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Research review of air traffic management

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As air transport demand keeps growing more quickly than system capacity, efficient and effective management of system capacity becomes essential to the operation of the future global air traffic system. Although research in the past two decades has made significant progress in relevant research fields, e.g. air traffic flow management and airport capacity modelling, research loopholes in air traffic management still exist and links between different research areas are required to enhance the system performance of air traffic management. Hence, the objective of this paper is to review systematically current research in the literature about the issue of air traffic management to prioritize productive research areas. Papers about air traffic management are discussed and categorized into two levels: system and airport. The system level of air transport research includes two main topics: air traffic flow management and airspace research. On the airport level, research topics are: airport capacity, airport facility utilization, aircraft operations in the airport terminal manoeuvring area as well as aircraft ground operations research. Potential research interests to focus on in the future are the integration between airspace capacity and airport capacity, the establishment of airport information systems to use airport capacity better, and the improvement in flight schedule planning to improve the reliability of schedule implementation.

1. Introduction

As air transport demand keeps growing, flight delays in the global air transport system increase as well. The Association of European Airlines (AEA) reported that 37% of intra-European flights departed late by > 15 minutes in the first half year of 1999 (*Airline Business* 1999c). It was found by AEA that airport operations and air traffic control accounted for > 45% of departure delays while late arrivals accounted for 40% and ground services of airlines for 15%. Lufthansa claimed that it had cost burning 26 000 tonnes of fuel in airborne holding patterns in 1999 alone and United Airlines claimed that $20 million of its costs were due to insufficient air traffic services by the Federal Aviation Authority in the USA (*Flight International* 1999b). Meanwhile, Austrian Airlines estimated that delays due to air traffic control (ATC) cost it $52 million in 1999 (*Airline Business* 1999a). According to Eurocontrol in Europe, > 80% of overall delays in 1998 were caused by insufficient capacity in ATC (*Airline Business* 1999b). According to delay statistics reported by Eurocontrol,

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19.5% of intra-European flights in 1997 were delayed by >15 minutes and total delayed flights accumulated to a high of 7.5 million in the same year (Eurocontrol 1998a). Moreover, a longer flight distance is needed for aircraft flying in the European airspace due to military-restricted flight zones and the sectoring of ATC control zones. Owing to increasing delays in the air transport system, Lufthansa tried to improve its schedule punctuality by reserving three aircraft (Airbus A310, A320, Boeing B737) at Frankfurt and Munich Airports as a back-up fleet (*Flight International* 1999b).

The efficient and effective management of the air traffic system, therefore, becomes important to improve the utilization of system resources. Significant progress has been achieved through considerable research about the air traffic system in the past two decades. The field of air traffic flow management has had a high profile due to the increasing shortage of air traffic system capacity with respect to soaring demand for air transport. The issue of airport capacity modelling and optimization has been studied since the 1970s. These researches have contributed to give a better understanding of airport capacity management as well as the higher utilization of airport capacity.

When the demand for air traffic reaches the ceiling of system capacity, the operation of a single airport starts influencing, both visibly and invisibly, the operational efficiency of the airport network due to the high interaction of air traffic operations between airports. Although the network effects of airport operations have become more significant, research which requires links between multiple operators (airport operators, airlines and airport ground handling agents) and multiple operational levels (enroute ATC and regional ATC) have not yet been well prosecuted. Therefore, the objective here is to review systematically the current research in the literature about the issue of air traffic management, so as to prioritize useful research areas.

The structure of the air transport system is briefly illustrated by figure 1. The air transport system is composed of airspace, airports and aeroplanes operated between airports in the system. The jurisdiction of ATC in the system is divided into three parts: oceanic & enroute ATC, which is responsible for aircraft operations in the airspace, and airport terminal manoeuvring area control (or terminal control), which is responsible for air traffic within the boundary area of ~ 50 miles of an airport (Horonjeff and McKelvey 1994). Hence, the research about air traffic management is categorized into two levels here: the system level and the airport level (figure 1). The system level of air traffic management includes two main topics: air traffic flow management (ATFM) and airspace research (figure 2). Four research areas under the topic of airspace research include airspace capacity & sectoring studies, aircraft conflict & automation studies, free flight studies and airport network flow optimization studies.

On the airport level, research topics include airport capacity, airport facility utilization and aircraft operations in airport terminal manoeuvring areas (TMA) (figure 3). Research areas under the topic of airport capacity include airport capacity studies and airport capacity optimization & artificial intelligence application. In the topic of airport facility utilization, research areas include airport gate capacity studies and airport gate assignment problems. Three research areas are discussed under the topic of aircraft operations in the TMA. They are aircraft sequencing in the airport TMA, airline schedule perturbation studies and aircraft ground operations. After a thorough discussion of relevant literature in each research area,

