MODELLING AIRPORT PASSENGER GROUP DYNAMICS USING AN AGENT-BASED METHOD

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Abstract

Passenger traffic in an airport reflects the level of economic development, business activity and tourism of a city. A good passenger experience is likely to result in repeat visits, which not only generate airport's financial profit, but also satisfy the need of other stakeholders such as operating airlines, retailers, passengers and visitors. Hence, passenger experience has become a major factor that influences the success of an airport. In this context, passenger flow simulation has become a significant approach in designing and managing airports.

The literature review in this thesis revealed that grouping is a common phenomenon among pedestrians. However, most research failed to consider the group dynamics when developing pedestrian flow models. In order to reflect more realistic passenger flow conditions, the group dynamics must be included in the model.

An agent-based model is a feasible and effective approach to model passenger movements in airports. Unlike many models that treat passengers as individual agents, the proposed model in this thesis incorporates group behaviour attributes as well and evaluates the simulation performance of passenger movement within airports. Results from experiments show that incorporating group behaviour, particularly the interactions with fellow travellers and wavers can have significant influences on the performance and utilisation of services in airport terminals. The impacts can be seen in terms of dwell time at each processing unit, discretionary activity preference, and the level of service (LOS) at processing areas.

Based on the airport passenger flow model that includes group dynamics, a case study of an airport evacuation event has been conducted. The simulation results show that the evacuation time can be influenced by passenger group dynamics. The model also provides a convenient way to design airport evacuation strategy and examine its efficiency.

For airport designers and operators, the model also provides a convenient way to investigate the effectiveness of space design and service allocations, which may contribute to the enhancement of passenger airport experiences. The model was

created using AnyLogic software and it was initialised using the data obtained through previous research existing in the literature.

The main contributions of this thesis are embodied in the following four aspects: (1) improve the understanding of group dynamics among pedestrians; (2) provide a more realistic agent-based passenger flow model by incorporating group dynamics; (3) demonstrate the influence of group dynamics on passenger flow in an airport departure terminal; and (4) introduce the potential application of the agent-based pedestrian flow model in design and management of pedestrian facilities.

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List of Abbreviations

AAA	Australian Airport Association
ABM	Agent-based model/modelling
ABMS	Agent-based modelling and simulation
ABS	Australian Bureau of Statistics
ACCC	Australian Competition and Consumer Commission
CA	Cellular Automata
CAFE	Cellular automata with force essentials
HiDAC	High-Density Autonomous Crowds
IATA	International Air Transport Association
LOS	Level of Service
OPC	Outgoing Passenger Card
STD	Scheduled Time of Departure

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: Lin Cheng

Date: 20/06/14

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Publications

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- Cheng, L., Reddy, V., Fookes, C., & Yarlagadda, P. K. D. V. (2014). *Agent-based modelling simulation case study: assessment of airport check-in and evacuation process by considering group travel behaviour of air passengers*. Paper presented at Measurement Technology and its Application III, Shanghai, China.
- Cheng, L., Reddy, V., Fookes, C., & Yarlagadda, P. K. D. V. *ANALYSIS OF PASSENGER GROUP BEHAVIOUR AND ITS IMPACT ON PASSENGER FLOW USING AN AGENT-BASED MODEL*. Paper presented at 4th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH), Vienna, Austria (in press).
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Chapter 1: **Introduction**

Passenger experience is one of the most critical aspects that measure the service quality of an airport. In order to enhance the passenger experience, it is worthwhile to investigate the passengers' activities during their airport experience. The main objective of this research is to understand the impact of group dynamics on passenger activities in the airport. This chapter provides an overview of the proposed research. Section 1.1 presents the research background and motivation. Section 1.2 addresses existing knowledge gaps and research questions. Section 1.3 describes the research aims and scopes. The methodology used to achieve the research goals is presented in Section 1.4. Finally, Section 1.5 includes an outline of the remaining chapters of the thesis.

1.1 BACKGROUND

Revenue of airports nowadays is gradually transferring from aviation related sectors to non-aviation sectors (retail revenues) and also from traditional airline sources (lease arrangements) to passengers (fees collected from ticket sales) (Harrison, Popovic, Kraal, & Kleinschmidt, 2012; Schultz, Schulz, & Fricke, 2010). In Australia, it is reported that 44% of airport revenues are generated from non-aeronautical segments in major airports (AAA, 2012). As a result, passengers are now considered as one of the most important stakeholders, which have led to airports becoming increasingly passenger focused. Despite facing the difficult global economic conditions in recent years, passenger air traffic is keeping a vigorous growing trend. In the past two decades, air travel growth is on average 1.8 times that of global GDP. This figure had increased to an unusually robust 2.5 in 2012, even under the pressure of rising jet fuel prices (IATA, 2013a).

Along with the growing profits driven by the passengers, strong growth in passenger numbers on the other hand has placed increasing pressure on existing aeronautical infrastructure and airport landside arrangements. Crowded airport and long queues directly lead to the degradation of passenger experience and Level of Service (LOS) in the airport terminal (Correia, Wirasinghe, & de Barros, 2008). Australian Competition and Consumer Commission (ACCC) pointed out that the overall rating for the quality of service in the monitored airports (including Adelaide, Brisbane, Melbourne, Perth and Sydney) decreased and no airport achieved the rating standard at least as ‘good’ in 2011-2012 (ACCC, 2013). A good passenger experience is likely to result in repeat visits, which not only generate airport’s financial profit, but also satisfy the need of other stakeholders such as operating airlines, retailers, passengers and visitors (Popovic, Kraal, & Kirk, 2010). On the contrary, a poor experience has been identified as a threat to a city/country’s economic stability (London First, 2008), and prosperity (Crawford & Melewar, 2003). Hence, passenger experience has become a major factor that influences the success of an airport. In this context, passenger flow simulation has become a significant approach in designing and managing airports (Schultz, Lehmann, & Fricke, 2007).

1.2 KNOWLEDGE GAP

Grouping is a universal social phenomenon among pedestrians. Literature shows that up to 70% of people in a crowd are actually moving in groups and social interactions in groups can greatly influence crowd behaviour, (Moussaïd, Perozo, Garnier, Helbing, & Theraulaz, 2010).

Models have been used in simulating pedestrian behaviour for decades. Most of the models treat pedestrians as individual agents and neglect the group dynamics among them (Ma, Fookes, Kleinschmidt, & Yarlagadda, 2012). Although treating pedestrians as individuals is a much easier way to model pedestrian dynamics and requires less computational load, it can lead to less realistic simulations results. Therefore, this research is designed to fill the existing knowledge gap by incorporating group dynamics in pedestrian flow modelling in an airport environment.

In airports, one can always see following scenes: friends chatting with each other in check-in queues; wavers or well-wishers saying goodbye to those who are leaving abroad; families sitting in a coffee bar waiting for boarding; tour groups at the duty-free shops purchasing souvenirs. Such ordinary moments indicate that the airport is a complex system where social interactions are ubiquitous. Therefore, it is necessary to consider passengers as collective social groups instead of individual unrelated units in the simulation.

1.3 RESEARCH AIMS AND SCOPE

The aim of this research is to develop an agent-based model for investigating the impact of group dynamics on passenger flow in an international departure terminal. To achieve this research aim, the primary research question which needs to be answered is:

- How do the group dynamics influence the behaviour of passengers' in an airport?

In an effort to have a better understanding to this question, several sub-questions are further developed:

- What are the differences between the behaviour of passengers travelling with groups and those who travel alone?
- How to interpret passenger social characteristics and behaviour using a simulation model?
- What are the simulation results and what do the results indicate?

The scope of work undertaken is to apply the model to a departure terminal of an international airport. The are two reasons why the departure terminal is used as the simulation subject of this research: (1) the departure terminal is a complex system that consists of areas with different functions and security levels, which enrich the activities of passengers; (2) passengers in the airport have diverse characteristics and abundant social interactions, which is perfect for studying group dynamics among heterogeneous agents.

1.4 METHODOLOGY

The methodology to achieve the research objective can be summed up as the following three main steps:

- Model selection
- Model development
- Result analysis

A valid modelling method is the foundation of this research project. Most findings and conclusions in this research are based on the results from the simulation model. Therefore, in the model selection stage, large numbers of pedestrian modelling methods are compared and the optimum method – the agent based modelling method is selected. After choosing the modelling technique, the model needs to be developed according to the simulation subject. The model was created using the AnyLogic platform and its parameters were initialised using recent research data published in the literature. A proper validation is necessary to ensure the model reflects the actual situation in the airport terminal. Once the model is completed, different inputs and settings can be used to simulate different scenarios in the airport terminal. Meanwhile, key data is collected to compare the behaviour of passengers that travelling with groups and travelling alone. By analysing the causes of the differences in the simulation results, the impact of group dynamics on passenger flows can be demonstrated.

1.5 THESIS OUTLINE

The overall structure of the thesis takes the form of six chapters, including this introductory chapter. The remainder of this thesis has been organised in the following way. Chapter 2 reviews the literature related to pedestrian modelling, and group dynamics. Chapter 3 demonstrates the implementation and configuration of the proposed agent-based model in this thesis. Chapter 4 uses the agent-based model to analyse the impact of group dynamics on passenger flow in the airport departure terminal. Chapter 5 applies the model to a case study investigating the influence of group dynamics on pedestrian evacuation process. Finally, Chapter 6 concludes the research contribution of this thesis and points out the limitations. Recommendations for future research are also provided in Chapter 6.

Chapter 2: **Literature Review**

This chapter demonstrates the existing technologies of pedestrian modelling and simulation. Section 2.1 explains the need for pedestrian models in understanding pedestrian behaviour and their applications in current society. Section 2.2 introduces current pedestrian modelling approaches and analyses the advantages and disadvantages of each modelling technique. Validation methods of pedestrian models are also investigated. Section 2.3 examines the characteristics of pedestrian behaviour and highlights the importance of group dynamics. Section 2.4 discusses the models for the purpose of airport passenger flow modelling. Section 2.5 describes the use of pedestrian models for studying crowd evacuation. Section 2.6 compares different pedestrian modelling software. Finally, Section 2.7 summarises the literature review and identifies the knowledge gap.

2.1 THE NEED FOR MODELLING PEDESTRIANS

Pedestrian behaviour has been persistently studied for approximately a century now. Early studies were mainly focused on designing traffic regulations and pedestrian safety protections (Ceder, 1979; Moore, 1953). As time progresses, improving the quality of construction projects to create more pleasant and user-friendly pedestrian facilities has been the relentless pursuit of modern architects and designers. With the improvement of computer technology, pedestrian models have been widely used and considered as an essential tool to assessing the performance of building design and quality of the pedestrian facilities (Helbing, Farkas, Molnàr, & Vicsek, 2002; Osaragi, 2004; Schadschneider et al., 2011; Teknomo, 2006).

One of the most important applications of pedestrian models is in urban planning. Not until recently, transportation models are focused on motorised transport in urban areas (Kitazawa & Batty, 2004). However, pedestrians are the most vulnerable elements in the traffic system and the largest road user groups, thus deserve more considerations (Harney, 2002). In order to implement a walking-friendly urban environment, efforts need to be placed on investigating the impact of the proposed plan on pedestrian behaviour. This can be achieved by analysing pedestrian flow and patterns through the pedestrian models. Furthermore, by using pedestrian models, urban planners can assess the attractiveness of certain locations for new projects such as shopping centres, theme parks or museums to make sure that the layout of urban space and land-use structure are optimised.

Pedestrian models are also helpful in improving efficiency and safety in public environments such as airport terminals, train stations and theatres. They are not only used as a tool for understanding pedestrian dynamics at public places, but also support transportation planners or managers to design timetables, assign and allocate staff, and predict potential delay or congestions. As a result, pedestrian models help creating a positive passenger experience. Simulation models play a significant role in the study of pedestrian evacuation. Research argued that in many instances, the victims' fatalities or injuries were caused by the behaviour of the crowd itself instead of fire, explosions, or other external hazards (Helbing, Buzna, Johansson, & Werner, 2005). Due to the potential threat of injury, full-scale evacuation practices are not the best approach for researchers to investigate pedestrian behaviour during the evacuation process. On the other hand, computer models are economical, time-saving, risk-free, and easy to modify. Moreover, they have the ability to conduct repeat experiments.

2.2 PEDESTRIAN MODELLING METHODS

2.2.1 **Model Classification**

In the past decades, large numbers of approaches have been proposed for modelling pedestrian behaviours. Modelling methods can be classified according to different characteristics. In terms of modelling scope, there are macroscopic models and microscopic models. The main object of macroscopic models is the temporal evolution of the crowd density (Bauer, Seer, & Brändle, 2007). Macroscopic models treat pedestrians as a whole and ignore the local dynamics of individuals and interactions between pedestrians. Because of this, macroscopic models have the advantage in terms of computational load. However, researchers found that they are also not well suited for illustrating the effect of environmental change on pedestrian flow performance (Teknomo, Takeyama, & Inamura, 2000). Moreover, macroscopic models often assume that the population is comprised of homogeneous agents in an equilibrium state, which cannot represent real-world situations (Johansson et al., 2012).

In contrast, individual properties are distinguished in microscopic models. These models focus on the behaviour and decision making of individual pedestrians, as well as the effect on other pedestrians around them. Microscopic models have the potential to overcome the limitations of previously discussed macroscopic models by incorporating a set of pre-determined rules. By defining the behavioural rules properly, the microscope models are able to present more accurate pedestrian behaviour in a greater variety of situations (Camillen et al., 2009; Pluchino, Garofalo, Inturri, Rapisarda, & Ignaccolo, 2013). However, a detailed pedestrian model needs support of rich data sets that slow down the computational speed (Bauer, et al., 2007). Examples of microscopic models are: physic-based social force models (Helbing & Molnár, 1995), geography-based cellular automata models that follow pre-designed rules (Fukui & Ishibashi, 1999), and agent-based models which allow agents to interact with others as well as surrounding environments according to their own attributes (Macal & North, 2005).

Apart from the modelling scale, pedestrian models can also be categorised by whether they are discrete or continuous, deterministic or stochastic, rule-based or force-based, high or low fidelity (Schadschneider, et al., 2011). In this thesis will mainly introduce the following three microscopic models: social force model, cellular automata model and agent-based model.

2.2.2 **Social Force Models**

Social force models are probably the most known method in the group of continuous models. Lewin and Cartwright (1952) suggested that the changes of human behaviour can be guided by *social forces* or *social fields.* Based on this concept, Helbing and Molnár (1995) proposed the basic equation of the social force model to describe pedestrian motion,

$$\vec{F}_\alpha = \vec{F}_\alpha^0 + \sum_\beta \vec{F}_{\alpha\beta} + \sum_B \vec{F}_{\alpha B} + \sum_i \vec{F}_{\alpha i} \ .$$

They assumed that a pedestrian's total motivation $\vec{F}_\alpha$ can be influenced by four main factors: (1) $\vec{F}_\alpha^0$ – the desire of this pedestrian α to reach a certain destination or goal; (2) $\sum_\beta \vec{F}_{\alpha\beta}$ – the total influence from other pedestrians β such as the *repulsive effect* of others; (3) $\sum_B \vec{F}_{\alpha B}$ – the total repulsive force generated to avoid a border or an obstacle *B*; and (4) $\sum_i \vec{F}_{\alpha i}$ – the attraction of other persons or objects *i*.

In addition to the above four main effects, the social force model can be applied to demonstrate complex pedestrian behaviour by adding a *fluctuation* term. This fluctuation term enables modellers to consider random variations of pedestrian behaviour and make extension from the basic formula. Therefore, a more general form of the social force model is now defined by,

$$\frac{d\vec{w}_\alpha}{dt} = \vec{F}_\alpha + fluctuations.$$

Using the social force model, several observed collective phenomena in pedestrian crowds have been successfully reproduced. This includes the lane forming behaviour in crowds and the oscillatory walking pattern at a narrow exit (Helbing & Molnár, 1995) as well as the mechanisms in escape panic situations (Helbing, Farkas, & Vicsek, 2000). Helbing, et al. (2005) conclude that the simplicity and small number of parameters are the main advantages of the social-force-based simulation. Moreover, it is suggested that those parameters in the model do not need to be calibrated for each new situation, which makes social force models adaptive when applying to different simulation environments.

However, some researchers suggested that it is not easy to model heterogeneity and complex behaviours using social force model since the goals, characteristics and interactions of pedestrians must be represented through equations (Manenti, Manzoni, Vizzari, Ohtsuka, & Shimura, 2012). Moreover, simulation update of Helbing's model is O(n^2) because each agent is influenced by all the other agents. This may limit the computational ability of the social force model to simulate many agents (Henein & White, 2005). Another disadvantage of the social force model is that in high density environments, agents will 'shake' or 'vibrate' unnaturally (Pelechano, Allbeck, & Badler, 2007). In spite of these drawbacks, the social force model is still very popular and has become the foundation of many other subsequent pedestrian models.

Derived from the social force model, a HiDAC (High-Density Autonomous Crowds) model had been used to address the problem of simulating high-density crowds in dynamically changing virtual environments (Pelechano, et al., 2007). Through analysing the crowd scenes, Mehran, Oyama, and Shah (2009) evaluated the interaction forces among pedestrians and successfully detected and localised abnormal behaviours in crowds. Parisi, Gilman, and Moldovan (2009) proposed a modification of the social force model that overcame the limitations of Helbing's model in describing the experimental data of pedestrian flow in normal conditions. Moussaïd, et al. (2010) had extended Helbing's model to simulate the walking behaviour of pedestrian social groups by adding an extra social interaction term into Helbing's social force formula.

2.2.3 **Cellular Automata Models**

A relatively novel model called Cellular Automata (CA) uses intuitive rules that make the model easy to understand without complex mathematical equations and thus demand less computation than social force models. In cellular automata models, space is represented by a uniform grid of cells. At each discrete time step, the values of variables in each cell are updated according to a set of local rules and the values of variables in the cells at its neighbourhood (Zheng, Zhong, & Liu, 2009).

