Optimized Integrated Runway Sequence Management

A solution for sustainable and efficient airport operations

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***Abstract*— Today the planning of arrivals and departures at airports are commonly performed as separate tasks, each without a complete view of the total use of the runway resources. As a consequence, the integration of the flows is handled too late, with a negative effect on capacity and environment. The planning of arrivals and departures into synchronized, integrated and optimized runway sequences will enable a long-term solution for effective and sustainable airport operations. In this paper, we present integrated runway sequence management, a solution applicable for most airports and demonstrated at Stockholm-Arlanda Airport. The solution includes a modern optimization algorithm able to dynamically provide integrated and optimized runway sequences in real time. It can also provide the users with effective support for tactical decision making based on holistic evaluations of effects. The solution has been validated to enable increased runway capacity by 5.1% and increased predictability of flights by 60.8%. Integrated runway sequence management is identified as an enabler for several ongoing initiatives for Stockholm-Arlanda airport with the goal of reduced environmental impact.**

***Keywords*—air traffic control; arrival management; departure management; advanced air traffic services; high performing airport operations; human factors and decision support tools; airport CDM; sustainable aviation; integrated runway sequence; real-time optimization; flight separations; what-if analysis; concept validation**

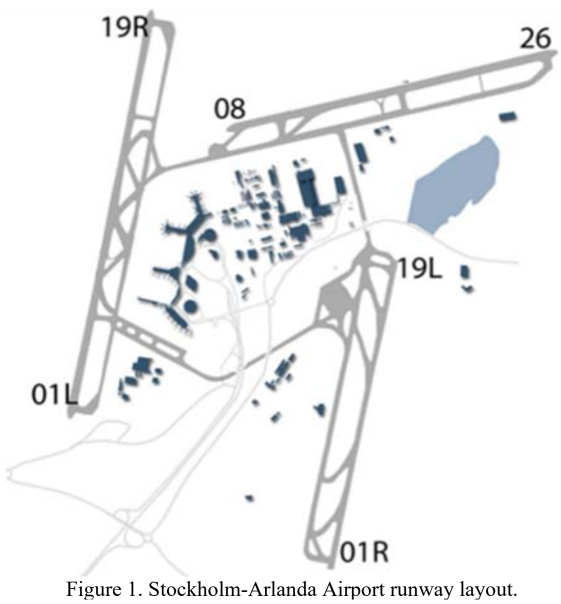

Figure 1. Stockholm-Arlanda Airport runway layout.

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I. Introduction

Large airports are working for an increased runway capacity to meet the high demand of arrival and departure flights. Integrated Runway Sequence Management (hereafter referred to as iRSM both when used as a concept, a role, and a system component) will bring benefits in runway capacity, predictability, punctuality, fuel efficiency and reduce the environmental impact. Improved efficiency can be achieved with use of integrated arrival and departure planning including development of early and dynamic planning of arrival and departure sequences into the runway of an airport. We are enhancing both arrival management and departure management linked to Airport-Collaborative Decision Making (A-CDM).

This paper presents the concept, processes and functions during validation and options for implementation of an integrated runway sequence addressing improvements for airport operator, airspace users and ATC at Stockholm-Arlanda Airport.

Figure 1 shows the runway layout at Stockholm-Arlanda Airport. The distance between the parallel runways is 2 300 m, making it possible to operate on independent parallel runways. Runway 08/26 have dependencies with flights operating on the other runways. The layout is representative for a large number of airports, including when operating on parallel runways, dependent runways, and also on a single runway. Integration of arrival and departure flights can be managed in all these runway configurations.

In SESAR exploratory research, the iRSM described below has been validated through a series of activities including real-time simulations and fast time simulations, focusing on a range of objectives from the high-level objectives in the SESAR validation strategies [5], [6], [7], and [8].

The key objectives were to validate improvements in fuel efficiency, airport capacity, predictability and punctuality when using an iRSM, as well as reducing the environmental impact. At the same time, validation addressed human performance and safety.

