ENABLING AIRCRAFT PERFORMANCE STUDIES IN AIRPORT AIRSIDE SIMULATIONS

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Abstract

Future aircraft designs need to address airport capacity challenges. Therefore, tools are required that enable to study the effects that altered aircraft performance characteristics and associated operational procedures may have on airport airside operations in general and airport capacity values in particular. This paper identifies the challenges that have to be met when existing simulation tools are to be used for this purpose. Based on those findings, a concept is presented that enables to study the effect of altered aircraft performance characteristics on airport airside operations using an existing standard analysis tool (Simmod). To demonstrate its feasibility, an exemplary application of the concept is outlined.

1 Future Aircraft Designs Need to Address Airport Capacity Challenges

The airside of airports in general and the runways in particular, have long been known as most constraining elements impacting overall airport capacity [1]. In the context of today's traffic concentration on hub airports [2], increasing environmental restrictions (e.g. noise) [3][4], rising delay levels at congested airports and resulting considerable financial losses for airlines [5], the maximisation of current airports' performance is one of the major challenges for future air transport [3]. In the past, different computer simulation tools were used alongside analytical and handbook methods to assess the capacity of runway systems [6] and also with the aim to optimize airport infrastructure [7]. Since in many cases constructional expansion of airports is impossible due to space restrictions and public opposition [6] it is important to design future aircraft that not only fit to existing airports [8], but help to save the valuable resource of overall airport capacity.

1.1 Aircraft-Airport Interdependencies

As an essential part of the air transport system, airport operations rely on the efficient interaction of its three major components/actors: The airport (incl. ATM), the airline (aircraft) and the user (passenger). Optimal conditions are reached when each of those actors reaches some form of equilibrium with the other two [9].

Thinking of potential future developments in

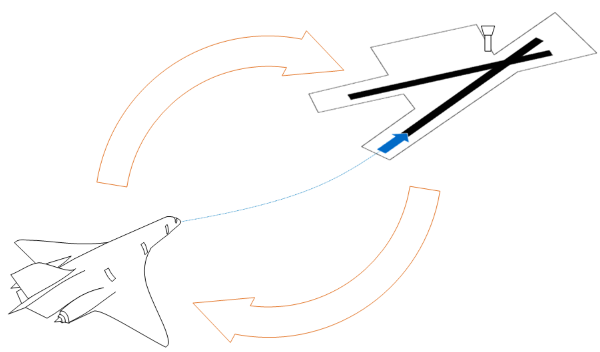

Fig. 1 New aircraft concepts operating at airports - a method is required to assess their impact on the sensitive airport operation system targeting airport capacity.

the air transport system such as

- new aircraft concepts (e.g. aircraft with short take-off and landing capabilities, flying wing aircraft [10][3])(Fig. 1),
- the introduction of new propulsion systems (potentially affecting aircraft performance), as well as
- new operational procedures (e.g. new landing sytems [3]),

the question arises how much these changes might affect the sensitive airport operation system.

1.2 Enabling Early Assessments of New Aircraft Designs' Impact on Airport Operations

The majority of currently available simulation tools were designed with the objective of conducting "what-if" studies concerning the airport infrastructure, e.g. runway and taxiway layout, approach and departure routes and procedures as well as different flight plans. As a consequence, those models rely on an extensive amount of measured operational "real-world" data to model and verify the simulation scenario [11]. With respect to the simulated aircraft, those data are only valid and available for aircraft already existing in the real world. How those challenges associated to the assessment of new aircraft designs regarding airport operations and airport capacity with existing methods and tools can be overcome is subject of this paper.

