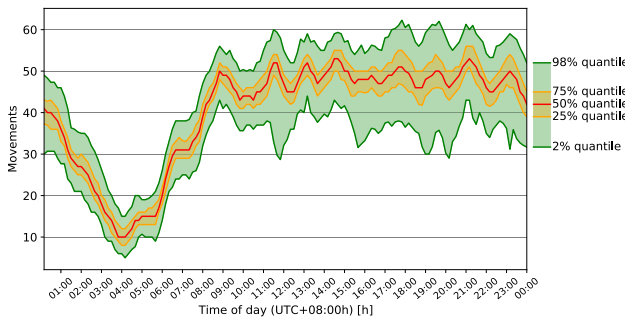


FIGURE 7. Statistics of arrival flows into WSSS (Apr.-Oct. 2019).

The performance of the airspace/airport system is driven by the available capacity and traffic flow. Due to limited capacity, an increasing number of aircraft movements also leads to an increased probability of mutual interference between flights. This probability also increases the more the existing capacities are utilized. As a result, the required traffic management leads to delays in arrivals and departures. 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. Since we are providing an approach for LR-ATFM, the derived regulations focus on the appropriate use of the approach sector capacity. Inside the approach sector, the local arrival management will ensure efficient aircraft sequencing. 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. 7 shows the number of flights between April 02 and October 27, 2019, as a function of time of day (rolling hour of the different time quantiles). From 6:00 am onwards, the number of aircraft movements increases significantly. In the first half of the day (until about 11:00) the continuous capacity is not exceeded and in the night hours, the utilization of WSSS is the lowest.

Both time intervals are not relevant for the application of LR-ATFM, since only a few long-haul flights are operated during these periods. In the second half of the day, the number

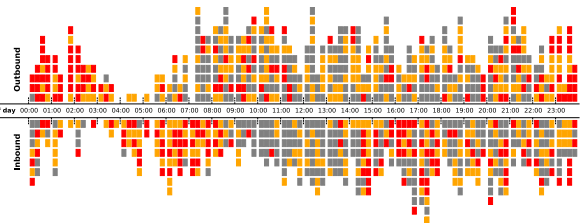


FIGURE 8. Inbound and outbound flows during a typical day at WSSS. Short-haul flights ( $\leq 1,000$  NM) are grey, long-haul flights ( $> 2,200$  NM) are red, and medium-haul flights (in between) are marked orange.

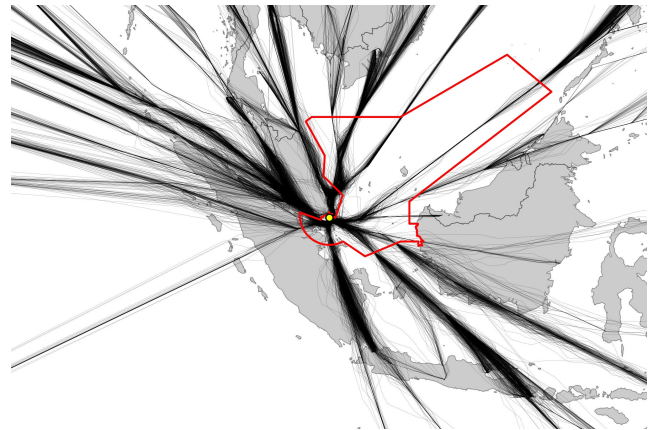


FIGURE 9. Pattern of arrival flows at WSSS.

of movements fluctuates at a high level and regular traffic peaks can be identified.

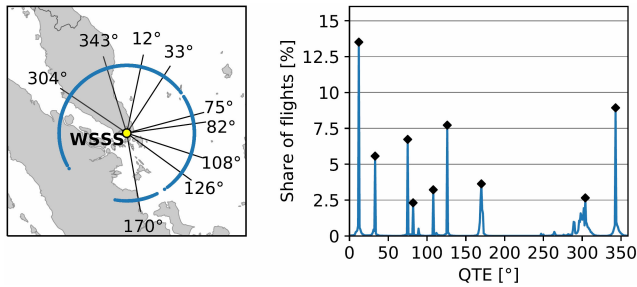
#### IV. ARRIVAL FLOW CLUSTERS AND NETWORK

The WSSS inbound and outbound traffic flows during an exemplary day are exhibited at Fig. 8. Here, every pile of blocks represents the traffic flow in a 15 minute time window and it consists of a specific block, which represents a single aircraft movement. These movements are divided into short-haul ( $\leq 1,000$  NM; grey), medium-haul ( $> 1,000$  NM and  $\leq 2,200$  NM; orange), and long-haul flights ( $> 2,200$  NM; red).

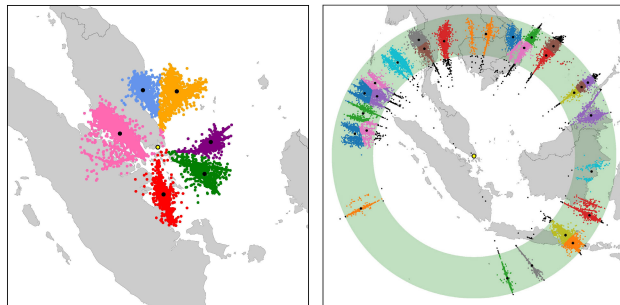
The inbound and outbound flows are separated to emphasize the typical time shifts between arrivals and departures at hub airports. In particular, two time frames with a high number of long-haul inbound flows (early morning and late afternoon) are of interest in the context of LR-ATFM.

As Fig. 9 emphasizes, the flights arrive from nearly all directions and regions of the world. Considering the airspace structures around WSSS, the corresponding traffic flows are gradually merged as the distance to the airport decreases.

Figure Fig. 10 illustrates the corresponding bearings of the arriving traffic flows near WSSS. We chose the TTO reference point defined in the LR-ATFM concept (see Fig. 2) as the separation between ATFM and local AMAN. To identify this point, we have analyzed the actual aircraft trajectories toward the Top of Descent (TOD) and find a distance of 170 NM to the airport to be appropriate, where most flights are about to begin their descent. 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. We derive



**FIGURE 10.** Bearing of arrival flows into WSSS measured at a distance of 170 NM out (TTO reference point, transition from LR-ATFM to Arrival Management).



**FIGURE 11.** Arrival flows into WSSS considering aircraft positions at 30 minutes (left) and 2h before landing at WSSS (right). The green area covers 98% of the observed flights.

a histogram from the directions with  $1^\circ$  steps and identify nine major arrival directions, marked in Fig. 10 with black lines (left) and black dots (right).

