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A Review of Models and Model Usage Scenarios for an Airport Complex System

Paul Pao-Yen Wu, Kerrie Mengersen

Queensland University of Technology, School of Engineering Systems, 2 George Street, Brisbane, Australia. Phone: 61-7-31389828, Fax: 61-7-31381827, Email: p.wu@qut.edu.au

Abstract

Airports represent the epitome of complex systems with multiple stakeholders, multiple jurisdictions and complex interactions between many actors. The large number of existing models that capture different aspects of the airport are a testament to this. However, these existing models do not consider in a systematic sense modelling requirements nor how stakeholders such as airport operators or airlines would make use of these models. This can detrimentally impact on the verification and validation of models and makes the development of extensible and reusable modelling tools difficult.

This paper develops from the Concept of Operations (CONOPS) framework a methodology to help structure the review and development of modelling capabilities and usage scenarios. The method is applied to the review of existing airport terminal passenger models. It is found that existing models can be broadly categorised according to four usage scenarios: capacity planning, operational planning and design, security policy and planning, and airport performance review. The models, the performance metrics that they evaluate and their usage scenarios are discussed. It is found that capacity and operational planning models predominantly focus on performance metrics such as waiting time, service time and congestion whereas performance review models attempt to link those to passenger satisfaction outcomes. Security policy models on the other hand focus on probabilistic risk assessment. However, there is an emerging focus on the need to be able to capture trade-offs between multiple criteria such as security and processing time. Based on the CONOPS framework and literature findings, guidance is provided for the development of future airport terminal models.

Keywords: concept of operations (CONOPS), passenger terminal, airport, modelling, complex systems

1. Introduction

The airport is a complex, large-scale socio-technical system comprising multiple stakeholders, multiple jurisdictions and complex interactions between many actors (Zografos and Madas, 2006; Lui et al., 1972; Eilon and Mathewson, 1973). Airports play a critical role in the aviation industry and in national infrastructure. In the year 2000, over 1.7 billion passengers were moved worldwide and annual industry revenue was on the order of $1 trillion USD (de Neufville and Odoni, 2003). However, airports face a number of challenges including ongoing growth in passengers and peak-hour demand, changes to aviation security requirements and the advent of low cost airlines (de Neufville and Odoni, 2003). This difficulty is further compounded by the high-cost and, by comparison, long time frame of building and operating infrastructure (Odoni and de Neufville, 1992).

In order to address some of the challenges faced by the airport and airline industries, it is necessary to understand and model the system and its dynamics. Typically, models of the airport and its passengers are used to aid planning and decision making as it is either impractical or prohibitively expensive to test changes on actual airport infrastructure (Lemer, 1992). Often, these models simulate or analytically or probabilistically evaluate anticipated airport operational scenarios. Literature surveys of existing airport passenger terminal models include those by Zidarova and Zografos (2011), Correia and Wirasinghe (2004), Correia et al. (2008) and Tosic (1992).

However, the existing literature does not consider in a systematic sense the potential usage scenarios for such models. In particular, modelling requirements are not well-defined (especially in a systems engineering sense (Jones and Maiden, 2005)) and the link between requirements and model usage within the organisational process or regulatory context is unclear. As a result, there is a risk that some of the modelling needs of airport stakeholders are not met, or the models are misinterpreted or under utilised. Verification and validation of models is made difficult in the absence of structured requirements and usage definitions. Development of extensible and hence reusable model frameworks is difficult due to a lack of clarity about modelling scenarios and requirements. Hence, there may be avenues and applications for modelling that are left unexplored.

This paper reviews existing models of airport complex systems, focusing specifically on passenger terminal models. The review is conducted within the context of a Concept of Operations (CONOPS) methodology using IEEE Std 1362-1998 (IEEE, 1998). Often used in military, government services and software engineering, a CONOPS provides a systematic approach to defining system usage scenarios and hence deriving system requirements (IEEE, 1998). In the presence of a highly complex system such as an airport, such a systematic methodology is instrumental in defining the modelling problem, scope, assumptions and boundaries. An important part of the CONOPS is the review of existing systems, in this case airport passenger terminal models, to ascertain specified aspects of their use including their operational objectives, policies and capabilities (IEEE, 1998).

Section 2 describes the CONOPS process which forms the context for the literature review. This is followed by reviews of existing airport terminal passenger models (section 3) with regard to model functionality (and hence the originating modelling requirements) and the described context (i.e. scenario) in which the model was envisaged to be applied. This represents a bottom-up approach of ascertaining existing model usage scenarios. The findings and utility of the proposed CONOPS approach are reviewed in section 4 and conclusions are made regarding future avenues for airport modelling.

2. Background

Due to the complex systems nature of the airport, it is not possible to employ traditional systems engineering processes, which are predominantly sequential and requirements based, since the requirements are not entirely known in advance and may change during system operation (Crisp, 2007). Additionally, the characteristics of an airport violate the boundary conditions assumed in traditional systems engineering approaches (DeRosa, 2008; Bar-Yam, 2003). Finally, traditional systems engineering approaches do not sufficiently capture the role that human entities, both passengers and staff, play within a system (Crisp, 2007).

Even though a systems engineering approach is not directly applicable to airport model development, there is still a need to ascertain model functionality and hence modelling requirements even if they change over time. A CONOPS provides a methodology for systematically developing model usage scenarios from which the modelling requirements can be derived.

2.1. The CONOPS

A CONOPS is a "user-oriented document that describes a system's operational characteristics from the end user's viewpoint" (IEEE, 1998). For this paper, the IEEE Information Technology CONOPS Std 1362-1998 (R2007), IEEE (1998) has been selected as the majority of modern day airport models are designed and developed in software; see, for example, Manataki and Zografos (2010), Tam (2011) and Lee et al. (2010). This section briefly reviews aspects of the CONOPS structure as described in IEE Std 1362-1998 (R2007) and derives from it a methodology for thinking about airport modelling and modelling requirements.

The focus of the CONOPS is to develop usage scenarios for the proposed system from which system requirements can be derived. CONOPS standard IEEE (1998) provides guidelines for the entire scenarios development process including the review of existing systems, justifying the need for changes, the proposed system, usage scenarios for the proposed system and their impact. A specific set of criteria are used to explicitly describe the existing and proposed system, and are used implicitly in the description of the usage scenarios:

1. System objective
2. Operational policy and constraints
3. System description:
   (a) Operational environment
   (b) System components
   (c) Interfaces
   (d) Capabilities

(e) Operation
(f) Cost
(g) Operational risk
(h) Performance
(i) Quality
(j) Emergency
4. Modes of operation
5. User classes
6. Support environment

2.2. *Benefits of Applying a CONOPS Framework to Modelling*

Consider the application of the CONOPS process to the modelling of complex systems. In this case, the CONOPS is used as a guideline to review existing models, justify the need for changes, present the proposed model and its usage scenarios. However, in applying the CONOPS to the development of model usage scenarios and modelling requirements, there are a number of simplifications that can be made. These arise because at the conceptualisation stage of model development, the focus is not so much on the implementation details of the model (such as the exact modelling components and interfaces), but rather what will be modelled (e.g. model capabilities). Additionally, given the diversity of modelling approaches, it is useful to first devise model usage scenarios which can then be used to select suitable modelling approaches.

Therefore, it is proposed that the criteria that are adapted from the CONOPS in evaluating existing models, the proposed model and modelling scenarios, are:

1. Modelling objective
2. Operational policy and constraints
3. Model capabilities (i.e. what is captured)
4. Users

From a review of the literature (see section 3), it is found that the performance metrics that are captured, such as service time and passenger flow rate, can be used as a descriptor of model capabilities.

The above CONOPS based framework provides a systematic means for reviewing existing models of airport passenger terminals. The review of existing models serve as a stimulus and starting point for developing usage scenarios and hence modelling requirements for the proposed model. Such usage scenarios are developed with the users which could be airport experts, thus tapping into a vast pool of operational experience. The criteria outlined above regarding the objective, policy, capabilities and users are used to describe these usage scenarios and from that the required capabilities of the proposed model.