1.3 Airport System Definition Relevant for Early Assessments of Aircraft Design Impacts on Airport Capacity

Appropriate system boundaries can be chosen by identifying key influence factors. Within the scope of this problem area, airport capacity can be defined as the maximum number of aircraft that can pass through the airport system within a given time span under specified conditions (based on [2]). Therefore, two general factors applicable

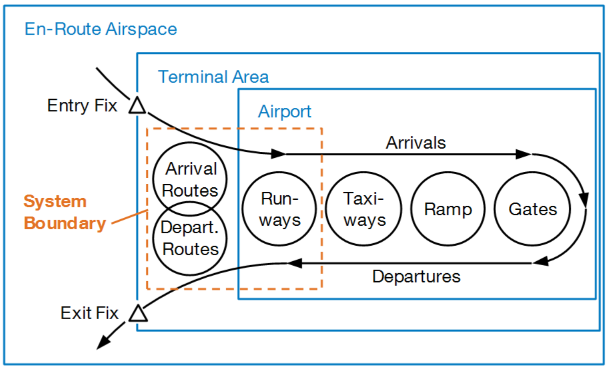

Fig. 2 The system boundaries for early airport capacity assessments of new aircraft technologies and procedures are chosen according to the most constraining elements in the airside airport process chain: the runway system including final approach.(Figure based on [12])

to all relevant system elements can be identified that have a direct impact on an airport system's airside capacity value: individual system occupancy times (e.g. runway occupancy time) and the frequency of occurrence (e.g. aircraft mix, arrival / departure rates) [13]. As aircraft arrive at and depart from an airport they pass different elements of the airport system (as presented in Fig. 2) which are capable to handle each flight within a certain time frame also dependent on the aircraft characteristics and the procedures applied. This process chain character of the airside processes at an airport is the reason that the whole air traffic flow is determined by those system elements with the lowest capacity and highest system occupancy times respectively. Therefore, the focus on the most constraining elements is justifiable.

Due to the high complexity of the landing and take-off procedures and the associated high safety relevance and resulting strict regulations (e.g. wake vortex and radar separation requirements, runway coordination) the runway system can clearly be defined as the most constraining element in the airport system (see also [1] and [2]).

Consequently, the relevant system boundaries comprise the runway system consisting of one or more dependent or independent runways including the associated final approach and departure routes (restricted on the initial climb phase). Fig. 2 displays the schematic system boundary applicable in the context of this paper. The other system elements outside of the selected area will have to be included in subsequent studies, once the capacity of the runway system has been established but should not be subject to initial studies.

1.4 Three Step Approach Using an Existing Airport Simulation Tool

A review of existing tools and methods to estimate airport/runway capacity revealed that they can not directly be applied for the intended aircraft parameter studies or variation of operating procedures. Analytical methods mostly lack the possibility to model complex systems with multiple runways and most simulation tools do not ensure the consistency of all model parameters with interdependencies to those parameters subject to a variation study.

Therefore, the proposed concept to enable aircraft performance driven airport operation studies builds on an existing simulation tool (Simmod PLUS! [14]), selected for its problem specific capabilities and application related aspects compared to other tools. Application related aspects may not be neglected since the selected tool has to be suitable for the software application in an university and research environment (e.g. tool availability/accessability, purchase price) and for the development of new tools which interface existing software (e.g. availability of support services).

Fig. 3 represents the developed simulation approach. The first step in performing aircraft parameter studies in complex operational airport environments is the definition of the study itself including the modeling of the aircraft concept, technology and/or procedure to be studied and the provision of consistent study scenarios. The simulation itself requires certain pre- and postprocessing capabilities to enable the chosen standard airport simulation tool to consistently

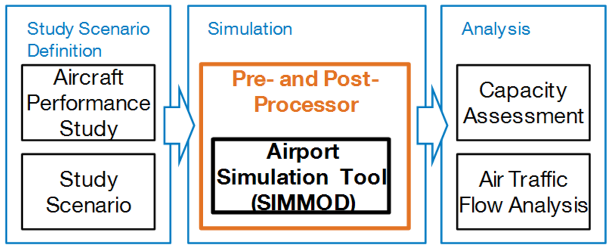

Fig. 3 To enable aircraft performance driven airport operation studies a concept based on an existing standard simulation tool (Simmod PLUS! [14]) was developed enhancing the simulation capabilities through specific pre- and postprocessing.

handle aircraft parameter variations or procedure changes. Those capabilities were incorporated in a software tool designed with the required interfaces to the airport simulation tool. Practical and theoretical airport capacity values are computed as primary study results. Air traffic flow data can also be provided for further analyses such as the identification of capacity bottlenecks during a day's traffic or related to airport infrastructure elements as well as the analysis of environmental aspects (noise / emissions).