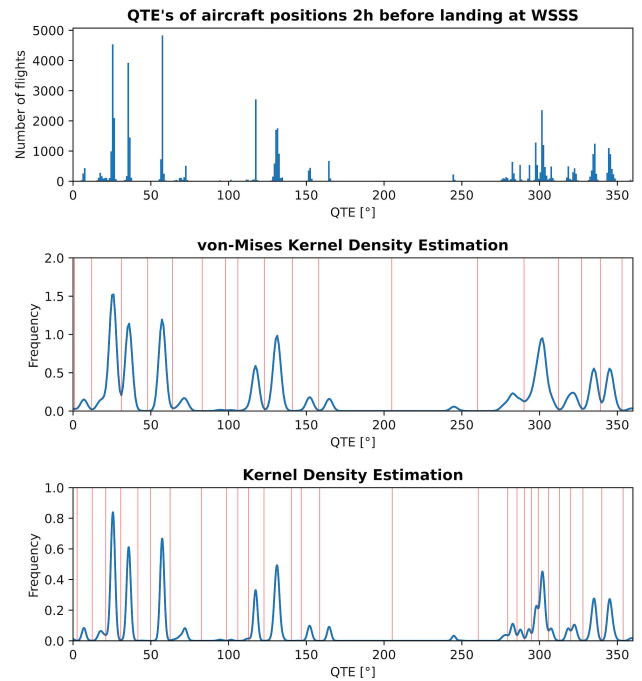
At this stage, we assume aircraft movements as being a significant traffic flow, when the share of flights is higher than 2%. Approximately 40% of the inbound traffic enters the WSSS approach sector from the north, 24% from east and west, and 12% reaches the sector from the south. Eastbound flows ( $75^\circ$ - $126^\circ$ ) consist of four aggregated arrival flows, whereas westbound flows ( $304^\circ$ ) are divided into a multitude of minor flows.

When aircraft start descending in the vicinity of the airport, the arrival flows are step-wise merged by the local arrival management for the final sequence at the corresponding runway. By displaying the arrivals in a time-based manner (time to land), different clusters can be separated from each other. Fig. 11 (left) exhibits the aggregated arrival flows using k-Means clustering [97] with 6 clusters for aircraft positions 30 minutes before landing at WSSS. Fig. 11 (right) shows the 51,163 aircraft positions 2h before landing at WSSS. The green area covers 98% of the flights, excluding outliers from the statistical analysis.

With an increasing distance to the airport, the clusters form a circular structure and the initial k-means approach fails to separate the flows.

### A. KERNEL DENSITY ESTIMATION

Due to the circular structure, we derived a 1-D representation of the observed frequency over the bearing angle (Fig. 12, top). Instead of using a histogram analysis for the probability



**FIGURE 12.** Overview from QTE's of flights 2h before landing at WSSS: histogram (top), KDE width von Mises kernel (center), and width Gaussian kernel (below).

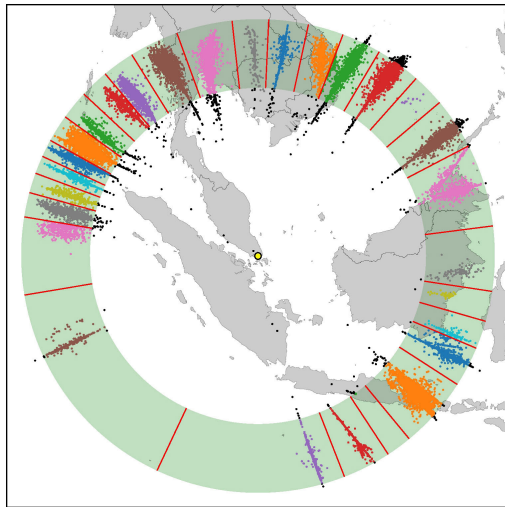
distribution, we implemented a Kernel Density Estimation (KDE), to prevent an inappropriate shift of bins and provide a uniformly consistent and continuous estimator. KDE is a non-parametric estimator of density. A solution for density estimation for circular data is also the use of the von-Mises distribution [98]. Here the data are coupled over the circular borders (angle  $> 360^\circ$  and  $< 0^\circ$ ) and no additional handling of these borders is needed. Unfortunately, this kernel does not fit the data, since this approach is not able to resolve the differently dense flows in detail. Especially in the area around  $300^\circ$  too many flows are grouped (Fig. 12, center).

Thus, we implemented a KDE considering a Gaussian kernel with periodic boundary conditions for the QTE, to properly account for the transition between  $0^\circ$  and  $360^\circ$ . Fig. 12 (below) shows the result achieved with this kernel approach using bandwidth for the Gaussian kernel of  $1.26^\circ$ . Using the convoluted distribution, we search for local minima (red lines) by a comparison of neighboring values.

This parameter setting results in a good differentiation between the arrival flows as highlighted in Fig. 13. The highly dense flows at  $300^\circ$  are separated appropriately, but at  $90^\circ$  a flow was identified with only a minor number of movements.

### B. ANALYSIS OF CLUSTERS

In Fig. 14 we compare two example clusters from 2 hours before landing at WSSS. These clusters are located in different directions to Singapore Airport. One cluster is located in the northern direction ( $36^\circ$ ) and the other cluster is located in the western direction ( $293^\circ$ ). To allow for an appropriate comparison of the along- and crosstrack distribution of aircraft



**FIGURE 13.** 28 Clusters from KDE for 2h aircraft positions before landing at WSSS.

positions, we normalized/rotated the orientation for both clusters. Thus, both clusters in Fig. 14 are now pointing consistently in the easterly direction ( $90^\circ$ ).

The cluster located in the northern direction ( $36^\circ$ ) contains 5,745 positions (top). The cluster located in the western direction ( $293^\circ$ ) includes 656 positions (bottom). Both clusters exhibit a higher deviation for the longitude component than for the latitude value. Due to the order of magnitude higher number of data points, there are significantly more outliers in the northern cluster than in the western cluster, but the density distributions of cross-track deviations show similar trajectories. These distributions of aircraft positions and the resulting flight times to WSSS are used as input variables for the following optimization. According to the crosstrack and alongtrack distributions, the traffic flows follow a straight route with small variances. However, depending on the route structure (e.g., merging of flows from different directions), these distributions can also have very particular features.

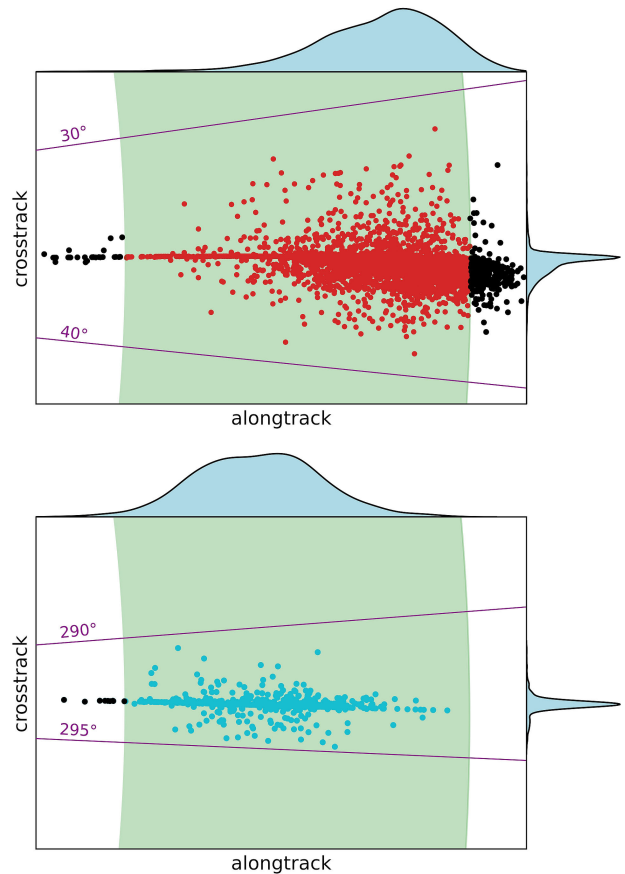
At this point, we want to focus on the distinction between temporal and spatial distances. Thus, the aircraft positions in Fig. 14 (top) are further away from WSSS airport than the positions in Fig. 14 (bottom). This may be caused by external factors (e.g., weather) or inefficient routing over certain areas (e.g., flying around military airspace).