In this way, there is a systematic development of modelling requirements from existing models to expert or user derived scenarios. As a result, this helps to ensure that that user needs are met and that models are correctly interpreted. Traceable and well defined modelling requirements are produced, which in turn assist in the verification and validation of models. Finally, the development of well defined usage scenarios enables the development of reusable modelling tools. Reusability and extensibility helps to alleviate the need for extensive reprogramming with its associated time and monetary costs when modelling different airport scenarios (Odoni and de Neufville, 1992).

The next section applies the proposed CONOPS based framework to the review of existing models.

3. Existing Models and Usage Scenarios

There is extensive literature on the modelling of different aspects of the airport passenger terminal. A complex system like the airport requires different models for different elements (e.g. airside and landside) using different approaches, such as analytic, simulation or hybrid approaches. The models require different levels of detail, have different characteristics (e.g. deterministic or stochastic model) and capture different performance metrics, including efficiency, security and passenger experience based metrics (Zografos and Madas, 2006). It has been proposed by Zografos and Madas (2006) that scenarios can be used to manage and/or coordinate the application of multiple airport models.

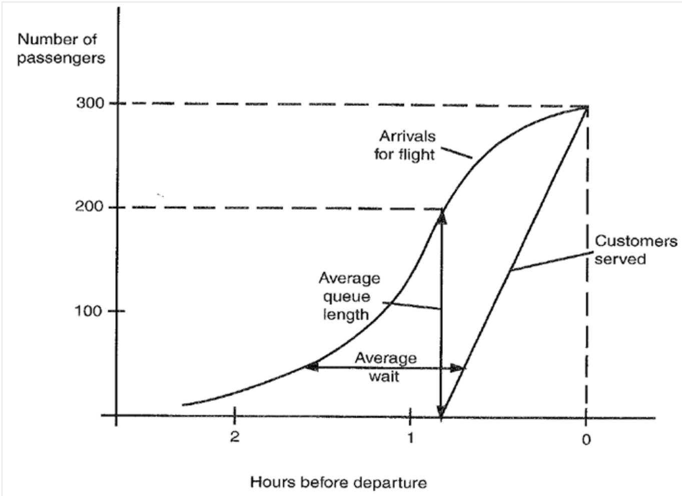

Figure 1: An example cumulative diagram (de Neufville and Odoni, 2003).

This section reviews and develops airport modelling scenarios and model usage scenarios using a bottom-up approach by reviewing existing airport terminal passenger models. In this context, a modelling scenario refers to the system and operational enviroment being modelled whereas the model usage scenario describes the model's operational characteristics from the end user's viewpoint.

The review is structured according to usage scenarios. Empirically, it is found that there is a loose correlation between model usage scenarios, the performance metrics being modelled and the modelling method. For each scenario, a high level scenario description is provided which includes the users, the usage context (e.g. as part of organisational policy or process) and an overview of modelling capabilities. Models that conform to this usage scenario are then discussed and links are made between the assumptions, constraints and capabilities (which correspond to modelling requirements) of these models and the usage scenario. Such an approach reflects a review of the current system or situation as part of the CONOPS method (IEEE, 1998).

3.1. Capacity Planning

A significant portion of the early literature on airport terminal modelling pertains to the scenario of capacity planning (Tosic, 1992). In these scenarios, the model is a tool to help inform planners, designers and decision makers, who are typically associated with the airport operator, in making decisions regarding future infrastructure. Typically, the model is used to help answer the question of whether the planned infrastructure will meet anticipated future demand (Odoni and de Neufville, 1992).

A number of capacity based models are based on the deterministic queue model first developed by Newell (1971). These models predominantly evaluate passenger waiting and service time, and queue length at individual facilities within the airport (refer to Table 1). They employ a graphical representation of the cumulative arrival profile and departure profile from the service facility under scrutiny. As can be seen from Fig. 1, the instantaneous queue length and average wait time can be easily derived based on the vertical or horizontal 'distance' respectively between the arrival and departure profiles for a given facility. However, the approach cannot determine the maximum wait time for individual passengers and does not consider uncertainty in the arrival and departure profiles. Additionally, it also assumes that passengers are served in the order of their arrival in the queue.

The key inputs to these models are the arrival and departure profiles which are either determined from collected data or from predicted arrival profiles and estimated departure profiles (Newell, 1971). Departure profiles can be estimated using a queue model such as that proposed by Lee (1966). Tosic, Babic and Janic (1983) (as reviewed by Tosic (1992)) extends the deterministic queue model to incorporate multiple flights. Tosic, Babic and Janic also explore a stochastic queue model in which arrival profiles are developed and Monte Carlo simulations are used to determine the average wait and service times and queue lengths. Horonjeff (1962) and Barbo (1967) (refer to (Tosic, 1992)) extend the approach to model two flows, namely arrival of passenger and arrival of bags for the baggage reclaim facility. McKelvey (1989) adopts a multi-channel queuing approach for analysing processing times under different system loads.

Models such as those proposed by Dunlay and Park (1978) consider a series of linked facilities where the departure profile of one facility is used as the arrival profile (often with some offset due to walking) for the following facility. Stojkovic and Tosic (1998) (reviewed by Tosic (1992)) further extends the framework to incorporate discretionary activities. Discretionary activities are "activities that occur while passengers are moving between processing points" (e.g. getting a coffee, shopping) (Popovic et al., 2009); these activities occur during passenger 'slack time' (Odoni and de Neufville, 1992). This differs from processing activities which form part of the passenger flow for enplaning or deplaning. With the advent of surveillance technologies (e.g. Gongora and Ashfaq (2006); Kim et al. (2008)), a deterministic queue model can make use of automated (potentially real-time) data collection to quantify arrival and departure profiles.

Bevilacqua and Ciarapica (2010) present a stochastic queue model for evaluating passenger processing and resource usage (e.g. number of counters) for airport check-in. Unlike deterministic queue models, Monte Carlo simulation is used to find the steady state system performance. The results are then used to evaluate a common check-in configuration versus a dedicated carrier check-in configuration. However, such an approach (and indeed queue based approaches in general) still does not fully capture the highly dynamic/transient aspects of the airport environment (Eilon and Mathewson, 1973; Joustra and Van Dijk, 2001).

Kim et al. (2004) describe a statistical model based on dwell time distributions to predict passenger volumes over the course of a day for departing passengers. Similarly, Solak et al. (2009) propose analytic approximation of maximum passenger delay (i.e. walking time, waiting time and processing time) for airport passageways and processing facilities. These approximations are derived from data (e.g. measured walking speeds and processing time fluctuations over a day) and assumptions such as the relationship between flow rates and the width of passageways. Similar to Dunlay and Park (1978), this model considers linked facilities in a more holisitic model of airport capacity. However, Solak et al. (2009) go further and present an algorithm using multi-stage stochastic programming for determining optimal capacity (according to the desired level of service) and optimal future expansion capacity.

It can be seen that Solak et al. (2009) present an advancement on the other capacity models discussed in this section. Instead of merely providing decision makers with a tool to simulate potential airport solutions, it can be used to suggest an optimal solution to the capacity planning problem. However, as the delay approximation function (especially for processing facilities) is developed from data without considering the contributing factors to processing time, the same model cannot be translated across airports nor across time periods with significantly different traffic patterns.

Solak et al. (2009) also review existing models that address a similar capacity optimisation problem. Saffarzadeh and Braaksma (2000) describe a resource utilisation model similar to Solak et al. (2009) and McCullough and Roberts (1979) presents a capacity analysis model. However, neither of these consider the holistic airport system. In a similar vein to Solak et al. (2009), Hassan et al. (1989) presents a resource schedule optimisation (i.e. number of servers open and passenger flow) model based on hierarchical control theory. This model, however, is deterministic.

The models previously discussed neglect a number of important performance metrics such as space. Brunetta et al. (1999) address this issue by combining space with the deterministic queue model in an integrated time and space Level Of Service (LOS) performance indicator. This indicator is based on the arrival profile, average dwell time and the spatial area. Brunetta et al. (1999) argue that this indicator is more useful for decision making than previous indicators based solely on time.