2 Simulation Concept Enabling Aircraft Performance Studies

Fig. 4 details the three previously described steps by providing information on the interrelations of the different concept elements, highlighting the core features of the proposed concept.

2.1 Study Scenario Definition

Typical aircraft performance studies with regard to airport operation and airport capacity questions involve the introduction of additional aircraft types with new performance characteristics and potentially associated new operating procedures. They have to be tested in a representative airport environment to ensure meaningful results.

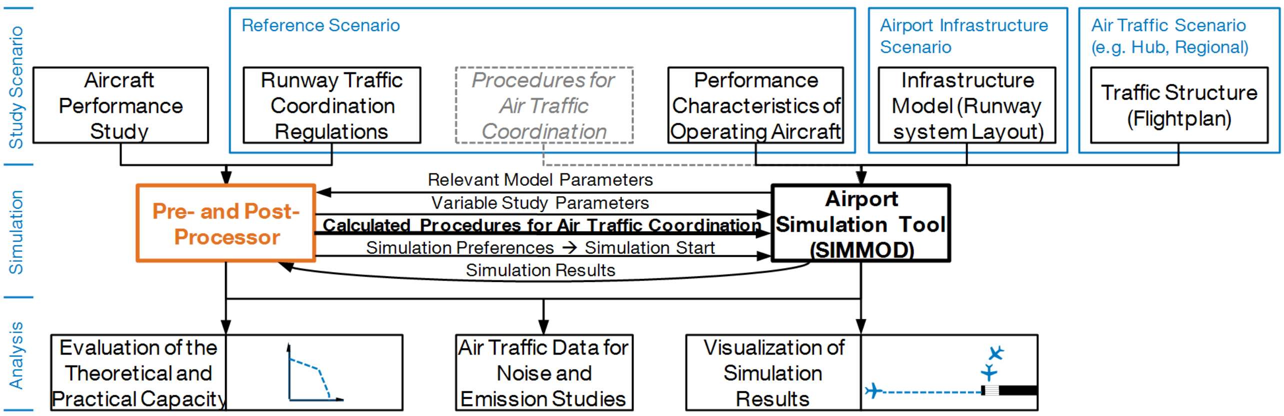

Fig. 4 Overview of the elements of the proposed simulation concept.

2.1.1 Configuration of the Simulation Study

The definition of the new aircraft type and associated procedures is required to configure the aircraft performance study.

2.1.2 Defining the Operational Airport Environment

The operational airport environment can be broken down into three parts which together define for which operational case the results are valid:

Reference Scenario: In the reference scenario, general air traffic related aspects are defined, comprising regulatory aspects and the characteristics of operating aircraft in general for example. For studies where the status quo of airport operations is to be modelled, current regulations and aircraft characteristics can be used. For studies addressing the future of the air transport system, possible changes in the operating conditions of aircraft (e.g. regulatory changes such as the implementation of NGATS [15] or SESAR [16]) may require further investigation for an adequate implementation in the simulation model.

Airport Infrastructure Scenario: This scenario combines all infrastructural elements focusing on the approach and departure route definition and the runway system layout according to the system boundary definition (see Fig. 2). It specifies which type of airport layout is used in the study (e.g. (in-)dependent parallel or intersecting runway system, etc.).

Air Traffic (Demand) Scenario: In order not to miss out one of the most important influence factors on airport capacity [13], the air traffic demand needs to be specified for each study. This is typically achieved by providing arrival/departure schedules which may represent demand structures that are typical for certain airport types (e.g. hub airport, regional airport, etc.). This scenario is mainly independent from the infrastructure scenario but typical schedules may vary for different reference scenarios. If for example the low cost sector may change its market share in the future, this may affect the traffic demand characteristics of a typical hub airport schedule.