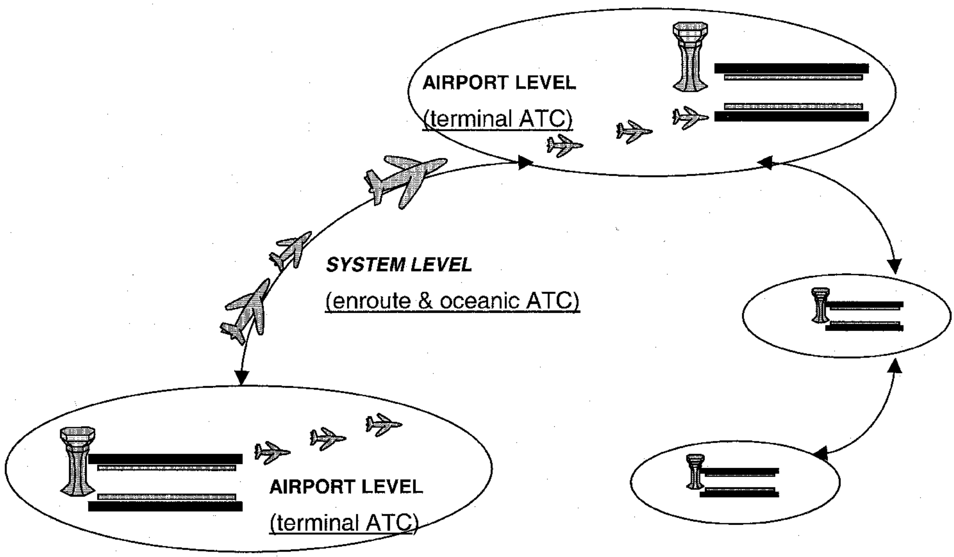

Figure 1. Structure of the air transport system.

potential research interests in the future are recommended. The goal here is to provide a system review of past research about air traffic management as well as to serve as a stepping stone for future studies in this field.

Researches on the system level are discussed in Section 2. Reviews of papers on the airport level are given in Section 3, which is followed by discussions of potential research interests in the field of air traffic management in Section 4. Conclusions and suggestions are given in Section 5.

2. System level

2.1. *Air traffic flow management (ATFM)*

The operation of an airport is influenced by the operation of the other airports through aircraft rotations, i.e. the continuous itinerary of aircraft among airports in one day. The flow management problem (FMP) occurs when the airport capacity at some airports decreases due to inclement weather conditions or other causes and results in significant delays in aircraft rotation, i.e. delays to inbound and outbound flights to and from those airports. To prevent airborne delays due to the shortage of airport capacity, aircraft may be assigned ground-holding delays at origin airports instead. The procedure of assigning ground holds to aircraft is a part of the ATFM. The purpose of ATFM is to allocate airport capacity optimally to all users during the shortfall of airport capacity to minimize foreseen negative impacts, e.g. severe flight cancellation and flight delays. The assignment of ground holds to departing aircraft has been used as an operational strategy to minimize flight delays as well as system costs due to delays. A thorough investigation and definition of FMP and ATFM was given by Odoni (1987), where it was concluded that FMP is a problem which has stochastic and dynamic features and strategies of air traffic flow management should be researched by means of simulation techniques.

Air traffic flow management problems were once investigated by using deterministic models at the early stage of the development of ATFM solutions

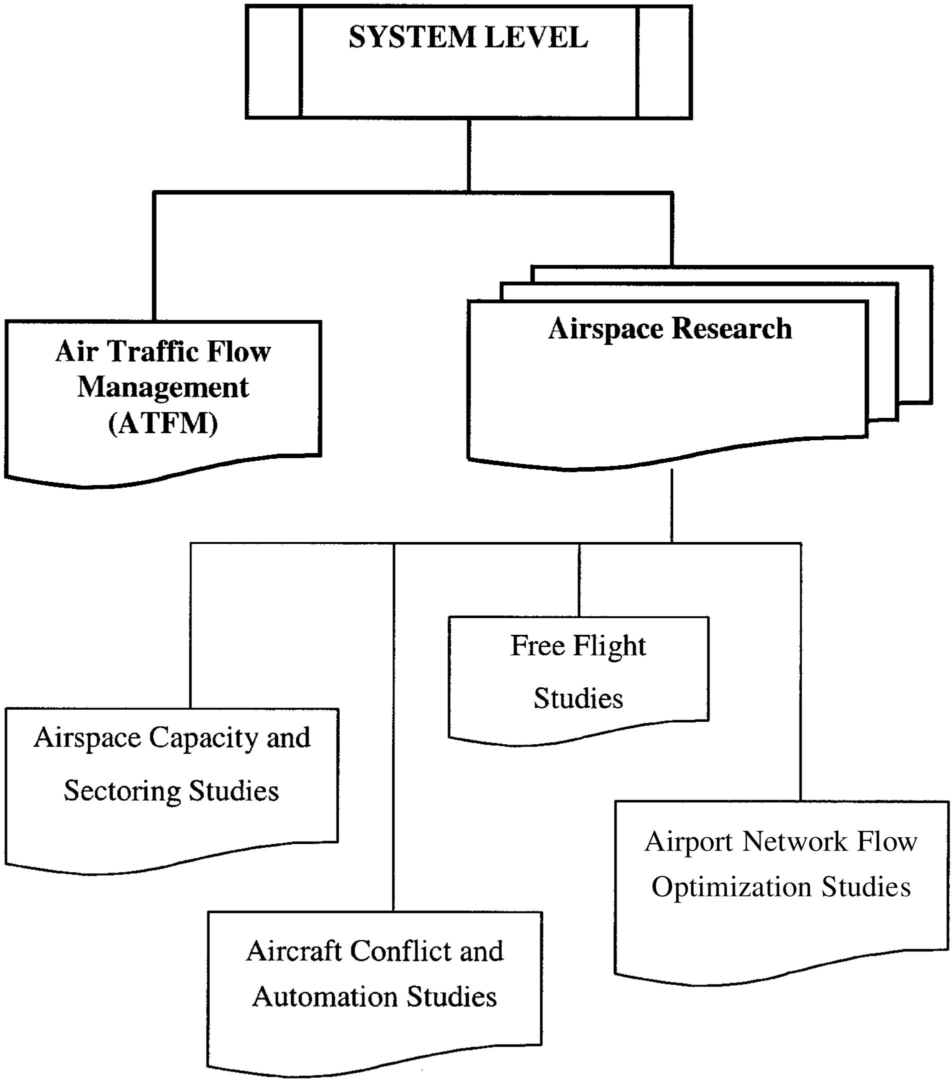

Figure 2. Literature review structure on the system level.

