AIRFIELD MODELLING – STATE OF THE ART

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ABSTRACT

Major airports, the core nodes of the air transportation network, are facing severe congestion problems due to continuously growing gap between air traffic demand and limited capacity. In such conditions, efficient capacity management and airport development planning are the most sensitive issues. Significant support in decision making in these areas comes from models specialized for airfield performance assessment and models for optimization of airport resource utilization.

This paper discusses the state-of-the art in airfield modelling, based on information gathered from a review of comprehensive literature. Existing methods and tools are classified by target area (runways/ taxiways/ aprons/ integrated systems), by modelling level (microscopic/ macroscopic) and by the role/application in decision making (performance assessment or utilization optimization). The review of existing airfield models should help identifying their characteristics and their capabilities (important for the current and future users), and the needs for further improvements and the areas to be improved (important for the researchers and other tool developers).

KEYWORDS: Airfields, Capacity, Modelling

INTRODUCTION

Major airports, the core nodes of the air transportation network, are facing severe congestion problems due to continuously growing gap between air traffic demand and limited capacity. In such conditions, efficient capacity management and airport development planning are the most sensitive issues. Significant support in decision making in these areas comes from models specialized for airfield performance assessment and models for optimization of airport resource utilization.

The infrastructure capacity is one of the most important operational and planning parameters of an airport (Janic, 2004). It is most common to identify airport overall infrastructure capacity with runway system capacity. However, overall airport capacity can also be constrained by ultimate capacity of other infrastructure elements (apron/gate area especially, or rarely taxiway system), as well as on how they are functionally related to each other.

Although runway and apron capacity are affected by almost the same factors, it does not imply that both of those resources reach their maximum throughput under the same conditions. By assessing maximum throughput of the runway system and maximum throughput of the apron complex we have a certain, but not a complete, picture of the overall capacity of the airfield and how it changes in time with demand changes. To complete the picture it is necessary to observe their functional relationship as well. We have a system in which runways represent aircraft entry and exit points to/from the system, taxiways represent transition to the apron area where aircraft are processed. In all three airfield elements we have interaction of arriving and departing flows, which requires the balancing of their individual maximal throughputs in order to achieve the best demand/capacity match, or to reach optimal usage of airport overall capacity.

This paper discusses the state-of-the art in airfield modelling, based on information gathered from a review of comprehensive literature. The review is conducted to support future research, which will focus on strategic planning of airport resources development to achieve (or maintain) balanced usage of overall airport capacity.

As an introduction to the airfield (performance assessment and optimization) models review, commonly accepted airfield capacity definitions are discussed in the first chapter of the paper, and the second chapter summarizes the factors affecting capacity of airfield elements.

In the third chapter of the paper the state-of-the art in airfield modelling is presented. Existing methods and tools are classified by target area (runways/ taxiways/ aprons/ integrated systems), by modelling level (microscopic/ macroscopic) and by the role/application in decision making (performance assessment or utilization optimization). Classical and modern approaches in airfields elements modelling are summarized in the paper. Only a few selected papers, which are considered to be the closest to the idea of future research, are described in more detail.

The review of existing airfield models should help identify their characteristics and their capabilities (important for current and future users) and needs for further improvements and areas to be improved (important for researchers and other tool developers).

1. DEFINITIONS OF AIRFIELD CAPACITY

Capacity is the ability of a component of the airfield to accommodate aircraft. It is expressed in operations (arrivals and departures) per unit of time, typically in operations per hour (Ashford and Wright, 1992).

In dependence on the dominant factors affecting capacity, different concepts of capacity may exist. Broadly, there can be operational, economic and environmental factors. They may work together, but in the most cases only one type of factors is dominant and thus determines airport capacity under given circumstances (Janic, 2004). This paper refers to operational capacity, assuming that the dominant constraining factors are operational.

In general, there are two basic capacity concepts: ultimate and practical capacity. Ultimate capacity is also known as saturation capacity or maximum throughput capacity. Both capacity concepts refer to conditions of saturation (the continuous demand for operations is assumed) and adherence to separation requirements set by the ATM system. The main difference is that ultimate capacity does not take into account the level of service (in other words it is determined regardless of delay), while practical capacity considers a certain acceptable level of service (specified average delay which is acceptable, usually 4min).

Concepts of ultimate and practical capacity are recognized and used in most relevant literature (Janic, 2009; De Neufville and Odoni, 2002; Ashford and Wright, 1992; FAA, 1983; Hockaday and Kanafani, 1974).

As a reflection of what occurs in the case of the most congested airports in the world today, the runway system is considered to be the major capacity constraint and that is why airfield capacity is usually expressed through runway system capacity. The definitions of ultimate and practical airport capacity by (De Neufville and Odoni, 2002) are given below:

- **Maximum throughput capacity** (MTC) or **saturation capacity** indicates the average number of movements that can be performed on the runway system in 1h in the presence of continuous demand, while adhering to all the separation requirements imposed by the ATM system.
- **Practical hourly capacity** (PHCAP), originally proposed by the FAA in the early 1960s, is defined as the expected number of movements that can be performed in 1h on a runway system, with an average delay per movement of 4 minutes. The runway system reaches its capacity when this threshold is exceeded. As a rule of thumb, the PHCAP of a runway system is approximately equal to 80-90% of its MTC, depending on the specific conditions at hand.

These two capacity concepts are used for planning purposes and they are delivered by all capacity estimation models. It is not always suitable to express capacity in a 1-hour period, like it is usually done for maximum throughput capacity or practical capacity. Some other time units (smaller or larger) can and probably should be used for better description of available resources potential to meet particular demand requirements. This is an especially sensitive question at hub airports, where demand comes in waves of successive arrivals followed by a wave of successive departures.

In addition to these two basic capacity concepts, there are also sustained capacity and declared capacity, defined by (De Neufville and Odoni, 2002) as it follows:

- **Sustained capacity** of a runway system is defined as the number of movements per hour that can be reasonably sustained over a period of several hours. Maximum performance often cannot be sustained in practice for a period of more than one or two consecutive hours. Sustained capacity is a more realistic target than maximum throughput capacity when it comes to operations over a period of several hours or an entire day of air traffic activity.

- **Declared capacity** is defined as the number of aircraft movements per hour that an airport can accommodate at a reasonable LOS (Level of Service). Delay is used as the principal indicator of LOS. There is no accepted definition of declared capacity and no standard methodology for setting it. In most instances, the declared capacity seems to be set at roughly 85-90% of the MTC of the runway system.