2.2 Simulation

To demonstrate the challenges associated with aircraft parameter studies using Simmod [14] (representative for a standard airport simulation tool), Fig. 5 illustrates the current practice in common airport simulation studies. Usually, baseline airport models are implemented and calibrated using a wide range of operational data taken from real operations. Those models are then used to study the effects of flightplan or infrastructural changes (e.g. new departure routes, new taxiways, etc.). Thus, those simulations typically rely on a high amount of surveyed input

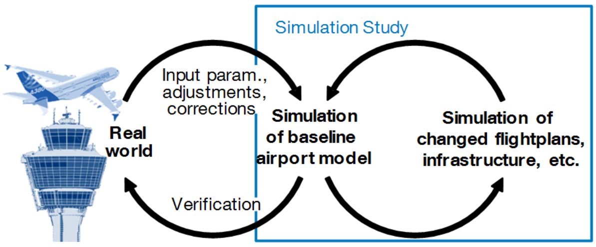

Fig. 5 Current practice in common airport simulation studies: Baseline airport models are implemented and calibrated using data taken from real operations. To simulate aircraft with new performance characteristics this data is not available.

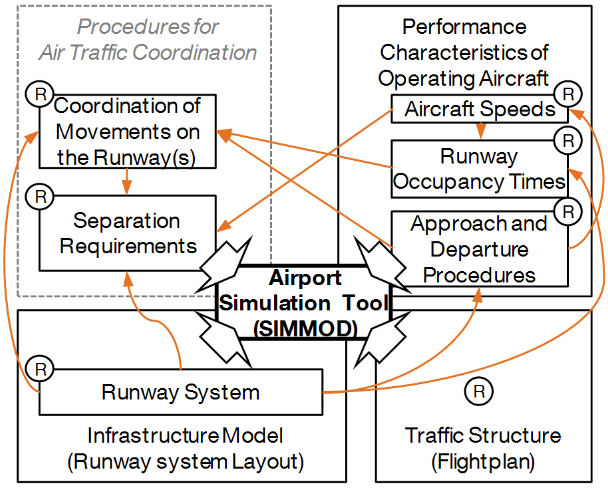

Fig. 6 Input data required for a standard airport airside simulation are normally taken from "real world" operations (R) and thus parameter consistency of the baseline airport model is ensured. Due to many internal parameter interdependencies in the simulation model (represented by the orange arrows), parameter changes for "what-if" studies may have effect on other parameters and have to be addressed.

data. Consequently, any deviation of the model from the "real world" requires a consistent adaptation of many parameters. Especially implicit interdependencies between parameters have to be properly defined and managed when conducting aircraft parameter studies, since implications on other model parameters are manifold and real world data do not exist for those cases.

2.2.1 Internal Model Parameter Interdependencies

To illustrate the parameter interdependencies, Fig. 6 shows a breakdown of the different input data required for a standard airport airside simulation. They can roughly be grouped into four categories: The infrastructure model containing all information defining the runway system, the procedures for air traffic coordination defining the air traffic controllers role, the data depending on the performance characteristics of operating aircraft and finally the traffic structure in form of a simulation flightplan.

Whereas the traffic structure as part of the air traffic scenario (see also 2.1.2) can be handled independently, all other parameters are mutually linked as indicated by the arrows in Fig. 6. The main driver is the runway system layout. It influences most other input parameters. The input data group summarized as "procedures for air traffic coordination" can clearly be identified to be mostly driven by other parameters - with aircraft parameters in the first place. Thus, if in an existing simulation model aircraft parameters are changed it is not obvious which other model parameters are affected and therefore require adjustments. (Example: If the landing runway occupancy time of an aircraft type is changed, this affects the required time and distance separations of subsequent departures and arrivals on the same runway respectively. Runway occupancy times in turn may be affected by the final approach speeds of an aircraft resulting from changed stall speeds or different approach procedures.) A solution to this problem is comprehensive preprocessing of model input data as proposed in this concept. The provision of correctly adjusted procedures for air traffic coordination is the core element of the required pre-processing capabilities since those model input data are most influenced by other parameters and it is therefore nearly impossible to correctly adjust them manually for aircraft parameter studies.