(Andreatta and Romanin-Jacur 1987, Bianco and Bielli 1992, Richetta and Odoni 1993, Terrab and Odoni 1993). Later, dynamic ground-holding assignments and stochastic models were proposed to solve ATFM problems (Richetta and Odoni 1993, 1994, Terrab and Odoni 1993, Vranas *et al.* 1994a, b, Richetta 1995, Tosic and Babic 1995). Recently, a systematic discussion of mathematical models and algorithms for air traffic flow management research was given by Tosic *et al.* (1995). A thorough investigation was made in the latter to test different model assumptions as well as the problem-solving efficiency of proposed heuristics to ATFM problems. More recently still, the research focus about ATFM has shifted to the optimization of air traffic flow control in a multiple airport network within a multiple time period framework (Teodorovic and Babic 1993, Vranas *et al.* 1994a, b,

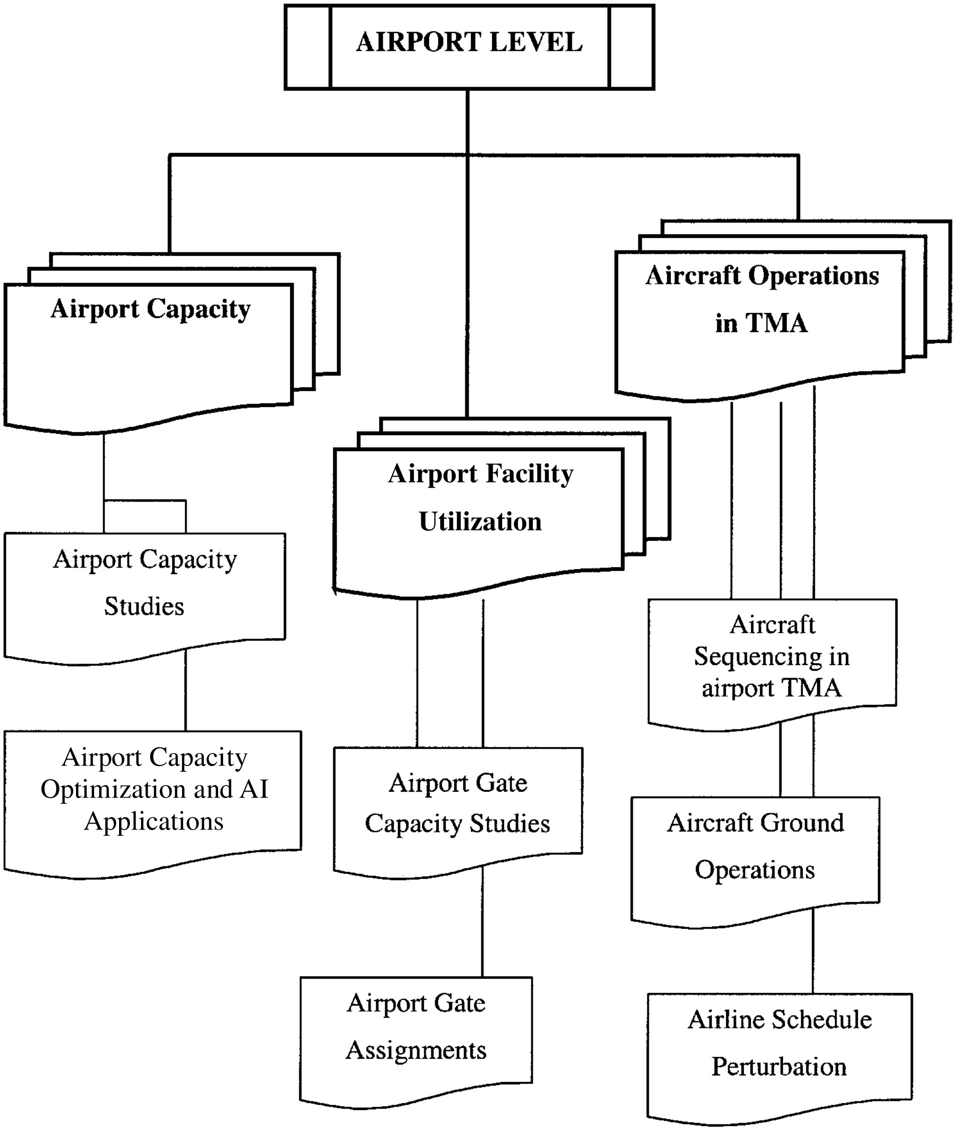

Figure 3. Literature review structure on the airport level.

Navazio and Romanin-Jacur 1998). The efficiency of implementing ATFM has also been evaluated by using real-time dynamic simulation methods as well as aircraft trajectory analyses (Tofukuji 1997).