The idea of cellular automata was originally introduced by Von Neumann and Burks (1966) with the purpose of modelling biology self-reproduction. It was then developed and applied to a wide variety of purposes because physical systems that containing many discrete elements and local interactions are convenient to convert into cellular automata (Wolfram, 1983). Cellular automata has been extended to model pedestrian movement by Blue, Embrechts, and Adler (1997) who analysed multidirectional microscopic behaviour in a crowded open space. Blue, et al. (1997) introduced a 'bump' rule to avoid pedestrian being locked in one position at high-density hypothetical floor area. At each time step, each entity in the matrix moves one step towards its destination according to the sequence of the entity number. If the forward movement is blocked by the other entity, the pedestrian will sidestep into the next cell relative to its movement. If the next cell is still occupied, the pedestrian will 'bump' the occupant to make sidestep, and so on, until an empty cell is found or one entity is bumped off the floor matrix (Blue, et al., 1997). Figure 2-1 illustrates the bumping rule between entities. At time step 2, entity 11 and 12 both desire to move into cell (2, 2). According to the bumping rule, entity 11 bumps entity 12 into the adjacent cell of its desired cell at time step 3. The entities move toward their destinations afterwards. Though Blue's model is based on simple local rules, it is instructive that cellular automata can be used to model pedestrian movement and more realistic pedestrian interactions can be demonstrated by optimising the rule set.

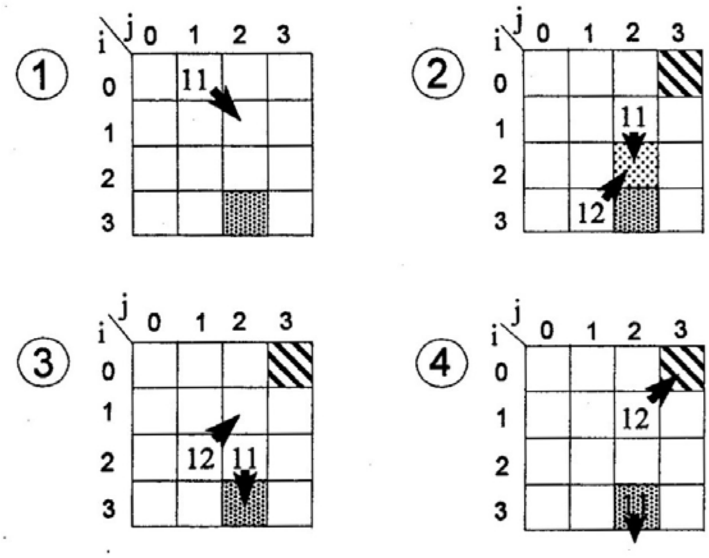


Figure 2-1 Illustration of pedestrian movement in 4 consecutive time steps (Blue, et al., 1997).

Schultz, Lehmann, and Fricke (2006) proposed an improved cellular automata model to simulate evacuation process in an airport terminal. The model considered the effects of repulsion potentials, friction and clogging behaviour, as well as a path finding/guidance algorithm. However, the author only proposed the methodology and no specific scenario is simulated to prove this method is valid to present passenger behaviour during emergency.

Yuan and Tan (2007) proposed a two-dimensional basic cellular automata model to simulate evacuation from a room with multiple exits. The simulation environment is divided into square cells with a dimension of 0.4×0.4 m, since it was suggested to be the typical space occupied by one pedestrian in crowded areas (Weidmann, 1992). The author set the standard time step to 0.29 s according to the 1.65 m/s nervous state velocity and the 0.48 m average movement per time step. However, setting the same speed for each pedestrian does not reflect real-world situations. The authors suggested that secondary time steps can solve the problem, but at the cost of increasing computation time.

Köster, Seitz, Treml, Hartmann, and Klein (2011) applied the cellular automata to study the influence of group formations in a crowd. In their work, they divided space into hexagonal cells (Figure 2-2), thus creating two additional natural directions than square cells. The local rules applied in this model are based on the intuitive of the designers, while lack of support from social science. Therefore, the authors highlighted the need for greater cooperation between social scientists and modellers.

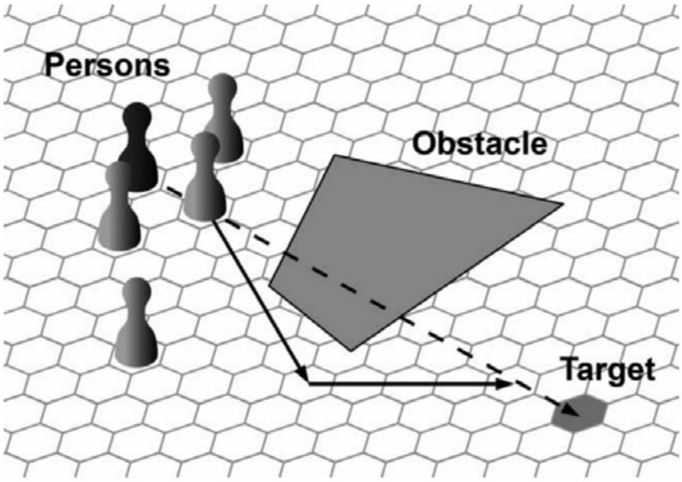


Figure 2-2 Pedestrian moving on hexagonal cells (Köster, et al., 2011).

To summarise, the cellular automata models portray the interactions between pedestrians by intuitively understandable rule sets, rather than complex mathematical functions. It also provides an easier treatment of complex geometries than models with long-range interactions (Schadschneider, 2001). Therefore, one can easily implement cellular automata on computers and the computational speed is exceedingly fast compared to other microscopic pedestrian models. However, CA models have the disadvantage of dividing space into coarse cells, which may lead to larger errors than social force models in which space is not discretised (Köster, et al., 2011). Moreover, no contacts are allowed between agents in Cellular Automata models, and individuals can only move when the adjacent cell is free (Pelechano, et al., 2007).

2.2.4 **Agent-Based Models**

Agent-based modelling and simulation (ABMS) is a relatively new approach to modelling systems comprised of autonomous decision-making entities called agents. Unlike the Systems Dynamics approach that applied the 'top-down' systems view, the agent-based models are built from the 'bottom-up' by simulating the interaction between individual agents (Macal & North, 2005; Zheng, et al., 2009). In agent-based models, agents follow some pre-determined rules of behaviour, which allow them to execute various behaviours appropriately in the modelled system. This unique characteristic makes ABM particularly suitable for the study of pedestrian behaviour in complex environments.

Bonabeau (2002) presented a comprehensive introduction to the basic principles of agent-based simulation. He pointed out that agent-based simulation is a mindset more than a technology. Therefore, even the traditional differential equation, as long as it describes the dynamics of one of the constituents of the system, is an agent-based model. Bonabeau summarised three benefits of ABM over other modelling techniques: (1) ABM captures emergent phenomena; (2) ABM provides a natural description of a system; and (3) ABM is flexible. In order to support this conclusion, Bonabeau provided examples of the application of agent-based modelling in the area of simulating flow (traffic, pedestrians), market, organizations, and diffusion. After the examples, Bonabeau concluded that ABM can bring significant benefits when simulating human systems.

A series of systematic tutorials on agent-based modelling and simulation (ABMS) have been presented by (Macal & North, 2005, 2006, 2010, 2011). In the tutorials, the authors described the theory and foundations of ABMS, identified ABMS development tools, illustrated the general procedures to build an agent-based simulation model and provided opinions on the relationship of ABMS to other conventional modelling techniques. It was suggested that a typical agent-based model composed of three elements:

- Agents: A set of agents as well as their characteristics and behaviour.
- Agent relationship: The relationship and interaction method between agents.
- Agents' environment: The agents' environment, including the interaction between agents and the environment.

These elements should be defined and programmed in order to create an agent-based model. Figure 2-3 shows the structure of a typical agent-based model.

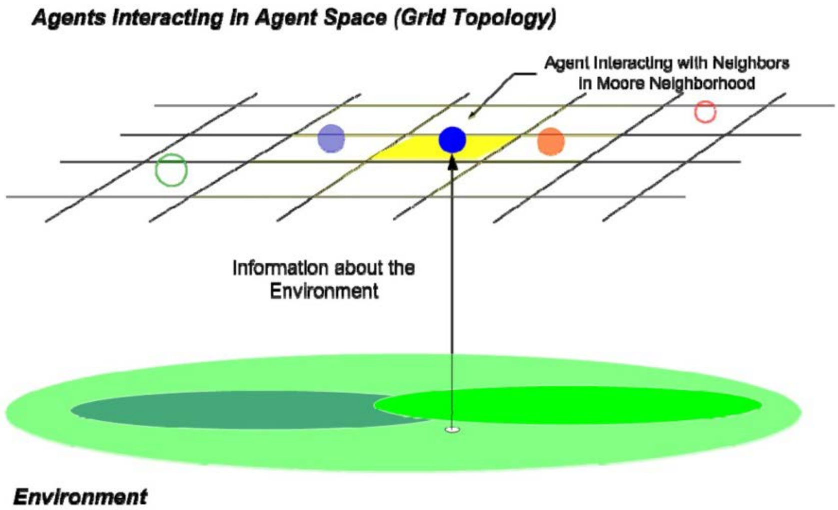


Figure 2-3 General elements of an agent-based model (Macal & North, 2011).

A STREETS model was proposed for investigating pedestrian behaviour in urban centres (Schelhorn, O'Sullivan, Haklay, & Thurstain-Goodwin, 1999). Pedestrians are initialised with *social-economic characteristics* and *behavioural characteristics*. Social-economic characteristics defined the attributes such as gender and income of the agents and are used to create pedestrians' travel plan. While behavioural characteristics include the detailed behavioural factors such as speed, visual range and fixation. Pedestrians were 'released' into the simulation environment according to a Poisson distribution. The whole simulation was controlled by a SWARM observer, which also collects the interaction information in the model. However, this STREETS model was under development and no experiment had been run on this model to test its performance. The authors pointed out that the navigation of pedestrians was sometimes unreliable and pedestrian group behaviour should be incorporated in the model.

In order to improve crowd safety in public places, Pan, Han, Dauber, and Law (2007) presented a multi-agent based framework for simulating human and social behaviour in emergency situations. Through modelling pedestrian interactions at the microscopic level, the simulation was able to capture emergent human behaviour such as competitive behaviour, queuing behaviour and herding behaviour during evacuation. Although the extension of the model to statistical analysis and other design parameters were still under development, it showed a potential usage of the framework in improving the crowd safety in designing pedestrian facilities.

Based on Reynolds's OpenSteer environment (Reynolds, 1999), Qiu and Hu (2010) proposed an agent-based simulation system for modelling crowd behaviour with group structures, in which agents can move randomly, avoid obstacles and maintain group structures. The group movement is governed by the rule that each group is assumed to have a group leader and the leader would influence the decisions of other group members. However, in real-world situations, pedestrian groups are often composed of friends and families, where it is not necessary to have a group leader.

Based on pre-determined behaviour and local interactions, agent-based models can provide unprecedented understanding to the emergent properties of interacting agents in complex circumstances where intuition fails (Farmer & Foley, 2009). However, human behaviour often includes soft factors which are difficult to quantify and calibrate. Plus, a complex agent-based model is hardly fully documentable for others to reproduce the similar results. Therefore, this has consequences on the trustworthiness of the results produced by agent-based models and it was suggested that the quantitative outcomes of a simulation should be interpreted only at the qualitative level (Bonabeau, 2002; Klügl & Rindsfüser, 2007). Furthermore, ABMs are generally more computationally expensive than cellular automata and social force models, thus, modelling large systems is still a challenge for agent-based models (Bonabeau, 2002; Zheng, et al., 2009).

2.2.5 **Combination of Modelling Approaches**

New pedestrian models have a trend to combine multiple traditional modelling approaches (Zheng, et al., 2009). Traditional pedestrian modelling approaches were mainly proposed to address some specific problems. For example, the social force models demonstrate how individuals' movement can be influenced by others and the environment; cellular automata models are good at describing behavioural rules and spacial relationships; agent-based models are often used to demonstrate emergent behaviour by simulating the interactions between heterogeneous agents and the environment. As pedestrian behaviour and simulation environments are becoming more and more complex, one modelling approach is often used in combination with the advantages of other techniques.

Bandini, Federici, Manzoni, and Vizzari (2006) presented a Situated Cellular Agents (SCA) model for simulating crowd dynamics. In the model, agents' actions take place in a discrete and finite space. Agents were defined with types, states, and the site of space. According to a set of sensors, agent can interact with others and the environment. A case study of an underground station is described in order to show how the methodology was applied (Bandini, et al., 2006).

Song, Yu, Wang, and Fan (2006) introduced a new CA model entitled cellular automata with force essentials (CAFE) to investigate crowd behaviour during evacuation. The model is based on traditional CA model that used a lattice to represent the evacuation area. While interactions between pedestrians are classified into three types of forces: attraction, repulsion and friction. The author stated that this improved model is both computationally efficient and included some crucial human behaviour in crowds. Kormanová (2012) also presented a pedestrian movement model that combined cellular automata and social force approach.

Henein and White (2005) created an agent-based local-interaction model which avoids the direct consideration of every agent's effect on all other agents. The space in the model is divided into square grid cells. Agents apply force to their neighbourhood agents according to preset rules. A *floor field* is used to provide local interaction information for individual agents. By adding a *force floor field* in the model, the model successfully demonstrated a typical arching structure at the exit when simulating crowd evacuation. This model combines the concept of cellular automata, social force and agent-based model. It overcomes the computational inefficiency of the social force model, but at the same time, shows the force effects on crowd behaviours.

Above examples show the combination of different modelling techniques only in the category of microscopic models. In fact, the combination of techniques is not limited to a certain modelling scope. Modelling approaches from different scopes can be applied in one pedestrian simulation. Asano, Iryo, and Kuwahara (2010) combined a microscopic pedestrian simulation model with a macroscopic tactical model in a cell-based network to evaluate pedestrian flow. There are two modules in the proposed model: a tactical model and an operational model. The tactical model is a macroscopic model. It determines the desired directions of each pedestrian, which are used in the operational model. Then the operational model determines the actual microscopic movement of pedestrians.

2.2.6 **Validation of Pedestrian Models**

Model validation is one of the most difficult issues in crowd modelling and simulation. The validation of pedestrian behavioural model requires large amounts of detailed data. Due to the complexity of natural systems and the non-determinism of human activities, it is hard to compare real-world observation data with outputs in pedestrian models. As a result, the validation of a pedestrian model still remains a significant problem for modellers (Xing, Lees, Nan, & Viswanthatn, 2012). Though there are no universal validating approaches, video films, photographs and direct observations are the most common evaluation methods to study pedestrian behaviour. Face validity and empirical validity are two commonly used criteria when assessing agent-based models (Gatersleben & Van der Weij, 1999; Klügl, 2008; Klügl & Rindsfüser, 2007; Zhou et al., 2010).

The face validity is the outcome of face validation. The face validation insures the process and the results are reasonable and plausible within the theoretical framework and the knowledge of domain experts (Klügl, 2008). Examples of face validation can be: experts examine the parameters defined in the model, the simulation environment and compare pedestrian behaviour between simulation and real-world observation. In contrast, empirical validity is conducted by quantitatively comparing key figures produced by the model and those collected from the experiment or the reference system (Klügl, 2008). It is suggested that empirical validity is the most effective approach to establishing model validity (Zhou, et al., 2010). These two validation criteria will be applied in the proposed model as well.

The validation method is explicitly mentioned or implicitly demonstrated in some research on pedestrian models. Klügl and Rindsfüser (2007) presented an agent-based model for simulating pedestrian traffic in a railway station. Data from a PDA-based observation at several stairways and all exits were used for model validation. In addition, the simulation system was able to save the simulation as a video, which is useful for face validation. Using the social force model, Helbing, et al. (2005) had successfully reproduced the phenomenon of stripe formation of two intersecting pedestrian streams (see Figure 2-4) that had observed by Ando, Ota, and Oki (1988) (see Figure 2-5).

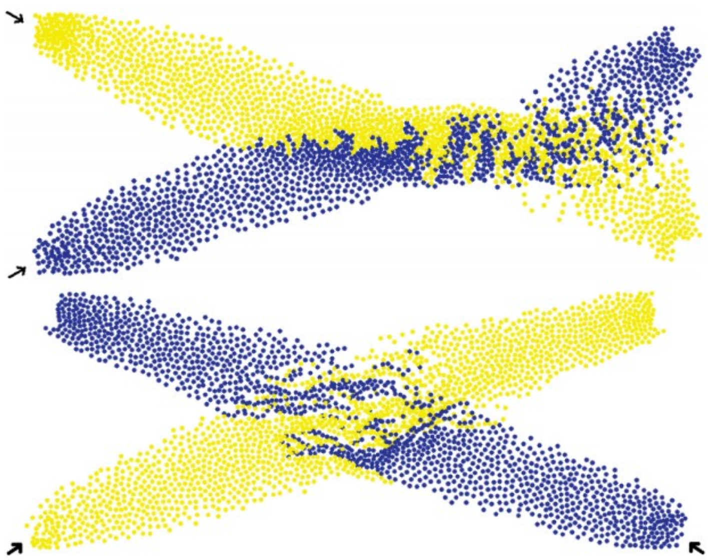


Figure 2-4 Representative simulation result of two intersecting pedestrian streams using the social force model (Helbing, et al., 2005).

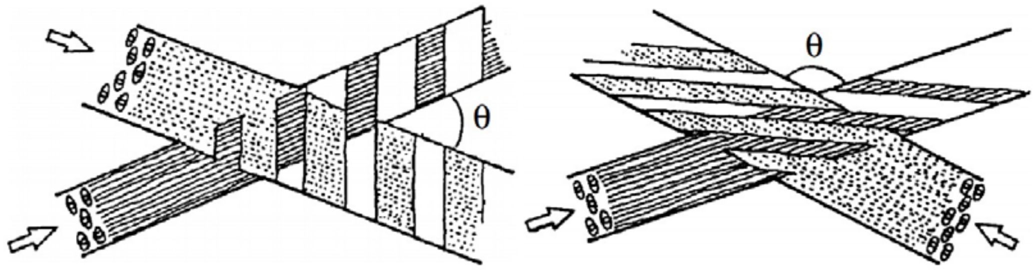


Figure 2-5 Illustration of the strip formation in two intersecting pedestrian streams (Ando, et al., 1988).