II. Concept of operations

A. The problem

Today there are limitations with lack of predictability and high manual workload when planning arrival and departure sequences into an airport, using static arrival departure patterns with pairwise spacing between aircrafts. To reduce extensive queuing in the air and on the ground, there is a need of early planning for improved operational efficiency and reduction of airline fuel consumption. The airport layout is one of the main constraints to the flexibility of traffic management. The single runway in mixed mode is the most constrained situation.

Traffic optimization with iRSM on single and multiple runway airports is applicable for all airport layouts that have dependencies between arrivals and departures. This includes runways operated in mixed mode as well as runway layouts with interdependencies between arrivals and departures.

Besides the number of runways and their geometry, the connecting taxiway system determines the “basic” runway and ground movement operations. The iRSM on single and multiple runway airports applies to complex as well as to non-complex taxiway layouts.

B. The proposed solution

The efficient use of an integrated arrival and departure view requires the development of early planning of arrival and departure sequences into the runways of an airport and that the planned sequences are continuously monitored and dynamically updated when necessary. The concept is illustrated in Figure 2 with arrival- and departure management activities in a timeline leading up to the landing and take-off events. The initial runway sequence should be set before top of descent to enable airspace users to fly optimal flight trajectories and to balance flights between alternative runways. A combination of early planning followed by dynamic updates while respecting the operational need of stable phases provides high predictability. With a planned integrated runway sequence all actors involved can focus on the same goal, although not removing the need of manual updates by air traffic control in tactical situations to ensure high runway throughput. To ensure high runway throughput in mixed mode operations it is also important that fine-tuning of arrival gaps and final adjustments of the departure sequence is performed.

Optimized integration of arrival and departure traffic flows with the use of iRSM addresses a number of significant operational improvements. The presentation of both arrivals and departures for all users will enhance awareness and coordination between arrival and departure management.

The main goal for the iRSM is to establish the best possible integrated arrival and departure sequence by providing accurate target take-off times and target landing times, including dynamic balancing of arrivals and departures. The integrated runway sequence is planned before the arrival flight's top of descent and synchronized with progress of departure flights, by use of the A-CDM. Fine tuning of arrival and departure target times is provided to ensure efficient runway throughput.

The eligible horizon (see Figure 2) is the time horizon when flights are presented in the integrated sequence. The stable sequence time horizon is the time horizon within which no automatic swapping of flights in the sequence will occur but landing and departure time will still be updated. The value of these time horizons is determined by the local implementation, and they are not necessarily the same for arrivals and departures. In the stable horizon there is always option to handle tactical decisions for update of the integrated sequence.

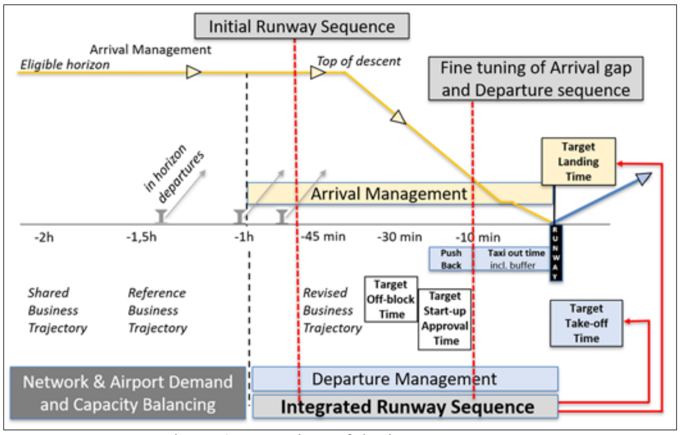

Figure 2. Overview of the iRSM concept.

The integrated sequence optimization of target landing times and target take-off times is firstly calculated by the iRSM in a look ahead time horizon balancing arrivals and departures according to demand. A set of configured parameters can be tuned in order to achieve the best trade-off between efficiency, predictability and optimized throughput.