These studies of the FMP have identified the modelling of airport acceptance rate (AAR), i.e. the short-term airport capacity, as the crucial aspect in the successful optimization of ATFM efficiency. Owing to the difficulty of predicting the AAR of an airport, AAR has been modelled by deterministic capacity profiles as well as stochastic ones in ATFM research (Andreatta and Romanin-Jacur 1987, Richetta and Odoni 1993, 1994, Terrab and Odoni 1993, Vranas *et al.* 1994a, b, Richetta

1995). The flow management problem is similar to a general flow problem with originating airports providing outflow of aircraft and destination airports receiving the influx. Hence, the assignment of aircraft ground holds depends on the capacity of destination airports. It was concluded in a paper by Vranas *et al.* (1994b) that 'the importance of finding proper models to simulate AAR is so essential to the efficiency of air traffic flow management that it is relatively not important when correct AAR forecasts can be given, but how precisely AAR forecasts can be made in advance'. Since the AAR is influenced by many factors such as airport configuration and weather conditions, stochastic models were found effective in capturing the variation of airport capacity with respect to time (Peterson *et al.* 1995). However, the integration of such models into the system of ATFM is still not thoroughly investigated, even though airport systems are expected to become bottlenecks to constrain the growth of air transport in the future (*Flight International* 2000).

In addition to the modelling of AAR, the timing of the provision of reliable AAR estimates was also found by Shumsky (1998) to be important. The imprecision of AAR forecasts accumulates with time and causes system users excessive delay costs when airborne aircraft are required to delay landing at a congested airport. Shumsky pointed out a way to improve the implementation of ATFM by optimizing the timing of updates of AAR forecasts for future events. Unfortunately, the problem-solving efficiency of the given methodology has not yet been investigated and further validation of the model implementation in an airport network is needed.

A further question in the implementation of ATFM strategies is about the issue of user equality. The assignment of ground delay and airborne delay to an aircraft is determined by unit delay costs, expected delay probability, and flight priorities. It was found in the literature that the First-In-First-Out (FIFO) principle remains the fairest control strategy to all airspace users but obviously not the optimal choice for solving FMP. In addition, the proper inclusion of models of aircraft enroute flight time will help improve the performance of ATFM. Since the enroute flight time of an aircraft in the airspace is influenced by many factors such as airspace congestion and ATC controls, the modelling of the arrival time of an aircraft at the destination airport was usually done by adopting simple assumptions, e.g. constant enroute flight time models (Zenios 1991, Vranas *et al.* 1994a, b, Janic 1997b). However, aircraft departure delay might be compensated by schedule buffer time in flight schedules or simply be caught up by flying faster. Therefore, how to assign ground-holding delays equally to balance ground and airborne delays among all users is still a future research topic (EC 1998a, b).

2.2. *Airspace research*

While much effort has been put into the improvement of air traffic flow management, the need to increase airspace capacity appears to have received relatively less attention. Research carried out by the European Community suggested that more research should also be done about ATC safety, airspace capacity and autonomous aircraft applicability studies (EC 1998a).

Dynamic sectoring of airspace in Europe has been under investigation by the European Community and the second phase of Air Traffic Service Route Network (ARN) has been launched in February 1999 to improve airspace capacity across Europe (EC 1998a, *Flight International* 1999a). The modelling of the ATC problem has been investigated by building up an airport network model to monitor the congestion of airspace on high altitude jet routes to optimize air traffic flows among airports (Zenios 1999). Despite the complexity of the network model and traffic assignments, Zenios proposed a prototype model of ATC that simulates the assignment of jet routes in congested airspace. More recently, Eurocontrol has carried out the development of a design and analysis model of airspace. The programme of 'European Air Traffic Control Harmonisation and Integration Programme' (EATCHIP) developed by Eurocontrol aims to model the structure of the European airspace as well as to simulate and optimize air traffic flows in the European region (Eurocontrol 1998c). A system model named 'System for Traffic Assignment and Analysis at a Macroscopic Level' (SAAM) has been successfully developed by the Airspace Modelling Service Unit of Eurocontrol to provide an integrated model and simulation system for macroscopic design, evaluation, and presentation of airspace as well as simulations of airport TMA operations.

The general objective function used in airspace network studies is the minimization of airspace congestion costs. However, due to the dynamic and stochastic features of aircraft operations in the airspace, it is difficult to quantify aircraft delay costs in the air. The fuel consumption problem of an aircraft on different jet routes was investigated by Janic (1994), who tried to optimize the enroute ATC problem by minimizing aircraft fuel consumption. Janic provided helpful modelling fundamentals, which serve as a sound base to approach the airspace congestion problem from an econometric point of view.

The modelling of ATC sector capacity has been approached by using mathematical models to calculate the theoretical capacity of an ATC sector (Janic and Tosic 1991). The modelling of ATC sector capacity was also approached by including human factors, i.e. the control and conflict solving efficiency of air traffic controllers (Tofukuji 1993, Ratcliffe 1994, Tofukuji 1996, Janic 1997a). These efforts enable the realization of the ultimate and operational capacity of an ATC sector to optimize the efficiency of ATC.

As the capacity of airspace is reaching its operational maximum under current control measures, the concept of Free Flight has emerged. The objective of developing Free Flight is to make the most use of available airspace capacity to optimize the efficiency of the ATC system. Since pilots are given more freedom to choose the optimal flight routes to fly, solving the flight conflict problem between aircraft in the Free Flight airspace becomes essential for the safety of implementing Free Flight in the future.