3.1.1. Discussion: Existing Capacity Planning Models

The models discussed in this section are summarised in Table 1. It can be seen that the reviewed capacity planning models represent a macroscopic approach to modelling as it provides "approximate answers to planning (primarily) and some design issues, with emphasis on assessing the relative performance of a wide range of alternatives" (de Neufville and Odoni, 2003). From a CONOPS perspective, this reflects a summary of the usage scenarios envisioned for these models. The average wait time, service time and queue length at a facility or a series of facilities within the passenger facilitation process are typically used for planning and decision making (Brunetta et al., 1999; Newell, 1971). In the CONOPS framework, these reflect the required capabilities of a model used for capacity planning. The users of such models are typically airport operators.

Usage Scenario	Modelling Approach	Existing Models
Modelling objective: estimate capacity of planned facility. *Capabilities*: simulates service times, queue wait times and lengths for single and multiple sequential facilities.	Deterministic queue model	(Newell, 1971), (Brunetta et al., 1999), and models reviewed by (Tosic, 1992), namely: Wirasinghe and Kumarage 1989, Dunlay and Park 1978, (McCullough and Roberts, 1979), Ceric 1988, (McKelvey, 1989), Tosic, Babic and Janic (1983), Horonjeff 1962, Barbo 1967.
Modelling objective: same as above. *Capabilities*: same as above and model proportion of passengers using and time spent in discretionary facilities.	Markov model	Model reviewed by (Tosic, 1992):Stojkovic and Tosic 1988.
Modelling objective: evaluate different check-in configurations with respect to capacity. *Capabilities*: simulates service times and wait times.	Stochastic queue model	(Bevilacqua and Ciarapica, 2010)
Modelling objective: evaluate and determine optimal capacity for stated LOS. *Capabilities*: simulates service times and wait times; determines optimal number of service counters.	Statistical and/or analytic approximation model and optimisation algorithm (e.g. multi-stage stochastic programming)	(Kim et al., 2004), (Solak et al., 2009),(Saffarzadeh and Braaksma, 2000),(McCullough and Roberts, 1979)
	Hierarchical control theory and optimisation	(Hassan et al., 1989)

Table 1: Summary of capacity planning models.

In summary, the typical methodology for these predominantly queue based capacity planning models are:

1. Determine the arrival profile (anticipated or historical).
2. Use data to populate model parameters including service rate and the number of counters.
3. Simulate for a single facility or a sequence of facilities to obtain cumulative diagrams for arrival/departure from each facility.

However, there are shortcomings to existing approaches because other criteria (besides time) also need to be considered in the rapid assessment of facilities as part of planning. Furthermore, especially in the scenario of planning for future facilities, there is significant uncertainty in projected arrival profiles. Ideally, such a model should have modest data requirements (i.e. easy to quantify the model) whilst providing an adequate evaluation of the suitability of facilities with respect to passenger demand.

3.2. Operational Planning and Design

This section reviews a number of models which are described to be suitable for operational planning and design. These models evaluate many of the same performance metrics as those used for capacity planning (refer previous section); however, due to a different usage perspective, the modelling requirements can be drastically different. The models discussed in this section are predominantly focused on those involved in the planning of day-to-day airport operations such as determining the number of service counters to open and its subsequent effect on passenger flow and congestion. It can be seen that a higher level of detail is required for these types of modelling scenarios compared to those described in section 3.1.

Eilon and Mathewson (1973) present an agent based simulation model for evaluating passenger processing time and congestion for facilities within the terminal. A comprehensive set of parameters is used to characterise passenger flow including flight schedules, service rates and resources, and the facilitation process and associated passenger characteristics (e.g. nationality as it influences which Customs lane the passenger can use). The model simulates the passage of individual passengers and collects statistics for the aggregate population of passengers.

Graphs depicting the evolution of performance metrics of interest over the course of a day or other period of time (such as the mean passenger waiting time, referred to as delay) are easily produced from simulation outputs. These are argued to provide an easily comprehensible means for analysts and managers to evaluate performance and alternative

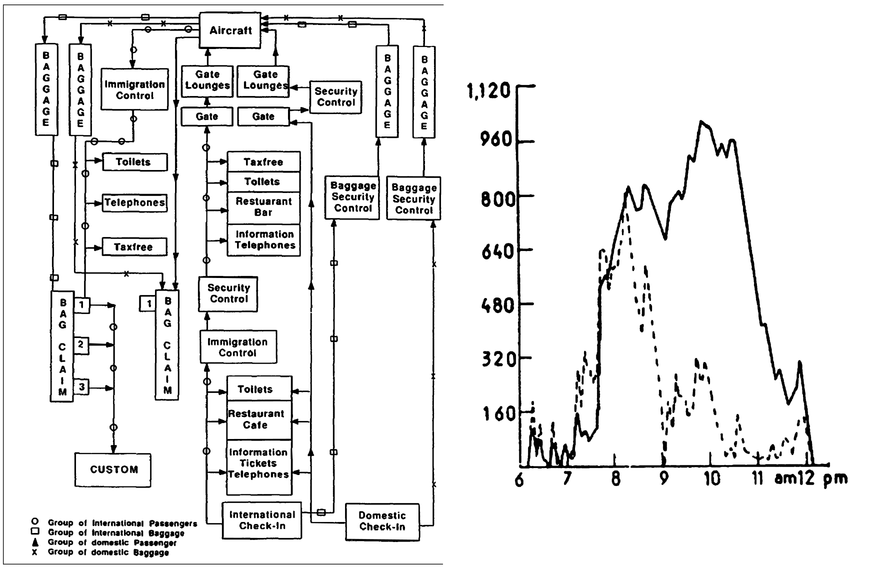

Figure 2: Agent based model depicting passenger flow representation (Jim and Chang, 1998) and graphical output possible with this method (Eilon and Mathewson, 1973).

airport solutions. However, graphs by themselves are limited in their capability to provide quantitative insight into the causal factors influencing the reported performance level. Eilon and Mathewson (1973) begins to investigate this using regression analysis and find that staffing levels and passenger delays are associated with congestion, but do not provide any further discussion on the matter. An illustration of the flow diagrams and graph based output of these type of models is provided in Fig. 2.

In this type of simulation model, it is typically assumed that all passengers follow the designated passenger facilitation process especially in terms of the order of process activities and their spatial location. Furthermore, the model does not typically capture the actual spatial location of individual passengers; rather, it assigns passengers to designated areas (e.g. Customs area, baggage reclaim hall) and calculates metrics such as congestion based on the number of passengers in the same area and the spatial footprint of that area.

There are a number of models that share similarities with or extend upon the early work by Eilon and Mathewson (1973). Tosic (1992) describes a number of these models including Baron and Henning (1974), Laing (1975) and Chang and Mangano (1978). For example, Baron and Henning 1974 applies a similar method to select the minimum number of service counters to ensure that the maximum waiting time is not exceeded. Braaksma and Cook (1980) describes a slight extension to the operational planning concept with an iterative methodology for sizing (with regard to capacity) a facility and its layout with respect to flight schedules, then using simulation to evaluate performance. Similarly, Crook (1998) discusses a model commissioned by British Airways to visualise the system of cross-flows and processes for evaluating changes to terminal facilities and layout. The model is proposed to help planners decide at what point extra service counters need to be opened.

The Airport Landside Simulation Model (ALSIM) (also reviewed by Tosic (1992)) provides a number of useful operational planning usage scenarios for models such as those proposed by Eilon and Mathewson (1973) (ALSIM itself adopts a similar approach to Eilon and Mathewson (1973)). These scenarios are similar to those discussed by Braaksma and Cook (1980) and Eilon and Mathewson (1973) and are posed as questions for a model to answer, namely (McCabe and Gorstein, 1982):

- Where are the bottlenecks?
- Are the resources balanced? Note that an imbalance in terms of resource capacity results in a bottleneck - this is known as the capacity matching problem (Manataki and Zografos, 2009).
- Is the space plan efficient? This is often addressed in terms of facility floor area and amount of space per person (IATA, 1995).

- Is the design capable of handling surges? Surges are also referred to as peak hour or peak traffic.
- How does the plan respond to the various levels of loading?
- What are the wait times?
- Is the service staff adequate?
- Is the facility equipment well located and sized?