Vizzari, Manenti, Ohtsuka, and Shimura (2012) investigated the pedestrian and group dynamics in crowds. They proposed a simple experiment to test the validity of the model. It was observed in the experiment that pedestrian pairs can easily form a line to avoid facing crowds. However, pedestrian groups with bigger numbers of members had difficulties to form such a line shape, thus they tend to form a triangular shape which is similar to the ‘V’ shape observed by Moussaïd, et al. (2010). Then, a simulation model was applied to the experimental scenario and showed consistent pedestrian dynamics with the previous experiment. After the validation, the model is further adopted to simulate real-world scenarios.

2.3 PEDESTRIAN GROUP DYNAMICS

2.3.1 **Ubiquitous Social Groups**

In real life, it is a common phenomenon that many of the pedestrians are walking in groups. It is easy to identify a group of people through the interactions and characteristics of the members such as appearance, gender and age. However, the existing crowd modelling approaches tend to neglect the existence of pedestrian groups, which leads to less convincing results.

Researchers have been studying the behaviour of pedestrian social groups for more than half-century. In order to investigate the size determinant in small human group interaction, James (1953) observed 22,625 pedestrian samples in 18 public situations in Eugene and Portland, Oregon. The observations were taken in the winter and spring, 1950. Several different places including public markets, playgrounds, schools, swimming pools, public beaches were chosen as observation sites. The diversity of observation times and locations ensures that the observation results reflect the common behaviour of pedestrians of different roles. The observation shows that crowds are split into 'free-forming' small groups with varying sizes. The group relationship was identified through the face-to-face interactions such as gesture, laughter, smiles, talk, play, or work. A total of 15,486 small groups were recorded in the observation. The observation results are consolidated into Table 2-1. Group size 1 indicated that individuals are also considered as small groups that only have one group member. From Table 2-1, it can be calculated that more than half of the observed population are in groups with at least two members.

Group Size	Frequency	Per cent of total
1	10,149	65.54
2	3,945	25.47
3	1,075	6.94
4	238	1.54
5	65	.42
6	14	.09
N	15,486	100.00
Mean	1.46	

Table 2-1 Frequency distributions of 18 observations (James, 1953).

A similar field study was conducted by Aveni (1977), who interviewed 204 celebrating fans in a football event. The findings of the study showed that three quarters of the crowd were with one or more friends. This result shows higher group proportion in crowds than James' observation. The reason for the this difference may be that the data in this research was collected in a special sports event, which may not reflect the group behaviour of mundane crowds in a variety of different locations. In spite of this, this study still suggests that crowds consist of both individual pedestrians and persons in groups.

It has been decades since the research carried out by James and Aveni. The social background has greatly changed, so are the ways people communicate and interact. Therefore, it is necessary to examine whether the crowd preserves group behaviour in more recent studies. Singh et al. (2009) investigated the behaviour of pedestrian subgroups by means of filming and observation. The behaviour of crowds was recorded every 10 seconds for half an hour in the following four locations: Nottingham train station, Broadmarsh shopping centre, Clumber Street and Nottingham University campus. Pedestrians in these four locations represent crowds in three environments: travelling, shopping and working. As can be seen from Figure 2-6, a large percentage of people in crowds are in subgroups of two or more members. In travelling environment (train station), the percentages of people in groups are about 55%. In shopping environments (Broadmarsh shopping centre and Clumber Street), the percentage is about 65%. On university campus where people study or work, the figure is about 47%. The varying numbers in different observation locations indicate that the proportion of people in groups can be influenced by the surrounding environment. One limitation of the observation approach is that the observation period is not long enough. Therefore it is possible that observers only captured a small section of the big picture which may cause deviation to the 'ground truth'.

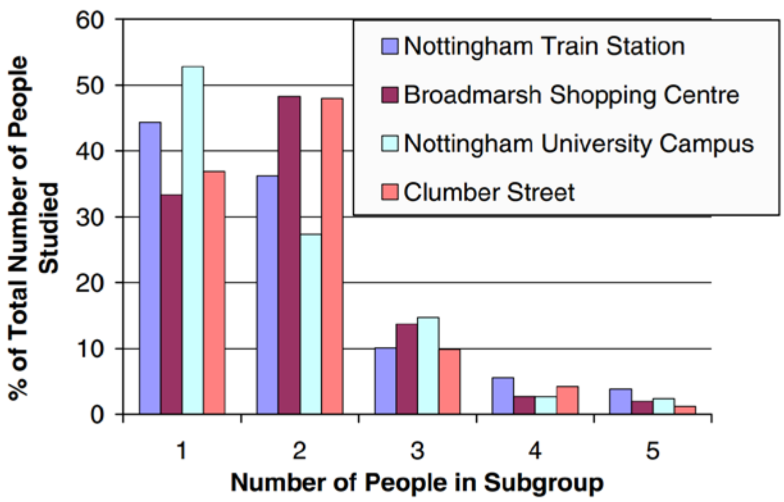


Figure 2-6 The sizes and proportions of subgroups within a crowd (Singh, et al., 2009).

To investigate the walking behaviour of pedestrian social groups, Moussaïd, et al. (2010) analysed pedestrian behaviour in a low population density condition A and moderate density B. Detailed observation time and location are not given in the research. The result shows that the proportions of pedestrians belong to a group are 55% in population A and 70% in B, which occupied the majority of total populations. The author made an explanation to the difference between populations A and B: population A was recorded in a working day, while population B was observed on a Saturday afternoon in a popular commercial walkway. This means one can expect a higher frequency of groups in leisure areas and spare times.

The above studies show that in the real-world, large proportions of pedestrians are in social groups. The percentage of people in groups within a crowd ranges from 40% to 70%. This percentage will change according to different times and environment situations. Generally, more groups can be observed in leisure areas in public holidays (Moussaïd, et al., 2010). The existence of ubiquitous social groups indicates that not only the individual-level, but also the group-level behaviour needs to be included in the modelling program in order to carry out realistic pedestrian simulations.

2.3.2 **Group Size in Statistic Models**

In order to quantitatively calculate the distribution of free-forming pedestrian group size, James (1953) fitted the sample group sizes (shows in Table 2-1) into two distribution models: the negative binomial model and the Poisson model. The goodness of fit was compared by the chi-square test. The result showed that the fitting of the negative binomial model was much closer to the observation data than the Poisson model. The explanation to this was that Poisson distributions require a constant mean throughout the observation, thus it is more suitable when the social situation is relatively stable. On the other hand, the negative binomial can be considered as a group of different Poisson distributions collected together, therefore it is more accurate to use the negative binomial model in fitting data collected from 18 different observations in this case. Although this is a reasonable explanation to the fitting results, the author failed to make further attempts to support his conclusion. Therefore, this study would have been much more convincing if the author had tested the Poisson model in a stable social context and compared the goodness of fit with the negative binomial model.

Coleman and James (1961) reanalysed the data collected by James (1953) and stated that the frequency distribution of group sizes can be fitted by the truncated-Poisson (T-P) formula. The derivation of this formula is based on the assumptions that there is a constant probability for a group to lose and gain a member at anytime, and finally the distribution of group sizes in the system will reach an equilibrium state. Using this mechanism, Moussaïd, et al. (2010) fitted his observation data with a zero-truncated Poisson formula. The fitting results in Figure 2-7 shows that the Poisson model well presents the observed group sizes in population A, while in population B, the model predicts a higher proportion of individuals and lower proportion of groups of size 2. Nevertheless, the model reflects a similar tendency of the group sizes in observation. The use of statistical models in fitting the distribution of the group size provides a reference for generating pedestrian groups in the proposed model in this thesis.

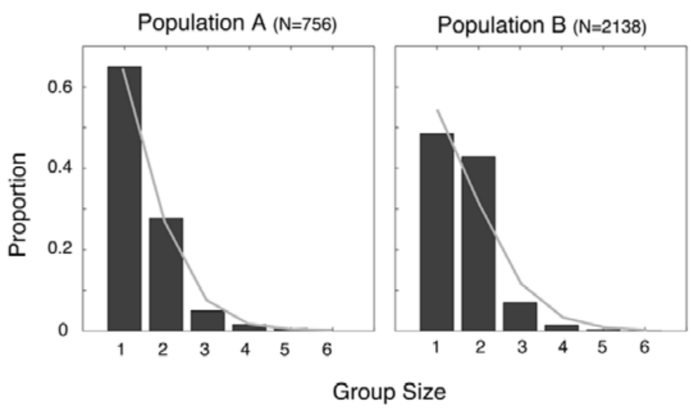


Figure 2-7 Observed group size distribution and zero-truncated Poisson fit (gray curve) (Moussaïd, et al., 2010).

2.3.3 **Pedestrian Speed and Group Size**

Henderson (1971) had suggested that the desired speeds within pedestrian crowd are Gaussian distributed with a mean value of 1.34 m/s and a stand deviation of 0.26 m/s. More recent research shows that pedestrian walking speed can be influenced by many factors. Those factors include environmental factors such as crowd density, widths of the walkway, and mixture of the flow as well as personal factors like age, gender, physical abilities and purposes of trip (Harney, 2002; Moussaïd, et al., 2010; Rastogi, Thaniarasu, & Chandra, 2011). In addition to these determinants, some research has observed that the group size significantly contribute to pedestrian speed.

Moussaïd, et al. (2010) measured the walking speed of pedestrian groups with different sizes and concluded that pedestrian walking speed decreases linearly as the size of the group increases (Figure 2-8). However, as can be seen from Figure 2-8, this linear relationship is obtained by fitting curve to merely three data points. Therefore, a more persuasive conclusion would include more data points that stand for group speed of different group sizes. Besides this, the speed of individuals (group size of 1) is also worth investigating. Nonetheless, this research reveals a trend that the group speed reduces with the increase in size of the group.

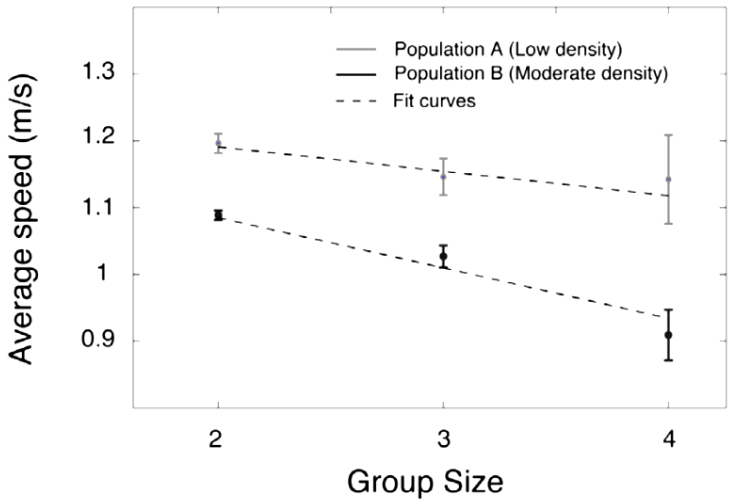


Figure 2-8 Effects of group size on pedestrian walking speed (Moussaïd, et al., 2010).

Similar findings were discussed in the research of Schultz, et al. (2010), who recorded and analysed the walking behaviour of passengers in Dresden International Airport. Figure 2-9 compares the differences in speed between groups with one and three members. As the author had expected, groups with three members are clearly slower than groups that only have one member. Since it was mentioned in many studies that the environment has great influence on pedestrians' waking speed (Finnis & Walton, 2008; Harney, 2002; Rastogi, et al., 2011), above research results can only be applied in airport environment and cannot represent the pedestrian speed at any other situations wilfully.

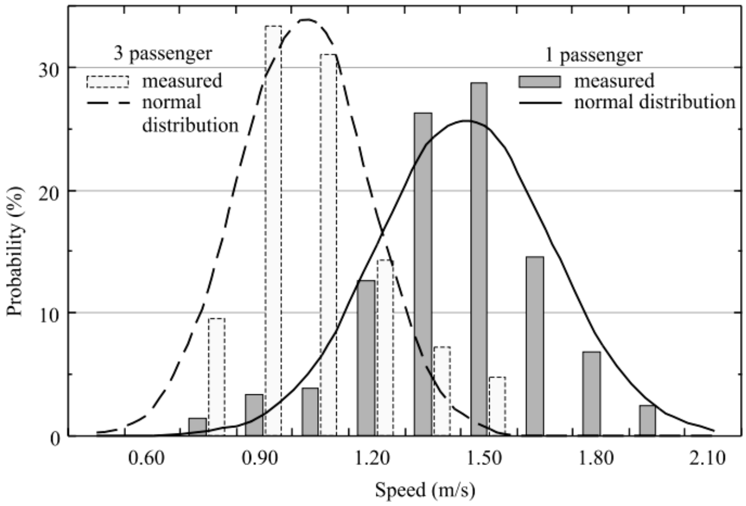


Figure 2-9 Group size interdependencies regarding to speed (Schultz, et al., 2010).

For comparison, Table 2-2 summarises the mean walking speeds for pedestrian group with varying sizes at different locations in previous research. Tarawneh (2001) investigate the speed of pedestrians when at 27 crosswalks in the Great Amman Area, Jordan. Results show that pedestrian group size with three or more people walk much slower than smaller groups when crossing the street. Tarawneh argued that the reasons could be: (1) pedestrians in small groups (single or couple) feel less secure in the crosswalk; and (2) larger groups of pedestrians are more likely to engage in conversations during the walk. However, the author overlooked the particularity of the environment. In crosswalks, the speed of pedestrians is often constrained by traffic signals. Moreover, dwelling in the crosswalk may cause potential safety hazards. Thus, pedestrians in crosswalks tend to finish crossing as fast as possible and the effect of group interactions is relatively weak during this time. This can be seen from that individuals or couples were faster than larger groups by only 0.02 m/s, which is hardly noticeable.

Source	Locations	Mean walking speed (m/s)					
		Group sizes					
		1	2	3	4	5	>5
Tarawneh (2001)	Crosswalk	1.35	1.35	1.33	-	-	-
Klüpfel (2007)	World Exhibition	1.38	1.28	1.24	1.24	1.22	1.10
Schultz, et al. (2010)	International Airport	1.36	1.06	0.96	-	-	-
Rastogi, et al. (2011)	Sidewalks	-	1.19	1.06	0.91	1.01	0.99
	Wide Sidewalks	-	1.13	1.01	0.98	0.90	-
	Precincts	-	1.09	1.00	1.00	0.89	0.83

Table 2-2 Mean walking speed (m/s) of pedestrians in different group sizes.

Rastogi, et al. (2011) reported that pedestrians travelling in groups walk at an average speed and almost 73% of the pedestrians who fall behind will catch up with other group members by increasing their speed. Rastogi also observed an interesting phenomenon: on sidewalks, pedestrians in large groups (have 5 or more people) often split into smaller sub-groups in order to avoid incoming pedestrian flow. This splitting behaviour decreases the group sizes, but increases the speed of pedestrian sub-groups. Therefore, it can be seen from Table 2-2 that the mean speed of five-people groups is faster than that of four-people groups on the sidewalks. This phenomenon is absent on wide sidewalks and precincts because there is no restriction in space and large groups are not necessary to split into small sub-groups.

2.3.4 Walking Behaviour of Groups

From the filmed evidence, Singh, et al. (2009) discovered the avoidance behaviour of pedestrians that walk in groups. Figure 2-10 shows the percentage of avoidance action taken when facing incoming pedestrians. It shows that in most cases, a person or a group of people will move to the right (34%) or left (44%) to avoid colliding with others (the ratio of people moving to the left is higher than that of moving to the right, a possible explanation of this phenomenon is that the experiment was conducted in UK, where left-hand traffic rule is applied). Only 22% of the groups will split in order to avoid colliding. This finding indicates a group of people are trying to remain together if possible. The social connection between group members creates an invisible bond that forces them to maintain a group structure, as is described in Helbing's 'social force' theory (Helbing & Molnár, 1995). Singh also noticed in their research that if a group is split to avoid more than one obstacle, the group will remain apart and regroup once all the obstacles have been avoided.

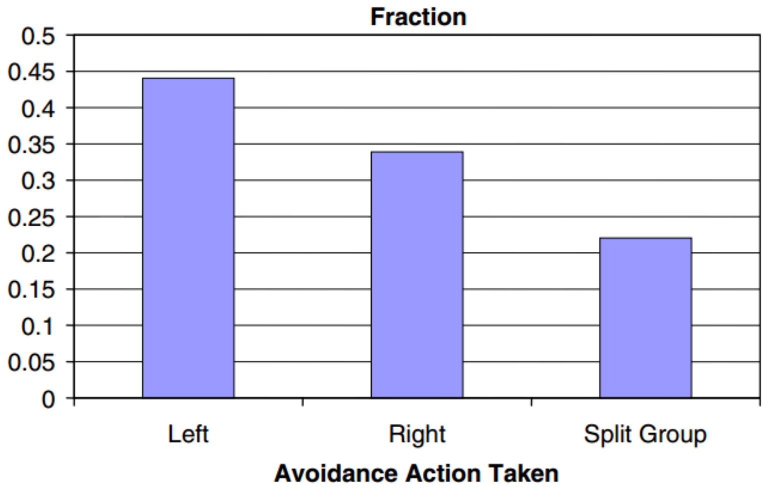


Figure 2-10 The avoidance action taken by people walking straight towards another (Singh, et al., 2009).

Moussaïd, et al. (2010) investigated the spatial organisation of walking pedestrian groups in two different population densities by analysing the average angle and distance between group members (Figure 2-11). It has been suggested that at low density, people in the same group walk in a horizontal formation which enables them to communicate with other group members easily [Figure 2-12 (a)]. While at moderate crowd density, this structure is hard to maintain without interfering with pedestrians outside the group. Therefore, the linear group structure will bend in the middle and form a 'V'-shaped formation. Moussaïd, et al. pointed out that this bending is forward in walking direction instead of backward, thus facilitates the social communication between group members [Figure 2-12 (b)]. Though bending backward is a more flexible structure against the opposite pedestrian flow, it impedes the interaction within the group. Finally, at high density, the physical constraints would prevail over the social interaction, group members will walk behind each other and form a 'river-like' formation [Figure 2-12 (b)]. This 'river-like' formation is also noticed in the crowd observation conducted by Singh, et al. (2009).