Target landing times will be set by the iRSM to calculate time constraints at the metering fixes. Procedures are in place to implement the arrival sequence, the target landing times from the integrated runway sequence are converted to time to lose, time to gain or controlled time of arrival and made available for air traffic controller and flight crew. Flights departing from airports inside the arrival management horizon, disturbing the arrival sequence, will instead be planned into the integrated sequence before these flights get airborne.

The target take-off times calculated from the iRSM are converted to target start-up approval times, made available for air traffic controller and relevant actors (e.g., de-icing, flight crew, stand management). The integrated sequence is built including departure aircraft that are not yet off-block (initial runway sequence). When the stability of flight progress is increased, an adjustment of the sequence can be made. This will normally mainly affect departure times.

Figure 3 illustrates the typical system components and the main type of data exchanged in an operational environment. The ATC systems include working positions of tower, approach and en-route, with interfaces to the existing systems. Basic AMAN and DMAN can already be used at the airport to support the separate flows of arrivals and departures. To fully benefit from the iRSM, the DMAN should preferably be enhanced to show information regarding arrivals in the departure sequence (an example is included in [8]), and the AMAN should preferably show departure information in the arrival sequence. In this way the holistic situational awareness is improved. The integrated display of arrivals and departures will enhance coordination

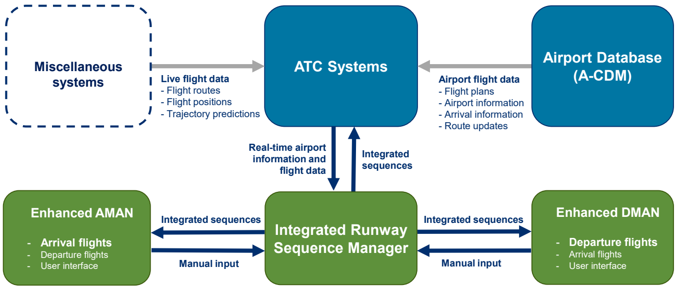

Figure 3. System components integrated with the iRSM.

between tower and approach e.g., change of runway configuration and planning of runway closure. The DMAN and/or AMAN could also allow for the user to provide manual input to override or guide the solution from the iRSM whenever necessary, e.g., in the handling of a missed approach.

III. Mathematical optimization approach

A. *Our approach to real-time optimization*

A vital component of the proposed solution is an optimization algorithm responsible for producing and maintaining integrated runway sequences. We have addressed the runway sequencing problem for many years, with the first research prototypes available as early as 2013 [2] and [3], and in a study of runway sequencing combined with surface routing [1]. Since then, the algorithm has been refined due to findings during validation exercises and feedback from operational experts.

The iRSM is designed to work in real-time environments where it is essential that it quickly responds to substantial amounts of new and updated information regarding the status of the flights and the airport resources. Classical optimization techniques have often been found to respond too slowly in such environments. We have therefore selected an alternative approach based on the following design: At any given point of time there will exist a model representing the most updated information received so far, as well as the solution from the previous optimization. The solution contains the sequence of flights for each runway orientation in use in each runway configuration period. For each flight, the optimal landing time or target start-up approval and take-off times are calculated.

In the scenarios we have studied, flight information was received up to 3 hours before the time of the runway event, and these flights are part of the solution from this point on and until the event is completed. As updated information is received, the change of the model due to the latest information is normally minor compared to the total set of information in the model. Hence, the difference in the optimal solution before and after the information is incorporated into the model is usually relatively small. The algorithm can therefore normally perform a quick optimization search when it starts at the old optimal solution.

We call this approach *incremental optimization*. It takes inspiration from approaches studied in the fields of *prescriptive analytics* with adaptation mechanisms in dynamic environments [4], *multi-agent systems* with the emphasis on distributed cooperation and coordination, *incremental computation* with the representation and propagation of changed data [11], *online optimization* with the representation of incomplete knowledge of the future and *streaming data processing* with the handling of big data with separate storage and processing layers.