The modelling questions above have been applied previously in a practical context. Lui et al. (1972) presents an agent based model similar to Eilon and Mathewson (1973) for New York JFK International Airport. This model was used to evaluate physical and operational plans for expansion given the advent of larger aircraft. The inbound passenger facilitation process was modelled, starting at the gate and terminating when the passenger and their bags exit into the lobby.

For the purposes of planning, which typically considers peak hour or peak periods (de Neufville and Odoni, 2003), a three hour peak period during the day was modelled. This model was validated by comparing simulated results to actual time based measurements of the process. Uncertainty in model parameters (such as service times) was captured using cumulative density functions (CDFs). The modelling outcomes were presented to the airport planning division, facility management and federal agencies; this triggered the development of modified facility plans and new operating procedures which were tested again using simulation.

Another practical application of modelling was for Athens International Airport in preparation for the 2004 Olympic Games. Zografos and Madas (2006) describe a framework combining multiple modelling methods to answer the following modelling questions:

- Will the airport infrastructure be able to handle forecasted temporary traffic increase for the Olympic Games?
- Will the airport infrastructure be able to sustain the forecasted increase on a more permanent basis?
- What will be the implications on airport operations in both cases (temporary Olympic games and permanent traffic increase e.g. due to traffic hubbing)?

Jim and Chang (1998) also present a holistic agent based simulation model along the lines of Lui et al. (1972) and Eilon and Mathewson (1973). The proposed method incorporates spatial movement using predetermined paths (that passengers are assumed to walk along) and passenger groups. Gatersleben and Van der Weij (1999) present a similar model for analysing inbound and outbound capacity bottlenecks – this was developed as part of a project for Schipol Airport. Roanes-Lozano et al. (2004) describe a similar time based model for outbound passenger facilitation and argue that the model can be used to aid terminal design. Appelt et al. (2007) and Joustra and Van Dijk (2001) both apply a similar approach for modelling check-in. Some check-in modelling scenarios that are proposed include the study of online check-in use, capacity studies and resource allocation and visualisation (using animation) to communicate potential future situations.

KiyIldI and Karasahin (2008) propose a fuzzy system model for check-in that uses fuzzy IF-THEN rules to link passenger and service attributes to processing time. Unlike the other models described in this section, this model represents and quantifies the causal link between time based performance metrics and the variables that influence them. This provides traceability and enables a more refined usage scenario where in addition to predicting the value and evolution of performance metrics (e.g. wait time or queue length), it is possible to identify what caused a certain level of performance.

Jim and Chang (1998) propose that an integrated process for terminal design should be adopted at the organisational level. There are four major steps, namely: programming, concept development, final design and design development. It is argued that simulation models can be applied at the final design stage, which involves:

- translating the concept and resource requirements into details such as size, location and shape of terminal facilities,
- determining and evaluating the relationships between system components, and
- evaluating the adequacy of each facility based on the airport user's perspective.

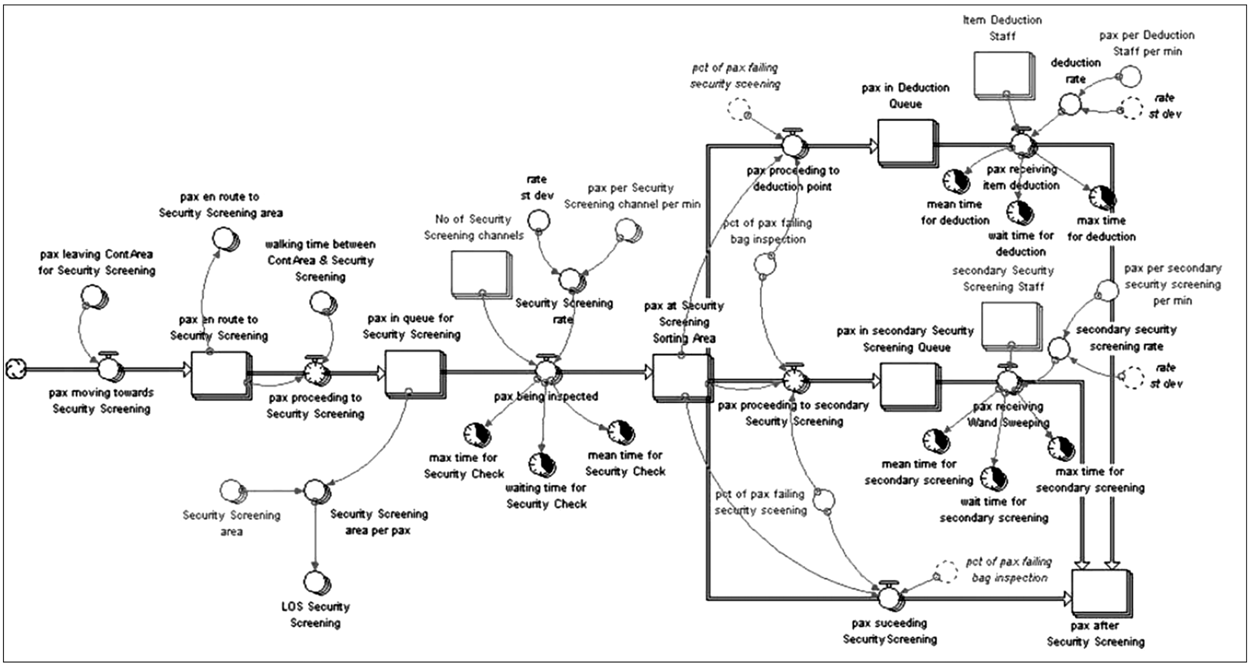

Figure 3: Stock and flow diagram (Manataki and Zografos, 2009).

Manataki and Zografos (2009) and Manataki and Zografos (2010) propose a different approach to answer effectively the same questions as ALSIM and aid with decision making on operational concepts (e.g. are more staff/servers needed at Customs, what is the proportion of users who use online or e-check-in). It is argued that macroscopic models are insufficient for handling the complexity, variability and stochastic nature of airport terminals whereas microscopic models are difficult to use (due to large data requirements for a high level of detail) and require tool familiarity. Therefore, a mesoscopic approach is proposed that focuses on aggregate characteristics (similar to a macroscopic model) while operating at an intermediate level of detail. Early examples of agent based models (e.g. Eilon and Mathewson (1973), ALSIM etc.) are more mesoscopic in nature as they do not incorporate detailed passenger interactions. For instance, passengers move from one area to another without considering their exact location and interaction with respect to walls, counters and other passengers.

Manataki and Zografos (2009) employ a system dynamics modelling approach that uses stock and flow diagrams (refer to Fig. 3). The passenger facilitation process and its corresponding physical facilities are modelled using stocks that represent the state of a process (e.g. accumulation of passengers in a queue) and flows that represent the rate of change of the stock. Factors such as walking time, rate of processing and the number of service counters can influence the flow elements in the model. Unlike Eilon and Mathewson (1973) and related works, Manataki and Zografos (2009) consider the actual spatial layout of the terminal and passenger walking paths. However, unlike microscopic models, these paths are predetermined. The path distance and passenger walking speed distributions are used to determine passenger flow from one area to another.

The availability of computational capacity has contributed to the proliferation of microscopic agent based simulation models in the past one and a half decade. Many of these use commercial simulation packages. Kiran et al. (2000) for example present an simulation implementation for Istanbul Ataturk Airport based on the ProModel simulation package. Such a model captures a wide range of performance metrics revolving around passenger processing time and resource usage for the outbound facilitation process including utilisation of check-in desks, customs desks, maximum queue size, average queue wait time, average passenger time in the terminal, maximum number of passengers in waiting rooms and expected daily revenue. In addition to the previous usage scenarios of capacity analysis and operations planning, it is possible to also use the model for training and demonstration of terminal activities. The model can be used to visualise the flow of passengers, baggage, and other aspects outside the terminal such as parking.