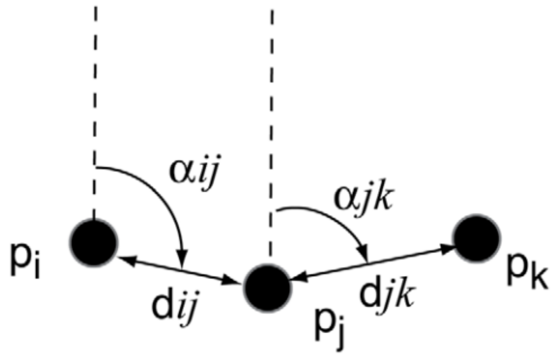


Figure 2-11 Illustration of the measurement method (Moussaïd, et al., 2010).

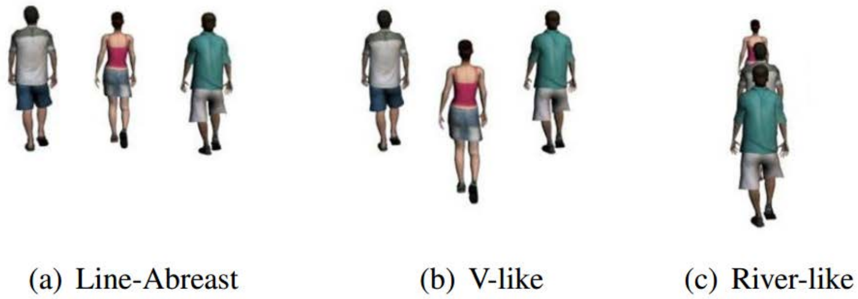


Figure 2-12 Group formations according to Moussaïd, et al. (2010) (Karamouzas & Overmars, 2010).

2.4 AIRPORT PASSENGER FLOW MODELLING

In recent years, there has been an increasing amount of literature on airport passenger terminal design, analysis and modelling. Tosic (1992) offered a comprehensive review about global airport terminal models. The review introduced the features and proposed applications of the models, along with their strengths and weaknesses. Generally, model inputs are physical layouts of the building, flight schedule, arrival time of passengers and processing rates. The evaluations of the model usually consist of the queue length, utilities and waiting times at all facilities. Although some literature had considered passengers as groups of people, how the group dynamic influence the group behaviour at each activity and overall system performance were not illustrated nor analysed. In spite of this, those models provided valuable references for future model designs.

Takakuwa and Oyama (2003) proposed a simulation model to examine the passenger flow in the departure terminal of Kansai International Airport in Japan. In their research, they found that only 4% of total time in the terminal was spent in formalities. While the most amount of time was spent in travelling between places

(48%). The rest of the time was spent in waiting (25%) and other discretionary activities (23%). The simulation showed that by adding supporting staff and making use of business class and first class counters for economy class passengers, the boarding rate can be dramatically improved.

Schultz, et al. (2010) investigated passenger dynamics in the airport terminal by analysing field data from Dresden International Airport. The research pointed out that about 50% of passengers were travelling in groups and the group size has significant influence on passenger speed. Other factors that influence passenger speed are gender, travel purpose (business/ leisure) and the amount of carry-on baggage.

Popovic, Kraal, and Kirk (2009) presented an observation technique that investigated how passenger activities mediate people's experience in the airport. In the study, detailed passenger behaviour in the airport was recorded. It was found that passengers travelling in groups had a considerable waiting time at the security process. The video showed that after the security screen, people wait for their group members in the middle of the walkway to passport control. The findings of the study provide valuable information for modelling passenger behaviour and group dynamics in this thesis. Using the same observation technique, Livingstone, Popovic, Kraal, and Kirk (2012) reported results of passenger landside retail experience in airports. Through the data collection from 40 passengers, researchers found that the existence of passenger's travel companion can influence passenger's landside dwell time and shopping behaviour in discretionary activities. The limitation of the observation technique is that passengers who participated in the research were aware that they were being recorded. On the other side, the low efficiency of video recording and data processing restricted the technique to only a small number of people.

Ma, et al. (2013; 2012; 2011) introduced an individual agent decision model to simulate stochastic passenger behaviour in airport departure terminals. Using Bayesian networks, the conditional probabilities of passengers' advanced traits (shopping preference, hunger level, technology preference, etc) were calculated through the basic traits (age, gender, nationality, flight class, etc.). By considering the restriction factors (such as remaining time and walking distance) passengers in the simulation can behave autonomously based on the results of Bayesian network inferences. However, the simulation did not explain how the group dynamics influence the passengers' decision making process and what will happen if passengers were in a group where group members have very different behaviour in their advanced traits.

2.5 EVACUATION MODELS

In previous studies of pedestrian evacuation, the vast majority of researchers chose to use computer modelling technique instead of the full-scale evacuation practice (Gwynne, Galea, Owen, Lawrence, & Filippidis, 1999b; Santos & Aguirre, 2004; Schadschneider, et al., 2011; Zheng, et al., 2009). The major concerns of a real evacuation trial are: (1) the potential threats of injury to volunteers; (2) the lack of realism reaction during experiment. For example, arising stress and panic; (3) the limit of reproducible results in repeat experiments; and (4) full-scale evacuation can be too expensive and time-consuming. As a result, many of the phenomena and laws during an evacuation are only carried out by the model simulation (Gwynne, et al., 1999b; Schadschneider, et al., 2011; Zheng, et al., 2009).

Gwynne, Galea, Owen, Lawrence, and Filippidis (1999a) summarised 22 different evacuation models in their review. Based on the nature of model application, those models are categorised into three different manners: optimization, simulation and risk assessment. The optimization models try to find out the optimal evacuation path, exit or flow characteristic, simulation models tend to demonstrate the behaviour and movement observed in the evacuation, while risk assessment models attempt to define potential hazards and bottlenecks in evacuation process.

Helbing, et al. (2000) summarised the characteristic features of escape panics and presented a model in the framework of the self-driven many-particle system. The model simulated several important phenomena in the escape panic: (1) transition to incoordination due to clogging; (2) 'faster-is slower' effect due to impatience; and (3) ignoring alternative exits due to the mass behaviour. The authors suggested that this model is based on plausible interactions and it is suitable for drawing conclusions about possible escape mechanisms. However, the crowd dynamic in this model is based on a generalised force model which fails to consider the group dynamics within pedestrian. Thus, a more realistic model could be adding a term of interaction force in the proposed acceleration equation to indicate the group interaction between pedestrians.

Santos and Aguirre (2004) also presented a critical review of emergency evacuation simulation models. They pointed out that one common shortcoming of the reviewed models lay in the absence of inclusion of social psychological relevant group level processes. However, they also noticed that in some extreme situations where mass behaviour exists, most potential evacuees do not have enough opportunities to interact with their fellow group members, thus in those situations, the distinction between group and individual level evacuation behaviour is less meaningful.

Bonabeau (2002) summarised the benefits of the agent-based model: (1) agent-based modelling (ABM) captures emergent phenomena; (2) ABM provides a natural description of the system; (3) ABM is flexible. These advantages make agent-based modelling ideal for simulating evacuation process. By using an agent-based fire escape example, the author demonstrated how a column in front of the emergency exit unexpectedly reduced the injury and increased the speed of the flow. The simulation result is verified by real-world experiments and indicated that the ABM can capture the emergent phenomenon in a natural way.

Based on an enhanced cellular automation model, Schultz, et al. (2006) proposed a stochastic model to evaluate pedestrian dynamics under emergency cases in airport terminals. They stated that airports are divided into public and non-public areas. Thus different security levels are required. They also suggested that a managed guidance system is necessary during the emergency situation, because in a static guidance system, the pre-defined routes cannot be guaranteed to be safe for evacuees.

Zheng, et al. (2009) discussed the advantages and disadvantages of seven evacuation modelling techniques. Those methods include cellular automata models, lattice gas models, social force models, fluid dynamic models, agent-based models, game theory models, and approaches based on experiments with animals. They concluded that all agent-based models are microscopic. They are more computationally expensive compared to other models but have the ability to model heterogeneous humans. They pointed out that a new trend of crowd evacuation models is based on the combination of multiple approaches because of the complexity of pedestrian behaviour.

In this thesis, a new evacuation model which incorporates group dynamics will be introduced in Chapter 5. The model is created using the agent-based model and simulates an evacuation event in an airport. It is assumed that the panic behaviour does not exist in the evacuation so that the pedestrian group behaviour can be preserved and analysed.

2.6 PEDESTRIAN MODELLING SOFTWARE

Along with the extensive utilisation of pedestrian modelling, an increasing number of pedestrian modelling software has been developed. Different software can be based on completely different modelling methods and computational algorithms. This can lead to the inconsistency of the results generated across different modelling software (Schadschneider, et al., 2011). However, some research showed that modelling with different software can produce results with no large differences. Castle, Waterson, Pellissier, and Bail (2011) compared the performance of a grid-based pedestrian modelling software – STEPS 4.0 with a continuous space modelling software – Legion Studio 2006. Two case studies of rail stations in UK were investigated and the performance of each model regarding gate-line clearance and passenger density was analysed. The results from two models were generally similar despite quite different approaches.

In the case study presented by Castle, et al. (2011), two modelling software applied different approaches to representing movement and collision avoidance algorithm. Despite this, the authors made every attempt to ensure the parameters in the two models (such as the building layout, passenger arrival distribution, walking speed distribution) to be the same. However, the two models are stochastic with respect to passengers' behavioural preference, which is impossible for the results to be identical, even for two runs of the same model. This example shows that comparable results can be obtained from simulation software with different modelling approaches as long as they have consistency between the configurations.

The Transportation and Planning Section of the Delft University of Technology developed two models for pedestrian flow simulation: NOMAD and SimPed (Daamen & Hoogendoorn, 2003). These two models were designed for different purposes. NOMAD is a microscopic model which models individual pedestrian behaviour. Hoogendoorn and Daamen (2004) used NOMAD to investigate the effects of installing entry/exit gates on pedestrian behaviour in the transfer station.

The modelling results showed that the simple rules used by the designers can provide satisfactory level-of-service to the transferring pedestrians, and the gates could be installed without compromising passenger safety. SimPed is a macroscopic model which describes pedestrian flows. By comparing the observed traffic flow characteristics on a platform with simulation results, Daamen and Hoogendoorn (2004) concluded that SimPed can reflect key characteristics of the passenger flow on the platform, which are valuable to assess the design of a transfer station.

Macal and North (2010, 2011) had reviewed simulation software that enables agent-based modelling method. Those software include public software that freely available such as Repast (2013), Swarm (2013), NetLogo (2013), MASON (2013) and proprietary toolkits such as AnyLogic (2013). Comparison between agent-based modelling software is summarised in Table 2-3 by Ma (2013). Figure 2-13 illustrates the ease of model development of selected example of ABMS environment against their modelling power. As can be seen in Figure 2-13, the AnyLogic simulation software stands out in comparison with others due to its strong modelling power and user-friendly feature. Therefore, it is chosen as the simulation platform to model passenger flow dynamics in this thesis.

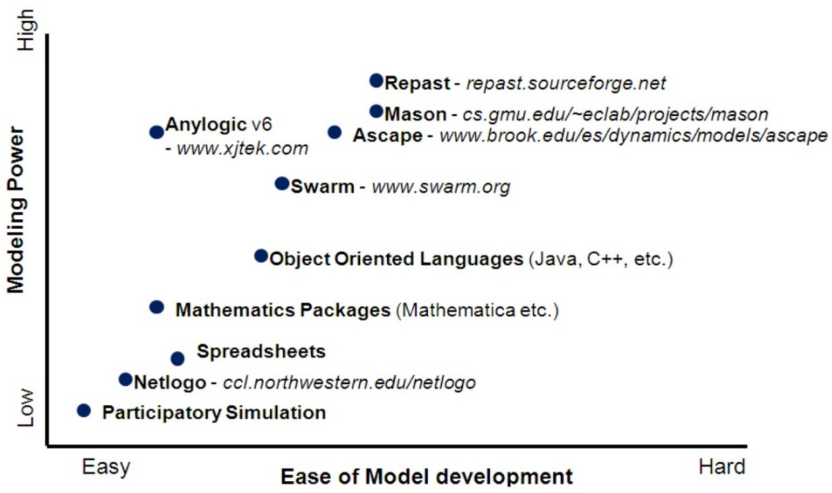


Figure 2-13 Agent-based modelling software [Macal and North as cited in (Ma, 2013)].

AnyLogic is the only simulation tool nowadays that supports all common simulation methodologies which include system dynamics, discrete event, and agent-based modelling (AnyLogic, 2013). The Pedestrian Library of AnyLogic software is dedicated to simulate pedestrian flows in ‘physical’ environments. In the software, pedestrian agents move in continuous space and interact with other pedestrians and different kind of obstacles. The pedestrian movement is governed by the customised social force algorithm, while the pedestrian dynamics are defined in the style of flowcharts.

Platform	*Primary Domain*	*License*	*Programming Language*	*GIS Capabilities*	*3D Capabilities*	*Model Power*
NetLogo	Social and Natural Sciences	Free, not open source	NetLogo	Yes	Yes	Low
MATLAB	Simulation; programming; scientific and engineering math and computation; data analysis	Proprietary	Matrix-based data structures, m-language, and extensive catalogue of functions	N/A	Poor (SimuLink)	Moderate
Swarm	General purpose agent-based	General Public License	Java	N/A	N/A	Moderate
Mason	General purpose; social complexity; Physical modelling, abstract modelling, artificial intelligence/machine learning	Academic Free (open source)	Java	N/A	N/A	High
Repast	Social Sciences	Berkeley Software Distribution	Java(RepastS); Python(RepastPy); .Net, C++	Yes	Yes	High
Anylogic	Agent-based; distributed simulation	Proprietary	Java; UML-RT (Unified Modelling language)	Yes	Yes	High

Table 2-3 Comparison of agent-based modelling toolkits (Ma, 2013).

2.7 CHAPTER SUMMARY

This chapter has introduced the need for pedestrian models. Pedestrian models have made an important contribution to understanding the behaviour of human crowds. By successfully simulating pedestrian dynamics, pedestrian models are widely adopted in designing the layout of street networks, examining the efficiency of building evacuation strategy, evaluating the performance of pedestrian facilities, and so forth.

Generally, there are macroscopic models and microscopic models. In macroscopic models, the details of pedestrians' movement and interactions are neglected. Research is mainly focused on the space allocation for pedestrians by assuming the agents are homogeneous. Therefore, it is not suitable for investigating crowd behaviour emerging from the interaction between agents. Microscopic models on the other hand, overcome the limitation of macroscopic models by considering pedestrians as individual agents. By defining behaviour rules properly, microscopic models present more accurate pedestrian behaviour in a greater variety of situations.

Memory and computational power are no longer the constraints as they used to be in large-scale simulation of many detailed interacting elements, which make microscopic model simulation becoming a practicable approach. Three typical microscopic models: social force, cellular automata, and agent-based models were introduced and their advantages and disadvantages were compared.

Research had demonstrated that large proportions of pedestrians are in groups. The percentage of people in groups within a crowd ranges between 40% and 70% at different places and times. Researchers also discovered that the size of a pedestrian group can influence pedestrian walking dynamics such as speed, group formation, and avoidance behaviour. It was proved that the group size can be modelled by the Poisson distribution, which provides a reference for quantitatively creating pedestrian groups in the model.

The aim of this research project is to simulate passenger flow in an airport terminal in order to provide better airport experience for passengers and easier management for airport operators. Since safety is considered to be the number one priority for an airport, it is necessary to investigate passenger dynamics during evacuation as well. Although many pedestrian models had been used in modelling airport passenger flow and crowd behaviour during evacuations, the literature reviewed appeared to show a very limited understanding of how passenger group dynamics affect the passenger behaviour in the airport environment. Grouping is a common social behaviour and it has been proved to have great influences on pedestrian behaviour. Therefore, it is essential to incorporate group behaviour when creating pedestrian models.

Among a broad range of pedestrian simulation software, AnyLogic is selected as the simulation tool in this thesis because of its advanced features in modelling agent-based models and user-friendly interface. This thesis aims to evaluate the impact of group dynamics on passenger flow in an international departure terminal using the agent-based modelling technique. Detailed implementation of the model will be presented in the next chapter.

Chapter 3: **Developing an Agent-Based Passenger Flow Model with Group Dynamics in an Airport Terminal**

3.1 INTRODUCTION

This chapter demonstrates the creation of an agent-based model based on fundamental considerations about group behaviour in pedestrians. The model describes the daily operation of an international airport terminal and simulates passenger activities from the moment of entering the terminal to boarding the airplane.

In an agent-based model, three key elements need to be identified and modelled: agents, agents' environment, the interaction between agents and the environment (Macal & North, 2010). This chapter describes the development of the model according to these three elements. Section 3.2 introduces the arrival of airport pedestrians and their characteristics. Section 3.3 defines rules of the interaction between pedestrians. Section 3.4 demonstrates the airport departure process and the detailed passenger activities at each processing unit. The validation method of the model is presented in Section 3.5.

3.2 AIRPORT PASSENGERS

3.2.1 **Arrival in the Airport**

Pedestrians in the model are categorised into passengers and wavers. Passengers are those who will complete all airport departure process and board on the plane, while wavers (or well-wishers) are fellow companions, who accompany the passengers in the airport but do not board the flight. In terms of air travel purpose, passengers are further divided into leisure and business class (see Figure 3-1).

Since the agents in this model were characterised as airport pedestrians (passengers and wavers), their arrival time in the model will possess general airport passenger attributes. One of the most critical influences of the passenger arrival time in an airport is his/her flight schedule. A flight timetable is provided by the reference international airport. The timetable includes information such as the flight number, destination, aircraft type and the scheduled departure time. There were an estimated 6,500 passengers that leave the airport daily. By allocating flight seats to each flight according to the flight types in the timetable and assuming every aircraft was at 80% capacity, a total 6202 passengers were calculated (Kirk, Cheng, Popovic, Kraal, & Fookes, submitted). This is the agent number in the simulation. The flight timetable is attached in Appendix A based on a typical Wednesday schedule in the international airport.