These two concepts are not meant for planning purposes, but rather for describing reasonable capabilities of existing systems. Declared capacity is widely used for airport benchmarking, although there are many different understandings of declared capacity which sometimes leads to inconsistency in comparison.

Capacity is a performance indicator which testifies about airport capabilities to accept certain demand. It is also important to know to what extent the available capacity is utilized. The available capacity utilization efficiency is another important performance indicator, not only for peak hour periods, but also for longer time horizons (day, week, and season). Capacity utilization level can indicate underutilization of the available capacity (as a consequence of traffic demand being lower than available capacity) or inefficiency in capacity management at congested airports (when delays occur due to inability to accept all scheduled operations on time). Cherniavsky and Abrahamsen (2000) explain how airport utilization metrics (as a subset of FAA aviation system performance) are calculated.

2. FACTORS THAT AFFECT AIRFIELD CAPACITY

In literature there are different approaches to classifying factors affecting airfield capacities (Janic, 2009; De Neufville and Odoni, 2002; Ashford and Wright, 1992; Newell, 1979).

Based on research and practice, major factors affecting runway capacity are classified in four groups in this paper. The factors belonging to each group are listed below.

1) **Runway system layout** – number of runways, runway length and runways' mutual position (parallel, crossing, extended runway centrelines crossing (V configuration)), number of simultaneously active runways, available runway configuration in respect to type of operations (departures/ arrivals/ mixed operations), number and location of runway exits, existence and position of crossing taxiways,
2) **Demand characteristics** – total demand, demand distribution, mix of operations (arrivals/departures), fleet mix, type of flights mix (scheduled, charter, cargo, business),
3) **Operational constraints** – separation requirements set by ATM, runway occupancy time,
4) **Local conditions** – meteorological conditions, environmental conditions.

It is very important to notice that these four groups of factors are not sharply separated, but that they overlap. For example, runway exit location is an infrastructural factor, but at the same time it is also an operational factor, because it directly affects runway occupancy time, which then affects separation of A-A and A-D aircraft at a particular airport; or local meteorological conditions, especially wind and visibility, have direct impact on runway configuration in use.

Although the runway system is identified as the major airport scarce resource, the capacity of other infrastructure elements should also not be neglected.

The taxiway system at major airports is most often designed to provide capacity which exceeds the capacity of the runway system and should not be observed as the factor limiting airport capacity (De Neufville and Odoni, 2002). This does not necessarily mean that some local constraints cannot be identified, especially in the areas of taxiway intersections, points where taxiways cross an active runway or where high-speed exits merge with taxiways. The general rule is that taxiway capacity problems are specific for each airport and must be resolved at the local level, for the specific configuration and under the local conditions.

On the other hand, apron capacity could be a limiting factor of the overall capacity, and airports have lately been facing this more often. It depends on similar factors as the runway system. The factors can be classified in 3 groups:

1) **Apron layout** – number of parking stands, apron stands configurations, number of stands which can be simultaneously used in respect to lateral separation, number of stands per aircraft types,
2) **Demand characteristics** – fleet mix, type of operations share (arrivals/departures), mix of users (classified by different criteria - airlines, or flights origin-destination combination, from the perspective of gate assignment policies typical for U.S. and Europe),
3) **Operational constraints** – turnaround time, buffer time between aircraft which use the same or laterally endangered stand, policy of parking stand usage (by airline in U.S., or by flight origin-destination in Europe)
4) **Local conditions** – meteorological conditions (particularly visibility).

The runway system is the entry and the exit point for all the operations that have to be processed in the apron area through the turnaround process. Although runway and apron capacity depend on almost the same factors, it does not mean that they reach their local ultimate capacities under the same conditions. To achieve a balance between runway and apron utilization, through efficient capacity management, it is also important to observe their functional relationship.

The remainder of the paper provides a review of the existing models for capacity assessment and management, both for each of the airfield elements separately, and integrated into a complete or a partial system. The possible gaps will be identified based on the capabilities of the existing model, especially in the area of strategic planning of airport resources development.

3. AIRFIELD MODELLING

Further on, airfield will be observed as a system consisting of runways, taxiways and apron areas, taking in account terminal airspace and the terminal building to the extent which is inseparable from the runway-taxiway-apron system.

This chapter presents a review of the airfield models that describe both separate airfield elements (runway, taxiway, apron) and integrated systems, an overview of the models for strategic planning or support to airfield elements development plan, as well as the models for tactical and operational planning mainly used for optimization of available capacities utilization of the RWY/TWY/APR system.

For models developed and published before 1997, the existing reports created for the FAA representing a detailed review and evaluation of the exiting models for air traffic modelling (Odoni and Simpson, 1979; Odoni, 1991; Gass, 1992; Odoni et. al, 1997) are used as a reference. For the period after 1997, research on modelling in air transport is done through published papers in scientific journals and in conference proceedings, official reports and other relevant documentations (over 100 bibliography references are covered).

3.1. Classification of airfield models

It is most common to classify airfield models with respect to three aspects: level of detail, methodology, and coverage.

Models can be classified according to the level of detail as macroscopic and microscopic. The main objective of macroscopic models is to provide approximate answers mainly for planning purposes and some design issues, with an emphasis on assessing the relative performance of a wide range of alternatives. Microscopic models are designed to deal with tactical issues and aim at a highly faithful representation of the various processes that take place at the airport. These types of models move entities, or objects (aircraft, passengers, bags, etc.) through the airport element(s) which is (are) represented by the model.

According to the methodology, models can be divided into analytical and simulation models. In practice there is a strong correlation between classification according to level of detail and methodology. Macroscopic models are mostly analytical, although sometimes they can be transformed into simulation. Microscopic models are always simulations. Analytical models consist of a set of mathematical relations that describe simplified operations of some of the airport elements. They are used for assessment of the performance indicators, usually capacity or delay. Simulation models move individual objects (which are aircraft in airfield models) through the system elements. Based on the parameters and flow intersections of each entity, the time which objects spend in each segment of the system is determined, and consequently system performance and the level of service. According to whether they are analytical or simulation models can be: dynamic or static, and stochastic or deterministic.

According to the scope or model coverage airfield models can be divided into models focused on the runway system, the taxiway system, the apron area, or integrated models.

3.2. Capacity assessment models

In the remainder of the paper the existing airfield models are classified according to the airport element that they mimic. The majority of models cover runway systems because of the fact that this airfield element is the greatest capacity constraining factor. There are very few models for taxiway systems. The apron area is very locally specific and this airport element is usually modelled as a part of integrated microscopic models that treat specific airfield. There are no generic models for aprons suitable for quick assessment of apron area capacity.