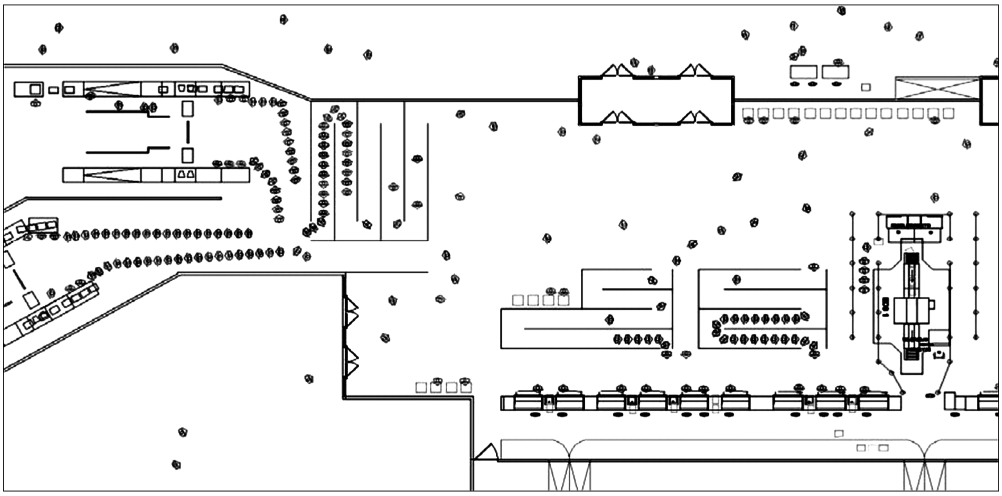

Figure 4: Illustration of a microscopic agent based model visualisation (Wilson et al., 2006).

Fig. 4 illustrates an example visualisation of a microscopic model. Such a detailed visualisation is possible because a microscopic model simulates individual passengers and their interactions at a high level of detail. It is reported that the use of a simulation model allowed the terminal to be opened ahead of schedule.

Takakuwa and Oyama (2003) present a similar microscopic simulation model for Kansai International Airport applied to outbound passengers. It captures basically the same time based and resource usage performance metrics as Kiran et al. (2000), and incorporates characteristics such as the flight schedule, passenger nationality, groups, walking speeds, number of bags and size of a passenger group. It is used to analyse capacity in the facilitation process where it is found that check-in was the key bottleneck and that using business class counters to serve economy class passengers can help alleviate problems such as missed flights. Such a usage scenario could potentially be addressed with some extension to the queuing methods described in section 3.1 but a microscopic model captures passenger characteristics, space and time all in one framework.

Ju et al. (2007) present a similar simulation model to Takakuwa and Oyama (2003) implemented using the Arena modelling package. Similarly, Fayez et al. (2008) describe a holistic model of the passenger facilitation process for inbound and outbound passengers. Due to the highly detailed nature of agent based simulation models, it is possible to evaluate a range of operational scenarios and configurations, and emergent system behaviour (Fayez et al., 2008). These include new trends in passenger arrival/departure patterns, airport capacities, availability of resources, new technology and security requirements, effect of natural disasters and public transportation factors.

Schultz and Fricke (2011) describe an agent based model primarily for outbound passenger facilitation for analysing passenger flow. It considers the correlation between passenger walking speed and density (passengers walk more slowly in dense crowds) and dynamic group behaviour (e.g. the fastest member waits if it walks too far from the group centre). In addition, passenger wayfinding (in terms of the visibility of signage) is also modelled. However, such an increased level of modelling functionality has a corresponding increased requirement for data to adequately populate model parameters.

The model proposed by Schultz and Fricke (2011) is demonstrated on the scenario of deciding the aircraft boarding policy by comparing boarding times for single door boarding versus two door, and random boarding versus block boarding (i.e. where passengers board in groups based on their seating assignment). Schultz and Fricke (2011) propose that the model can also be used to identify performance targets based on current performance levels. In addition, the model can be used as part of the airport planning, management and optimisation process.

Wilson et al. (2006) present an agent based model for security checkpoints. The previously reviewed agent based models already begin to address the need for using multiple criteria, equivalent to multiple performance metrics in this context, to assess airport facilities (e.g. wait time and congestion level). Wilson et al. (2006) take the multiple criteria concept further to evaluate, separately, security effectiveness (probability of detecting a prohibited item or person), operational costs, resource utilisation, and passenger and bag throughput. The additional capability of evaluating security effectiveness is implemented based on the multiplication of probabilities of detecting prohibited items at different points in passenger facilitation model, similar to Chawdhry (2009). This model supports the evaluation of different designs and configurations (i.e. 'what-if' scenarios) against the performance metrics described previously. For example, physical space configuration can be evaluated for passenger flow, and bottlenecks and the checkpoint procedure can be evaluated (e.g. percentage of passengers subjected to secondary checks) for its effect on staffing. Pendergraft et al. (2004) also describe a model for security screening with similar modelling objectives to Wilson et al. (2006) but does not provide any implementation details.

Virtually all of the microscopic agent based models discussed here can also be used for the purposes of visualisation. However, there are two models in particular that specifically target the visualisation usage scenario. Crook (1998) (reviewed above) reveals that British Airways requested the ability to visualise the system of cross-flows and processes to aid in evaluating possible changes to the internal design of the terminal. Koch (2004) similarly applies an agent based model for visualising airport security operations. This enables users to explore new technologies and procedures and visualising their effects on passenger flow; in effect, it provides a level of realism for the decision maker.

3.2.1. Discussion: Existing Operational Planning and Design Models

This section reviewed a number of existing models targeted at airport operational planning and design scenarios. A summary of the reviewed models is provided in Table 2. These models in many instances were also applied to the capacity planning task, however the reverse, applying capacity models described in section 3.1 to operational planning is typically insufficient due to a lack of detail. This highlights the need for a trade-off between the detail provided by a model and the data complexity of the model where the trade-off should be decided by the intended usage of the model.

Compared to the macroscopic capacity planning models reviewed in the previous section, the models in this section tend to require flight schedules (predicted or historical), service rates of each airport facility and the actual spatial layout of the airport. The differences between mesoscopic and microscopic models can be summarised thusly:

- Microscopic models capture individual interactions, mesoscopic captures population interactions.
- Spatial detail and passenger movement interactions – microscopic models simulate interactions between individual passengers and walls, facilities and other passengers whereas mesoscopic models tend to use predetermined paths and walking speed distributions to determine travel time between facilities. Hence, microscopic models are better suited to evaluating terminal layout as part of 'final design' (Jim and Chang, 1998).
- Microscopic models tend to capture passenger group interactions and their effect on passenger movement.
- Visualisation – both types of models can produce graphs of performance metrics (over time), but microscopic models can also visualise individual passengers moving in the terminal.

From a CONOPS perspective, the above reflects the varying capabilities of existing operational planning models.

Note that the accuracy of both modelling approaches are dependent on model assumptions and the accuracy of model parameters. At a minimum, they both assume that passenger behave according to some flow chart like representation of the facilitation processes (which in some cases includes discretionary activities, such as with Jim and Chang (1998)). Microscopic models require even more data to accurately characterise all the individual interactions in the simulation model (i.e. model parameters) including passenger walking speeds, navigation and group interactions. Note that the model parameters needed for a mesoscopic or microscopic model (such as processing rates and walking times) can be derived from collected data or approximated using other techniques such as genetic algorithms (Gongora and Ashfaq, 2006).

However, a highly detailed model can provide misleading results if assumptions are violated or if model parameters are incorrect beyond tolerable bounds. These bounds are difficult to determine even with a sensitivity analysis due to the large number of variables and a highly dynamic and non-linear system. Model validation is paramount and the reviewed models tend to employ expert validation of modelled processes and comparison between predicted and recorded traffic patterns.

One of the common assumptions that can significantly affect modelling outcomes is that of peak-hour traffic (i.e. worst case) (de Neufville and Odoni, 2003). However, unlike the capacity planning usage scenario, the potential variations in passenger traffic levels between peak and non-peak periods are also important to operational planning. Existing models, such as that by Schultz and Fricke (2011) and Takakuwa and Oyama (2003), use flight schedules to randomly generate passenger arrival (or input) profiles as part of a Monte Carlo simulation. The aim of this is to incorporate, to an extent, the dynamic nature of passenger traffic and capture some of the uncertainty and extreme conditions that may affect passenger facilitation performance (de Neufville and Odoni, 2003; Hargreaves, 2007). An example of an 'extreme' condition is an off-schedule arrival of aircraft coinciding with the arrival of other aircraft, therefore resulting in a sudden, large influx of passengers. However, none of the existing models provide a methodology for systematically incorporating these types of variations in passenger traffic and their effect on the facilitation process.