Fig. 15 shows a histogram of the remaining distance to WSSS from 7,961 aircraft positions 2h before landing in the cluster at  $26^\circ$  (northern direction, green dots in Fig. 13). Based on these distances the average value ( $\mu$ ) and variance ( $\sigma^2$ ) are determined, which characterize the corresponding normal distribution (red line).

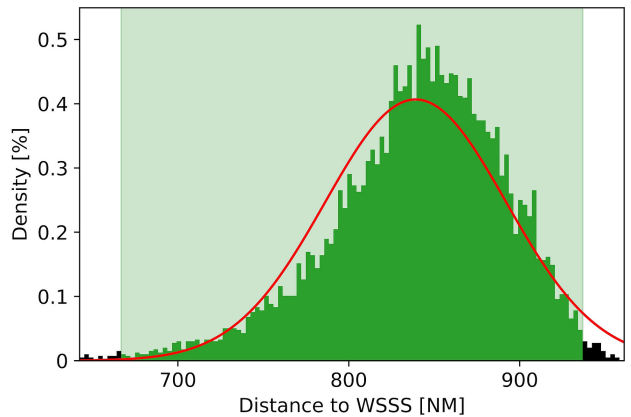
Since LR-ATFM is a time-related concept, the distance parameters  $\mu$  and  $\sigma^2$  need to be converted using the speed of the aircraft.

**C. NETWORK ANALYSIS**

In Section IV-A, KDE is applied for clustering of flight positions concerning the flight hours remaining before landing

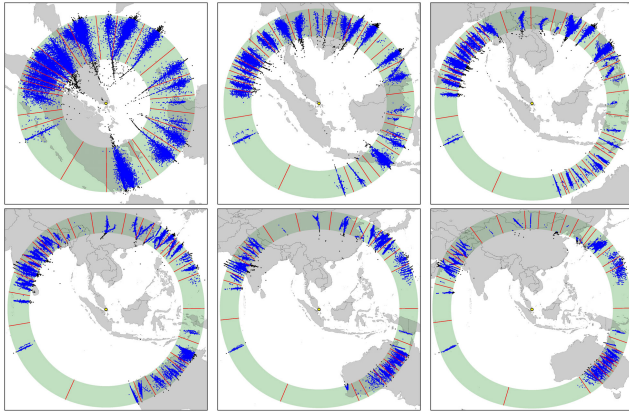


**FIGURE 14.** Distribution of aircraft positions 2 hours before landing at WSSS, taking cluster at  $36^\circ$  (top) and  $293^\circ$  (bottom) as an example. The clusters are both uniformly rotated in the easterly direction ( $90^\circ$ ) for better comparison.

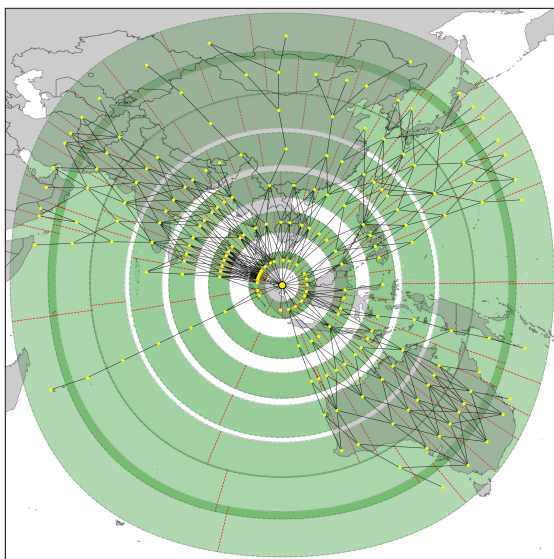


**FIGURE 15.** Histogram (blue and black boxes) and normal distribution (red line) of remaining distance to WSSS from 2h aircraft positions before landing (using cluster at  $26^\circ$ ).

at WSSS. The corresponding aircraft positions and resulting clusters for 6 hours up to 1 hour before landing are shown in Fig. 16.



**FIGURE 16.** Clustering results for 1h (top left), 2h (top), 3h (top right), 4h (bottom left), 5h (bottom), and 6h (bottom right).



**FIGURE 17.** Network of clustered positions and deviation of positions with hourly-based distance circles around WSSS. 7h radius is used to cover Japan and Australia.

A simplified network of the arrival flow can be derived from the cluster centers (mean position of an hourly differentiation). This network is shown in Fig. 17. Here, each circular area represents a flight time from 7 to 1 hour before landing at WSSS, with inner and outer boundaries defined by the 1% and 99% quantiles of the assigned positions.

More specifically, the 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. Three main traffic directions to WSSS airport can be derived from this time-based network. From the northwest, traffic flows from Europe are connected to those from the Middle East and India. From the northeast, flights from Northeast Asia and North America arrive at WSSS Airport. From the southeast, flights arrive from Australia and New Zealand. Information derived from aircraft positions



**FIGURE 18.** Isochrone with flight time of 7 hours to Singapore airport (green = data available, red = interpolation).

and time-to-fly are joined to provide an aggregated view of isochrone-flows to WSSS. 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. 18, where the color-coded (green to red) line represents the average position of the isochrone with a flight time of 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. 17.

As an example, Fig. 19 depicts the deviation of aircraft locations per average flight time of the corresponding circle (see Fig. 17). 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. 19. 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.

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. 20. 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.

## V. DEVELOPMENT AND IMPLEMENTATION OF THE LR-ATFM CONCEPT

To demonstrate the potential of the LR-ATFM concept, we have implemented two approaches: (a) a mathematical

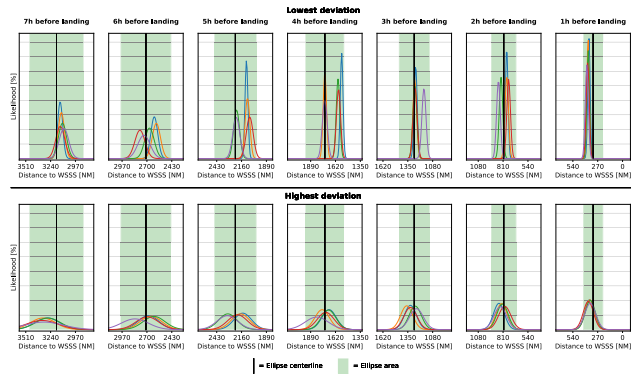


FIGURE 19. Distance related deviations in the hourly-based circles around WSSS.