B. *Ensuring separation of flights*

The solutions produced by the iRSM will always satisfy the stated separation requirements between the separate events on the runway. The separation minima are time-based and depend on:

- Runway configuration
- The type of the leading and following events (e.g., take-off, landing, runway closure, change of runway configuration)
- Wake vortex turbulence separation standard (e.g., ICAO, RECAT-EU)
- Radar separation at the runway threshold (converted to time based on expected speed)
- Runway occupancy time
- Departure route dependency, i.e., taking into consideration the geometry of the route, the capacity at the TMA exit, and the aircraft speed
- The *visibility meteorological condition*, i.e., the level of visibility that determines the flight rules to be followed.
- The *runway condition code*, i.e., the condition of the runway and apron surfaces regarding friction

C. *Ensuring stable solutions*

The runway sequences are used to make tactical and operational decisions by the air traffic controllers. Hence, it is important to build sequences proactively that can absorb typical operational deviations without altering the sequence. For departing flights, these deviations may be due to deviations of actual off-block times, taxi speed, deicing, or for lineup of the aircraft at the runway before take-off. It is particularly important for departures during peak traffic using runways operated in mixed mode that aircrafts are present and ready near the runway at the assigned departure time. Hence, to compute the ideal take-off time for a flight, we add two soft time-buffers between the off-block and take-off events as illustrated in Figure 4. The *off-block buffer* is added to absorb deviations of actual off-block times while the *holding buffer* is added to ensure pressure at the runway and to absorb deviations in taxi speed and lineup time. Departing flights at Stockholm-Arlanda are permitted to perform the actual off-block up to 5 minutes later than the target start-up approval time. Therefore, the off-block buffer was set to 5 minutes and the holding buffer was set to 1 minute. The duration of pushback and taxi time depends on stand assignment, entry point to the runway, weight category of the aircraft and visibility condition. During off peak periods or for segregated departure runways the additional time buffers may be removed to reduce fuel consumption before take-off.

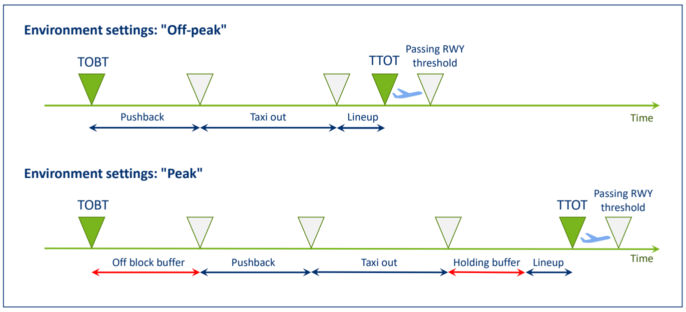

Figure 4. Option to insert time buffers to ensure throughput.

While smaller deviations are handled proactively by the means of time buffers, larger deviations are handled reactively. Such larger deviations are often due to events from the turnaround processes and will normally be identified during the A-CDM process as updated target off block times and hence reacted to.

For arriving flights, the ideal times at the runway are provided as trajectory predictions. The deviations we need to take into consideration may be due to deviations from the flight plan before take-off at the origin airport or inaccuracy in the trajectory predictions. The main purpose of planning the runway sequences is to guide the execution of the plan to be as effective as possible. Only when the execution deviates to a level where the plan cannot be followed in an effective way should the plan be regarded as infeasible and therefore be modified. In the scenarios we have studied, the trajectory predictions were not complemented with information about the feasible range for arrivals (between maximum time to gain and maximum time to lose). We have therefore calculated these times based on a function taking the progress of the flight into consideration. Figure 5 shows an example of predicted times at the runway threshold and how the feasible range is reduced as the flight progresses towards the airport. In the example, the planned time needs to be revised only three of the twelve times the trajectory prediction is updated and at the actual landing time.

In addition, the iRSM stabilizes the times for landing, target start-up approval and take-off by adding the previously planned times as part of the optimization objective for the subsequent optimization run. Hence, unmotivated changes in the planed times are avoided.