In the Table 1 the most common models being applied worldwide for airfield analysis are classified by the level of detail and by model coverage/scope. They will be discussed further in the text.

Table 1. Airfield models for performance assessment classified by level of detail and coverage

	model coverage/scope		
level of detail	*aprons and taxiways*	*runway and final approach*	*RWY+TWY+APR*
macroscopic	Horonjeff model and extensions*	Blumstein model and extensions* FAA Airfield Capacity Model* DELAYS* LMI Capacity and Delays Model*	MACAD#
microscopic		ACATS *runway* Simulator STROBOSCOPE	SIMMOD TAAM The Airport Machine HERMES RAMS Plus Total AirportSim AirTOp

* analytical model
\# analytical model, except the apron module

3.2.1. Runway modelling

In the long history of airfield planning, runway capacity has always been the crucial parameter and this is still the case. There are plenty of models for estimating runway system capacity.

The basis for analytical probabilistic models for runway capacity estimation (in conditions of saturation) was set by Blumstein in 1959. Blumstein (1959) set the method for calculating landing capacity for a single runway as the reciprocal of mean time interval between two consecutive passes “over” the runway threshold, while adhering to the ATM system separation requirements, assuming continuous demand for operations. The mean time interval between two consecutive aircraft passes over the runway threshold depends on the length of the common final approach path and on separation requirements at final approach set by the ATM. Mean inter-arrival time also depends on the fleet mix (share of aircraft types in total traffic). Even today the same approach for ultimate capacity estimation is used. All existing runway analytical models are in fact certain extensions and/or modification of Blumstein method.

The first step in Blumstein model improvement was done by Harris (from: Ashford and Wright, 1992). He adapted the model for runway capacity estimation for departures and mixed operations, and introduced stochastic to aircraft arrival at the final approach fix. After that, Hockaday and Kanafani (1974) upgraded Harris' model. They incorporated a number of additional features. These include accounting for the effect of wake turbulence created by large jet aircraft separations, and the derivation of optimal operating strategies for specific proportions of arrivals and departures in the mix. The model also extends runway capacity analysis to the case of multiple runways of various configurations.

In the meantime, numerous modification of Blumstein runway capacity estimation model were developed, referring to capacity estimation after introduction of new procedures, or technological improvements. For example, Tosic and Horonjeff (1976) analyzed the effects of the MLS (Microwave Landing System) introduction on runway landing capacity. The Microwave Landing System (MLS) describes multiple and curved approach paths to the runway whereas the Instrument Landing System (ILS) describes only a single straight path. Runway landing capacity is analyzed assuming that the vertical separation within the operating area of the MLS is not permitted, i.e. horizontal separation is crucial. Runway landing capacity is also analyzed for the case where horizontal and vertical separation between aircraft approaching a runway is possible. One of the latest runway capacity estimation modifications is done by Janic (2008). Janic (2008) developed analytical models for calculating the ultimate arrival, departure, and mixed operation capacity of closely-spaced parallel runways using innovative approach procedures. In particular, the capacity model for arrivals assumes the use of two rather innovative approach procedures – the Staggered Approach Procedure (SGAP) and the Steeper Approach Procedure (SEAP) in combination with the baseline Conventional Approach Procedure (CNAP) under Instrument Meteorological Conditions (IMC) and Instrumental Flight Rules (IFR).

The basic runway capacity estimation method set by Blumstein and its extensions served as the basis for FAA Airfield Capacity Model and LMI Capacity and Delays Model, which represent the same method translated into computer language, enabling faster calculation and thus being more convenient for analysis of different scenarios.

The FAA Airfield Capacity Model calculates maximum throughput capacity of the runway system under conditions of constant demand for service. It is coded in FORTRAN. It has the ability to estimate capacity for 15 different runway configurations. All runway configurations are observed as the combination of 4 fundamental configurations: single runway, closely-spaced parallel (dependant), medium-spaced parallel (independent departures) and crossed runways. The first version of FACM is developed during the 1970s by Peat, Marwick, Mitchell and Company and McDonnell Douglas Automation, which was later modified by the FAA supported by the MITRE Corporation (Enhanced FAA Airfield Capacity Model) (Odoni et al., 1997).

A key feature of the LMI Capacity and Delays Model is that it attempts to explicitly take into account probabilistic aspects of airport operations (approach speeds, runway occupancy times and delay in communication time between airport controllers and pilots are all incorporated into the model as random variables). The LMI Capacity Model is designed to compute the so-called "runway capacity curve", i.e. the set of points that define the envelope of the maximum throughput capacities that can be achieved at a single runway, under the entire range of possible arrival and departure mixes. The model determines four points on the runway capacity curve: “all arrivals”, "freely inserted departures" (departures that can be inserted into arrival stream “for free” i.e. without stretching arrival sequence), "alternating arrivals and departures" (achieved through an arrival-departure-arrival-departure-... sequencing, implemented by "stretching", when necessary, the interarrival gaps, so that a departure can always be inserted between two successive arrivals) and "all departures" (Odoni et al., 1997).

The CAMACA (Commonly Agreed Methodology for Airport Capacity Assessment) can also be included in the group of analytical runway capacity models. This is an analytical model developed by Eurocontrol to estimate theoretical runway capacity. It is available free of charge as a web-based application [38]. Divaris and Psaraki-Kalouptsidi (2008) estimated runway capacity for Athens International Airport using CAMACA as the analytical, and SIMMOD as the simulation model.

Modern tools from this category that are used for capacity estimation of complex runway systems are: Airport Capacity Analysis Through Simulation (ACATS), described by Barrer and Kuzminski, (2005) and runway Simulator, by Barrer (2007). These two models are developed by the MITRE Corporation and are used for runway system capacity estimation. They were made to overcome certain problems of previously available tools, which were mainly that of low efficiency, with calculation time significantly increasing with the complexity of the runway system. Furthermore, they are very flexible, and unlike the abovementioned models, they can be easily applied to any airport in the world, without changing the simulation code itself. Both ACATS and runway Simulator are somewhere in-between analytical and simulation models. When applied to complex runway layouts, they are much more accurate than analytical models and can produce results much faster than other simulation-based models. The required input parameters are: the configurations of airport runways, the traffic demand characteristics (fleet mix and arrival-departure ratio), and the ATC separation rules that apply to operations on the set of runways. For estimation of maximum throughput capacity the model uses unscheduled flights (flights are generated according to the fleet mix distribution specified by the user) which enables full runway utilization when the throughput is the best that can be achieved. These two simulators can be used for other purposes besides estimating capacity. It is possible to use a schedule of flight arrival and departure times. In this mode tools can model the experience of each flight in the vicinity of the airport and thereby estimate the effect of separations from other flights, tactical sequencing and runway assignment decisions. In particular it is possible to estimate the delay induced by the demand pattern, the runway layout, and the ATC rules used for separation, which is a broadly used measure of system performance.