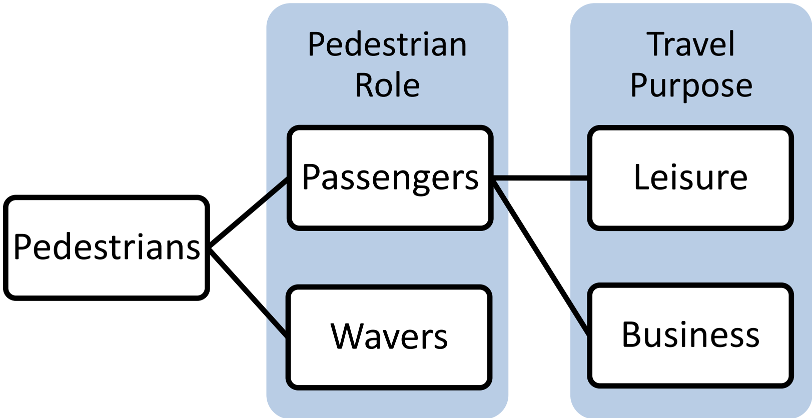


Figure 3-1 Pedestrian classification according to role and travel purpose in the simulation model.

The overall flow rate of arriving passengers for a single flight has shown some general arrival pattern. Ashford, Mumayiz, and Wright (2011b) provided an example of accumulative passenger arrivals before Scheduled Time of Departure (STD) for a British airport is shown in Figure 3-2. As can be seen in Figure 3-2, almost all passengers of an international flight had arrived 60 minutes before scheduled flight departure time. While this figure for domestic flights are 20 minutes.

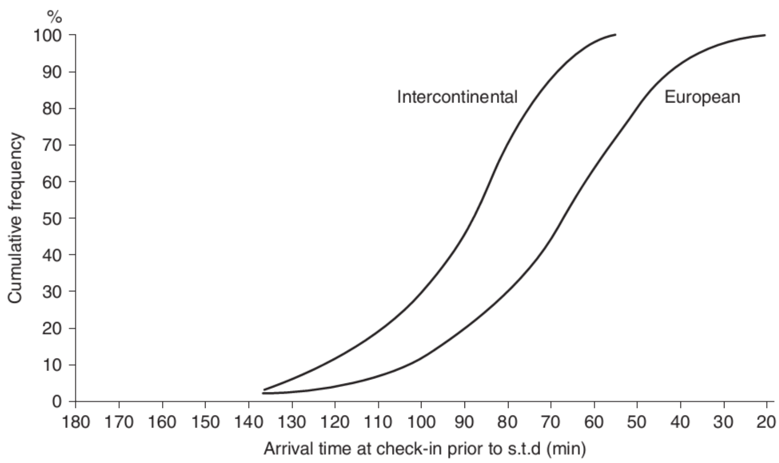


Figure 3-2 Example of relationship of arrival time for enplaning passengers and type of flight (Ashford, et al., 2011b).

The arrival pattern can be influenced by many factors such as airport accessibility, public transportation, security requirement and traffic situation. Even for one airport, the arrival pattern can vary at different periods of the day (Ahyudanari, 2003; Stefanik, Kandera, & Badanik, 2012). In spite of these, airports share some universal arrival behaviour for international travellers: (1) almost all passengers had arrived 60 minutes before scheduled flight departure time; (2) leisure passengers arrive earlier than business passengers; (3) for each flight, its check-in peak hours usually happen 100 – 120 minutes prior to scheduled departure time; and (4) peak hours in the morning are relatively shorter but busier compared with that in the afternoon and in the evening (Ahyudanari & Vandebona, 2005; Ashford, et al., 2011b; Stefanik, et al., 2012).

International Airport Transport Association (IATA, 2004) showed an example of the passenger arrival rate at check-in counters at three different periods of a day in an airport in Table 3-1. For most departure passengers, it is noted that they tend to complete their processing, travel related activities before other discretionary activities (Popovic, et al., 2010). Because check-in is the first processing activity in the departure terminal, it is reasonable to assume that the passenger arrival rate at the airport equals to the rate they arrive at check-in counters. Assuming the arrival rate of 00:00 to 06:00 is the average of the time periods: 18:00-24:00 and 06:00-10:00, the passenger arrival rate at an airport can be transformed to an accumulative passenger arrival pattern (Figure 3-3).

Period of day	Percentage of passengers per flight arriving at the Check-in counters by 10 minute periods prior to flight departure											
	120-110	110-100	100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
06:00-10:00	0	0	1	2	6	10	20	26	20	12	3	0
10:00-18:00	0	1	3	8	11	15	17	18	15	10	2	0
18:00-24:00	3	4	6	9	11	14	15	15	15	7	1	0

Table 3-1 Example of passenger arrival rate at check-in counters in three periods of the day (IATA, 2004).

Compare Figure 3-3 with the passenger arrival pattern presented in Figure 3-2 by Ashford, et al. (2011b), the characteristics of the IATA arrival pattern is more likely to be a domestic flight (the latest passengers arrive in the airport about 20 minutes prior to flight departure) rather than an international flight. Thus, to obtain the distribution of passenger arrival for international flights, the time axis in Table 3-1 need to be shifted forward for 60 minutes, as is shown in Table 3-2.

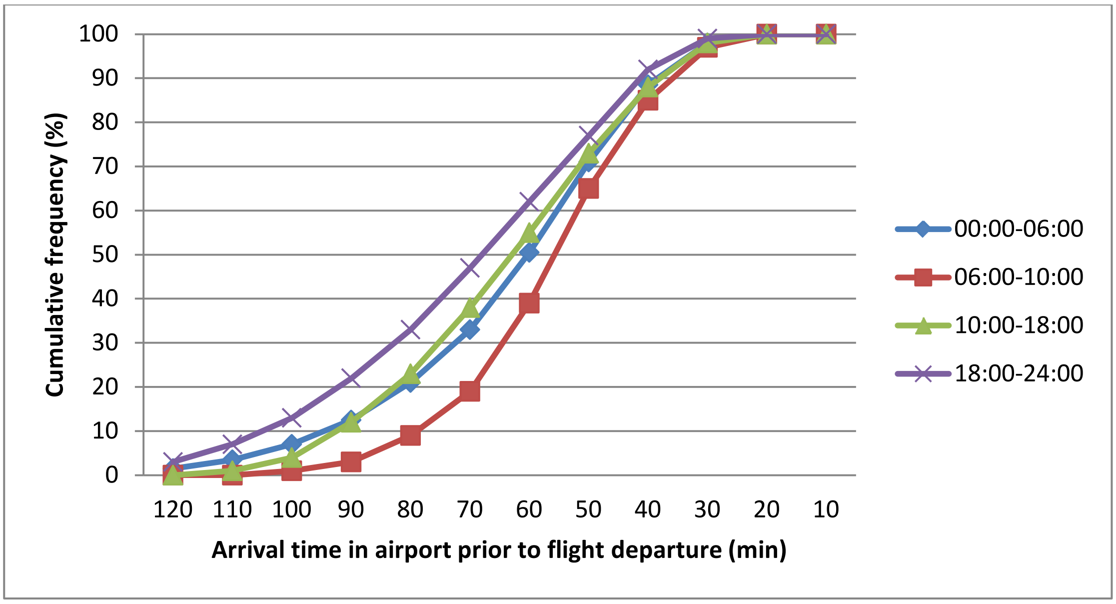


Figure 3-3 Accumulative passenger arrival pattern in an airport at three different time periods of a day.

Period of day	Passengers per flight arriving at the airport by 10 minute periods prior to flight departure											
	180-170	170-160	160-150	150-140	140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60
00:00-06:00	1.5%	2%	3.5%	5.5%	8.5%	12%	17.5%	20.5%	17.5%	9.5%	2%	0%
06:00-10:00	0%	0%	1%	2%	6%	10%	20%	26%	20%	12%	3%	0%
10:00-18:00	0%	1%	3%	8%	11%	15%	17%	18%	15%	10%	2%	0%
18:00-24:00	3%	4%	6%	9%	11%	14%	15%	15%	15%	7%	1%	0%

Table 3-2 Adjustment of IATA passenger arrival pattern in international airport departure terminals.

Given the airport timetable (Appendix A) and the passenger arrival pattern (Table 3-2), it is able to calculate the arrival intervals between passengers and introduce passengers into the airport successively. A flow chart of the passenger generating procedure in the model is presented in Figure 3-4. Take the first flight on the timetable as an example, it departs at 3:30 a.m. and has 222 passengers on board. According to the passenger arrival pattern in Table 3-2, the pattern in the period of 00:00 to 06:00 should be adopted in this case. Arriving passenger number at each 10 minute period before flight departure can be calculated and the arrival intervals can be obtained (see Table 3-3). The program can therefore 'inject' agents into the simulation environment at the predetermined rate.

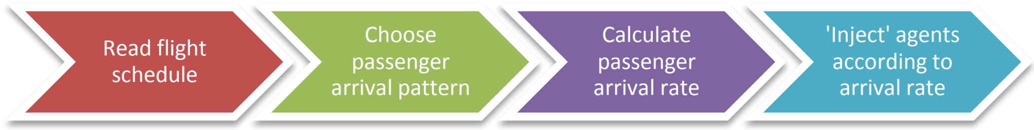


Figure 3-4 Flow chart of passenger generating process.

Time prior to departure (min)	180-170	170-160	160-150	150-140	140-130	130-120	120-110	110-100	100-90	90-80	80-70	70-60
Passenger number	3	4	8	12	19	27	39	46	39	21	4	0
Arrival rate (passenger/min)	0.3	0.4	0.8	1.2	1.9	2.7	3.9	4.6	3.9	2.1	0.4	0

Table 3-3 Passenger arrival time distribution and arrival intervals for the first flight on timetable.

3.2.2 **Pedestrian Group Assemble**

Agents will be assembled into groups with predefined sizes while they are entering the simulation environment. The distribution of pedestrian group sizes in the model was calculated by a zero-truncated Poisson distribution with an expected group size value: $\lambda = 1$ (Moussaïd, et al., 2010),

$$N_i = e^{-\lambda} \frac{\lambda^i}{i!(1-e^{-\lambda})},$$

where N_i is the probability for an agent to have the group size of i(i = 1,2,3…).

While an agent is generated, the program calculates its group size i based on the group size probability N_i in the above equation, and assembles this agent with subsequent $(i-1)$ agents as a group. Once the predetermined group size is reached, and a passenger group is generated, wavers are added into the group. The distribution of waver number of a passenger group is assumed to be a zero-truncated Poisson distribution as well, with an expected value: $\lambda = 1$. Therefore, a complete pedestrian group in the model is composed of passengers and wavers. The group assembling process in the model is illustrated in (Figure 3-5).

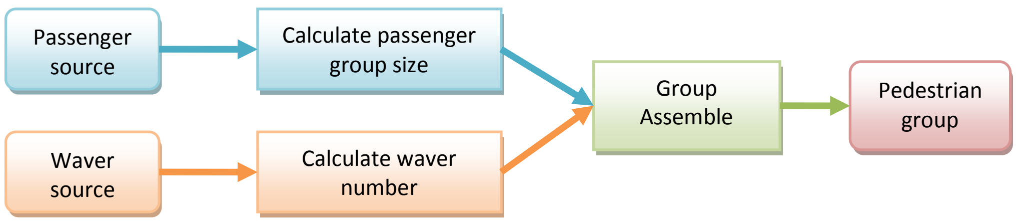


Figure 3-5 Pedestrian assemble process.

Pedestrian arrival in the model has two modes: 'Individual arrival' and 'Group arrival'. Under the 'Individual arrival' mode, there will be no group assembles in the model. The group size will be automatically set to 1. This kind of setting enables the comparison between dynamics of passengers who are travelling alone and those who travelling in groups and therefore allows the investigation of the effect of group dynamics. The model is also able to 'switch off' wavers in order to examine the influence of wavers on passenger behaviour.

3.2.3 **Pedestrian Characteristics**

In the real-world, airport passengers have their personal characteristics which influence their behaviour and activity choices in the airport. Those characteristics include physical related factors (e.g. age, gender, mobility) and psychological related factors (e.g. familiarity with the airport and departure processes). All these factors need to be considered in order to develop a complete model. Due to limited access to detailed passenger information in the reference airport, the characteristic data used in this model is referred to aviation organisation reports, previous research and assumptions which will be stated later in this section.

Age, gender, residential status and travel purpose are four basic characteristics of passengers in the model. These four factors can influence advanced passenger characteristics such as mobility and shopping preference through defining certain rules. How these rules are defined will be explained later in this section. Table 3-4 and Table 3-5 summarise the distribution of airport passengers' age and gender provided by the global passenger survey carried by IATA (2013b). According to the country of residence, passengers in the model are divided into Australian resident and overseas visitors. Australian Bureau of Statistics (ABS) provided the information of departure passengers' country of residence in 2012-2013 financial year (refer to Table 3-6) (ABS, 2013). ABS had also investigated passengers' main reasons for their journey. Those reasons include convention/conference, business, visiting friends/relatives, holiday, employment, education, and 'other & not stated'. For convenience, these travel reasons are categorised into two travel purpose: business and leisure (see Table 3-7).

Age range	<25	25-34	35-44	45-54	55-64	>65
Percentage in total passengers	10%	31%	23%	18%	11%	7%

Table 3-4 Age distribution of global airport passengers (IATA, 2013b).

Gender	Male	Female
Percentage in total passengers	59%	41%

Table 3-5 Gender distribution of global airport passengers (IATA, 2013b).

Country of residence	Australian resident	Overseas visitor
Percentage in total passengers	58%	42%

Table 3-6 Country of residence of airport departure passengers in 2012-2013 financial year in Australia (ABS, 2013).

Travel purposes	Detailed reasons	Percentage	Total
Business	Convention/conference	3%	15%
	Business	10%	
	Employment	2%	
	Education	1%	
Leisure	Visiting friends/relatives	23%	85%
	Holiday	58%	
	Other & not stated	4%	

Table 3-7 Percentage of departure passengers travelling for business and leisure purpose in 2012-2013 financial year in Australia (ABS, 2013).

The four basic characteristic factors: age, gender, country of residence and travel purpose will be initialised to each agent according to the percentage rate showed in the above tables. The age and gender are assigned to each agent when the agent enters the system. Since passenger groups usually share common features of country of residence and travel purpose, these two factors are initialised to each agent after the pedestrian group had finished assembling and will assume passengers in the same group have a common country of residence and travel purpose. Based on the four basic characteristic factors, two advanced characteristics: speed and activity preference can be defined.

Previous research had shown that passenger walking speed in airport terminals can be influenced by passenger characteristics such as age, gender, travel purpose and group size. Table 3-8 summarises the influence of these four factors on passenger walking speed in airport terminals. Calculation of agents' speeds in the model has following three steps:

(1) Using Table 3-8, calculate the agent's speed under each one of the four factors separately: v_{age}, v_{gender}, $v_{purpose}$, and v_{group}.

(2) The agent's speed is initialised by the average speed calculated in step 1: $v = average(v_{age}, v_{gender}, v_{purpose}, v_{group})$.

(3) Agents in a group with group size i will adjust their speeds so that each agent (numbered by 1, 2, 3… i) can have the same speed:

$$v_1 = v_2 = \cdots = v_i = average(v_1, v_2 \dots v_i).$$

Influence factor	Source	Category	Mean speed (m/s)	Standard deviation (m/s)
Age	Finnis and Walton (2008)	Age < 15	1.38	0.24
		15 < age < 30	1.46	0.22
		30 < age < 55	1.49	0.23
		Age > 55	1.37	0.28
Gender	Schultz, et al. (2010)	Male	1.40	0.22
		Female	1.27	0.22
Travel purpose	Schultz, et al. (2010)	Business	1.36	0.22
		Leisure	1.00	0.23
Group size	Schultz, et al. (2010)	Group size = 1	1.36	0.23
		Group size = 2	1.06	0.21
		Group size >= 3	0.96	0.19

Table 3-8 Influence of age, gender, travel purpose and group size on passenger walking speed in airport terminals.

Beside the mandatory processing activities such as check-in, security check and customs, passenger in the airport often undertake discretionary activities which include: buying food and drinks, duty-free products, using airline services, etc. The choices of these discretionary activities are controlled by the activity preferences which vary with different passenger characters. Table 3-9 illustrates the probabilities for passengers to undertake airport discretionary activities. The probability values shown in the table are based on assumptions along with related research findings. Past research showed that passengers under 26 are more likely to shop in souvenir shops and café while passenger with elder age more inclined to brand-name commodities (Perng, Chow, & Liao, 2010); female passengers spend more time in shopping than male passengers (Castillo-Manzano, 2010; Freathy & O'Connell, 2012); individuals on business spend less time in shopping than those travelling on leisure purposes (Freathy & O'Connell, 2012); foreign passengers like to dispose all foreign currency before returning to one's country of origin; passengers travelling in groups or have accompanies to see him/ her off consume more on average than individuals (Castillo-Manzano, 2010).

Similar to the calculation of agents' speed, there are two steps in calculating the activity preference for an agent:

(1) Using Table 3-9, calculate the probabilities for the agent to undertake certain airport activity under each one of the five influence factors separately: P_{age}, P_{gender}, $P_{purpose}$, $P_{residence}$ and P_{group}.

(2) The probability for the agent to conduct this activity is initialised by the average speed calculated in step 1:

$P = average(P_{age}, P_{gender}, P_{purpose}, P_{residence}, P_{group})$.

(3) Repeat step (1) and (2) to calculate the probability for all the four activities listed in Table 3-9.

Influence Factors \ Activities		Food and beverage (%)	Specialty retails (%)	Duty-Free shops (%)	Airline services (%)
Age	<25	15	8	8	2
	25-35	10	12	10	5
	35-50	10	11	12	8
	>50	8	10	11	5
Gender	Male	10	8	10	5
	Female	12	15	12	5
Travel purpose	Business	10	5	6	8
	Leisure	13	15	9	5
Country of residence	Australian	10	8	9	7
	Foreign	12	12	15	8
Group size	1	8	8	10	5
	2	10	12	12	6
	>=3	10	15	12	6

Table 3-9 Passenger activity preference in airport.