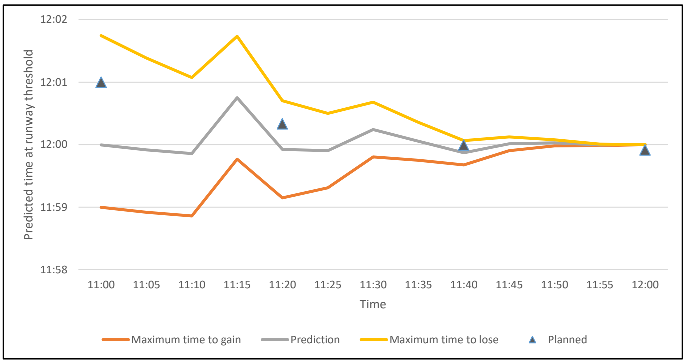

Figure 5. Example of plan revisions due to trajectory predictions.

D. *Optimization of sequences and times*

We include flights in the sequence as soon as we know about them. Since this can be several hours into the future, they can even be planned before they depart from other airports. In this way we will have an early indication of the total demand of the runway, which again can be used for making tactical decisions with the goal of maintaining a smooth and uninterrupted flow of flights. These decisions may be regarding the best runway configuration to be used or the best time for a planned runway closure.

The sequence is optimized and maintained using a local search algorithm that evaluates changes in the solution through *moves*. A move may represent the insertion of a new flight into a specific position in a sequence, the reallocation of a given flight into a different position in the same sequence or to a different runway configuration period. The implication of applying a move is forwarded to a sub algorithm which calculates the optimal time for each flight according to a *minimum-cost flow formulation* of the model. The objective function represented in the minimum-cost flow problem includes:

- Costs for deviating from the ideal times
- Costs for deviating from the previously planned times
- Costs due to the total duration of the taxi-out phase
- Costs due to reduction of time buffers during the taxi-out phases (see Figure 4)
- For departures with calculated take-off times (CTOT) also the additional costs if the time windows cannot be satisfied.

The local search algorithm will then apply the moves that reduce the sum of these costs.

E. *Balancing between alternative runways*

With the long planning horizon of the iRSM, it is possible to predict imbalances between alternative runways at an early stage, e.g., before the arrivals reach top of descent or before target off block time for departures. Balancing moves are evaluated for flights that still can be rerouted to alternative runways. An extra cost is added to the objective value from the minimum-cost flow solution to avoid balancing moves with only marginal improvement. The iRSM supports three different modes for how runway balancing is done:

- Manual mode: The user can manually select flights to balance to other runways while the iRSM will select the optimal time and position in the new sequences.
- Semi-automatic mode: The iRSM can identify and suggest flights to balance to other runways. The user can accept or reject these suggestions. For accepted suggestions, the iRSM will select the optimal time and position in the new sequence.
- Automatic mode: The iRSM identifies flights to balance and select the optimal positions and times for the flights in the new sequences.

During system- and concept validation we have seen that iRSM can detect such imbalances earlier than a human expert, with the advantage that the change of the flight trajectory can be applied with better fuel efficiency.

F. Supporting What-If analysis

While the iRSM can produce integrated runway sequences automatically, it also supports decision-making involving human experts. Through the support of what-if analysis in the iRSM, the expert can evaluate the implication of tactical decisions "offline" before they are implemented. This can be decisions with respect to which runway configuration to use and when it should start, setting the best time for a planned runway closure (e.g., snow sweeping), manually swap flights in the sequence, lock the time for flights, reallocate flights to a different position in the sequence or to other runways.

Within the iRSM, the incremental information received from the users or other systems is organized by a separate *scenario management* component. When a user starts a new what-if analysis, a scenario is added. The assumptions that the user wants to test is then added to this scenario and sent to a dedicated instance of the algorithm. A set of KPIs assists the user in the evaluation of the overall quality of the what-if scenario compared to the live scenario. The KPIs can include measurements of capacity and throughput, arrival- and departure delays, and taxi times. The values are aggregated into time charts covering the relevant time horizon. Hence, once the user has found the best set of decisions to be implied, the assumptions in the what-if scenario is merged into the live scenario. Alternatively, if the what-if analysis did not result in any improvement, the user can simply cancel the what-if scenario and revert to the live scenario.