From a CONOPS usage scenarios perspective, both mesoscopic and macroscopic approaches have been used to evaluate the effects of resource allocation and scheduling on performance metrics such as wait time, queue length and passenger throughput. This information is then used to help airport operators and other stakeholders (such as immigration) allocate and schedule resources (e.g. staff to service counters). Alternatively, operational planning and design models can be applied to evaluate the performance of the terminal given anticipated future flight schedules and traffic patterns. Integrated with the 'final design phase' of airport planning (as defined by Jim and Chang (1998)), the model is used to evaluate the adequacy of proposed future facilities. There are many real world example applications of the reviewed models such as for British Airways and airports such as Schipol, New York JFK, Istanbul Ataturk and Athens International.

In summary, the typical methodology for modelling operational planning involves:

1. Identify the passenger facilitation process and the sequence(s) in which facilities are visited.
2. Obtain, through prediction or historical data, the passenger or flight schedules of interest.
3. Use data to populate the spatial and service parameters (e.g. processing time) for each facility.
4. Validate the model by comparing predicted performance with actual performance for historical scenarios.
5. Simulate performance metrics (e.g. wait time, congestion) given different resourcing levels and facility configurations.

Traditionally, airport stakeholders are reactive to changes in technology, regulatory requirements, and passenger and flight characteristics (Fayez et al., 2008). Modelling can also be used to predict the effect of changes and help airports proactively prepare for or initiate change. Such changes could include new security procedures, e-ticketing, remote or online check-in. This has lead to a need to evaluate multiple performance metrics (or multiple criteria) and the trade-offs between them.

A number of models (such as those by Eilon and Mathewson (1973) and KiyIldI and Karasahin (2008)) begin to look at the causal factors that influence system performance. KiyIldI and Karasahin (2008) for example use fuzzy IF THEN rules to predict capacity at check-in based on passenger numbers and the amount of baggage. Eilon and Mathewson (1973) for example use statistical studies and especially regression on simulated results to find correlation and dependencies. Both of these hint at a more advanced usage scenario beyond simply evaluating whether there is sufficient capacity or not or determining the level of performance given a certain configuration (e.g. number of counters open) and/or policy or procedure (e.g. boarding strategy). In this scenario, the model provides the user with further insight into what aspects of the design, configuration or policy are affecting the performance and to what extent.

3.3. Security Policy and Planning

A number of models have been proposed that specifically address the problem of security for airports. The concept of security is very broad in scope, however, the majority of existing models focus on evaluating security as a function of the ability or inability of the "combined procedures and technologies in the process to successfully filter out all threats (harmful substances/prohibited items and malicious persons) from reaching an aircraft through the passenger facilitation process" (Chawdhry, 2009). Due to the highly regulated nature of aviation security, many of the models reviewed here are intended as an aid for policy makers.

Chawdhry (2009) presents a model that evaluates the overall security of the passenger facilitation process based on the probability of harmful substances/prohibited items and malicious persons reaching an aircraft (also referred to as the process permeability or missed detection). This model is intended to help quantitatively assess the impact of

Usage Scenario	Modelling Approach	Existing Models
Modelling objective: Mesoscopic operational planning – evaluate resource levels (e.g. number of counters to open), perform capacity matching across multiple facilities, peak traffic analysis of planned facilities. *Capabilities*: simulate service/wait times and congestion for different resourcing levels.	Agent based model	(Eilon and Mathewson, 1973) (also regression analysis), (Lui et al., 1972), (Crook, 1998), (Jim and Chang, 1998), (Gatersleben and Van der Weij, 1999), (Roanes-Lozano et al., 2004), models reviewed by (Tosic, 1992): Baron and Henning 1974, Laing 1975, Chang and Mangano 1978, (Braaksma and Cook, 1980), ALSIM
Modelling objective: Mesoscopic operational planning (same as above). *Capabilities*: same as above.	System dynamics model	(Manataki and Zografos, 2009, 2010)
Modelling objective: Mesoscopic operational planning (similar to above) for check-in. *Capabilities*: same as above.	Agent based model	(Appelt et al., 2007),(Joustra and Van Dijk, 2001) (including causal factors)
Additional capabilities: analyse factors influencing time based performance	Fuzzy model	(KiyIldI and Karasahin, 2008)
Modelling objective: Microscopic operational planning – evaluate resource levels, perform capacity matching, peak traffic analysis. *Capabilities*: simulate service/wait times and congestion, detailed passenger interactions with space and services.	Agent based model	(Kiran et al., 2000),(Takakuwa and Oyama, 2003),(Ju et al., 2007), (Fayez et al., 2008), (Schultz and Fricke, 2011)
Modelling objective: Microscopic operational planning (similar to above) for security screening. *Capabilities*: similar to above and evaluates passenger risk.	Agent based model	(Pendergraft et al., 2004),(Wilson et al., 2006)
Modelling objective: Microscopic operational planning – visualisation and communication. *Capabilities*: Visualise physical passenger and crowd interactions and movements.	Agent based model	(Crook, 1998), (Koch, 2004)

Table 2: Summary of operational planning and design models.

deploying security technologies and policies on overall security. The overall process permeability (i.e. probability of a missed detection) is determined using the multiplication of probabilities of the permeability of individual processes in the facilitation chain (therefore assuming independence). Expert opinion is used to determine the permeability probability for individual processes. Chawdhry (2009) provides an example implementation to assess the proposed registered traveller scheme where passengers are subjected to different levels of screening (with different detection rates) according to prior passenger risk assessment. However, the model proposed by Chawdhry (2009) only considers security without considering its effect on passenger flow. Wilson et al. (2006) combine the underlying concept with passenger flow in an agent based model (refer to section 3.2).

Babu et al. (2006) describe a Bayesian probabilistic model that extends the concept described in Chawdhry (2009). This model incorporates conditional probabilities (which overcomes some of the assumptions on independence) and considers both the probability of a false alarm (detecting a threat when one does not exist) and a false clear (not detecting a threat that was there). The model is targeted at the same policy scenario of dividing passengers into groups based on risk and goes further to provide an algorithm to optimise the number of passenger 'risk' groups in the registered traveller scheme. Again the model is proposed to help authorities such as the Transportation Safety Authority (TSA) evaluate the impact of proposed policies and goes further to recommend to decision makers how aspects of that policy can be optimally implemented.

Nie et al. (2009) extend the model by Babu et al. (2006) by overcoming the assumption that all passengers are equally risky and considers further the number of security screeners at the security checkpoint. The algorithm presented here can be used to optimise for the number of passenger 'risk' groups and the number of screeners at security screening.

Akgun et al. (2010) present a framework entitled the Fuzzy Integrated Vulnerability Assessment Model (FIVAM). This framework adopts a different approach which explicitly incorporates multiple experts and their opinions as well as multiple criteria related to the vulnerability of airport facilities to attack. The criteria that have been identified for the airport case study are: deterrence, detection, delay (impede terrorist penetration into or exit from facility), and response and recovery. Note that the previously discussed risk models focus only on the detection criteria. Each airport function and/or component is rated by experts using fuzzy linguistic variables according to each of the five criteria. At the same time, the dependencies between pairs of functions and/or components are similarly rated as well as the dependency between functions and/or components and the overall airport mission. This approach thus captures the dependencies (i.e. causal links) between airport functions and/or components and risk criteria, as well as the overall risk. Through simulation using a fuzzy cognitive map, it is possible to identify 'hidden vulnerabilities' that arise due to interdependencies.

The framework proposed by Akgun et al. (2010) highlights the importance of identifying dependencies and their effects on vulnerability and risk. It is proposed that this model can also be used to support policy making by regulatory authorities such as the TSA. However, it is also targeted at airport operators to support policy making, allocation of resources and identification of airport functions and/or components that need to be improved with respect to security. Note that this model does not specifically consider passenger flow or indeed spatial or temporal context.