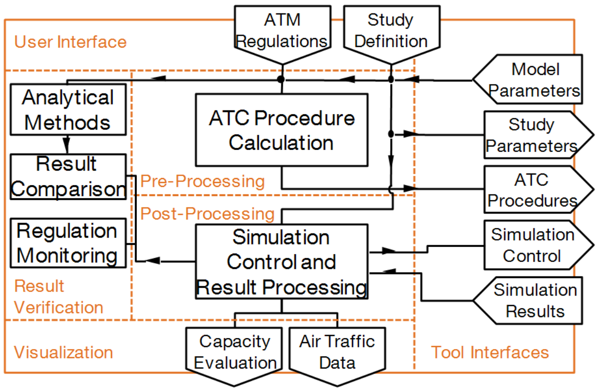

Fig. 7 Functionalities and external links included in the proposed pre- and post-processing tool.

2.2.2 Data Pre- and Post-Processing to Consistently Manage Internal Parameter Interdependencies

Pre-processing (the automatic calculation) of internal dependencies involving procedures for the coordination of air traffic is the key enabler to perform aircraft performance studies. Post-processing of simulation results is required for any airport capacity study to produce the final results (e.g. values for the theoretical and practical capacity of an airport) and is therefore included in the proposed pre- and post-processing tool to support aircraft performance and parameter studies. Fig. 7 shows all external links (see also Fig. 4) of the proposed tool and its main functionalities:

User Interface: The data preparation for every study has two steps: An airport simulation model has to be implemented as for conventional airport simulation studies using the input means provided by the standard airport simulation tool. Additional information for aircraft parameter studies have to be provided for the pre-/postprocessing. Therefore, the user interface requests all information required to define the intended study (e.g. which aircraft parameter is to be changed) and to complement the data already defined in the airport simulation model.

Tool Interfaces: The tool interfaces manage the data exchange to the airport simulation tool. Imported data is required by the data pre-processing alongside the data provided by the user interface to calculate the study-specific air traffic coordination procedures. They are then exported to the airport simulation tool together with other relevant study parameters. The post-processor controls the simulation process through dedicated interfaces and collects imported data after a simulation was successfully completed.

Pre-Processing: The main function of the data pre-processing is the calculation of air traffic coordination procedures which will be explained in more detail in the subsequent section. Furthermore, it provides all data to the airport simulation tool that has to be adjusted for the intended aircraft parameter study.

Post-Processing: Simulations are controlled by the post-processing functionality of the tool. It allows multiple simulation runs and data collection for the efficient preparation of study results as presented in section 2.3.

Result Verification: To ensure valid results a verification step has to be included which is able to check simulation results for plausibility. Since real world reference data do not exist for the simulation scenarios, the best possibility is to implement reliable analytical methods (e.g. Blumstein model [17] [18]) to produce reference values for simple sub-systems of the study scenario which can be handled by those methods (e.g. verification of the capacity values for single runway operations). This can be further complimented by the monitoring of basic air traffic regulations (e.g. monitoring of aircraft entering active runways, etc.).

Visualization: Built-in visualization capabilities are required to produce graphical representations of the post-processed simulation output in form of diagrams (e.g. theoretical and practical capacity curves).

2.2.3 Pre-Processing: Calculation of Air Traffic Coordination Procedures

For the implementation of a software tool that provides automatic pre-processing capabilities all aircraft parameter dependent simulation variables are to be identified and analyzed. Subsequently, functions have to be established describing how the identified simulation variables are related to the relevant aircraft parameters. Along with the aircraft parameters concerned, those functions usually incorporate information concerning general ATM regulations and influencing infrastructural elements (usually taken from the simulation model) as input.

As already indicated in section 2.2.1 and Fig. 6, most pre-processing effort is required for the calculation of air traffic coordination procedures - the core enabler for successful aircraft parameter studies. In this case the functions have to be applied for all possible combinations of aircraft and procedure pairings.