3.3 PEDESTRIAN INTERACTIONS

Pedestrians in the airport are mainly driven by specific goals: passengers want to finish airport processes and board their flights; wavers accompany passengers in the airport and send them off. Therefore, this thesis mainly considers the interactions within pedestrian groups. There are some rules that govern the relationship and interactions of a group:

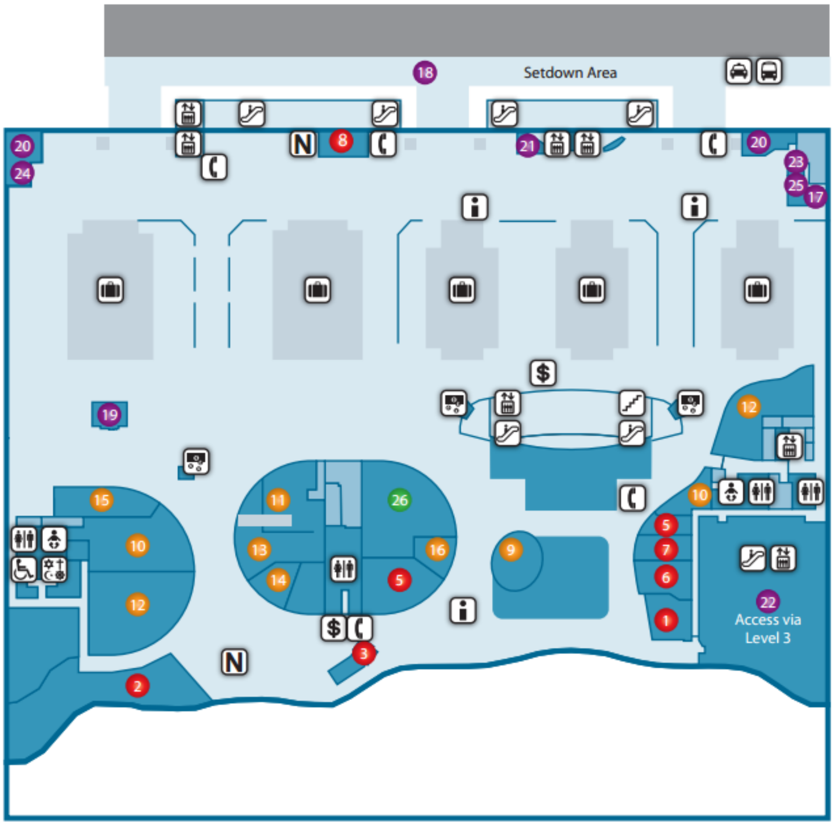
- During movement, pedestrians in the same group have the same target.
- While moving, a group of people will try to maintain a 'V' shaped special structure in order to facilitate communication as described in Section 2.3.4.
- All group members will try to keep a uniform speed, except the situations such as avoiding obstacles and collision with other pedestrians.
- If group members fall behind due to any reason other group members will slow down their speeds until the stalled group member catches up.
- At mandatory processes such as check-in, security and customs, passengers who finish the process faster need to wait for all other group members to complete the process and assemble the group before moving on.
- If time is allowed for discretionary activities, the activity to undertake is decided by the all group members. Once the activity is chosen, pedestrians in the same group will undertake the same activity together.
- In the condition that a pedestrian group is allowed to undertake discretionary activities, all group members will decide whether to undertake or not. The chance for a group to undertake discretionary activity is assumed to be high in the model. If anyone of the group member decides to undertake discretionary activity, the whole group will go together. According to activity preference defined in previous section, each pedestrian has a certain chance for not taking any discretionary activity. Suppose a group is composed of three pedestrians (numbered as 1, 2, 3), whose probabilities of not taking any discretionary activities are p_1,p_2 and p_3 respectively. Then the probability for this group not taking any discretionary activity is calculated as $p = p_1 \times p_2 \times p_3$. On the contrary, the probability for this group to undertake discretionary activity is $1 - p_1 \times p_2 \times p_3$. As a result, it can be expected that the probability for a group to undertake discretionary is higher for larger groups.
- If a pedestrian group has decided to conduct certain discretionary activity, the detailed activity is decided by the average activity preferences of each group members. For example, if a group is composed of three pedestrians

(numbered as 1, 2, 3) whose probabilities of undertaking activity A are a_1,a_2 and a_3 respectively. Then the probability for this pedestrian group to undertake activity A is: 1/3($a_1 + a_2 + a_3$). In the same way, the probabilities for all possible activities can be calculated.

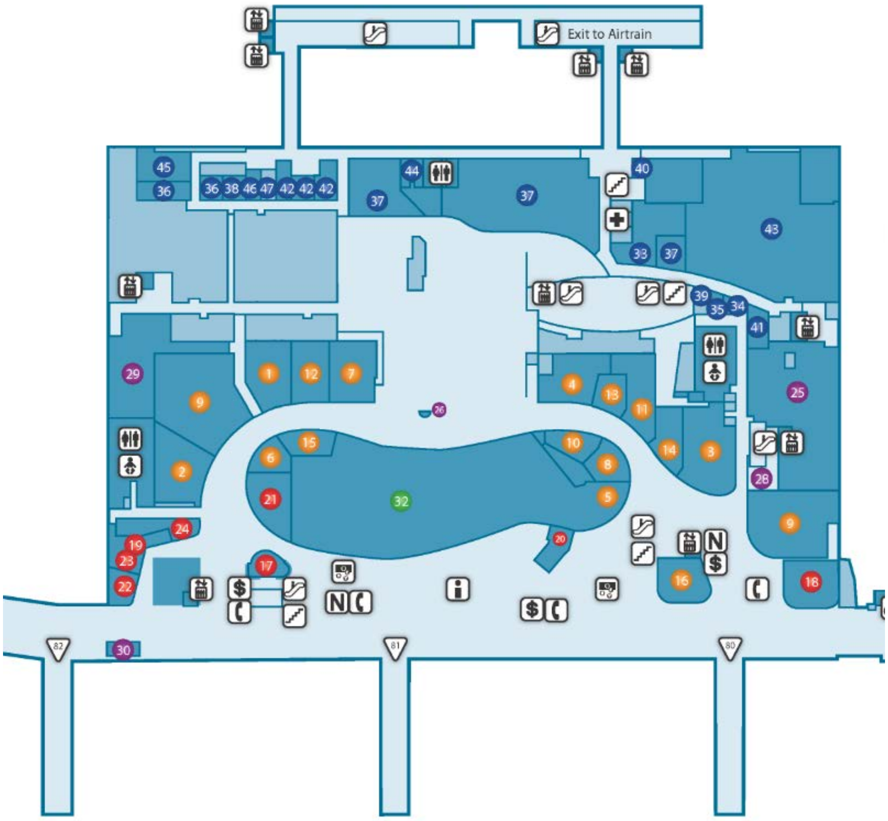
3.4 AIRPORT ENVIRONMENT AND PASSENGER INTERACTION WITH THE AIRPORT SERVICES

The model environment is an airport departure terminal, which is divided into landside and airside. The landside of the terminal is open to the public and is used more for social activities between passengers and wavers, while the airside of the terminal is only accessible for passengers. Level 4 (Figure 3-6.a) is the landside of the airport, where check-in counters are located. Level 3 (Figure 3-6.b) is the airside of the airport, where passengers need to pass through security check and customs before boarding. Similar retail shops and airport services are located at both landside and airside to provide passengers with convenience. The red dots in Figure 3-6 represent food facilities, yellow dots are for specialty retail, purple and blue dots indicate airport and airline offices. Additional facilities such as ATMs, public toilets, phone booth and money exchange services are illustrated using symbolic signs.

Figure 3-7 illustrates a high-level description of passenger departure processes in the model. Passenger activities are categorised into processing activities and discretionary activities (Kraal, Popovic, & Kirk, 2009). Processing activities are mandatory for passengers before boarding the plane. On the landside of the terminal, passengers check-in for their flights, while on the airside, they pass through security check and customs before entering airside and boarding. Discretionary activities are considered as any other activities undertaken by passengers during non-processing time (Kraal, et al., 2009; Livingstone, et al., 2012). It can happen between two sequential mandatory activities as is shown in Figure 3-7. Examples of discretionary activities in the proposed model include random walking, store browsing, having food and using airport services.



(a)



(b)

Figure 3-6 Overview of the terminal (a) landside of the terminal; (b) airside of the terminal.

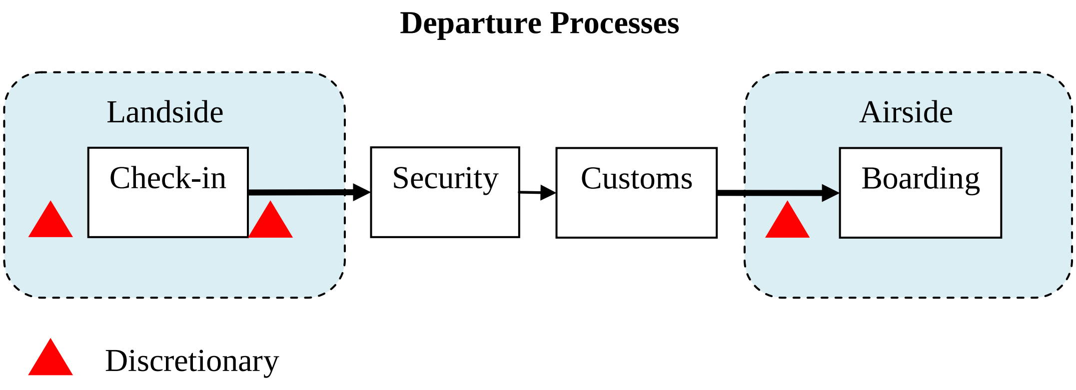


Figure 3-7 Airport departure processes.

3.4.1 Pedestrian Interaction at Check-in Area

In order to guarantee there is ample time left for security measures, passengers are often advised to arrive at the airport three hours before the standard flight departure time. In the model, the flight check-in process starts at 2.5 hours prior flight departures and closes on 25 minutes before the departure time. At level 4 of the international airport, passengers are required to undertake the check-in process. Figure 3-8 illustrates the layout of a row of check-in counters on level 4 of the departure terminal. In the model, a row of check-in service counters (eight counters per row) are assigned to the check-in process of each flight. Among the eight counters, there are two counters for business class passengers (passengers travelling for business purposes) and six counters for economy passengers (passengers travelling for leisure purposes).

Passengers who arrive at the airport before check-in start will wait in waiting area close to the check-in counters. At the time of check-in, the model assumes that all eight check-in counters are open for passengers to check-in. Passengers enter the check-in area and queue before the check-in counters if necessary. When they reach the head of the queue, they will approach an available staff member to process their check-in documents and hand over their baggage that they do not wish or are not allowed to carry on to the aircraft's cabin. Once they are processed, they leave the check-in area. The time passengers spend interacting with check-in personnel has been attained in the airport (Kirk, 2013). In the model, the interaction time is set according to Table 3-10.

Activity	Minimum (min)	Maximum (min)	Average (min)
Interacting with check-in staff	0.68	6.92	2.95

Table 3-10 Time passengers spend interacting with check-in personnel (Kirk, 2013).

For passengers travelling in groups, they will wait for stalled group members before they enter check-in queues, and after check-in, they will wait in the waiting area until the group is reassembled and then move on to other destinations as a group. If the group contains wavers, wavers will not enter check-in queues. Instead, they wait outside the queues until passengers finish the check-in process and will move on together after the group is reassembled.

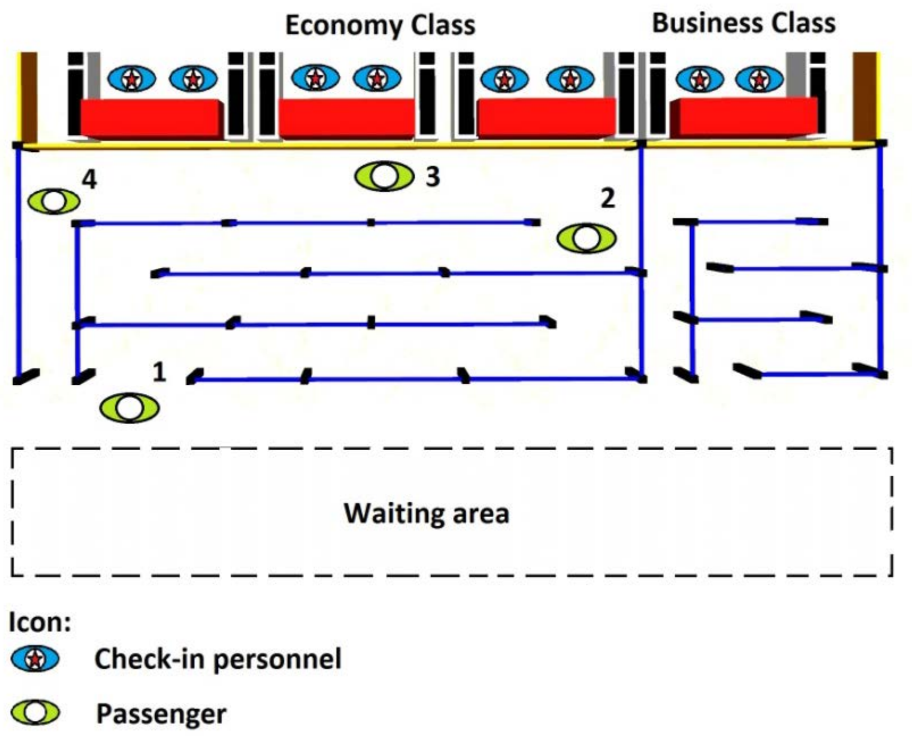


Figure 3-8 Illustration of airport check-in area and check-in process.

3.4.2 **Passenger Interaction at Security Control**

At security control, all passengers and their baggage are checked. Figure 3-9 shows the layout of the security control area and detailed security checking sequence. Passengers queue at the security checking entrance. When they reach the head of the queue, security personnel will lead the passenger to an available security desk. At the security desk, any bags carried by passengers are placed on the X-ray machine and passengers pass through the metal detector. If a passenger successfully passes the metal detector and his/her baggage successfully pass the X-ray examination, the passenger will go to the end of the X-ray machine to collect the baggage.

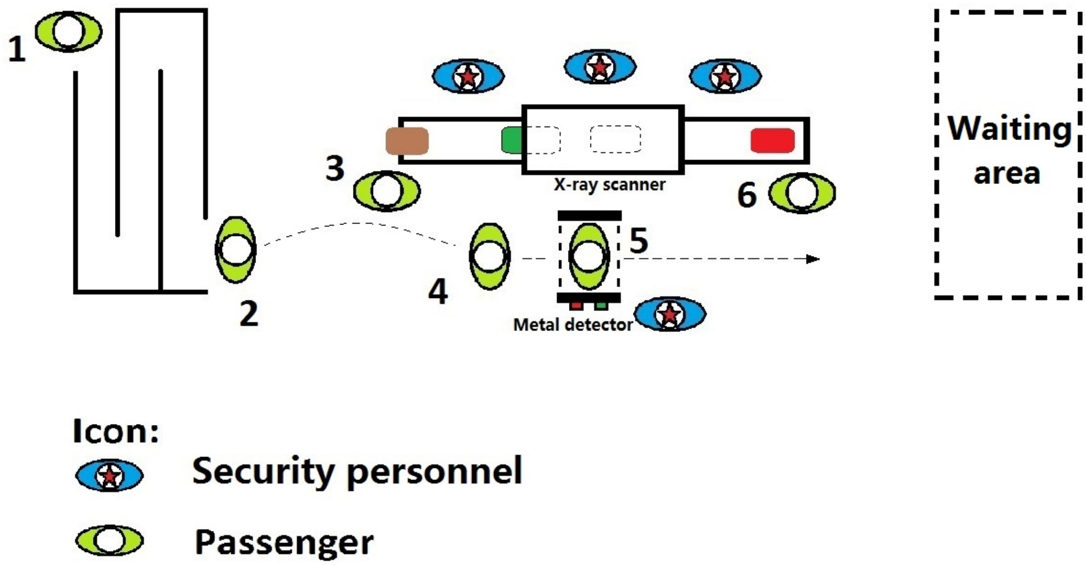


Figure 3-9 Illustration of airport security control area and detailed processing sequence.

There are possible failures for both passengers and bags. Processing failure rates for passengers at their first attempts listed in Table 3-11 are estimated through the observations conducted by Kirk, et al. (submitted). Passengers who fail the metal detector are required to pass through it again or undertake an extra body check. If any bags fail the X-ray check, the passenger will be asked to unpack their bag. Time statistics of each detailed activity at security have been collected by Kirk (2013) (refer to Table 3-12) and the activity time in the model was set accordingly.

Domain	Problem	Fail at 1st attempt
Security	Bags through X-ray	15%
	Metal detector	10%

Table 3-11 The percentage of passengers failing certain mandatory activities at security (Kirk, et al., submitted).

Activity	Minimum (min)	Maximum (min)	Average (min)
Unpacking	0	2.58	0.83
Being scanned	1 (second)	5 (second)	2 (second)
Interacting with staff	0	1.48	0.25
Repacking	0	7.55	0.83
Extra security check	0.37	4.02	1.53

Table 3-12 Time passengers spend in each activity at security (Kirk, 2013).

It is unlikely that passengers who travel in a group can finish the security process simultaneously. Passengers who finish the process earlier will wait for the remaining group members at the small waiting area between security and customs processes. There are seven desks with X-ray machines and metal detectors available at security checking area. In the simulation, not all seven desks are available at all times. Available desks can be automatically calculated by the program. In the default setting, two desks are available at all times and two additional desks are opened each time the passenger number in the queue increases by fifteen.

3.4.3 **Passenger Interaction at Customs**

The security control process is closely followed by the customs process. Figure 3-10 shows the sequence of the customs operation process. Similar to the check-in and security control process, passengers queue before being processed by customs personnel. Once finished document checking, passengers will wait for their group members in the waiting area right behind the customs area and then move on to their next discretionary period. At customs, there are six desks available to process passengers. In the simulation two desks are available at all times to process passengers, and two additional desks are opened each time the queue length increases by fifteen passengers.