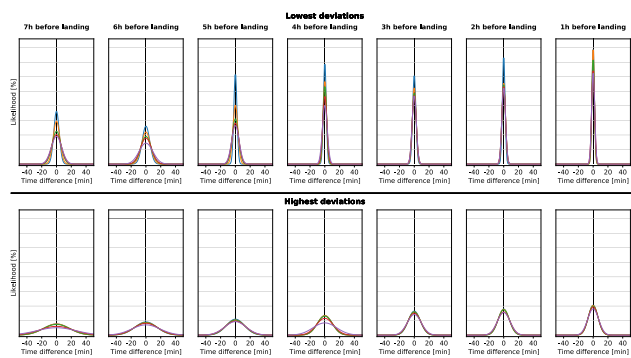


FIGURE 20. Time related deviations in the hourly-based circles around WSSS.

model to provide optimal solutions for the regulation of long-haul flights and (b) the setup of a one-day traffic scenario considering the WSSS airspace structure in an agent-based simulation environment (AirTop).

### A. OPTIMAL SHIFT OF FLIGHTS

In the following, we are using the results of the prior clustering to provide the input for the LR-ATFM approach. Therefore the TTO reference point (170 NM radius around WSSS as the entry point into the approach sector) is relevant. At this point ends the influence of the LR-ATFM and other ATC regulations take place (e.g., AMAN). After passing the TTO reference point, the flight remains in this approach area until it lands at WSSS. During this dwell time, the limited airspace capacity at WSSS approach area is utilized more with each new flight.

LR-ATFM aims to control the entry times of long-haul flights into the approach sector assuming the opportunities of aircraft to change track and speed and so the flight time left before entering. To receive better accuracy a fine-grained capacity breakdown is applied, which considers 10-minute time windows for capacity between 7:30h and 0:10h before arriving at the approach sector. Our concept considers regular points of decisions, where the remaining flight times will be predicted (based on actual positions of long-haul flights) and

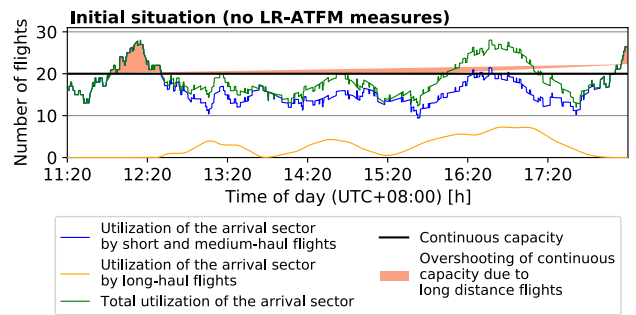


FIGURE 21. Characteristics of the expected arrival flows in the approach sector of the WSSS as of 11:20.

is used as input for regulations, through required times for being at TTO. These decision points may be also triggered during operations, if boundary conditions change significantly (e.g., diverted flights or forecast of severe weather at the airport (reduced capacity)).

In our first attempt, we derived the time to fly from the actual aircraft positions, which are mapped to the generated arrival network. For each flight, we get a normal distribution defined by a mean value ( $\mu$ ) and a standard deviation ( $\sigma$ ) for the time to fly. These temporal distributions of the arrival times result in a specific capacity-demand situation at the arrival sector and serve as input for the optimization of the capacity situation in the approach sector within the LR-ATFM concept. At this stage, we explicitly address the only approach sector capacity and exclude the downstream arrival management. This particular aspect is not considered until the agent-based simulation in the next section (Section V-B).

An exemplary view of the expected capacity situation at WSSS approach sector is given in Fig. 21. We used April 19, 2019, as the reference day of operations, because this day contains the highest amount of long-haul flights and arrivals in general. The exemplary view of the capacity situation at 11:20 emphasizes three arrival peaks driven by the arrival of long-range flights. In particular, the expected high utilization of the total approach capacity between 16:00 and 17:30 is caused by the fact that long-haul traffic flows coincide with short-haul/medium-haul traffic flows.

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 (maximum number of movements to be planned in a period) 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 (e.g., route, track, level, speed), we assume that on average each flight could be accelerated or decelerated by an appropriate amount of time from  $\pm 1$  minute

to  $\pm 6$  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.

To solve the optimization problem of an efficient shift of flights (distributions), we set up a linear integer program to derive an optimal ATFM regulation for long-haul flights using time restrictions. We additionally consider WSSS approach capacity and expected demand. The objective function will minimize the integral of over-demand over time.

### 1) OPTIMIZATION MODEL

The principle to regulate long-range flights belongs to the category of the well-known Resource Leveling Problem (RLP). In the general RLP problem, there is a capacity level for each interval of time, and the capacity utilization must be below this level. Activities can be shifted in their respective time slots to reduce congestion. The problem can be formulated as follows.

Sets:

- $N$  set of all flights  $\{1, 2, \dots, n\}$ .
- $T$  Set of the time period  $\{1, 2, \dots, t\}$ .

Parameters:

- $O_t$  constant occupied capacity in time by short haul flights  $t$ .
- $C$  capacity level for arrival flights.
- $DW$  dwell time in the approach sector  $i$ .
- $CDF(i, \mu, \sigma^2)$  cumulative density function of normal distribution for point  $i$  with mean value  $\mu$  and variance  $\sigma^2$ .
- $\mu_n^{Max}$  maximum of allowed mean value for flight  $n$  (depending on the scenario).
- $\mu_n^{Min}$  minimum of allowed mean value for flight  $n$  (depending on the scenario).
- $M$  big M parameter.

Variables:

- $\mu_n$  mean value of flight  $n$ .
- $z_t$  binary variable – equal to 1 if aggregated probability is above capacity line in time  $a$  is assigned to stand  $k$  and aircraft  $b$  to stand  $l$ , and 0 otherwise.

$$\min \sum_{t=0}^{t=N_n-1} \left[ \frac{x_{t+1} + x_t}{2} \right] z_t z_{t+1} \quad (1)$$

S.t.

$$x_t \geq \sum_{n \in N} \left[ CDF(t, \mu_n, \sigma_n^2) - CDF(t - DW, \mu_n, \sigma_n^2) \right] + O_t \quad \forall t \in T \quad (2)$$

$$x_t - C \leq M z_t \quad \forall t \in T \quad (3)$$

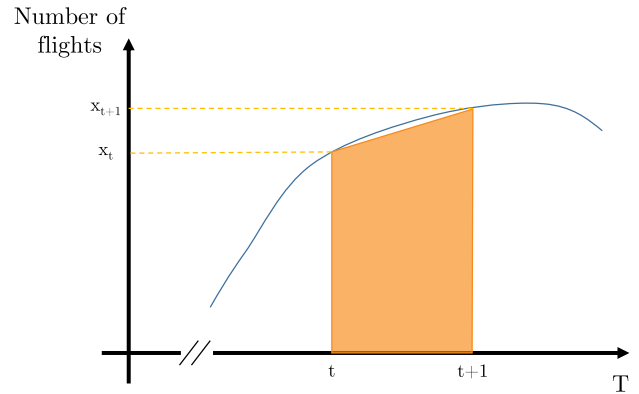


FIGURE 22. Trapezoidal calculation of the penalty area in Eq. 1.