Pirelli and Chawdhry (2009) present a method specifically for the evaluation of usability and security risk over the passenger facilitation process for disabled persons. The presented approach is an expert based evaluation methodology using cognitive walkthrough. Even though the resultant 'model' does not support simulation or inferencing, the methodology helps to identify issues and areas where facilities and/or technologies can impact on usability and security. Hence, the method can be used to assist in devising risk management and inspection policies for disabled persons. Such an approach is advantageous for the early stages of design as a cognitive walkthrough can be conducted with experts based on simple textual descriptions of the process (Scholtz, 2004). However, more detailed analysis of a process and facilities would benefit from a model based approach (such as using a detailed agent based model).

3.3.1. Discussion: Security Policy and Planning

A summary of the reviewed models is provided in Table 3. As the primary CONOPS usage scenario for these models is to evaluate the risk arising due to policy decisions (such as implementation of new technology or procedures), virtually all of the models reviewed adopt the same fundamental Bayesian probabilistic approach. This typically involves:

1. Expert elicitation to identify the factors influencing the risk metrics (e.g. permeability) of interest.

Usage Scenario	Modelling Approach	Existing Models
Modelling objective: Evaluate risk for proposed security policy. *Capabilities*: Calculate process permeability probability.	Simple probability model	(Chawdhry, 2009)
Modelling objective: Evaluate risk for proposed security policy. *Capabilities*: Calculate probability of false alarm and false detection.	Bayesian model	(Babu et al., 2006)
Modelling objective: Evaluate risk and passenger flow for proposed security policy; aid with operational planning for security. *Capabilities*: Simulate risk and passenger service/wait time at given facilities.	Bayesian model integrated with another method	(Nie et al., 2009) - optimisation algorithm, (Wilson et al., 2006) - agent based model
Modelling objective: Evaluate risk and usability of facilities for disabled persons. *Capabilities*: Identify using expert elicitation areas that impact on security and usability.	Cognitive walk-through	(Pirelli and Chawdhry, 2009)
Modelling objective: Evaluate vulnerability of proposed security policy; aid in operational planning with respect to security. *Capabilities*: assess vulnerability of individual facilities and overall airport; identification and quantification of causal links impacting on vulnerability.	FIVAM (Fuzzy model)	(Akgun et al., 2010)

Table 3: Summary of security policy and planning models.

2. Expert elicitation to obtain estimates of probabilities/conditional probabilities.
3. Evaluate facilities/policies using developed model.

However, this is a difficult modelling task especially due to the difficulty of obtaining data for the model especially when considering terrorism where the event is rare and the adversary is adaptive (Akgun et al., 2010). As a result, all of the reviewed models rely on expert opinion for quantification.

Compared to the other models, Akgun et al. (2010) proposed an alternate vulnerability assessment based approach that explicitly takes into account the opinions of multiple experts. From a CONOPS perspective, Akgun et al. (2010) provides an additional capability compared to other security policy models. This approach can also potentially be used for reviewing the vulnerability of the current airport configuration and identify areas for improvement. However, for both the Bayesian and the FIVAM approach, model validation remains a challenge.

Evaluation of policy based solely on risk without regard to passenger flow can result in long queues and congestion which in itself presents a different safety risk. As a result, it is recognised that the capability to evaluate both security and passenger flow, and indeed other performance metrics and the trade-offs between them is needed (Wilson et al., 2006; Nie et al., 2009). In addition, it is found that detailed models (such as agent based models) could also be applied to evaluate technologies and policies and their impact on passengers with special needs.

3.4. Airport Performance Review

The recent literature on airport modelling suggests a trend among airport operators and airlines where the focus is shifting towards the passenger (Park, 1999; Chou, 2009). In these usage scenarios, the user (typically airport operator, airline or government agency) seeks to evaluate the level of passenger satisfaction with the current facilities and processes. Many of these models use some form of passenger survey or questionnaire and statistically aggregate the survey outcomes across all passengers (or passenger demographic groups) to obtain 'global' evaluations of satisfaction. Note that in many of these models, level of service is used to refer to a broad range of performance metrics revolving around passenger satisfaction. However, the usage of the term level of service in these models is not necessary consistent with the IATA definition of level of service (IATA, 1995).

There are a number of models which seek to predict or relate aspects of airport performance (such as delays and congestion) or airport characteristics (e.g. availability of restrooms) to the level of service (i.e. passenger satisfaction). Ndoh and Ashford (1994) present a model for evaluating the factors influencing the level of service using fuzzy logic and linguistic variables. Passengers and experts are asked to rate individual airport facilities (processing, circulatory, holding, amenities, concessions, ground access) and a fuzzy weighted sum is used to ascertain the overall rating. It is argued that subjective perceptions of service are not appropriately captured in existing methods that use numerical ratings (referred to as crisp value representations). A fuzzy approach is capable of capturing uncertainty and ambiguity in passenger satisfaction ratings. It is argued that ensuring passenger satisfaction is a key management objective and regular reviews (or assessments) are necessary. The work presented by Ndoh and Ashford (1994) for example is sponsored by the British Airports Authority.

Yeh and Kuo (2003) also employ a fuzzy weighted sum approach similar to Ndoh and Ashford (1994) to determine overall satisfaction with an airport. The model is then used to compare different airports for the purposes of benchmarking and identifying problems with respect to passenger satisfaction. However, the model does not capture dependencies between model factors and satisfaction beyond a weighted sum aggregation. Paul (1981) employs statistical methods to predict the level of service based on factors such as temperature, crowding and delays. It is proposed that the model can be used to inform terminal design; however, the model is found to use qualitative data without proper quantification (Correia and Wirasinghe, 2004). Correia and Wirasinghe (2004) reviews a model proposed by Muller 1987 that uses psychological scaling to form equations for the level of service; however, these were not calibrated with data.

Gkritza et al. (2006) present a model that fits a logit model to passenger satisfaction survey results. Based on the fitted model, it is then possible to quantitatively characterise the relationships between passenger facilitation factors and satisfaction. Some of the factors surveyed include gender, income, education and class of travel. The modelling approach is demonstrated for security screening and is proposed as a method to help evaluate TSA policies similar to the usage scenarios described in section 3.3. de Barros et al. (2007) propose a similar model using regression to evaluate overall satisfaction for transfer passengers. This model was tested at Bandaranaike International Airport, Sri Lanka. It is proposed that the outcomes of the review can be used to guide investment policies when deciding on airport expansion. Chou (2009) describes a deterministic weighted sum model of passenger satisfaction similar to de Barros et al. (2007).

Liou et al. (2011) also presents a model to help identify areas for improvement with regards to level of service and specific passenger demographics. This model employs a dominance based rough sets approach to infer dominance rules (again based on survey outcomes) for determining overall satisfaction. Such an approach does not require statistical assumptions. However, the strength of influence of specific factor on the overall satisfaction is not captured; rather, it is inferred based on the number of occurrences of the factor of interest in the rules. Ren (2011) proposes an alternate approach to improving passenger satisfaction using the six sigma method. The method seeks to reduce the mean and variance of the check-in service time. Suggestions are made using cause and effect diagrams and simple statistical studies based on data.

Park (1999) describes a model for determining performance targets based on Total Quality Management (TQM) survey results. It uses the perception response method first proposed by Mumayiz (1985) which maps passenger perception ratings (classified as ‘good’, ‘tolerable’ or ‘bad’) to metrics such as processing time. However, a shortcoming of the perception response model is the lag between passenger experience and when the questionnaire is conducted (Park, 1994). Yen et al. (2001) also use a perception based approach involving a fuzzy assessment of perceived and actual waiting time. This is extended to include an evaluation of congestion by Yen and Teng (2003).