IV. VALIDATION RESULTS

Early prediction of an integrated runway sequence provides air traffic control and other stakeholders with enhanced ability to exchange information, plan for optimized flight profiles and jointly work for realistic target times in order to meet today's requirements for sustainable aviation. The iRSM is designed to work in real-time environments.

In the SESAR large scale demonstration project VLD3-W2-SORT the iRSM was demonstrated in shadow-mode use. Feedback from air traffic controllers confirmed the value of increased awareness with early planning of an integrated runway sequence, including functions to update the plan progressively based on real time flight events. Safety and human performance areas have been addressed where the air traffic controllers confirmed the concept of integrated runway sequence with the ability to handle the balance between predictability, flexibility, and stability, while meeting requirements for operational acceptability.

Improved runway throughput. Results from the SESAR PJ02-08 V3 real time simulation [6], is based on a number of comparable runs in reference and solution modes, which show with use of the iRSM an average increase of the peak runway throughput by 5.1%. This is achieved by optimized use of the

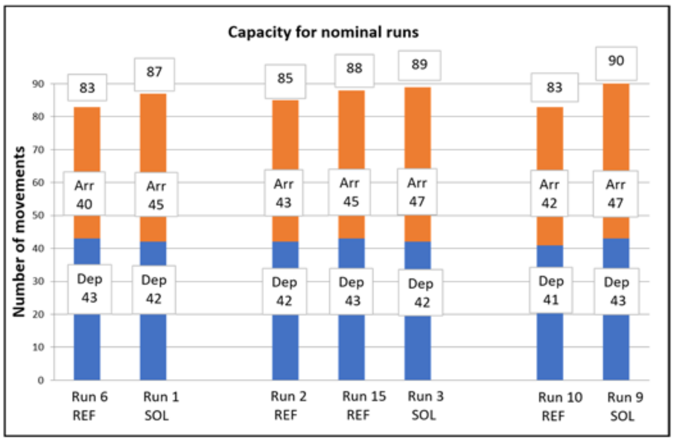

Figure 6. Results from SESAR PJ02-08 V3 Real time simulation.

parallel runways in mixed mode (both arrivals and departures), tailormade gaps between arrivals to accommodate departures and balancing of flights between runways. During the previous V3 real time simulation a capacity increase could be verified with ATCOs working to handle 90 movements per hour, see Run 9 Solution in Figure 6. During simulation of this type of peak traffic the off-block and holding buffers shown in Figure 4 were applied to ensure a pressure of one to three departures at runway holding position.

Early prediction of runway sequences into the parallel runways include balancing of flights between the two runways for improved efficiency to ensure high-capacity levels.

The SESAR large scale demonstration confirmed the ability to increase runway throughput by early and enhanced planning of an integrated runway sequence, applicable both in single runway operations, dependent runways and when using the two parallel runways in mixed mode.

According to the environmental permit for Stockholm-Arlanda Airport, up to five additional arrival flights per hour can land on the runway mainly used for departures (when runway configuration is set to use the parallel runways in segregated mode), see [10]. When the iRSM was set to semi-automatic or automatic runway balancing modes for parallel runways in segregated mode, we observed that the system was able to identify and plan five landings on the departure runway, thereby with a potential increase of the capacity from forty to forty-five landings per hour. This is equivalent to a capacity increase for arrivals of 12.5%.

Improving predictability. Results from the SESAR PJ02-08 V3 real time simulation show with use of the iRSM an average decrease of variation between actual flight and the planned flight (duration in flight plan/reference business trajectory) of 60.8%, thereby improving predictability. Observations of improved predictability were confirmed during the SESAR large scale demonstration for flights that were monitored with the iRSM but not altered.