$$C - x_t \leq M (1 - z_t) \quad \forall t \in T \quad (4)$$

$$\mu_n \geq \mu_n^{Min} \quad \forall n \in N \quad (5)$$

$$\mu_n \leq \mu_n^{Max} \quad \forall n \in N \quad (6)$$

$$x_t \geq 0, z \in \{0, 1\} \quad \forall t \in T \quad (7)$$

The objective function (1) aims to minimize the total penalty cost caused by the violation, more specifically the area between the aggregated long-ranged flights and the capacity line (orange area in Fig. 21) the area is calculated using trapezoidal area calculation since the time interval is considered short, the error is negligible (see Fig. 22). Constraint (2) determines the maximum number of flights in ATFM. It is calculated by each flight's cumulative density function at time  $t$  minus the cumulative density function of that flight in time  $t - DW$ . Since the calculation of the penalty cost is based upon only positive deviations (above the capacity line), Constraints (3) and (4) determine if the binary variable  $z$  should be considered or not. Limitation constraints (5) and (6) ensure that each mean value does not deviate from the allowed mean value in both directions (left and right). Constraint (7) states that the number of flights cannot be negative.

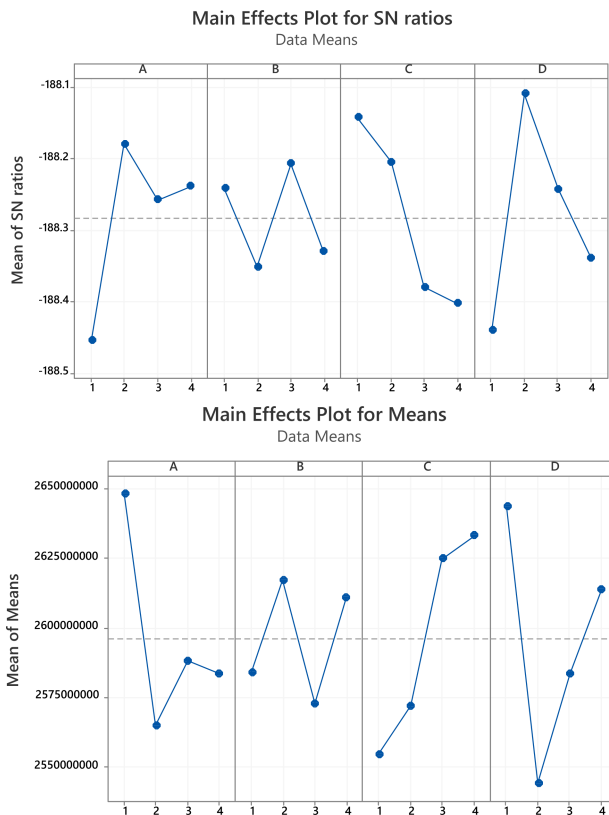
### 2) RESULTS

Since the proposed model is non-linear and belongs to NP-hard class, a Simulated Annealing (SA) algorithm is used to optimize the problem. A Taguchi experimental design [99] is used for parameter tuning of the SA approach to finding the best level for each parameter in the SA algorithm. Thus, after finding the best-performed parameters by solving test problems with different problem sizes, four different levels for each parameter are defined and the most appropriate level for each parameter is selected by analysis of experiments in Minitab<sup>®</sup> statistical software. The parameters for SA algorithm are (A) main iteration of the algorithm (Iter<sub>1</sub>), (B) inner iteration (Iter<sub>2</sub>), (C) initial temperature (T), and (D) reduction factor of the temperature after each iteration ( $\alpha$ ).

**TABLE 1.** Different levels of initial parameters to run SA algorithm.

Row	Parameters	Levels			
		Low (1)	Medium-low (2)	Medium-high (3)	High (4)
A	Iter <sub>1</sub>	30*	50	70	100
B	Iter <sub>2</sub>	10	20*	30	40
C	T	5	10	20	30*
D	$\alpha$	0.80*	0.90	0.95	0.98

\* Chosen level for the corresponding parameter.

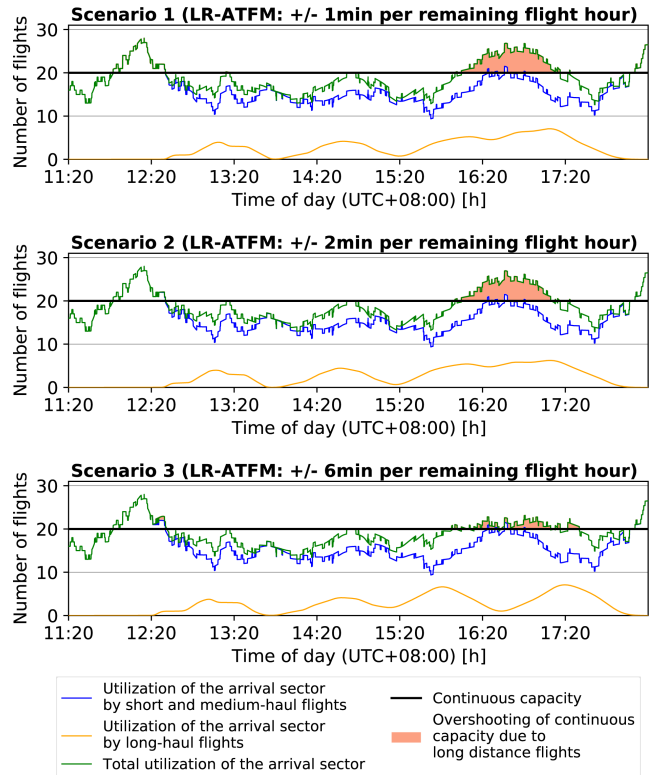


**FIGURE 23.** Parameter tuning for SA algorithm.

Table 1 emphasizes the results for parameter choice, consists of different levels of the specific parameters (applied to the scenario, where we assume a shift of 3 minutes per remaining flight hour). To select the appropriate level for each parameter the mean of means and the mean of signal-to-noise ratios are used as evaluation criteria. Generally, the signal-to-noise ratio is applied to determine parameter settings that reduce variability, followed by an identification of parameters that move the mean to the target with only minor effects on the signal-to-noise ratio (cf. [99]).

Fig. 23 exhibits the result of the parameter tuning process in detail. The appropriate parameter level is indicated by a low value for the signal-to-noise ratio and a high value for the mean value.