Correia and Wirasinghe (2007) propose a model that extends upon the capabilities of Park (1999) using a probabilistic method to determine, for airport performance metrics, global satisfaction rating boundaries (i.e. unacceptable, poor, fair, good and excellent performance) from individual passenger ratings. Therefore, a given wait time can be categorised as poor, fair or otherwise. An overall satisfaction level is derived using a weighted sum model. Correia et al. (2008) extend on Correia and Wirasinghe (2007) and maps the following performance metrics to satisfaction: wait time, processing time, walking time, walking distance, level changes, orientation/information[1], space for cars at curbside and the number of seats. This model can be used for performance review, linking qualitative satisfaction assessments to quantitative performance values (noting that mutual effects between variables is neglected) as well as determining performance target boundaries for specified metrics. The model was tested at Sao Paulo International Airport.

[1]Orientation/information was quantified by dividing actual walking distance by the shortest path distance.

Usage Scenario	Modelling Approach	Existing Models
Modelling objective: Performance review of airport – identify areas impacting passenger satisfaction and areas for improvement. *Capabilities*: Simulate passenger satisfaction given airport performance (e.g. delays, congestion) and airport characteristics (e.g. restroom and seating availability); identification and quantification of links between satisfaction and airport performance/characteristics; quantification of overall satisfaction given satisfaction with individual facilities.	Fuzzy model Statistical/regression model Dominance based rough sets Psychological scaling Six sigma method	(Ndoh and Ashford, 1994), (Yeh and Kuo, 2003) (Paul, 1981), (Gkritza et al., 2006), (Correia and Wirasinghe, 2007; Correia et al., 2008), (de Barros et al., 2007) – for transfer passengers, (Chou, 2009) (Liou et al., 2011) Muller 1987 from (Correia and Wirasinghe, 2004) (Ren, 2011)
Modelling objective: Performance review of airport – determine performance targets to ensure passenger satisfaction *Capabilities*: Map passenger perception to airport performance (e.g. service/wait time); determine good/tolerable/bad performance boundaries.	Perception response Fuzzy perception	(Park, 1999) (Yen et al., 2001),(Yen and Teng, 2003)

Table 4: Summary of airport performance review models.

3.4.1. Discussion: Airport Performance Review

Unlike the previous usage scenarios (capacity, operational and security), the models reviewed in this section tend to map performance metrics (especially waiting and service time) and terminal facility characteristics to passenger satisfaction. From a CONOPS perspective, this reflects the capabilities of these models. The end-user of these models is primarily airport operators and airlines. This reflects a trend where passenger satisfaction is tied to the reporting and review procedures (i.e. the CONOPS model usage policy) for these organisations. A summary of the models reviewed in this section is provided in Table 4.

However, passenger satisfaction is subjective and difficult to reflect on for the purposes of airport improvement. One of the criticisms of early work was that too many metrics are reported without regard for their importance/effect on the overall process (Correia and Wirasinghe, 2004). Hence, many of the reviewed models not only report an aggregate satisfaction value (typically using a weighted sum), but also start to establish through regression and fuzzy weighting the importance of factors influencing overall satisfaction.

In summary, the typical methodology for modelling passenger satisfaction involves:

1. Design surveys, questionnaires, observational studies and/or expert elicitation workshops to gather data.
2. Collect data.
3. Use data to populate model parameters and structure the model (e.g. determining boundaries for positive or negative satisfaction and hence performance targets or benchmarks) (Correia and Wirasinghe, 2007; Park, 1999; Yeh and Kuo, 2003). Numerous models also evaluate the aggregate overall satisfaction.
4. Identify relationships between airport performance metrics (factors such as processing time, congestion) and satisfaction. This is used to help identify airport problems (e.g. trace dissatisfaction back to the cause(s)) and guide investment decisions (i.e. areas for improvement) (Correia and Wirasinghe, 2007)

In order to provide quantitative justification in identifying and characterising airport problems, the models need to map subjective data (obtained through surveys for example) to quantitative measurements. Hence, there is a need to incorporate uncertainty and ambiguity using methods such as fuzzy linguistic variables and probability distributions.

4. Discussion and Conclusion

Existing models have not considered in depth the usage scenarios and their requisite modelling requirements (i.e. capabilities). No structured framework, such as that captured by a CONOPS (refer to section 2), has yet been presented that attempts to organise the possible usage scenarios for an airport terminal complex system. This paper presented such a CONOPS approach for a range of usage scenarios, reviewing existing models with respect to modelling objectives (i.e. modelling questions), user classes, operational policies, and a description of model components and capabilities.

Having such a framework helps to ensure that the needs of the users are addressed without misinterpretation. Additionally, it assists in the verification and validation process (as capabilities translate to modelling requirements) and is invaluable for designing extensible and reusable models. Furthermore, the review of existing models and their usage scenarios creates a basis for developing future models as part of a systematic CONOPS process. For instance, the modelling methods used to address specific usage scenarios with associated airport performance metrics of interest were identified in section 3.

By applying the proposed CONOPS based framework to the review of existing models, it is found that the four major usage scenarios, capacity planning, operational planning, security planning and airport performance review are consistent with the findings of Eilon and Mathewson (1973). Eilon and Mathewson (1973) propose that there are three types of model usage scenarios: explorative, predictive and operative. Explorative usage is where the model is used to aid in the review of the system and highlight its performance, often in qualitative terms. This reflects the airport performance review CONOPS usage scenario, characterised typically by a capability to map performance metrics (such as wait time and congestion) to passenger satisfaction, and to aggregate satisfaction from individual facilities into an overall satisfaction rating.

Predictive usage involves the evaluation of 'what-if' questions for future operational scenarios. This is similar to the capacity planning usage scenario where, typically, airport operators (the user) use the model to simulate queues (the capability) for airport facilities. In addition, predictive usage can refer to scenarios involving security policy and planning where false alarms and missed detection risks are evaluated; the users in this case are often government agencies.

Finally, operative scenarios are where the model is used to aid in developing optimal solutions to operational problems. Operative scenarios are similar to the operational planning models reviewed in this paper which typically simulate resourcing levels, and time and space based performance metrics (e.g. wait time, congestion). It can be seen that the three usage scenarios proposed by Eilon and Mathewson (1973) reflect to an extent the findings of a CONOPS based review of the literature, almost 40 years on.

In addition, the review went further and identified the key model capabilities and modelling methods used for each of these four usage scenarios. These findings serve as a reference point for the development of future models as part of the proposed CONOPS framework.

For example, future models targeted at the capacity planning scenario (discussed in section 3.1) need to be able to estimate the dwell time and throughput for given passenger arrival profiles. Due to the future-planning nature of this scenario, existing work suggests that a macroscopic approach should be adopted as there is limited information and high uncertainty. Candidate methods for this scenario include queue based models.

On the other hand, future models for operational planning and design (discussed in section 3.2) need to be able to capture greater detail such as with a mesoscopic (capture population interactions) or microscopic (capture individual interactions) approach. More information is available and a higher level of precision is required for this scenario. Such a model needs to capture the effects of flight schedules and resourcing on wait time, queue length and throughput. Candidate methods for this scenario include agent based models and system dynamics models.

Future models for security policy and planning (discussed in section 3.3) need to be able to capture the uncertainty and risk of undesirable events such as those related to terrorism. Candidate methods for this include Bayesian approaches and fuzzy expert driven approaches.

Finally, future models targeted at airport performance review need to be able to evaluate, among other factors such as dwell time and congestion, the level of passenger satisfaction given an operational configuration. Typically, data driven approaches are taken such as that based on statistical or fuzzy models.

It can be seen that the plethora of existing airport models for different aspects of the same airport terminal passenger system reflects the complex systems nature of the airport. In addition to the specific scenarios based findings above, there are a number of general findings. Firstly, there is a recognition of the importance of capturing the interdependencies within the system and hence the need for capturing multiple criteria (or performance metrics) which cannot be treated independently. In addition, the large number of fuzzy models, probabilistic models and Monte Carlo simulations highlights the need to incorporate uncertainty in the facilitation process and uncertainty associated with qualitative measurements (such as in relation to passenger satisfaction). Finally, an emergent trend in going further and finding the factors and cause of observed phenomena has been identified.

By applying a CONOPS based framework to the review of existing models and development of future models, it is possible to systematically develop modelling requirements and help address some of the challenges of an airport complex system.

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