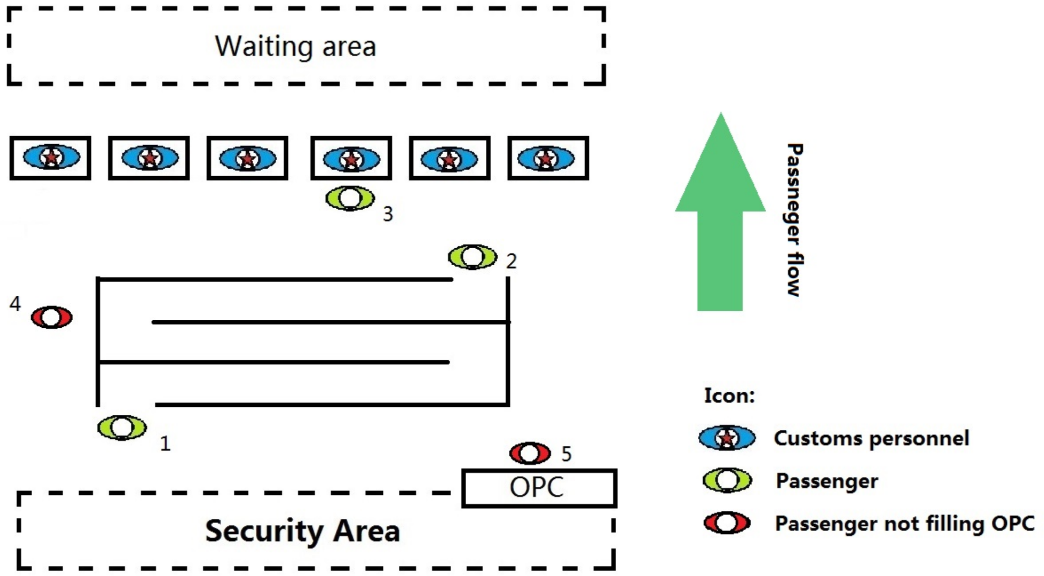


Figure 3-10 Illustration of airport customs area and detailed processing sequence.

At customs, passengers can either approach customs with their Outgoing Passenger Card (OPC) completed or incomplete. If the OPC is incomplete they have to return to the desk area before the customs queue and complete the document. The passenger then either proceeds to the customs staff member, or joins the queue if one is present. The failure rate for filling OPC is 15% by default in the model (Kirk, et al., submitted). The time for undertaking activities involved in the customs processing is set according to Table 3-13.

Activity	Undertaking (%)	Minimum (min)	Maximum (min)	Average (min)
Interacting with check-in staff	100	0.18	2.47	0.8
Filling out OPC	15	1.77	4.83	3.22

Table 3-13 Time passengers spend in each activity at customs (Kirk, 2013).

3.4.4 Passenger Discretionary Activities

Based on agents' characteristics, Section 3.2.3 had defined the discretionary activity preference for following four categories of activities: (1) food and beverage; (2) specialty retails; (3) duty-free shops; and (4) airline services. However, it was assumed in the model that passengers' personal traits have no influence on some of the passenger activities and passengers have uniform probability to undertake these activities in the airport. These activities are categorised into 'Public services'. The probability for one passenger to use any of the public services was assumed to be 20% in the model. Among those who will use public services, the probabilities of pedestrian doing certain sub-activities in the model are assumed in Table 3-14.

Public services	Percentage of undertaking
ATM	20%
Telephone	10%
Money exchange	10%
Restroom	50%
Net kiosk	10%

Table 3-14 Probabilities for passengers to use public services in airport departure terminal.

By adding 'Public services', all possible discretionary activities in the model have been introduced. Though the probability of passengers undertaking each discretionary activity has been defined, agents' activity choices are not merely based on probability. Another major constraint in passenger activity choices – the remaining time to the flight departure, needs to be considered. Since the ultimate goal of all passengers is to board their flight, all discretionary activities can only be undertaken when time permits. Ma (2013) had summarised passengers' dwell time distribution at each discretionary activity (see Table 3-15). In the model, passengers' dwell time in corresponding activities were set according to the data presented in Table 3-15.

As can be seen in Table 3-15, the longest time passengers spend in discretionary activity is about 30 minutes. In the model, the time from boarding start to flight departure is 30 minutes in the default setting. Given the information that all mandatory processes take about another 30 minutes for passengers to complete (Kirk, 2013), passenger decision making rules for discretionary activities can be established.

Activity	Minimum (min)	Maximum (min)	Distribution
Food and beverage (landside)	27.50	29.17	Normal distribution, mean = 28.48
Food and beverage (Airside)	21.67	23.33	Normal distribution, mean = 22.22
Specialty retails and duty-free (landside)	5.00	7.50	Normal distribution, mean = 6.18
Specialty retails and duty-free (airside)	10.00	12.50	Normal distribution, mean = 11.4
Airline services*	5.00	15.00	Uniform distribution
ATM	1.00	1.17	Uniform distribution
Telephone	1.00	5.00	Uniform distribution
Net kiosk	26.67	28.33	Uniform distribution
Money exchange	2.33	3.17	Uniform distribution
Restroom (landside)	2.67	3.83	Uniform distribution

* Time data of airline services are estimated by the author.

Table 3-15 Dwell time distribution for airport discretionary activities (Ma, 2013).

Interval number	Definition	Location	Minimum time required prior departure
1	Arrival to start check-in	Landside	90 minutes
2	Finish check-in to start security check	Landside	80 minutes
3	Finish customs process to start boarding	Airside	30 minutes

Table 3-16 Discretionary activity occurrence time, location and criteria.

Discretionary activities in the departure terminal can occur between three processing intervals. According to the time sequence, these process intervals are (1) from arrival to start check-in; (2) from finish check-in to start security check; and (3) from finish customs process to start boarding (refer to Figure 3-7 and Table 3-16). When passengers are on processing intervals, they will assess the remaining time to flight departure to make sure the time is enough to continue unfinished processing activities and successfully board their flights. The required minimum time to the flight departure in the model is summarised in Table 3-16. Only after the minimum time requirement is met, can passengers start deciding whether they are going to undertake discretionary activities and what activity they should undertake according to their group activity preference.

3.5 MODEL STRUCTURE AND MODEL VALIDATION

After introducing passenger behaviour and group dynamics at each processing activity (check-in, security control and customs) and discretionary activity, passengers' interaction with an international airport departure terminal from passenger arrival to departure can be concluded in the flowchart shown in Figure 3-11. According to the flowchart, agents in the model can interact with each other and airport services autonomously and form the whole structure of airport operation system. Since the agent-based model is based on individual agents' behaviour and their interactions with airport services from the 'bottom-up', it is highly important to ensure each functional unit in the model performs correctly. The validation process of this model is conducted using the face validation (or empirical validation) and statistical validation as was introduced in Section 2.2.6, and will be demonstrated later in this section.

The default input parameters of the airport passenger flow simulation model are listed in Table 3-17. The flight timetable presented in Appendix A is imported into the model to provide flight information. The model is built on the AnyLogic 6.8 (http://www.anylogic.com/) platform to simulate the daily operation of the airport. Activities of each agent in the system were updated successively according to preset characteristics within a discrete-event structure of the AnyLogic simulation software.

Parameters	*Value*
Basic time parameters	
Time from check-in open to flight departure	150 minutes
Time from check-in closure to flight departure	25 minutes
Time from boarding start to flight departure	30 minutes
Pedestrian parameters	
Arrival pattern (individual / group)	Group arrival
Existence of wavers	Yes
Processing parameter	
Add one (Check-in) staff when passenger number in queue increases by	1
Add one (Security) staff when passenger number in queue increases by	15
Add one (Customs) staff when passenger number in queue increases by	5
Passenger failure rate at metal detector	10%
Bag need extra security check	15%
Passenger complete OPC before customs	85%

Table 3-17 Default parameter setting in the simulation.

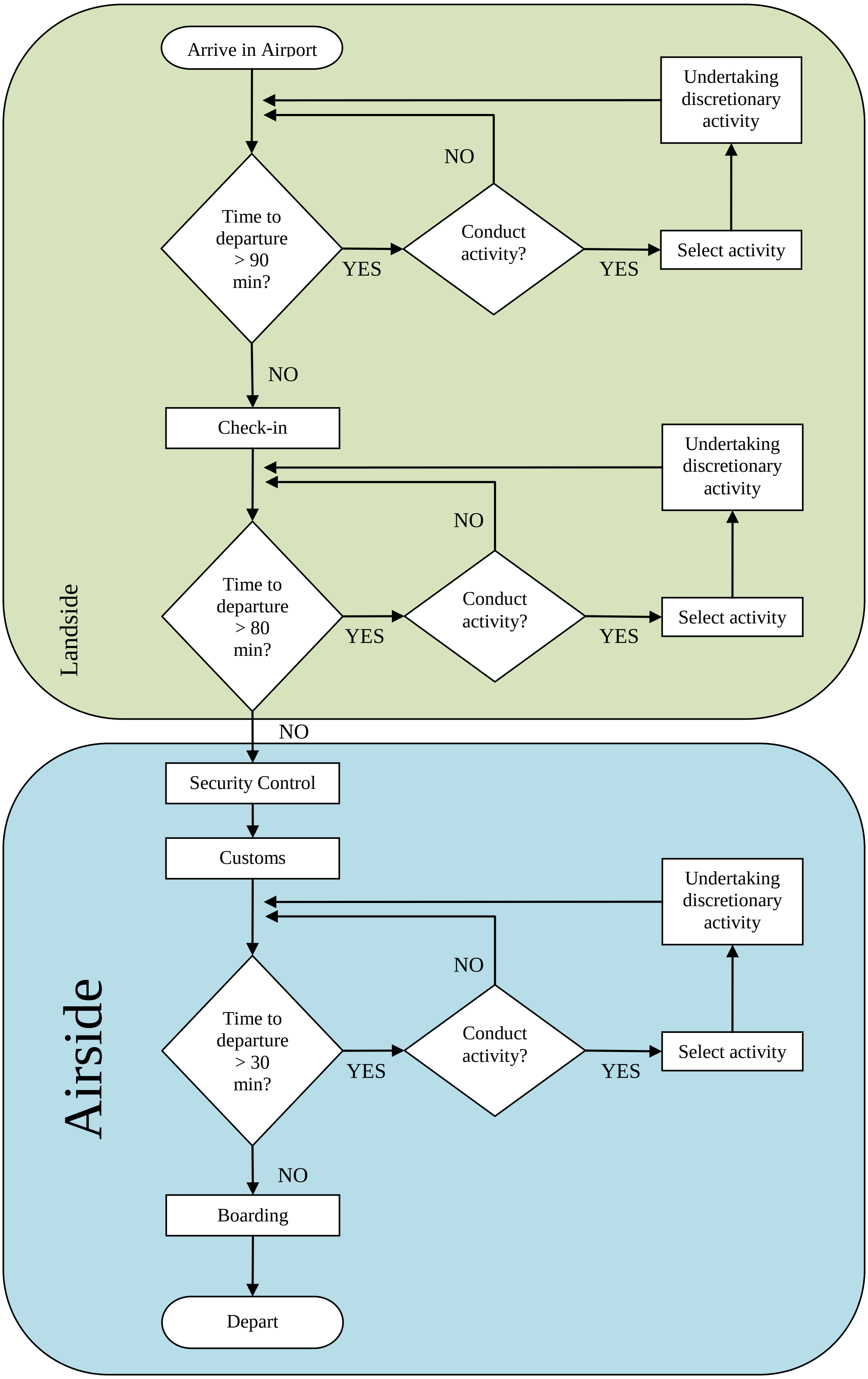


Figure 3-11 Passenger activity and decision making process in an international departure terminal.

The face validation is based on the knowledge of domain experts. The 2D/3D animation of the model not only gives an overview of the simulation, but also plays an important role in face validation. In the animation, passenger behaviour such as walking, waiting and grouping can be directly seen. The interaction between passengers and the airport environment in different areas like check-in, security and customs can also be analysed. Figure 3-12 and Figure 3-13 show the overviews of the 3D simulation environment of an international airport departure terminal on landside and airside. Detailed pedestrian dynamics at different areas in the airport terminal are illustrated in Figure 3-14, Figure 3-15, Figure 3-16 and Figure 3-17. By comparing the visualised crowd behaviour with the experience of airport experts, the processes and structures of the model can be assured.

The statistical validation is conducted by comparing key figures generated from the simulation model (Figure 3-18, Figure 3-19 and Figure 3-20) with the observation data from the airports. Since the collection of observation data from a real airport environment is extremely labour intensive and time consuming (Livingstone, et al., 2012), available data are limited in the areas of interests such as average queuing time and total dwell time at each departure process. After the data comparison, parameters in the model are calibrated in order to adjust the model output data to the observation data within tolerable differences (differences between average observation times and simulated times less than 2 minutes). Table 3-18 compares the actual data obtained at each process and the simulation results. It shows that the simulation is reflective of the actual situation.

Domain		**Queue times [min]**		**Dwell times [min]**	
		Actual (Kirk, 2013)	**Simulation**	**Actual** (Kirk, 2013)	**Simulation**
Check-in	**Min**	0.58	0.48	1.95	3.60
	Max	42.81	56.85	53.56	62.00
	Average	12.88	12.58	16.65	18.76
Security	**Min**	1.23	0.74	1.90	3.28
	Max	17.09	8.39	21.06	20.02
	Average	3.75	3.53	6.88	7.86
Customs	**Min**	0.33	1.16	0.55	2.13
	Max	15.46	30.22	18.58	36.40
	Average	4.80	5.57	6.00	7.50

Table 3-18 Comparisons of queue and dwell times at check-in, security and customs between the actual time and the simulation.

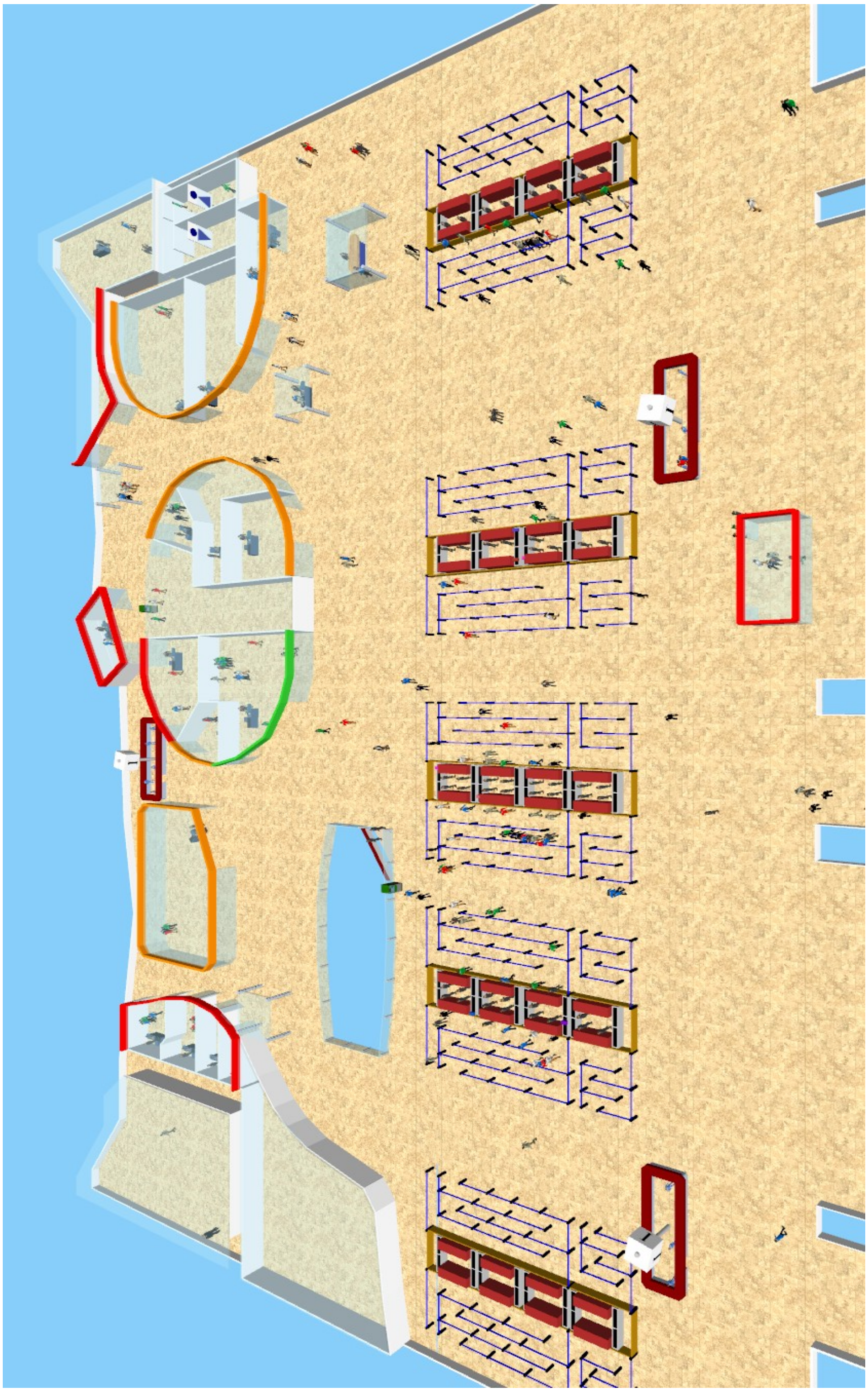


Figure 3-12 Overview of airport departure terminal simulation environment (landside of the terminal).