One of the latest papers on the runway capacity estimation modelling is presented by Kim and Hansen (2009). It deals with validation of one of the first (ACM) and one of the latest (runway Simulator) runway capacity estimation models. This paper proposes and demonstrates two validation methodologies that can be used to test model predictions against reality. Estimates from runway capacity models are compared with empirical counts of the number of operations for two airports SFO and LAX. The validation results indicate that the models predict wider ranges of capacities, which are seen empirically, and that both models predict greater differences between average VMC and IMC capacity than the data indicates, as they typically appear to overestimate VMC capacities. Overall, it appears that the runway Simulator estimates are typically better than those of ACM, as expected.

Another tool for capacity and delay estimation is the activity-based simulation system called STROBOSCOPE, described by Martinez, Trani and Ioannou (2001). Unlike the classical simulation approaches to predict runway capacity and delays at airport, based on objects moving through the model’s network, STROBOSCOPE models are developed from the perspective of activities and their interactions. Network nodes represent activities or tasks performed by various resources working together. Links indicate how resources flow from node to node. Queues are also defined in the network, to hold inactive resources of a specific type.

DELAYS is an analytical macroscopic runway model which is not used for runway capacity estimation, as all the previously discussed models. This model actually uses capacity assessed in other models and, based on demand, estimates delay generated on runway system. The runway system is described as a queuing system whose customers are aircraft requesting landing or take-off, and whose capacity is equal to the arrival, departure or total capacity of the runway system, depending, respectively, on whether one is interested in delays to arrivals, to departures or to the "average operation". The principal deficiency of DELAYS is that it does not distinguish among individual aircraft or types of operations in cases when the aircraft or operations share the same runway. For example, when a runway is being used for a mix of arrivals and departures, DELAYS will compute an average delay for all operations, without considering the fact that arrivals often receive priority over departures. In practice arrivals may incur less delay and departures more delay than the average value computed by DELAYS.

3.2.2. Apron modelling

Apron areas are very locally specific and therefore usually observed, modelled and resolved on a case-to-case basis. There are few trials of generic apron modelling, which appeared not to be capable delivering good approximation of capacity, as is the case for runways. Later, when we stepped into microscopic simulation modelling, aprons are modelled and analyzed as part of integrated airfield models, and not many researchers seemed to be interested in trying to create a generic model that would provide fast analysis of different apron layouts, as is the case, for example, for runway Simulator.

For quick apron capacity there is a probabilistic analytical model which is based on the Blumstein's model and adapted for other purposes (Horonjeff and McKelvey, 1994). Apron capacity is determined as the quotient of number of parking stands and mean stand occupancy time. Mean stand occupancy time depends on the fleet mix (different aircraft type share in the traffic) and average stand occupancy time for each aircraft type. This way dynamic apron capacity can be determined for certain apron layouts described by the total number of stands and number of stands per aircraft type (static apron capacity), for the given traffic demand structure. The same relation can also be used for the calculation of the required number of stands, if total demand and its structure, and average stand occupancy time are known.

Modifications of the basic model include other parameters in the calculation: aircraft positioning time, buffer-time between two consecutive aircraft which use the same parking stand and/or parking stand utilization factor. The role of buffer-time is to absorb disturbances caused by delays which are typical for the airport in question. Utilization factor represents the relation between the time the parking stand is being used and the total time when it is available. Extensions of this simple analytical calculation also include restricted usage of parking stands by different parameters such as: aircraft size, airline (U.S. gate usage policy), type of flight (low cost, charter, traditional), origin-destination pairs (European gate usage policy - Schengen, non-Schengen, international).

Existing analytical apron models are not suitable for quick analysis of apron areas that have flexible layouts, several available configurations in respect to aircraft types that can be simultaneously accommodated on parking stands. This is the case with a majority of large airports where the same space can be used by one large aircraft or by two smaller aircraft simultaneously in other variants.

Steuart (1974) deals with estimation of the required number of parking stands at an airport, or the number of flights that can be accommodated at a given number of parking stands. He introduces the influence of airline scheduling and airport operating procedures on parking stand utilization efficiency.

To the best of our knowledge, and as a result of this survey on airfield modelling, there are no macroscopic models for apron performance assessment (whether it is capacity or delay) that address only the apron area, separately from other airfield elements. The apron area is determined by the total number of stands, number of stands per aircraft type, gate usage policy (by airline: exclusive, preferable, shared; or by origin-destination pair: Schengen, non-Schengen, international), its position in respect to the runway system, and their mutual functional relations through the taxiway system, as well as by the apron taxiway system, ground handling characteristics, and other relevant factors. This implies that apron capacity problems are specific for each airport and should not be generalized, but rather resolved at the local level. It is very difficult to isolate these relations from the entire airfield system, which is why apron microscopic (high-level-of-detail) models usually exist as a part of integrated simulation models.

3.2.3. Taxiway modelling

Unlikely runways (especially) and aprons (in some cases), the taxiway system is not a capacity constraint in most cases. Taxiway system models for performance assessment do not exist, and there is no need for them. However, they do exist as a part of microscopic simulation models of entire airfield.

Although they are not a constraining capacity factor, it does not mean that local bottlenecks are not generated on the taxiway in certain cases. That occurs in intersection areas, when taxiways cross the active runway, or between two taxiways with opposite traffic flows. This issue will be addressed in the part where airport optimization models are summarized.

3.2.4. Integrated airfield (RWY-TWY-APR) modelling

Models of complete airfield (runways/taxiways/apron areas) are usually simulation models which model airport elements and their interaction to a high level of detail. The most common airfield simulation models are:

- The Airport and Airspace Simulation Model (SIMMOD), developed by the ATAC corporation,
- Total Airspace and Airport Modeller (TAAM) developed by Preston Aviation Solution,
- Reorganized ATC Mathematical Simulator (RAMS Plus), the first version of which was developed by Eurocontrol, and then taken by ISA Software for further development and distribution,
- Heuristic Runway Movement Event Simulation (HERMES), developed by the British Civil Aviation Authority/ National Air Traffic Services (CAA/NATS),
- The Airport Machine, produced by Airport Simulation International,
- The Total AirportSim, developed by IATA, and
- AirTOp as the representative of the newest generation of fast-simulation models, produced by Airtopsoft SA.