Stochastic approaches were widely adopted to model the probability of aircraft conflicts along airways (Geisinger 1985, Prashker *et al.* 1994, Ratcliffe 1994, Anderson and Lin 1996, Paielli and Erzberger 1997, Reich 1997, Yang and Kuchar 1997). Conflict resolution advisory systems have been developed by avionics manufacturers to provide conflict resolution advisories to pilots according to the nature of aircraft conflicts and airway configurations. In addition, the potential aircraft conflict probability can also serve as a measure to quantify the workload of air traffic controllers as well as the risk level of aircraft collision in the air (Geisinger 1985, Quon and Bushell 1994, Anderson and Lin 1996, Reich 1997).

The automatic guidance of aircraft has been studied by Niedringhaus (1995). A model for automated integration of aircraft separation, merging and stream management was proposed to form the foundation of the aircraft conflict resolution advisory system. An alternative approach was investigated by Ratcliffe (1995) to assess the feasibility of providing an airborne aircraft with clearance by taking into account conflict probability and resolutions. The success of the four-dimensional guidance of aircraft in the airspace also relies on the advance of avionics technology (Benoit and Swierstra 1990, Simpson 1997).

The success of Free Flight relies on the conflict advisory and resolution system as well as the optimal trajectory advisory system. Currently, the 'European Programme for Harmonised Air Traffic Management Research' (PHARE) by Eurocontrol has successfully demonstrated the feasibility of four-dimensional trajectory negotiation in the future European air traffic management system (Eurocontrol 1998b). In the USA, Phase I of National Airspace System (NAS) lasting from 1998 to 2002 is based on the Free Flight concepts as well. Hence, the successful use of advanced avionics and communication technologies might dramatically change the nature of ATC and management in the near future.

Potential research interests come from the integration between the use of advanced aviation technology, airspace users (pilots) and air traffic controllers. In a Free Flight environment, the capability of air traffic controllers to cope with a fast change of system capacity will be essential to the success of delivering reliable traffic control advisories. Advanced computer technology will be helpful for air traffic controllers to reduce ATC delays in peak hours and safely reduce airspace congestion in low-capacity situations (Simpson 1997). However, the issue of human factors in ATC and the human interface with advanced control systems is still under investigation and requires more attention in the future development of modern aviation technology (Yang and Kuchar 1997). Future research may also focus on solving congestion problems in the TMA of airports as well as airspace bottlenecks as it has been widely realized that the fluctuation of the operational capacity of a major airport influences the operation of the whole airport network due to the interaction between airports by aircraft rotations (Evans 1997).

3. Airport level

3.1. *Airport capacity*

The improvement of airport capacity has been progressing slowly due to the difficulty of airport expansion. Research about airport capacity has been focused on two subjects: the modelling of airport capacity and the optimization & utilization of airport capacity. The concept of 'airport system capacity' of an airport was proposed to define the ultimate capacity and the practical capacity of an airport (Hockaday and Kanafani 1974). Stochastic factors of aircraft operations near the TMA of an airport were also investigated in the paper. A thorough discussion about airport capacity modelling was carried out by Newell (1979). Airport capacity calculation, runway configuration, aircraft mix and the aircraft queuing problem were discussed in the paper, which provided fundamental concepts for the modelling of airport capacity.

The modelling of airport capacity under constraints was studied by Fan (1992) to investigate the change of airport capacity due to marine vessel crossings near Changi Airport. The concept of 'airport capacity curves' to model the trade-off between arrival and departure airport capacity (especially for single runway airports) was first given by Gilbo (1993, 1997). Airport capacity under constraints of arrival and departure approaching-route fixes (i.e. the mix point of arrival/departure flight routes in the TMA of an airport) was discussed by taking into account the interaction between runway capacity and the capacity of airway fixes to optimize the traffic flow through the airport system (Gilbo 1997). It was found that the airport capacity is mainly influenced by the layout of an airport and operational constraints.

As far as airport capacity optimization is concerned, the aircraft-sequencing technique of Maximum Position Shift (MPS) was proposed to optimize the utilization of airport capacity by Trivizas (1994, 1998). Since the runway capacity is influenced by the mix of arriving aircraft types, aircraft-sequencing techniques such as MPS are adopted by air traffic controllers to adjust the sequence of approaching aircraft to safely reduce separations between aircraft and to utilize runway capacity. It was also found that runway capacity models should be modified to meet modelling needs of local airports because of the difference between two operational environments (Urbatzka and Wilken 1997). Although it is generally realized that weather conditions influence airport capacity, the modelling of airport capacity hardly considers the weather factor due to difficulties in modelling weather uncertainties. A Markov/Semi-Markov model was proposed in a paper trying to model it (Peterson *et al.* 1995). The major contribution of this stochastic airport capacity model was to justify the feasibility to precisely estimate airport capacity in a relatively short period by considering weather factors.

Owing to uncertainties in the estimation of airport capacity, artificial intelligence (AI) has been employed in recent airport capacity research because of its capability to model uncertainties. Knowledge-based system (KBS) models that use high-level programming languages to simulate the logic of human knowledge such as expert systems, have been proved effective in modelling stochastic effects in airport operations (Gosling 1987, 1990, Wayson 1989, Taylor 1990). Therefore, it is recommended that future work may focus on the dynamic and real-time estimation of airport capacity and its application link with ATFM system on a network scale. Research papers using stochastic models and KBS models in the literature have demonstrated the effectiveness of stochastic models in providing real-time airport capacity information to airport operators. It is expected that the introduction of stochastic models and AI models in airport capacity research in the future would help use airport capacity as well as provide a better understanding to the modelling of airport capacity.