These parameters will now be used for the optimization of the associated scenario. The optimization model was

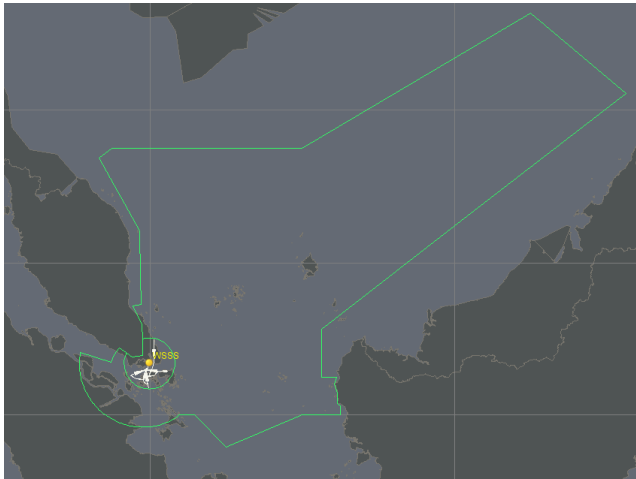


**FIGURE 24.** Arrival peaks at WSSS and optimized regulation of long-range flights by individual speed advisories of stochastically distributed flight times.

implemented in Matlab 2018b environment and runs on a Windows 10-64bit system with 24-kernels and 32 GB RAM.

Fig. 24 shows the influence of long-range flight regulations at an example time (11:20 o'clock). 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 amounts of time shifts in the LR-ATFM concept leads to a less severe phase of excessive arrival demand. A shift of  $\pm 1$  minute per remaining flight hour results in a reduction of 14% of the value of the objective function (integral of over demand), shifting flights by  $\pm 2$  and  $\pm 6$  minutes reduces this value by 20% and 80% in comparison to the original scenario, respectively (cf. Fig. 24). The  $\pm 1$  minute shift is comparable to moderate speed control for arriving flights, which has already been shown to be operationally feasible during flight tests [20]. We expect that changes with more than 3 minutes per flight hour will be associated with more complex trajectory management (e.g., re-routing).



**FIGURE 25.** Volume of airspace where Singapore provides ATS, modeled in the AirTop simulation environment.

### B. AGENT-BASED SIMULATION OF ARRIVAL MANAGEMENT

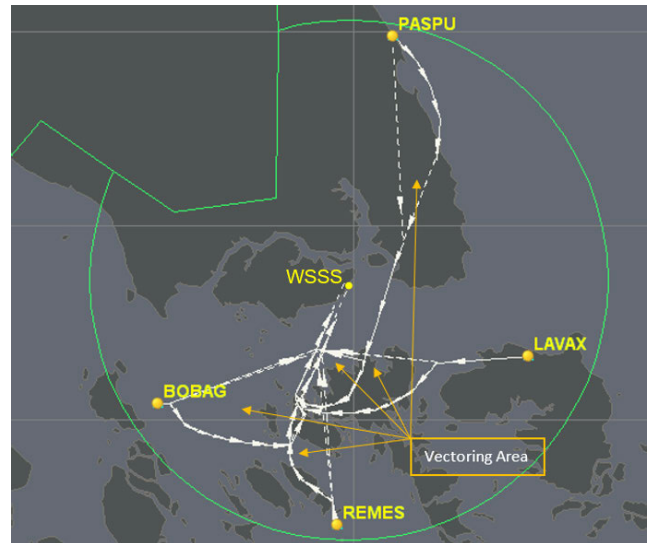
Using the optimization approach previously applied, we identified the general potential to manage the expected over-demand in the approach area by introducing new arrival times for long-haul flights. By using an agent-based simulation environment (AirTop), we will demonstrate in the next step that the local arrival management can operationally handle these additional constraints from the LR-ATFM concept. Thus, we created a simulation setup that replicates the real-time arrival traffic at WSSS which also will be used as a reference implementation to check new approaches and procedures to improve arrival management.

#### 1) SIMULATION SETUP

AirTop is used to carry out simulations of airspace and airport operations and could be also used to assess air traffic and airport complexity, measure controller workload, or improve airspace and airport capacity. In the context of LR-ATFM, the simulation setup covers the vectoring area, runway operations, and runway arrival management for sequencing the inbound traffic. The AirTop simulation environment includes a runway arrival management system to ensure appropriate flight performance and valid aircraft sequencing.

The volume of airspace where Singapore provides Air Traffic Services (ATS) was created based on the Singapore Aeronautical Information Package 2020, section ENR 2 [18]. Fig. 25 exhibits this airspace volume. The inner circle around the airport represents the arrival sequencing and metering area (ASMA, cf. [100]) with a radius of 40 NM around WSSS, where a minimum lateral separation of 3NM is applied, similar to the minimum lateral separation used in the approach area as indicated in Singapore Aeronautical Information Publication (AIP).

Singapore Changi Airport has two runways for the arrival and departure of commercial aircraft, runways 02L/20R and 02C/20C. The airport makes use of these independent parallel



**FIGURE 26.** Vectoring areas for each entry gate in the ASMA around the Singapore Changi Airport (radius of 40 NM).

runways based on wind direction during North Wind Operations, runway 02L is mainly used for arrivals and runway 02C for departures; during South Wind Operations runway 20R is used for arrivals and runway 20C for departures. In both cases, runways could be used for arrivals and departures simultaneously based on traffic needs and intensity. In the simulation, we used R02L and R02C for arrivals. Departure movements are not included in the simulation. The vectoring area for runways 02L/02C is created based on the observed aircraft movements derived from ADS-B messages. Fig. 26 shows the final implementation of vectoring area created for runways 02L/02C.

For each flight, the earliest and latest touchdown times are calculated based on the shortest and longest path to the runway. The actual touchdown time is calculated by adding the planned touchdown time and the time needed to maintain the required arrival separation. Furthermore, the arrival sequence is checked whether the vectoring area is sufficient or not to maintain the separation standards between two consecutive touchdowns. If the vectoring area does not provide enough space to stretch the arrival paths, then the arrival management uses holding areas. To enable an appropriate evaluation of the LR-ATFM concept, we first implement the selected reference date (April 19, 2019) in a baseline scenario. The results obtained with this then serve as a reference for the test case scenario in which we can control the incoming long-haul flights by accelerating/decelerating (to a limited extent). To show the benefits of the LR-ATFM approach, we measure the number of flights sent to holdings and the time spent in the holdings. These two values are good indicators of congestion in the approach sector.