All of the listed models, except last two, are discussed in details by Odoni et al. (1997), covering their input requirements, output, major assumptions, application, availability, etc. They will be mentioned here only in few words, regarding their coverage, application in practice and some latest extensions.

All of the models are high-level-of-detail network models. SIMMOD, TAAM, RAMS Plus and AirTOp cover airspace and airport operations. They are so called gate-to-gate models, while The Airport Machine and HERMES are limited only to the airport area. The Total AirportSim except airspace, runways and aprons and gates, includes terminal building in its scope as well.

RAMS Plus is used worldwide for en-route and terminal area analysis. On the other hand, the so-called ground module (for aircraft surface movement at the airport) was released in late 2003, but based on practical experience to the best of our knowledge it is still not widely accepted among the users performing airport operations analyses. Ground operations at airports are more often simulated using TAAM or SIMMOD. It can be concluded from practice that for gate-to-gate analysis it is most common to use either TAAM, or the (cheaper) combination of RAMS for en-route and terminal airspace and SIMMOD for surface (ground) operations.

One of the tools that belongs to this group of gate-to gate models is AirTOp [37]. It represents a new generation of fast-simulation tools. In comparison with other fast-time simulations it does not introduce much innovation in modelling the airfield itself, but its competitive advantages are the possibility to integrate future or customer-specific ATC concepts much faster than using any other tools on the market. Also, the AirTOp interface has been specifically designed to reduce the time needed to set up and debug simulations, in order to achieve faster results and better cost efficiency.

The Airport Machine is a typical network (node-link) airfield model that covers all aircraft activities from a few minutes before landing until a few minutes after take-off. Similar to it is HERMES, but while full airport operations, including taxiing, are simulated, HERMES puts greatest emphasis on runway operations. It is the least known model from this group, since it has been designed to account for the specific rules used at Heathrow and Gatwick airports, for computing very accurate capacity estimates for these two special cases.

Airspace, runway, apron, gate and passenger terminal studies can all be carried out using Total AirportSim [66]. The model is designed to offer a comprehensive solution that covers a wide variety of demand/capacity and level of service applications for the simulation of aircraft and passenger flows. It contains the so-called airfield/runway module, which allows for the simulation of aircraft flows from the airspace to the gate, including runway, taxiway and apron. It can be used to determine the existing capacity and limiting factors, and for assessing the impact of improving operations in airspace studies. The model can be used to identify the nature, location and degree of congestion and to measure delays. It also contains a terminal module for passenger flow simulation, which can be a stand-alone application. It also contains gate assignment module, as a connection between these two modules. The gate system is the start and end point of a gate-to-gate journey and is used in runway and apron simulations to determine the airside dynamic capacity of an airport. The gate simulation results can be used in terminal simulation where the aircraft flow at the gates impacts the passenger demand in the terminal building.

Fast-simulation airfield models are of great importance for airport planning, especially at the strategic level, but it can be used for tactical planning as well. With airfield simulations one can determine the effects caused by demand changes (demand increase, demand characteristics changes, temporary changes caused by the occurrence of certain events, etc.), by changes on the supply side (new runway, new parking stands, new runway exit, closure of runway or apron due to reconstruction, etc.), or by operational changes (procedural or technological improvements, new concepts introduction, etc.) in a quick and reliable way, which makes it possible to analyze different scenarios and to choose the optimal solution based on that.

Unlike all the previously mentioned models which are microscopic, one of the rare integrated airfield macroscopic models is MACAD, Mantea Airfield Capacity and Delay (Andreatta et al., 1998; Andreatta et al., 1999; Stomatopulos, Zografos and Odoni, 2004), developed by the Athens University of Economics and Business. MACAD integrates macroscopic airside models to provide approximate estimates of the capacity and delays associated with every element of the airfield. It is fast, flexible and easy to use. All of this makes MACAD very suitable for strategic decision-making. It is primarily meant for studies that require only approximate answers while examining a wide range of hypotheses and scenarios regarding future conditions at an airport. The abovementioned microscopic models are inappropriate for such studies since they require huge effort for creating models with incorporated high levels of detail of system specification and data required both for creating and running the model. MACAD obtains reliable approximations quickly even with a limited set of inputs. The MACAD consists of five modules: airside, weather, detailed schedule generation, coordination and user interface. The airside module is the most important and estimates the capacity, utilization and delays at the various elements of the airside, given the dynamic configuration of the airfield, operational characteristics, and the demand profile for a 24-hour period. The airside module consists of a runway system capacity model, a runway delay model, and an apron/taxiway macroscopic simulation model (Figure 1).

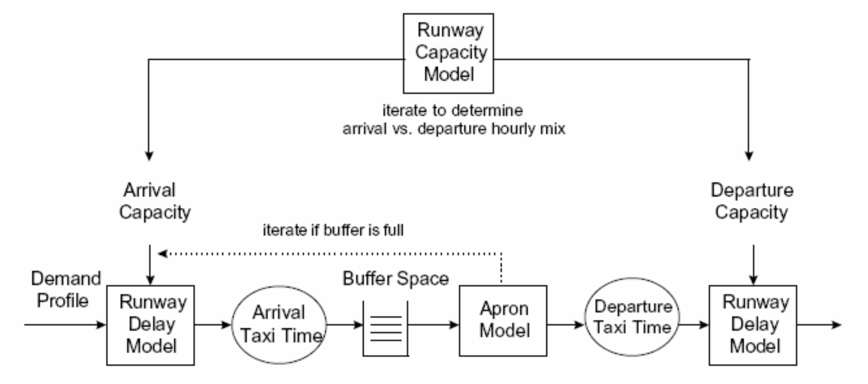

Figure 1. Airside Module, MACAD

A runway system capacity model is a generalized stochastic analytical model for the estimation of the capacity envelope of the runway system, for a wide variety of runway configurations. It identifies capacity limits for all mixes of arrivals versus departures and explicitly takes into account the stochastic nature of aircraft operations. Existing methodology for runway modelling is used but it is further extended and modified. A runway delay model is an analytical model for computing the distributions of delays throughout the time interval of interest, given dynamic capacity and demand. A version of the DELAYS model is used in MACAD. An apron/taxiway macroscopic simulation model has the main role of computing the delays due to limitation of apron stands and the utilization of apron area. The model identifies the stands which are most limiting (depending on the aircraft types, the type of flights, and the handler/airline that they serve) as well as the ones that are underutilized for the examined configuration and demand scenarios. Taxiways are represented by probability distributions for the taxi-in and taxi-out times for each runway configuration.