This could be for example the calculation of a simulation variable describing the required time separation between a study aircraft with changed performance characteristics (leading aircraft) landing on runway 1 (performed procedure) and the subsequent clearance for a conventional aircraft (following aircraft) waiting for departure on a second intersecting runway 2 (performed procedure).

Thus the calculation of air traffic coordination procedures presents the most demanding pre-processing functionality. The main preprocessing result is the provision of the procedure and separation input values required for the simulation model while taking all relevant influencing aircraft variables into account.

Current regulations can be implemented according to the rules of air traffic operations published by ICAO[19] and FAA[20] to incorporate fundamental ATM regulations. They cover the following cases: (i) final approach separation, based on wake vortex as well as (ii) takeoff/landing clearances on single, (in-)dependent parallel and intersecting runways for in- and outbound traffic, both in a mixed mode and a departures/arrivals only scenario. The simulation model relies on the problem specific definition of separation values in either time or distance values to allow different events to take place, such as: enter final approach path behind another aircraft, issue line-up clearance for departing aircraft, etc.. For runway coordination issues, aircraft speed (final approach and initial climb), runway occupancy times (landing and departure) as well as the time required to pass a runway crossing are necessary (among other parameters) to compute the correct procedure separation values for each aircraft pairing.

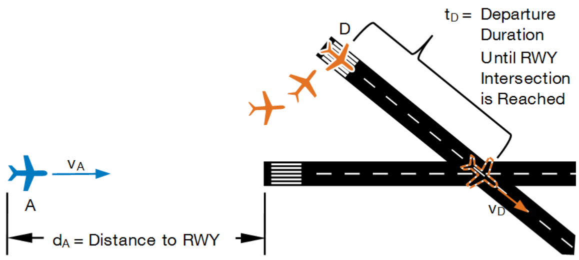

Fig. 8 Exemplary calculation of the minimum allowable distance of an approaching aircraft (A) from the runway (RWY) threshold to issue a departure clearance to an aircraft on an intersecting runway (D).

To reduce the complexity of the system, all operating aircraft should be assigned to a limited number of different aircraft groups according to their performance characteristics based on the wake vortex categories. Usually the groups heavy, medium and light are used. For turboprop aircraft a further differentiation into prop and jet aircraft may be advisable. For aircraft parameter studies an additional "study" class is to be introduced representing the aircraft model with varied performance or operational characteristics.

Exemplary Implementation of a Function to Calculate Air Traffic Coordination Input Values: An important input value for the simulation model with major impact on the aircraft operations rate is the minimum allowable distance ($s_{A,D}$) of an approaching aircraft (A) from the runway threshold to issue a departure clearance to an aircraft (D) on the same or a dependent parallel or intersecting runway. This value has to be calculated for all possible combinations of aircraft groups (e.g. heavy aircraft arrival and medium aircraft departure, etc.). In the following the calculation of this value ($s_{A,D}$) for an intersecting runway system will be demonstrated for the situation shown in Fig. 8.

The primary factor in the determination of $s_{A,D}$ is the basic separation requirement which defines how close an arriving aircraft A may be at the time a departing aircraft D is passing the runway intersection following a previously issued departure clearance. This separation requirement may coincide with the missed approach point of that arrival route at the distance d_A from the runway threshold (Example value: $d_A = 1.0\text{NM}$). The time elapsed between the departure clearance is issued and the departing aircraft's crossing of the runway intersection t_D contributes the second part in determining $s_{A,D}$. For a simulation model implemented in Simmod, t_D is a function of the take-off roll distance of aircraft D, the airborne speed of the departing aircraft v_D, and the position of the runway intersection assuming constant acceleration from $v_D = 0\text{kts}$ to $v_D = v_{D,Airborne}$ (Example value: $t_D = 25.2\text{s}$). In order to add this contribution to the value of d_A it has to be multiplied by the approach speed v_A of aircraft A (Example value: $v_A = 130\text{kts}$).

$$s_{A,D} = d_A + t_D \cdot v_A \tag{1}$$

Equation 1 shows the calculation of $s_{A,D}$. Using the example values given, the minimum distance from the airport at which an inbound aircraft blocks a waiting departure can be calculated to 1.91NM. This value can then be exported as one of many procedure definition data required in the Simmod simulation model.