In addition, regarding the fluctuation of airport capacity, a question raised in research by Evans (1997) was how to reduce aircraft delays safely in an airport TMA in an adverse weather condition. The decrease of the operational capacity of a major airport does not only result in delays at that airport, but also cause ripple effects to the operation of an airport network. It was found that delays due to weather-related reasons accounted for 75% of total delays at US airports in 1998 (*Airline Business* 1999d). Further delays were also found to result from the poor coordination between National Air Space users (i.e. airports) and the regulatory and operating body of air transport (i.e. the Federal Aviation Authority in the USA) in such a condition. Therefore, there seems a need to pay more attention to the investigation of the operational strategies of ATFM on a network scale to cope with low-capacity situations at airports.

3.2. *Airport facility utilization*

Aircraft operations at airport gates influence the number of gates needed to meet peak hour service demand. Different gate occupancy time is required for different types of aircraft and for different types of aircraft ground operations, e.g. turnaround, end-of-line or transfer. Steuart (1974) studied the stochastic effects of aircraft gate occupancy time on gate requirements. A scheduling strategy that took into account the stochastic effects of aircraft turnaround time was developed in the paper to minimize the requirement of gate numbers and meanwhile maintain a required level of service. The use of schedule buffer time in aircraft turnaround was discussed to account for extra aircraft gate occupancy time due to arrival delays of turnaround aircraft (Hassounah and Steuart 1993). Similar approaches using stochastic models have shown the effectiveness of stochastic algorithms in solving the gate number problem (Bandara and Wirasinghe 1988, Wirasinghe and Bandara 1990).

In addition to the gate number problem, the gate assignment problem is also an important topic in airport operations. An aircraft is assigned to use an apron stand to undergo aircraft ground services and a boarding gate to board/unboard crewmembers and passengers. Airport gates are assigned to aircraft according to the planned flight schedule as well as special requirements such as the type of aircraft and the hubbing requirements of airlines. Linear programming techniques have been widely used to solve the gate assignment problem (Mangoubi and Mathaisel 1985, Hamzawi 1986). More recently, efficient heuristics for solving the problem of gate reassignment have been proposed to minimize passenger walk distance as well as to minimize the time for the task of gate reassignment when delays cause serious disruption to the original gate assignment plans (Haghani and Chen 1998, Gu and Chung 1999). Owing to the dynamic feature of the gate reassignment problem and the complexity of the gate assignment problem, the knowledge-based system (KBS) method has been applied recently (Cheng 1997). A knowledge-based airport gate assignment system was integrated with mathematical programming techniques to provide real-time solutions to airport operators. Earlier research work has also shown the value of AI methodologies in solving airport gate assignment problems (Gosling 1987, 1990).

It has been realized recently by airport authorities that insufficient apron and gate capacity has started to constrain the allocation of airport gate uses for airlines. The better utilization of apron facilities becomes an effective and economically efficient way to improve airport operational performance and airport capacity utilization (Caves 1994). Since it is usually difficult to expand airport terminals, the research focus on airport gate problems has been shifted from the optimization of gate assignment to the utilization of airport gates. Recent research conclusions have shown that different airline hubbing strategies and scheduling strategies result in different levels of apron facility utilization (Caves 1994, Gittell 1995). The utilization of airport facilities can be achieved by more efficient aircraft ground operations by airlines and ground handling agents. The improvement of aircraft ground operations reduces aircraft gate occupancy time and better uses airport facilities on the one hand, and maintain good schedule punctuality on the other.

3.3. *Aircraft operations in the airport terminal manoeuvring area (TMA)*

Aircraft operations in the TMA of an airport are mainly controlled by terminal ATC, which consists of two control authorities: terminal radar-approach control (TRACON) and the ATC tower (ATCT) at an airport (Horonjeff and McKelvey 1994). The goal of TMA ATC is to maintain aviation safety in the TMA of an airport to expedite air traffic and meanwhile to maximize the utilization of airport capacity. The operation of TMA ATC influences the utilization of terminal airspace capacity as well as airport capacity. As a consequence, the improvement of aircraft processing efficiency in the airport TMA will enhance the utilization of airport capacity as well as minimize aircraft delays due to TMA congestion.

Algorithms about the optimization of TMA aircraft operations mainly focus on aircraft sequencing in the TMA area to minimize the time gaps between two aircraft. This problem is generally described as the Runway Scheduling Problem (RSP). The Constrained Position Shift (CPS) method and the Maximum Position Shift (MPS) method were developed to minimize aircraft landing delays by dynamically controlling aircraft shifts, i.e. changing the sequence of approaching aircraft in the TMA of an airport (Dear and Sherif 1991, Venkatakrishnan *et al.* 1993). Similar approaches were also adopted in a recent paper to develop MPS that also features dynamic programming techniques to solve the runway-scheduling problem (Trivizas 1994, 1998).

The assignment of aircraft landing priority at a congested airport was studied by Janic (1997b). Total system delays were optimally distributed to all aircraft by assigning landing priorities to aircraft according to given criteria such as delay time and delay costs. Different aircraft-sequencing strategies were discussed, and Janic concluded that the principle of First-Come-First-Serve is still the simplest and most straightforward aircraft-sequencing method available, though not the optimal control strategy from the viewpoint of total system delays. Although other aircraft ranking criteria may achieve the system optimum, these aircraft shifting rules always penalize low-ranking aircraft and hence cause high delays to these aircraft. The concept of Route-Oriented Planning and Control (ROPAC) was studied by Mohleji (1996) to calculate the minimum time path for an aircraft flying in an airport TMA. A flying time estimation model was used to maximize airport capacity by estimating the arrival time of inbound aircraft and dynamically adjusting traffic flow rates into an airport. Landing aircraft were given different routes to approach the landing runway and therefore, to maximize the runway system capacity of an airport.