Another tool, called SLAM (Simple Landside Aggregate Model), was developed at the University of Padova, in close cooperation with Milan Airport Authority, with an aim to creating a decision support tool for strategic airport planning, which would (together with MACAD) cover both airside and landside areas of the airport. It is an analytical aggregate model for estimating capacity and delays at airport terminals. Andreatta et al. (1998) and Andreatta et al. (1999) propose the integration of MACAD and SLAM through a common database where information on the airport configuration, the airport usage, and flight schedule are shared by the models. The delays estimated for one of the elements of the airport (landside or airside) can be taken in account in the analysis of the other (airside or landside) through the relevant modification of the flight schedule in the database.

The MACAD model is also included as one of the components of the advanced decision support tool for total airport performance assessment and capacity management, which is proposed by Zografos and Madas (2007). The proposed system introduces a modelling approach that integrates different existing tools for landside and airside (including airport surrounding affected by the traffic through noise and emissions) in a problem-oriented (i.e. decision making question-driven) environment. The decision support system (DSS) is expected to provide support to decision makers both for strategic and tactical airport planning, by covering wide range of potential questions that can be raised (supply side changes through infrastructural changes or changes caused by introduction of new operational procedures, concepts, or technological improvements, and demand side changes). The following models are selected for strategic module of analysis: MACAD for airside, SLAM for landside, INM for noise assessment and prediction, TRIPAC for third party risk analysis, EDMS for emissions, CBM for cost-benefit analysis and FLASH as flight schedule generation tool. The module for tactical planning includes: TAAM, SIMMOD, RAMS Plus, INM, TRIPAC, CBM and TRAFGEN for flight schedules configuration compatible with and used by SIMMOD, RAMS and TAAM simulation tools.

Wijnen, Warren and Kwakkel (2008) and Kwakkel et al. (2009) describe another decision support tools for airport strategic planning. Authors put emphasis on the fact that there is a limited ability to explore variety of alternatives, their consequences for airport performance, and possible strategies for ensuring that airport meets its business objectives. These researches are driven by similar state-of-the-art based conclusions as for the previously discussed DSS - that existing tools and techniques for airport performance analysis are not integrated and do not produce the information relevant for decision-makers. The proposed tool would integrate available macroscopic tools for capacity, noise, emission, and 3rd party risk analysis. Regarding the macroscopic model for airfield capacity analysis, the usual approach is applied – the runway system is taken as constraining factor and the FAA Airfield Capacity Model is used for airfield capacity modelling. Again, the apron area is not taken in account as a possible constraining capacity factor.

It can be seen that modern tendencies in strategic airport planning are aimed in the direction of integrating different disciplines that are important for decision makers. But still there is lacks of a tools for quick airport capacity analysis, which encompasses apron areas in addition to the runway system.

Among the new generation models that cover activities and processes at or in the vicinity of the airport, there is another recently published approach, the so-called Airport Logistic concept (Lindh et al., 2007; Norin et al., 2009). The Airport Logistics concept is an attempt to create an integrated airport model which is intended to serve as the fundamental base for a decision support system for efficient resource management, containing strategic, tactical and operational components. The overall efficiency of the system is observed as a function of individual efficiencies of every single participant in the system (airport, airline, ATC, ground handler, etc.). The Airport Logistic concept is still in the development phase. Furthermore, this concept will be presented in the next chapter which gives an overview of models for airport resources utilization optimization.

All the above-mentioned models are models that describe airport processes in more or less detail, and they are used for airport performance (with an emphasis on capacity) parameters, and are used for supporting airport planning (strategic or tactical). On the other hand, there are models whose primary purpose is not performance assessment but support for resource management, through utilization optimization. Decision support tools for limited airport resources management have been developed, tested and introduced in practice in the past 15 years, when it became obvious that airports are becoming the most critical area in the air transportation network in terms of capacity-demand misbalance.

3.3. Resources utilization optimization models

In order cope with traffic increase airports can react by expanding their capacities by building new runway, or by using nearby airfields with low demand and underutilized existing runways (secondary airports, military airports). However, before making huge infrastructural investments airport can do something to increase efficiency of existing resources utilization through technological improvements, by introducing decision support tools for efficient capacity management. There are such tools meant for tactical and operational purposes and they are mostly microscopic models of one airport element or more than one integrated in the system.

As expected, the first tools were developed for runway system capacity management, since the major bottlenecks on the airfield come from the runways. The first among runway capacity management tools were AMANs (Arrival Manager-s), which were developed and introduced to support arrival sequencing in order to increase runway throughput and avoid the generation of delays in peak periods (e.g. CALM [18]). Very soon they were followed by DMANs (Departure Manager-s), for sequencing departing aircraft in order to minimize waiting time and queue lengths (e.g. Feron et al., 1997; Hasselink and Basjes, 1998; Idris et al., 1998; Anagnostakis et al., 2000; Jonge, Tuinstra and Saljee, 2005; Boehme, 2005b). In addition to runway utilization optimization there were also SMANs (Surface Managers), (e.g. Lowson, 1997; Atkins and Brinton, 2002; Atkins et al., 2003; Atkins et al., 2004) and TMANs (Turnaround Managers), for surface movement optimization and turnaround process optimization (e.g. Wu and Caves, 2004b).

According to the state-of the-art given in 2005 by Boehme (2005a) AMANs and DMANs are fully developed and implemented decision support tools. The same is with TMANs, while SMANs are still in the development phase, as is the case with coordination between these tools (AMAN to DMAN, and both of them with SMAN).

Some of the latest papers on modelling of surface movement that focus on optimization of this segment of airfield operations are: (Gotteland et al., 2001), (Gotteland, Durand and Alliot., 2003), (Smeltink et al., 2003) and (Pina and de Pablo, 2005).

Gotteland et al. (2001) and Gotteland, Durand and Alliot (2003) propose new tool for assisting air traffic controllers in choosing the best taxiways and the most suitable holding points for aircraft. The model takes into account the airport layout, restrictions on taxiway usage (passing, unidirectional, bi-directional, etc.), speed uncertainty, safe separation during taxiing, runway capacity, as well as target take-off time (determined by slot). The goal is to minimize the time spent from gate to take-off (including queuing time), or from landing to gate, respecting separation from other aircraft and the runway capacity. The tool was successfully tested on one-day traffic sample at two airports in France, Roissy Charles de Gaulle and Orly.