A Multitude of Functions and Calculations is Required to Provide all ATC Procedure Input Values Resulting in High Complexity. In this example the links between different aircraft, airport, operational and regulatory parameters become evident which have to be combined to define one function for the procedure input value calculation. In total, 20 fundamental functions have to be provided to address all common runway configurations and all relevant arrival-departure combinations (see Fig. 9) providing both, time and distance values as input for the simulation. Those functions are part of a function library and are used within the preprocessing as required by the specific simulation model.

As visualized in Fig. 9 many calculations are involved in providing the required model input data for all possible combinations of successive aircraft movements for all defined aircraft groups and all available runways. If in a simulation model all n defined aircraft groups are allowed to operate on all m available runways, up to $n^2 \cdot m^2 \cdot 2$ input value pairs comprising time and distance separation values have to be calculated. Thereby each runway/procedure pair determines the function to be used. For a simple model with $n = 5$ defined aircraft groups and $m = 2$ runways this amounts to up to 200 value pairs.

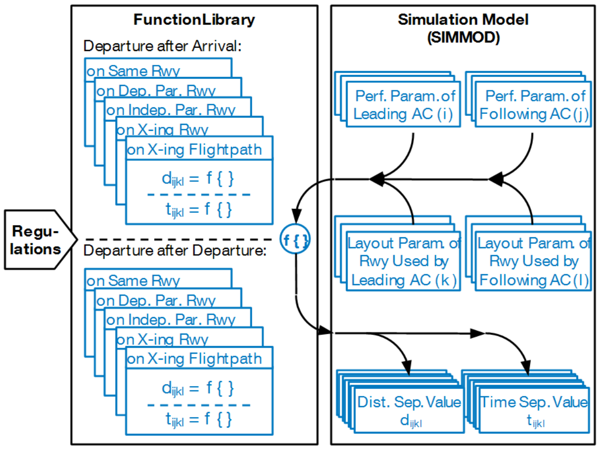

Fig. 9 A function library enables the calculation of all required air traffic coordination input parameters for all common runway configurations. The simulation requires input values for all possible combinations of successive aircraft movements for all defined aircraft groups and all available runways. Thereby each runway/procedure pair determines the function to be used.

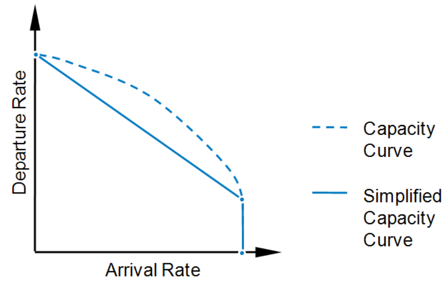

Fig. 10 The capacity impact of altered aircraft performance characteristics can be evaluated by using capacity curve representations according to E. Gilbo[21]. The calculation of three key points of the capacity curve is sufficient as basis for a straight line interpolation of the trade-off area[22] to produce a simplified capacity curve for quick and meaningful results.

This multitude of required input values substantially contributes to the complexity of the pre-processing underlining the requirement for an automated pre-processor where all relevant interrelations are properly defined and implemented.

2.3 Analysis of the Simulation Results

Theroretical and practial capacity curves according to E. Gilbo [21] are an ideal means to present capacity data of a simulation scenario and to analyse the impact of aircraft parameter changes. The calculation of only three single points of the capacity curve diagram is required for a simplified presentation of the theoretical capacity by using a straight line interpolation for the trade-off area of the capacity curve [22] (see fig. 10 and the example given in section 3). A systematic calculation of a capacity curve representing the practical capacity values incorporating average delay levels can also be performed according to the methodology presented by Stefan Theiss [23].