The utilization of airport capacity can be improved by applying aircraft-sequencing models to ATC in an airport TMA. However, the arrival time of an aircraft is so uncertain that terminal air traffic controllers can only react to a real-time situation unless more information is available through the four-dimensional flight management system (4D FMS) (Benoit and Swierstra 1990, Simpson 1997). From the system level's point of view, the optimization of aircraft operations in TMA is a local optimum. What is still absent in the literature is the integration of local optimum on the airport level with the ATFM system on the system level. Accumulated delays (called 'delay memory') are usually not considered in the optimization of aircraft operations in TMA, though an arrival aircraft could have already been delayed due to flow controls at the origin airport or flying en route in the airspace. Hence, the integration of aircraft TMA operations with the ATFM system will provide such a system link to utilize the air transport system capacity by minimizing system delays (from airport operations and enroute aircraft operations) as well as system delay costs.

3.4. *Airport ground operations*

Ground operations at an airport include the provision of ground services to aircraft and the scheduling of ground services. Owing to uncertainties from the implementation of flight schedules, ground service schedules are sometimes perturbed. Relevant research about airport ground operations can be mainly grouped into two areas: the airline scheduling problem (ASP) and aircraft ground operations research.

ASP deals with flight schedule-related problems, which include flight schedule changes, aircraft and flight crew scheduling, and daily airline scheduling operations.

Etschmaier and Mathaisel (1985) gave a thorough investigation of past research about ASP. The general objective of solving ASP is to use airline resources under constrained situations, e.g. aircraft fleet size and market demands. On the other hand, flight schedules are sometimes disturbed and forced to change because of operational disruptions in aircraft rotations. Then the flight operations decision problem (FODP) is encountered by airline schedulers to manage the escalation of delays in flight schedules and potential flight cancellations (Cao and Kanafani 1997).

Dynamic programming techniques were used to solve the FODP by minimizing total passenger delays, flight cancellations or airline costs (Teodorovic and Stojkovic 1990, 1995). A decision support framework for airlines was proposed by Jarraah and Yu (1993) to help airlines minimize schedule perturbations on a real-time base by delaying/cancelling flights, swapping aircraft among scheduled flights or requesting the usage of backup aircraft. The FODP problem has been advanced to integrate both the flight cancellation model and the aircraft delay model into a decision support system for airlines (Cao and Kanafani 1997). The problem of using airline resources at an airport was discussed to improve schedule punctuality after the occurrence of schedule disruptions from ground delays of ATFM in the US (Luo and Yu 1997). The research objective in this paper was to deliver as many punctual flights as possible when schedule disruption occurs.

Schedule perturbations may also happen due to inclement weather, flight delays due to aircraft rotation, aircraft engineering problems and so forth. When serious schedule perturbation occurs, an airline has to decide how to alleviate the consequences of schedule disturbance. Airline schedulers usually judge the consequences of schedule perturbations by experience. However, it is difficult to estimate the consequences of schedule perturbations because delays at an airport might ripple into the airport network through aircraft rotations on the one hand, and flight cancellations will cause broken links in aircraft rotation schedules on the other. Hence, there seems a need to develop a Schedule Disruption Management (SDM) model to manage the consequences of schedule perturbations on the network scale as well as to minimize airline operational costs due to schedule perturbations. In addition, the timing problem of rebuilding aircraft rotational schedules should also be considered in the SDM model to minimize the operational cost of reconstructing flight schedules. Research about the timing problem of updating airport capacity information in ATFM provides a clue to the development of its counterpart in the SDM model (Shumsky 1998).

There is relatively less research done in the field of aircraft ground operations. The gate occupancy time of an aircraft was first studied by using critical path method (CPM) (Braaksma and Shortreed 1971). Then, the stochastic effects of aircraft gate occupancy time on the gate number problem were discussed by Hassounah and Steuart (1993). It was found from empirical studies that departure delays of turnaround aircraft have a significant relationship with arrival delays of inbound aircraft, especially when arrival delays consume available aircraft turnaround time. The departure process of an aircraft has been discussed by using stochastic models and simulation techniques to take into account the stochastic nature of aircraft ground operations (Herbert and Dietz 1997). The problem of encountering delays in the departure process of an aircraft on the apron was investigated by using heuristic approaches as well as event-driven simulation approaches to reduce delays to departing aircraft (Teixeira 1992, Cheng 1998b). A rule-based model was then applied to simulate the gate occupancy behaviour of an aircraft including aircraft turnaround operations, simulation of aircraft arrival delays and passenger transfers between aircraft (Cheng 1998a).