Smeltink et al. (2003) also describes a similar model for taxiing planning optimization, supporting the ground controller in tactical planning and scheduling of individual aircraft, to provide safe, expeditious and efficient movement from the current position (gate or runway) to its intended location (runway or gate). The model was tested at the Amsterdam Schiphol airport and based on the results the difference between the total and ideal taxiing time can be decreased from 20% to 2%. This reduction of the taxi delay makes the taxi process more efficient, and it also reduces fuel emission levels (a major environmental problem at busy airports) due to taxiing.

Another taxiing optimization model is the so-called dynamic taxi planner, introduced by Pina and de Pablo (2005) developed by AENA in cooperation with the Polytechnical University, Madrid. A prototype of the dynamic taxi planner is integrated and tested through the LEONARDO system, developed for the Madrid Barajas airport, which will be discussed in more details further on in the text. The dynamic taxi planner is a mathematical model that optimizes aircraft surface movement through network flow optimization. The model assigns an optimal route to each aircraft, taking into account the current and the predicted traffic situation. It calculates taxiing time for each aircraft, based on the optimal route. This model also calculates waiting time at points where the taxiway intersects active runways and departure queuing time. Taxiing times are not fixed values but they are calculated depending on the runway in use, the allocated parking stand, operational procedures, runway utilization, traffic congestion, meteorological conditions, etc.

Boehme, Brucherseifer and Christoffels (2007) describe a new concept for the coordination of arrival and departure management, when applying mixed operations at an airport, later developed by the German Aerospace Centre (DLR). This is the so-called CADM (Complete Arrival Departure Manager) and it consists of AMAN and DMAN which are coordinated through an arrival-departure coordination system ADCO (Arrival Departure Coordinator). The coordination is based on an appropriate tailoring of arrival-free intervals (AFI) and a corresponding path stretching for the respective arrivals. Thereby the coordination system takes into account both the departure traffic situation on the ground and the arrival situation in the TMA. The simulation results support the hypotheses that the CADM concept can enhance total throughput, and for departures it can increase punctuality and compliance with CMU slots with only minor extension of the arrival flight time.

A similar concept is given by Deau, Gotteland and Durand (2009). They focus on the interactions that have to be developed between the runways scheduling (AMAN-DMAN) system and the surface management (SMAN) system, in order to reduce ground delay. It was developed for the specific case of Paris Roissy Charles de Gaulle airport. In this case, the previously developed model (described above) for surface movement optimization is integrated in the model for optimal runway sequencing which suggests departure sequence to fit to arrival sequence (given by AMAN) and the assigned CFMU slots. The ground traffic simulation results show a reduction of both arrival and departure delays as a benefit of SMAN synchronisation with the AMAN-DMAN system.

General tendency is to integrate all those managers into a single overall manager, which would be able to support all airfield resource management, aiming at optimization of available resources utilization or exploitation from the viewpoint of all stakeholders. One such tool has been developed by the German Aerospace Centre, together with Eurocontrol's experimental centre. The first research results are presented by Guenther et al. (2006) describing the operational concept and logical architecture of TAM (Total Airport Management).

In order to observe airport system from viewpoint of all the stakeholders (airport, airline, air traffic control, ground handler) and all their interests, a very important concept is CDM (Collaborative Decision Making), which considers an exchange of information between all parties and therefore represents a link to all other system components (e.g. Martin et al., 1998; Ball et al., 2000; Gilbo and Howard, 2000; Martin, Delain and Fakhoury, 2001). By being familiar of the current situation at every moment and all the stakeholders' needs, one is capable to performing an overall optimization of system performance.

German Aerospace Centre (DLR) together with the Dutch National Aerospace Laboratory (NLR) is working on development of TOP (Total Operations Planner). TOP is a support tool, optimizing the use of airport resources, taking into consideration stakeholder needs and targets. TOP integrates all managers (TAM concept) through the CDM concept. The TOP prototype, known as CLOU (Co-operative Local resOUrce planner) was tested at Frankfurt airport. The results are presented by Pick (2007). Departures are handled significantly more punctually, while arrivals have to accept very little disadvantage.

Another project integrating different managers through CDM is the so-called LEONARDO (Linking Existing on Ground, Arrival and Departure Operations) (Mas and Pina, 2004; Pina, de Pablo and Mas, 2005). It is a research project promoted by the European Commission, with the participation of companies from France (ADP, DNA and Air France), The Netherlands (NLR), Italy (Sicta) and Spain (Aena, Iberia, Indra, Ineco and Isdefe), together with Eurocontrol. The objective of Leonardo is to demonstrate the feasibility of implementing Collaborative Decision Making (CDM) processes, supported by the integration of existing tools for arrival (AMAN), departure (DMAN), surface (SMAN), stand allocation, and turn-around management. The integration of these decision supporting tools promotes information sharing among airport stakeholders and makes it possible to provide airlines, airports and air traffic service providers with early and reliable planning updates. In order to achieve these objectives, systems integrating the abovementioned planning tools were developed and tested at the Madrid Barajas airport and at the Paris Charles de Gaulle airport. The results of the Leonardo experiments provide evidence of the benefits achievable at the airport level. It has been demonstrated that the airport operator and the airlines improve safety and efficiency of their ground processes by using ATC planning updates and that the ATC improve air traffic management thanks to information provided by the airport and the airlines.

The integrated optimization models also include the Airport Ground Operation model and the Airport Logistics concept. The first dates from 2000, while the second is a new concept currently under development.

Andersson et al. (2000) propose three models to capture the dynamics of busy hub airport operations: arrival (taxi-in), departure (taxi-out) and ground (aircraft-turn) model. The first model encompasses operations from landing to gate arrival; the second from push-back to take-off, and third from gate arrival to gate push-back. Integrated, they are expected to enable analysis and traffic optimization under conditions typical for a hub airport. There are three possible applications of the proposed models: to improve predictions of aircraft movement times on the ground (through the full integrated model), to evaluate the impact of congestion control on the airport surface (through the departure model), and to quantify the benefits of procedural changes and decision support tool enhancements (through the arrival and the ground operations models). At the moment that the paper was presented at the ATM R&D seminar 2000, complete integration had not been achieved. Only Airline Sequencing Model (ASM), based on the ground operations model, was developed. ASM can be used by airlines for efficient gate and ground handling resource management. In Andersson et al. (2000) the emphasis is on the ground model which is the link between the arrival and the departure model. The ground model mimics airline (which manage gates in the U.S.) operational decisions regarding aircraft push-back times under resource constraints. It considers the departure schedules, aircraft type - gate compatibility, gate availability and ground handling personnel availability in determining push-back times that minimize passenger delays. One of the biggest challenges in modelling ground operations for the case study was selecting resources and activities that would be included in the model (for the specific case, Boston Logan airport, it is, for example, assumed that baggage handling is a potential bottleneck in the turn-around process, based on the opinion of airline personnel). The ground operations model also determines the trade-off of delaying an aircraft to allow for passenger connections and re-routing passengers who miss connecting flight. The total delay to a passenger is not equal to the arriving flight delay, but includes the time until the next departure to the same destination. No further work on development of those three models and their integration has been published up to now, to the best of our knowledge.