Environmental sustainability and fuel efficiency. The SESAR PJ02-08 V3 real time simulation [6], showed when

Figure 7. Curved approach to runway 01L

using iRSM a positive impact on flight overall fuel efficiency, addressing the combined arrival/departure fuel burn and also CO2 emissions.

Increased number of curved approaches. The use of an iRSM was confirmed by air traffic controllers to provide valuable support to enable an increase in the number of planned and assigned curved approaches, particularly when used together with performance-based navigation. In this way the arrival flying time can be reduced and noise levels to be minimized over noise sensitive areas. An example of a curved approach route is shown in Figure 7.

Efficient de-icing of departure flights. During the SESAR large scale demonstrations tower controllers/supervisors, airport operators and ground handling, all expressed the importance in the use of an iRSM to support efficient planning and execution of de-icing at the airport. By including planned de-icing start/end times into the calculation of runway sequence, the quality of departure target off block times and target take-off times can be increased and met during the winter period. With this improved planning de-icing of departure flights can be executed in the correct sequence order to respect the integrated runway sequence, to be used in all runway configurations and in adverse weather conditions.

Quality in predictions. The SESAR large scale demonstration identified the value of flight trajectory predictions with high quality and the option to also include ground surveillance data (including target-time to threshold) to further enhance the quality in predictions made by the iRSM.

Implementation of the iRSM has been identified as an enabler to support ongoing initiatives for Stockholm-Arlanda airport:

- New airspace design
- Curved approaches
- Time based separation in approach

V. Conclusion and Next Steps

In this paper, we presented the concept of iRSM and a proposed solution which already has been validated and demonstrated at Stockholm-Arlanda airport with good results. We also presented details about the iRSM component and how to make it effective for interaction with air traffic controllers working in real-time environments. We will now present some specific benefits enabled by implementing the iRSM solution as well as next steps to further enhance the positive effects.

Sustainable airport operations with use of an iRSM will enable a long-term solution for enhanced use of single runway, dependent runways, and the use of parallel runways for increased runway throughput and high airport capacity.

Early prediction of runway sequence provided by the iRSM will enhance planning of flights when operating the parallel runways in mixed mode (departures and arrivals on both runways), including balancing of flights between the runways to further improve efficiency and ensure high runway throughput.

Increased runway throughput with the iRSM used as an enabler provides early planning and high flexibility to reduce emissions. The operational use of an iRSM can support an efficient management of 90+ movements per hour at Stockholm-Arlanda by predictable use of the parallel runways, when operated in mixed mode. The report *"Arlanda Airport – a plan for the future"* [9] recommended "introduction of parallel mixed operations at current runways (both departures and arrivals)", including advise for start of the linked environmental assessment process. However, we have seen that even when using parallel runways in segregated mode, the iRSM was able to increase the capacity from forty to forty-five landings per hour, by assigning five arrival aircraft per hour to land on runway mainly used for departures.

Advanced curved operations based on performance-based navigation can be planned early by the integrated runway sequence and set before the arrival flight's top of descent to increase flight efficiency where an optimal flight profile can be used. The iRSM can support a higher number of curved approaches and departures to increase capacity and minimize noise over noise sensitive areas.

Trajectory predictions with a high quality and integration of ground surveillance data will further enhance the quality of the integrated sequences made by the iRSM.

Increased predictability for de-icing will enhance winter operations. With an iRSM linked to A-CDM and a developed interface, there will be an increased awareness on the planned departure sequence for the companies providing de-icing. In this way the airport winter operations can be predictable and enhanced, both during normal and adverse conditions.

Proposed stepwise implementation of an iRSM at Stockholm-Arlanda airport [8]:

- Enhanced dynamic optimized departure management including display of arrivals.
- Display departures in the arrival management planning for approach controller.
- Fully optimized integrated runway sequence for enhanced departure and arrival management.

Options for international airports. Validation and demonstration of an integrated runway sequence management performed for Stockholm-Arlanda airport, demonstrate ways to meet requirements for sustainability, predictability, and efficiency. Many of these enhancements are applicable also for other international airports.

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