It was found from a survey by London Gatwick Airport that delays due to airline ground operations accounted for 25% of total delay causes, while delays due to ATC accounted for 30% during the survey period (European Civil Aviation Conference 1996). Since air transport delays are increasing gradually, airlines tend to schedule more ground time and/or airborne time in flight schedules to control schedule punctuality and the reliability of aircraft rotations (*Sunday Times* 2000). It was found that the operational efficiency of aircraft ground services by an airline influences the punctuality performance of its flight schedule and consequently the profitability of the airline (*Airline Business* 1999a). The aircraft turnaround time was found to differ among air carriers and consequently the operational efficiency of an airline was influenced as well (Gittell 1995). The improvement of aircraft turnaround operation becomes more important when it gets more difficult, as nowadays, to maintain aircraft rotational links due to unforeseen schedule disruptions from ATC and aircraft turnaround operations (Trietsch 1993, Chin 1996). This is especially true for low-cost airlines that rely on the high utilization of aircraft to increase revenue (Airport Council International 2000). A study by Southwest Airlines in the USA found that with the increase of its passenger load factor in the past few years, aircraft turnaround operations become the major determinant to its on-time performance and the reliability of its aircraft rotational schedules (*Air Transport World* 2000). Therefore, potential research interests still remain in the field of aircraft ground operations to improve aircraft turnaround operations at an airport as well as to maintain aircraft rotational links between airports (Wu and Caves 2000).

4. Goals for future work

Previous research has shown that the air traffic system has the characteristics of high complexity of operation and manipulation with the involvement of multiple users as well as inherent stochastic effects on system operation. The following summarizes potentially productive research areas in air traffic management.

First, a link for system-wide integration is needed between broad-network air traffic flow management and local ATC in the airport TMA. Recent research has already revealed the benefit of optimizing operational efficiency of ATFM in a network of airports. The utilization of air transport system capacity, i.e. enroute airspace capacity and airport runway capacity, influences the performance of ATFM. Relevant ATFM studies have shown the importance of airport capacity control to the success of ATFM. On the other hand, techniques to increase enroute airspace capacity, e.g. Reduced Vertical Separation Minima (RVSM) by Eurocontrol in Europe, also help improve the efficiency of using scarce airspace capacity. However, the three major fields of air transport research, i.e. ATFM, airport TMA operations and enroute airspace operations, have not yet been well integrated to achieve the optimum of system performance. Eurocontrol predicts that all enroute delays in Europe can be eliminated by 2006–8 when capacity-enhancing measures start functioning. By then, the capacity bottleneck in air traffic system will become airports if demands for air transport keep growing as predicted. Hence, it is suggested that future research about ATFM should focus on the system integration of enroute ATFM with local air traffic operations in the TMA of airports. Advanced methodologies for the modelling of air traffic flow distributions on the system level are needed to improve the reliability of system capacity allocation. In addition, the integration between airspace capacity and airport capacity is needed to achieve the higher utilization of air transport system capacity and meanwhile minimize system costs due to capacity shortage.

Second, the optimization of air traffic operations in the airport TMA influences the operational performance of an airport as well as schedule delivery performance of airlines. It was found feasible to improve the utilization of constrained runway capacity at an airport by using aircraft-sequencing techniques and advanced navigation technology. In addition, the optimization of airport capacity utilization will not succeed without a comprehensive and precise airport capacity information system. Relevant literature has demonstrated the feasibility and capability of modelling airport capacity by stochastic models and artificial intelligence techniques. Recent studies also showed the feasibility of integrating knowledge-based systems with stochastic simulation models to dynamically update airport operational information to maximize airport performance. Hence, future work should focus on the establishment of an airport information system which includes functions for aircraft processing in the TMA (metering, spacing and sequencing aircraft) as well as a reliable airport capacity allocation and prediction mechanism.

Third, there is relatively less attention paid to the issue of airport ground operations research in the literature. It has been shown in the literature that there is a need to increase apron capacity at airports and to encourage the use of large aircraft to use airport facilities. Regarding the operational efficiency of airlines on the apron, recent papers have shown that ground service performance varies among carriers and influences the productivity and profitability of airlines as well. It is realized that the improvement of ground operational efficiency and the punctuality of airlines is essential to reduce airline operational costs especially for non-intensive hubbing airlines (Hansen and Kanafani 1989, Nero 1999). With the increase of operational delays in the air transport system, airlines have to design more buffer time in flight schedules to maintain schedule punctuality as well as aircraft rotational links. However, a longer schedule time for a flight does not always guarantee the improvement of schedule punctuality and similar situations have been already realized from other studies about transport scheduling (Carey 1998). Therefore, potential research interests arise in the establishment of a reliable flight schedule that can use available resources of airlines and airports as well as maintain the reliability of schedule implementation and aircraft rotations. Artificial intelligence (AI) and stochastic models are suitable methodologies to build a decision support system for the purpose of aircraft rotation management which includes schedule disruption management functions to deal with unexpected schedule perturbations.

5. Conclusions

The development goal of the air traffic system as stated in the *Air Traffic Management Strategies for 2000+* by Eurocontrol is to establish a safe, reliable and environmentally sustainable gate-to-gate air transport system (Eurocontrol 1998). The project of National Airspace System by the Federal Aviation Authority in the USA also reveals the same goal for the development of air transport system in the future (Simpson 1997). The air transport system is composed of many subsystems in which the operational efficiency of individual components has been optimized, but not yet been integrated with each other. To achieve the system optimum, the integration between subsystems in the air traffic system is required in future work.

Therefore, future research interests in air traffic management are suggested to focus on three fields. First, a link for system-wide integration is needed between broad-network air traffic flow management and local ATC in the airport TMA. Second, future work is recommended to focus on the establishment of an airport information system which includes functions for aircraft processing in the TMA (metering, spacing and sequencing aircraft) as well as a reliable airport capacity allocation and prediction mechanism. Third, there should be research to improve the regularity and reliability of schedule implementation. Artificial intelligence (AI) and stochastic models are recommended methodologies to establish a decision support system for the purpose of aircraft rotation management which includes schedule disruption management functions to deal with unexpected schedule perturbations.

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