#### a: BASELINE SCENARIO

We simulated the whole day of operations but only consider the inbound traffic. Arrival flights were simulated from their departure at the origin airport to WSSS (landing on

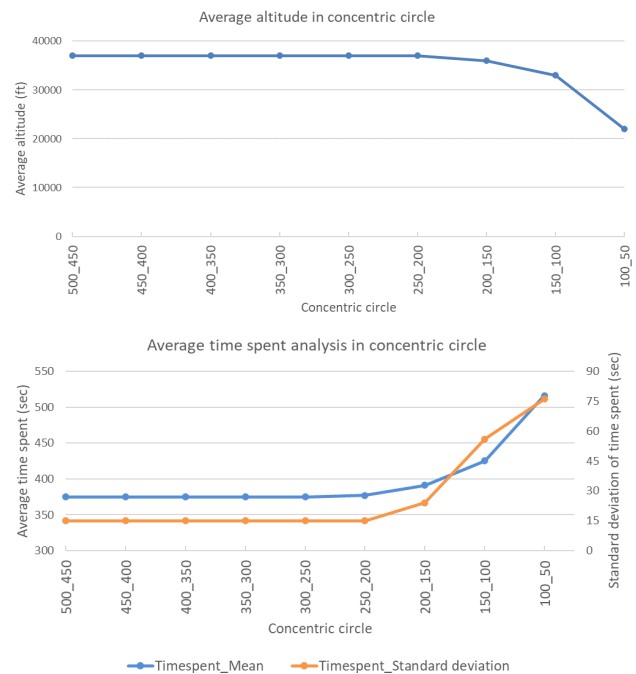
the runway). The routes for all flights are provided by Civil Aviation Authority of Singapore (CAAS) together with flight plan information such as Estimated Time of Departure (ETD), Estimated Time of Arrival (ETA), ETO at waypoints within and close to Singapore FIR. The simulation environment allows defining separation required between two arrivals, which is used as a decision variable. We performed a simulation with 3 NM as the separation requirement between two arrivals. Arrival flights were added to the sequence at 220 NM, based on the arrival sequencing. The runway arrival management calculates the touchdown times by considering the separation needed between two arrivals.

If flights have to be separated, the arrival management checks whether the vectoring area is sufficient for this purpose. If the vectoring area is not sufficient, holding patterns must be used. An example: Flight A must generate a time shift of 6 minutes to ensure the required separation in the arrival sequence. Arrival management checks to what extent the vectoring area is sufficient for this and whether additional measures are necessary. If only 3 minutes of time-shift are possible through the vectoring area, the remaining 3 minutes must be realized in the holding area. In real-time operation, each holding has a typical duration of about 5 minutes (a racetrack pattern). Regardless of the duration, each use of holdings is counted and reported together with the total duration as evaluation metrics (see Table 2). Each flight had different Requested Flight Level (RFL) along the route. For simplification purposes, we used only one RFL for the entire route for each flight. The RFL that was most commonly used based on the ADS-B data observations was chosen. We further assume that there are no speed restrictions along flight paths.

*b: TEST CASE SCENARIO*

The LR-ATFM concept only considers flights in the cruise/on-route phase to be able to sustainably vary the flight time to allow significantly different arrival times at the approach sector. Thus, flights with at least 1 hour of cruise phase are considered for LR-ATFM regulations. This regulation ends when the flight reaches TTO reference point. This is a specific predefined point along the flight plan route where the TTO is calculated for each flight. The location of TTO reference points affects the ability of the flight to meet the agreed TTO, so it is necessary to identify the best location. Thus, we carried out an analysis to find this location for each arrival flow using equidistant, concentric circles around WSSS. The concentric circles are created with steps of 50 NM up to 500 NM around the airport, and the traffic is divided based on the airway route taken by flights. From this, the points in time at which the time spent increases and the flight altitude decreases can be determined. Fig. 27 exemplarily depicts the average time spent and average altitude in the concentric circles for flights along N892 airway route (arrivals from North-East).

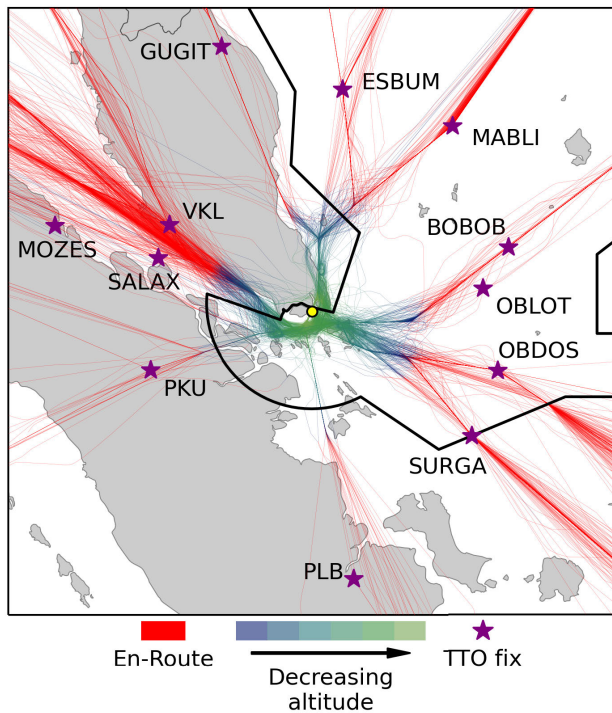
This analysis indicates that the flights were subjected to some form of regulation from 250 NM onwards. Thus,



**FIGURE 27. Average altitude (top) and average time spent (below) by flights in each concentric circle coming along N892 airway (arrivals from North-East).**

we assume that the location of the TTO reference point must be at/or beyond 250 NM. As there was no predefined waypoint at 250 NM, the next nearest waypoint MABLI, which is at 220 NM, was chosen as TTO reference point for the N892 route. In this way, we carried out the equidistant analysis for all arrival routes. Fig. 28 depicts the location of the chosen TTO reference points for all arrival routes. To identify the starting point of the regulation horizon, we carried out a cruise phase analysis. To identify the location of Top of Climb (TOC) (cruise phase starts) and TOD (cruise phase ends), we analyze the ADS-B messages as follows. If Flight Level (FL)  $\geq 280$  and the flight stays in the same level for 15 minutes, we assume it reaches TOC. We assume that TOD has been reached when the flight starts descending after TOC and the flight time is less than one hour. FL 280 was chosen because the highest flight level of aircraft coming from the nearest major airport (Kuala Lumpur International Airport) is FL270. So, we assume flights coming from farther airports will choose flight levels greater than 270 as their cruise level.

Fig. 29 exhibits the percentage of flights in the cruise phase with regards to their distances (at 100 NM units) to WSSS. By the mathematical optimizations previously performed, we aggregated flights based on their distances in clusters (color-coded in Fig. 29). These clusters are derived such that a significant change in the proportion of flights triggers the formation of new clusters. As a second criterion, we minimized the variance of the distances within the clusters. Each cluster represents a TTO passing time horizon. This means flights start reducing/ increasing their speed from the horizons. The



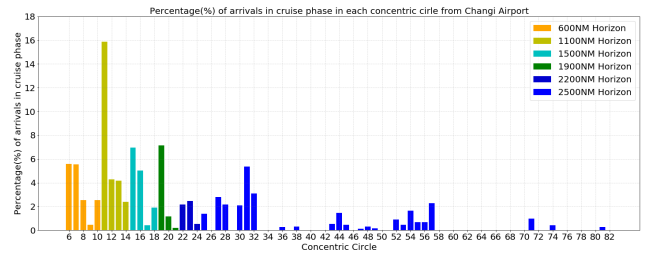
**FIGURE 28.** TTO reference points around WSSS considering different arrival flows.

maximum and minimum distance of horizons were selected based on the following reasons.