The Airport Logistics concept is proposed by Lindh et al. (2007). The idea of the concept is to develop a complete picture of all processes and activities the airport system encompasses. The airport system includes the airside area (all activities related to aircraft movements), terminal area (all activities occurring inside the building associated with passenger movements) and landside area (curb side in this research). This picture is the basis for a DSS that is expected to assist in resource management by finding solutions optimal for the entire airport, rather than those optimized for an individual actor. The overall efficiency of the system is a (complex) function of the individual efficiency of each individual participant in the system. Some planning tasks have to be accomplished jointly by more than one participant. The overlapping of the interests of different participants in the most common resource management tasks is given in Figure 2. With such a DSS it would be possible to optimize the planning and utilization of all the resources at a tactical level, and to be able to reschedule due to disturbances in the system at an operational level.

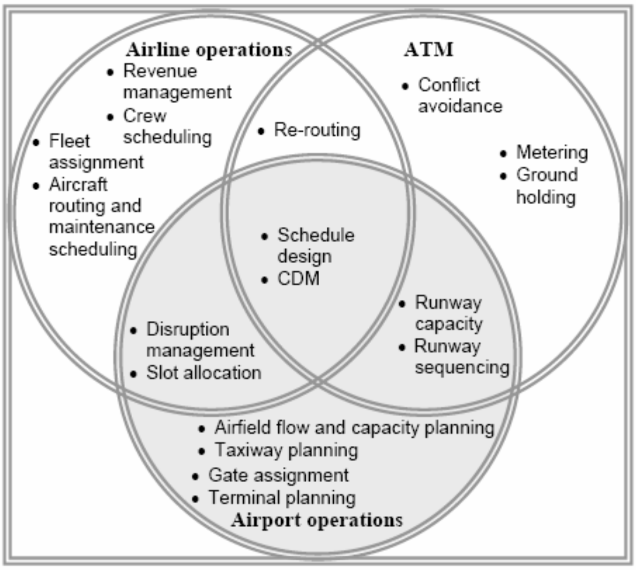

Figure 2. Resource management challenges and initiative in the air transport system

An activity-based network representation of the turn-around process is developed and analysed for the case of the Stocholm Arlanda airport, by Lindh et al. (2007). All activities are included in the network, and all actors that are in charge of those activities. It was followed by a simulation model for the turn-around process at the Stocholm Arlanda airport, presented by Norin et al. (2009). Then the optimization algorithm for de-icing trucks scheduling was developed and integrated in the simulation model. The overall objective was to investigate whether it is possible to obtain more efficient airport logistics by optimizing one of the turn-around services, while taking into account overall airport performance. The schedule based on the optimization solution provides the lowest flight delays and shortest waiting times, which is promising and encourages development of scheduling tools for other turn-around activities. Although the complete concept of Airport Logistics appears very promising based on its conceptual design, from what has been published up to now, only some early steps have been completed.

In order to improve efficiency in capacity management and balancing of available runway and apron capacities utilization under conditions of heavy traffic (peak hours), it is important to bring estimated taxi times (from RWY to assigned parking stand, and vice versa) as closer as possible to actual taxi times. Usually taxi times are given as fixed values that represent an average taxi time at the observed airport, or through mathematical distribution. There are not many models for taxi time estimation. One of them is described by Idris et al. (2002). It is a queuing model for aircraft taxi-out time estimation. For each aircraft, the queuing model assumes knowledge of the number of departure aircraft present on the airport surface at its pushback time and estimates the size of the airport surface during its taxi-out. The model was developed for the Boston Logan airport, for each combination of runway configuration and airline (different airlines use different terminals and apron areas).

Another interesting and very common optimization problem which does not treats entire system, but one of the resources, is the gate assignment problem (optimization of gate/parking stand utilization). Many papers deal with this issue (e.g. Babic, Teodorovic and Tosic, 1984; Cheng, 1997; Haghani and Chen, 1998; Bolat, 2000; Yan and Huo, 2001; Yan, Shieh and Chen, 2002; Ding et al., 2005; Dorndorf et al., 2007; Yan and Tang, 2007; Todesco and Mueller, 2008). A majority of them are based on the same goal function – minimization of passenger walking distances from check-in to gate and from gate to baggage claim area, and from gate to gate for transfer passengers. Cheng, (1997); Haghani and Chen (1998); Dorndorf et al. (2007) give thorough literature review on research results in this area classified by methods, goal functions, etc. These models do not cover only airside, and the objects moving through the model are not only aircraft, which is the main characteristics of airfield models, but rather they include a high level of interaction with the terminal building and passenger flows.

4. DIRECTIONS OF THE FUTURE WORK

Since runway modelling is pretty much resolved issue up to now, the focus of future research would be on apron/gate area. The idea is to develop an integrated airport capacity model by linking existing (or new, if necessary) runway capacity models with apron/gate area capacity models (generic ones, for quick analysis), through models of the functional relationship between airport infrastructure elements runway/(taxiway)/apron (taking into account terminal airspace and passenger terminal processes only to the extent that is necessary).

In addition to treating the airport as a complex system in the infrastructural sense, another complexity layer should be included in research. The airport would not be observed separately, but as a subsystem of the airline-airport-air traffic control relationship, especially in the light of SESAR's business/mission trajectory concept.

Integrated airport capacity assessment/management tools are expected to be a support to strategic airport planning and to tactical planning under conditions of unplanned events by enabling fast analysis of a greater number of schemes of balanced usage of airport infrastructure elements under different internal/external changes, their impact on airport performance, sensitivity to traffic characteristics changes, level of achieved stakeholder needs, etc. Based on this, decision makers would be able to propose dynamics of future airport expansions to meet capacity needs, by matching true airport capacity (not only the runway capacity) to expected demand.

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