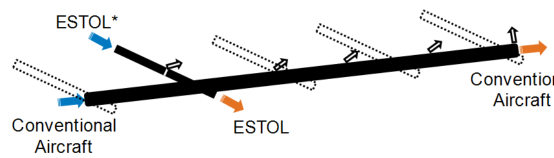

Fig. 11 Simulation of different positions of an additional intersecting runway for exclusively ESTOL operations. (*Note: Simultaneous operation of both runways can only be realized using land and hold short operations - LAHSO - for the ESTOL arrivals.) [24]

3 Exemplary Application of the Simulation Concept: Simulation of the Theoretical Capacity Potential of ESTOL Operations on an Intersecting Runway at Hub Airports

In an exemplary study, the theoretical capacity increase potential of the operation of aircraft with extremely short take-off and landing capabilities (ESTOL) on a generic airport with an intersecting runway configuration had to be evaluated. All procedure inputs for the simulation were produced using the pre-processing steps described above. As a result, maximum allowable throughput values were calculated for a generic hub-airport scenario. Multiple simulations addressed the influence of the intersecting runway's location on maximum throughput as illustrated in Fig. 11. For more details on this particular study please refer to [24].

Fig. 12 shows one of the capacity curve diagrams in a reduced key point representation as produced within the study. This provides an insight how the aircraft parameter and procedure variations' effects on airport capacity may be visually presented.

For the applied study scenario the simulation results revealed a theoretical capacity increase potential of up to 7 movements per hour (equalling 13% of all movements) when 10% of the operations are shifted from conventional medium class aircraft to ESTOL aircraft. Up to another additional 25 movements per hour can be

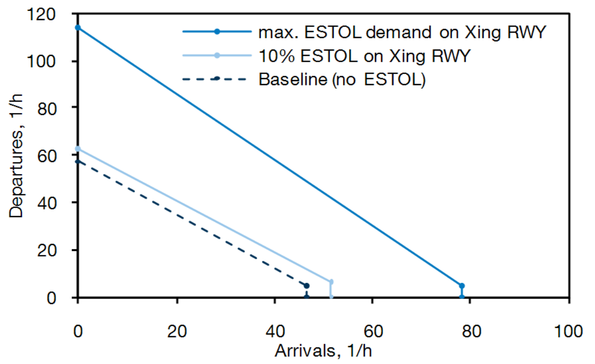

Fig. 12 Reduced key point representation of the capacity curve diagram as produced within the exemplary study. The displayed data show the maximum values of all survey positions for the crossing ESTOL runway which were achieved for the case when the intersection of both runways is located at the runway threshold of the conventional runway. [24]

achieved, if ESTOL traffic is further increased on the crossing runway to its ultimate capacity. Those maximum values were reached when the intersection of both runways is located at the runway threshold of the conventional runway (touch down area).

4 Conclusions

A feasible concept could be developed enabling to study the effect of altered aircraft performance characteristics on airport airside operations using Simmod, representative for an existing standard analysis tool in this field. The main challenge is the definition of generic relations between a wide range of interdependent variables in the simulation model. So far the concept proved its feasibility in an ESTOL aircraft parameter study where the multitude of parameter relations involved was manually defined and managed. The considerable amount of effort required for the manual study preparation and also its high susceptibility to data input errors makes an automation of the concept inevitable in order to provide an efficient means for the study preparation.

Important enablers to perform aircraft performance studies in airport airside simulations were identified: Study results are only valid for one specific study scenario which involves a specific reference scenario, an airport infrastructure scenario and an air traffic demand scenario. For general statements regarding a new aircraft's impact on airport capacity a multitude of different scenario combinations will have to be studied. All relevant parameter interdependencies in the simulation model have to be properly defined to ensure data consistency. A verification of the simulation results needs to be incorporated for example by using analytical calculations for non-complex sub-systems such as single runway operations for comparison. A basic regulation monitoring functionality can help to automatically detect errors in the simulation data preparation.

The presented concept is the status quo of current work at Technische Universität München to define a standard simulation approach for aircraft performance studies in airport airside simulations. Key element is the the automation of the consistent management of aircraft-dependent simulation parameters to allow more efficient aircraft performance driven simulation studies enabling the assessment of new operational concepts including complex runway system layouts.

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