- 1) Maximum distance horizon (2500 NM) was chosen based on ATFM operations. Flight time for the flights coming from Guangzhou Baiyun Airport is approximately 4 hours (which is the farthest airport to which Singapore ATFMU is assigning CTOT) and ATFMU provides CTOT at least 1.5 hours in advance. This suggested that ATFMU is currently applying ATFM measures 5.5 hours ahead. This duration corresponds to a distance of 2500 NM from Changi Airport.
- 2) Minimum distance horizon (600 NM) was chosen based on cruise phase reach by flights. Flights that have at least 1 hour of cruise time start their cruise phase from 600 NM onwards.

In addition to these two horizons, we created four other horizons. These were set to minimize the unused distance for regulating flights in the cruise phase when selecting the representative horizon. The result is shown in Fig. 29, where the unused distance has an average length of 153 NM per flight.

To implement the time-based regulation of long-haul flights, we used an iterative what-if probing approach. In contrast to the optimization presented in Section V, flights are now treated as agents within the AirTop environment and are subject to operational constraints during local WSSS arrival management. This results in complex interactions in the approach sector and solutions that were previously identified as optimal no longer achieve the expected improve-



**FIGURE 29.** Share of flights in cruise phase according to distance to land at WSSS (100 NM units). Flows are aggregated by distance and emphasized by different colors.

ments. Thus, we start with an appropriate initial solution for LR-ATFM regulations and gradually improve this solution taking into account the results of simulated approach times and trajectories.

AirTop takes into account one reference time per flight, where reference time can be for example the departure time, arrival time, or time over a waypoint. Based on this reference time, a 4D profile is estimated for the flight. In our case, we use the time at waypoint (TTO reference point) as a reference and the time was taken from the CAAS flight plans. Taking into account the estimated arrival times, a decision is made as to which flight will be delayed or gain some time in the en-route phase. After that, arrival times were recalculated for flights that conflicted with others. Here, a conflict means that two arrivals are within 95 seconds of distance from each other. This value was taken out of the analysis of actual flight observations (ADS-B messages). After the calculation of the new arrival time, TTO was determined by subtracting the time needed from TTO reference point to touchdown ( $TTO = \text{revised arrival time} - \text{flight time from TTO reference point to touchdown}$ ).

The following considerations are used to determine the revised ETA (at the airport) for long-haul flights. Based on this revised ETA, the TTO is then calculated.

- 1) If a flight has less than 60 seconds delay/ gain, the slot remains unchanged, i.e. no TTO is calculated for the flights, but ETO simply becomes TTO.
- 2) If a flight is required to implement more delay/ gain than its maximum delay/ gain amount through speed adjustment, it implements delay/ gain equal to its maximum limit.
- 3) To have a conflict-free slot, the deceleration of a flight is prioritized. If a conflict-free solution is still not possible with this, an attempt is made to speed up the flight ahead.

With these regulations of long-haul flights, the traffic scenario is simulated within AirTop and the results are analyzed with a focus on the occurrence of holdings. The proposed regulations will be gradually improved and their effectiveness will be reassessed each time.

## 2) SIMULATION RESULTS

We conducted simulations on one day of arrival traffic at WSSS. In Table 2, the results of the simulation exercises are

**TABLE 2. Results of the simulation runs.**

Measurement	Baseline	Test case	Improvement
<b>all flights</b>			
Aircraft in holdings	64	47	26.5 %
Time spent in holding (min)	161.5	115.8	28.3 %
<b>long-range flights</b>			
Aircraft in holdings	30	18	40.0 %
Time spent in holding (min)	72.1	43.2	40.1 %

shown. To evaluate the baseline and the test case scenario, we concentrated on how the number of holdings and the overall holding time is changing by the regulation of long-range flights. The total number of holdings was reduced by 26.5% associated with a reduction of the overall holding time of 28.3%. If only the long-range flights are considered, these measurements increased over 40%.

In particular, with our iterative improvement, we could reduce the holding-affected long-range flights from 30 to 18. This promising result also indicates additional room for further enhancements. However, to realize this, the implemented regulations would need to be applied in more detail. Regular updates of aircraft positions and forecast of time-to-fly should then be taken into account in any case.

## VI. 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. Key elements for a successful implementation are the cross-border collaboration between ATFM units and 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 Airport, an analysis of the operational environment was conducted (arrival flows) to exhibit the potentials of the long-range flight regulations during their en-route phase. We choose a two-step approach: (1) macroscopic, flow-oriented optimization of the approach area capacity, and (2) implementation of regulations in an agent-based simulation environment. In the first step, we implemented a mixed-integer optimization method considering both stochastic distributions of flight times and specific values for time to gain/ to lose. The results show that the LR-ATFM does

indeed have the potential to improve the performance of the air transportation system by mitigating periods of over-demand. In the second step, we provide a deeper analysis of the LR-ATFM regulations by also considering particular arrival management procedures at WSSS. In this more complex and closer to reality implementation, we were able to demonstrate that the performance measured by the number of holdings and the holding time can be improved by 26.5% for all flights and 40.0% among the long-haul flights.

Although it is to be expected that our results cannot be fully extrapolated to operational reality, it remains to be noted that in aviation savings of only 5% are assumed to be significant. Considering our LR-ATFM approach, a clear separation should be made between the management of short/medium-haul and long-haul traffic in the daily operational management of inbound traffic. Due to the larger lead times of long-haul flights, they can be efficiently included in tactical planning despite statistical deviations. However, timely and collaborative cooperation between all actors (airport operators, airport coordinators, airlines, air navigation service providers) in an airport operations center is a prerequisite (cf. [101]). The number of long-haul flights per day is manageable, but these flights tend to be more frequent during particular arrival peaks. They are easy to track (airborne, large lead times) and the impact of observed deviations could only be assessed in a first step. Should these deviations have a sustained impact on the airport performance at the respective landing times, appropriate regulatory measures could be tested in simulations and communicated to the involved parties. Especially at the beginning, a limited willingness to be regulated by an airport that is still far away can be expected. Therefore, the airport could offer appropriate incentives to the airlines.

Like the LR-ATFM approach, an adapted approach for short/medium-haul flights should also be developed. For example, while long-haul flights are approaching WSSS, many short-haul flights have not yet departed (or even landed) at their airports. In contrast to the LR-ATFM approach, communication between airports is a more important aspect, as local arrival/departure capacities in particular need to be balanced in the air traffic network. In the following studies, we will gradually remove our simplified assumptions and implement an integrated optimization-simulation approach. Through an iterative feedback loop, observed deviations from planning can then be continuously taken into account during optimization. All stakeholders then have shared (real-time) situational awareness and can jointly make necessary management decisions and adjust operational processes on time. Airport operations can be divided into regular, recurring and non-nominal processes. In the presented concept, we have focused on the regularly recurring processes, but in the next research step, less frequent events will also be included in the LR-ATFM approach. In addition, individual flight operations and airline management, airspace capacity constraints, and environmental conditions will also be considered.

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