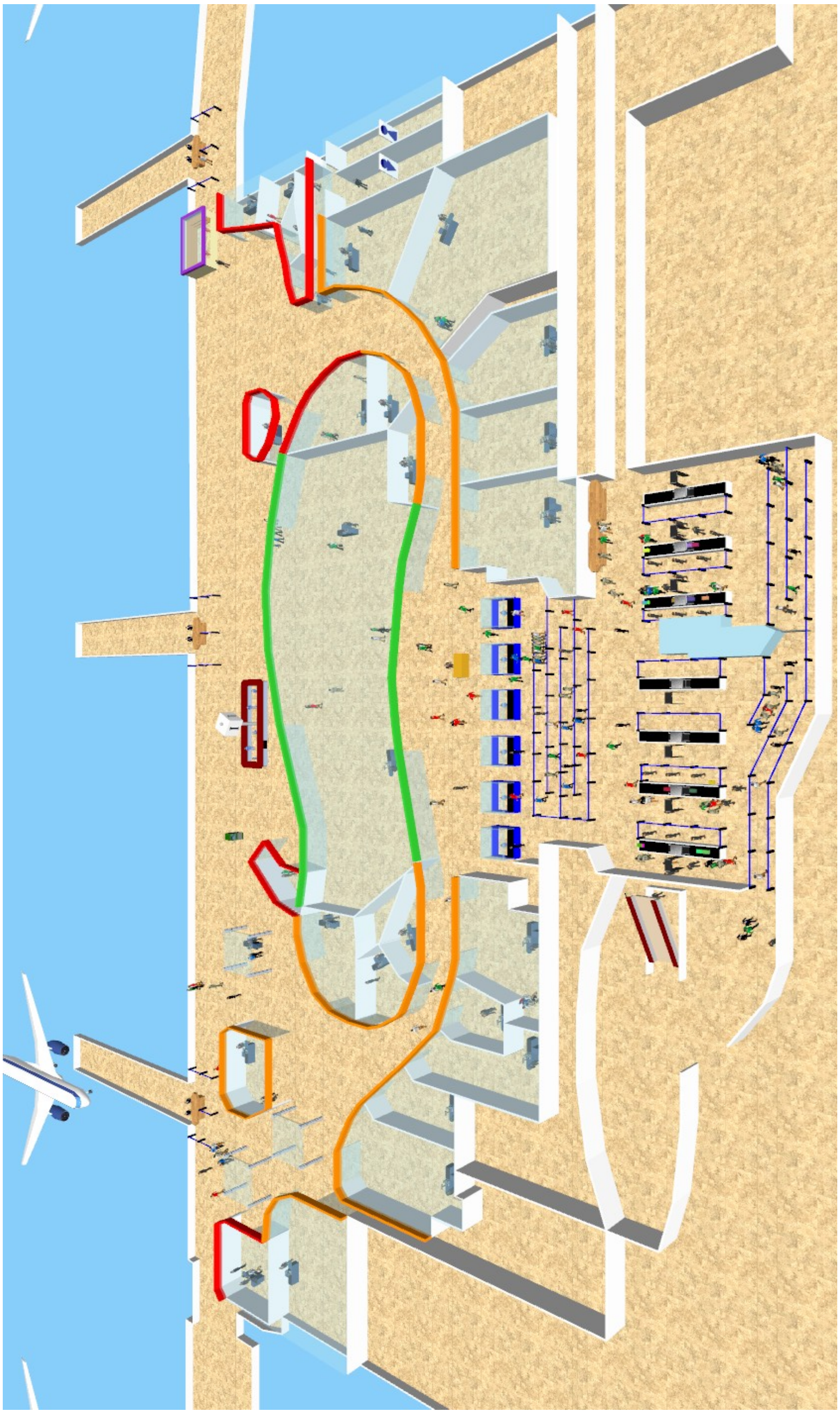


Figure 3-13 Overview of airport departure terminal simulation environment (airside of the terminal).

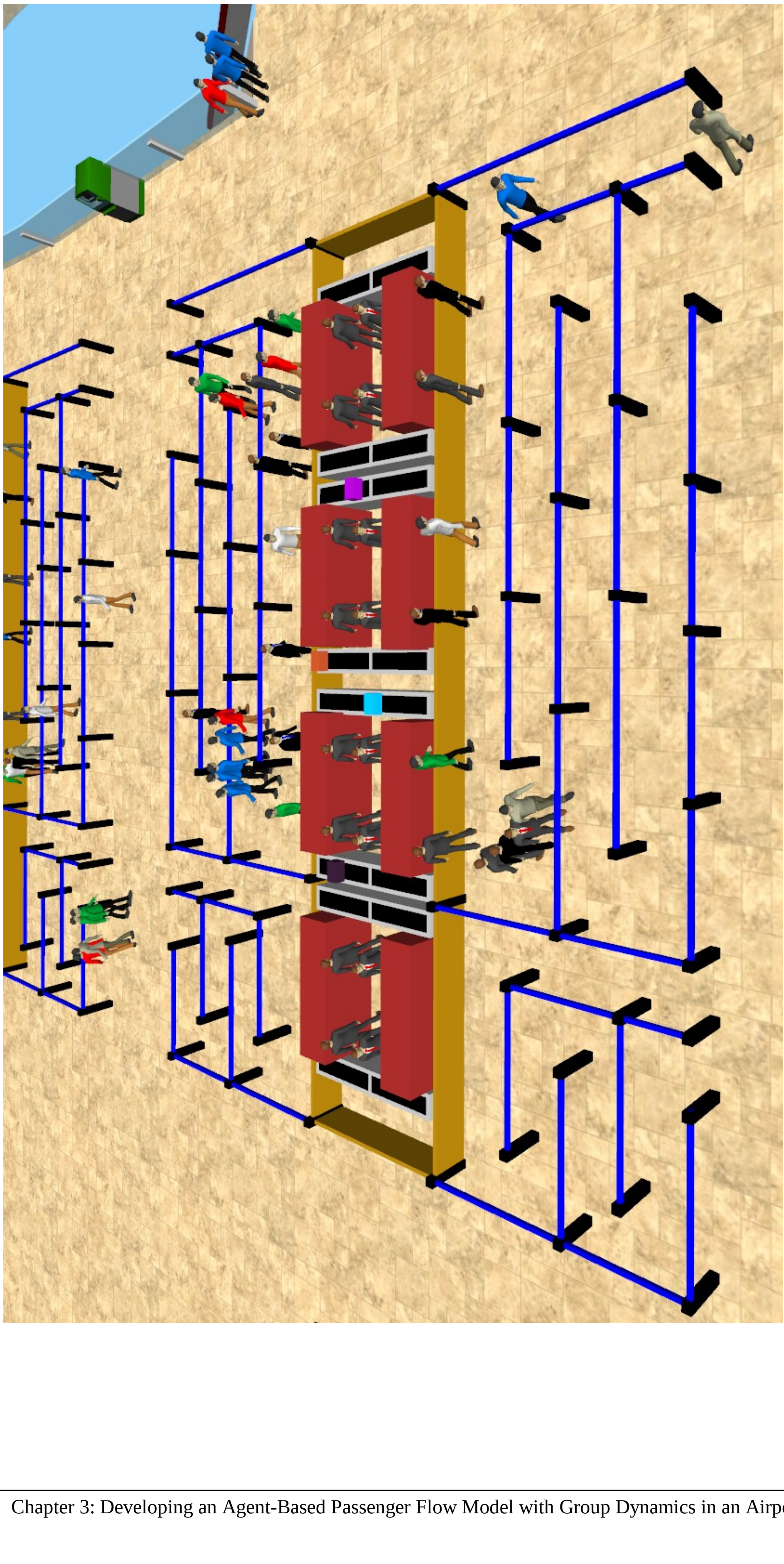


Figure 3-14 Illustration of pedestrian dynamics at check-in area.

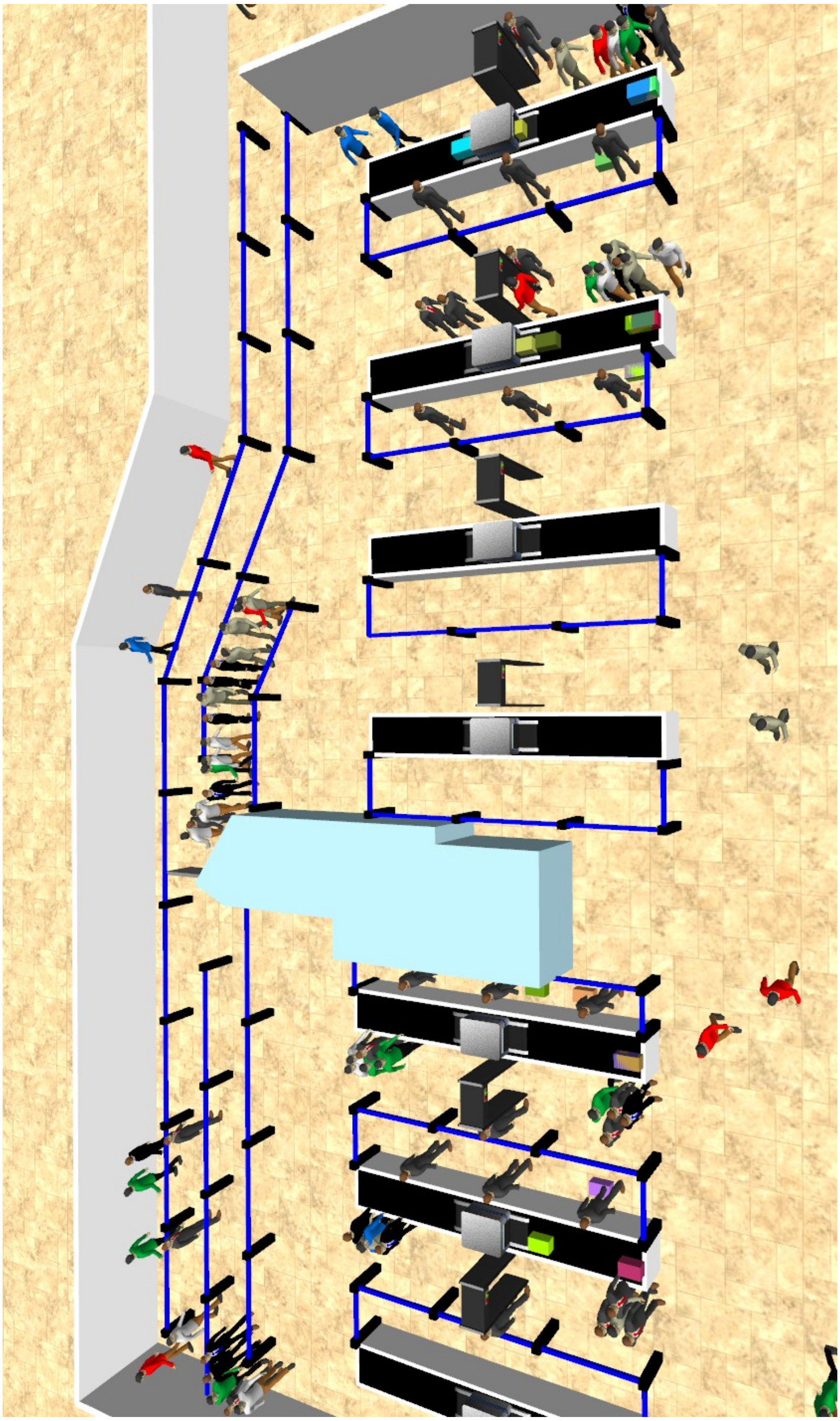


Figure 3-15 Illustration of pedestrian dynamics at security area.

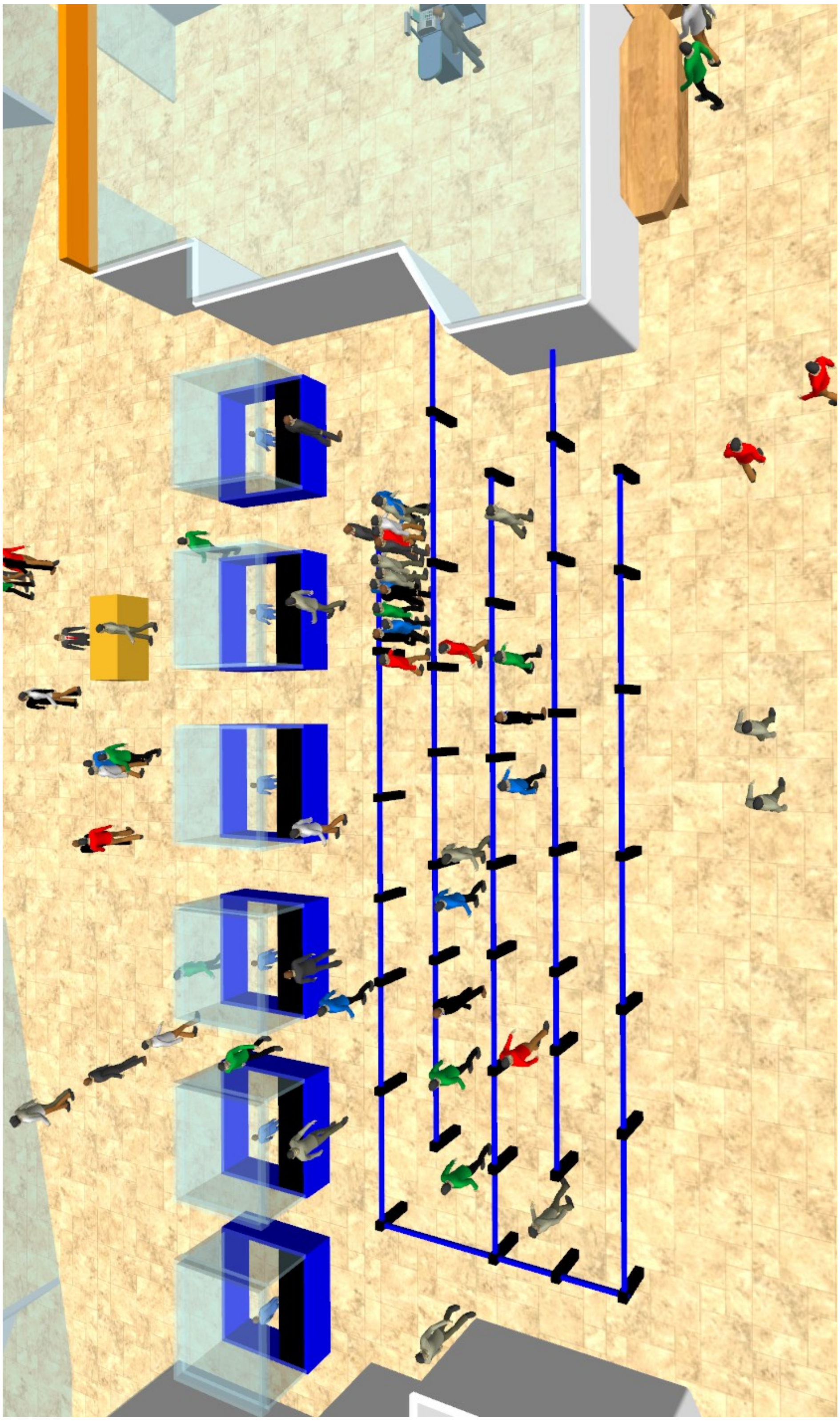


Figure 3-16 Illustration of pedestrian dynamics at customs area.

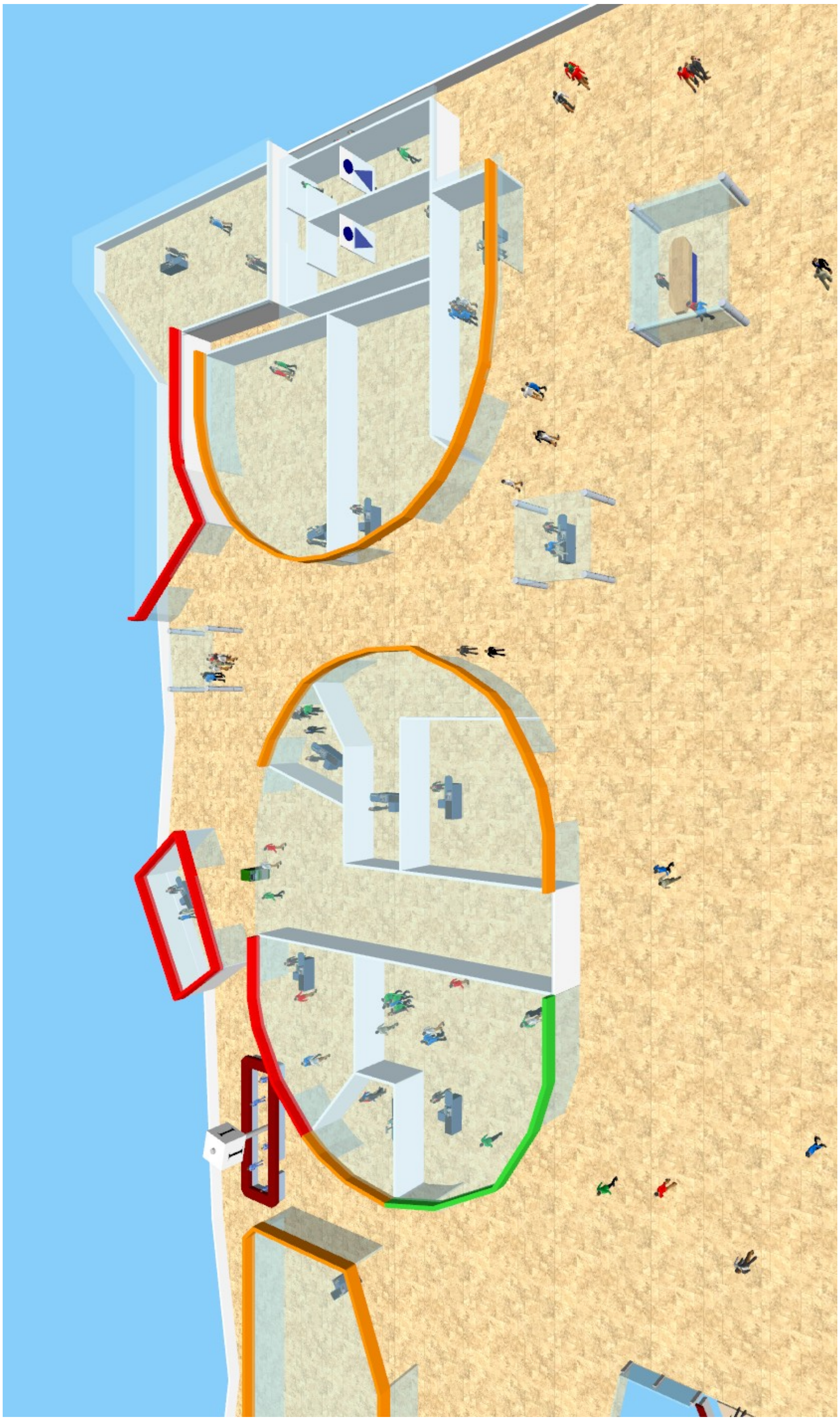


Figure 3-17 Illustration of pedestrian dynamics at discretionary area.

Figure 3-18 Simulation data of passenger dwell time distribution in the airport departure terminal.

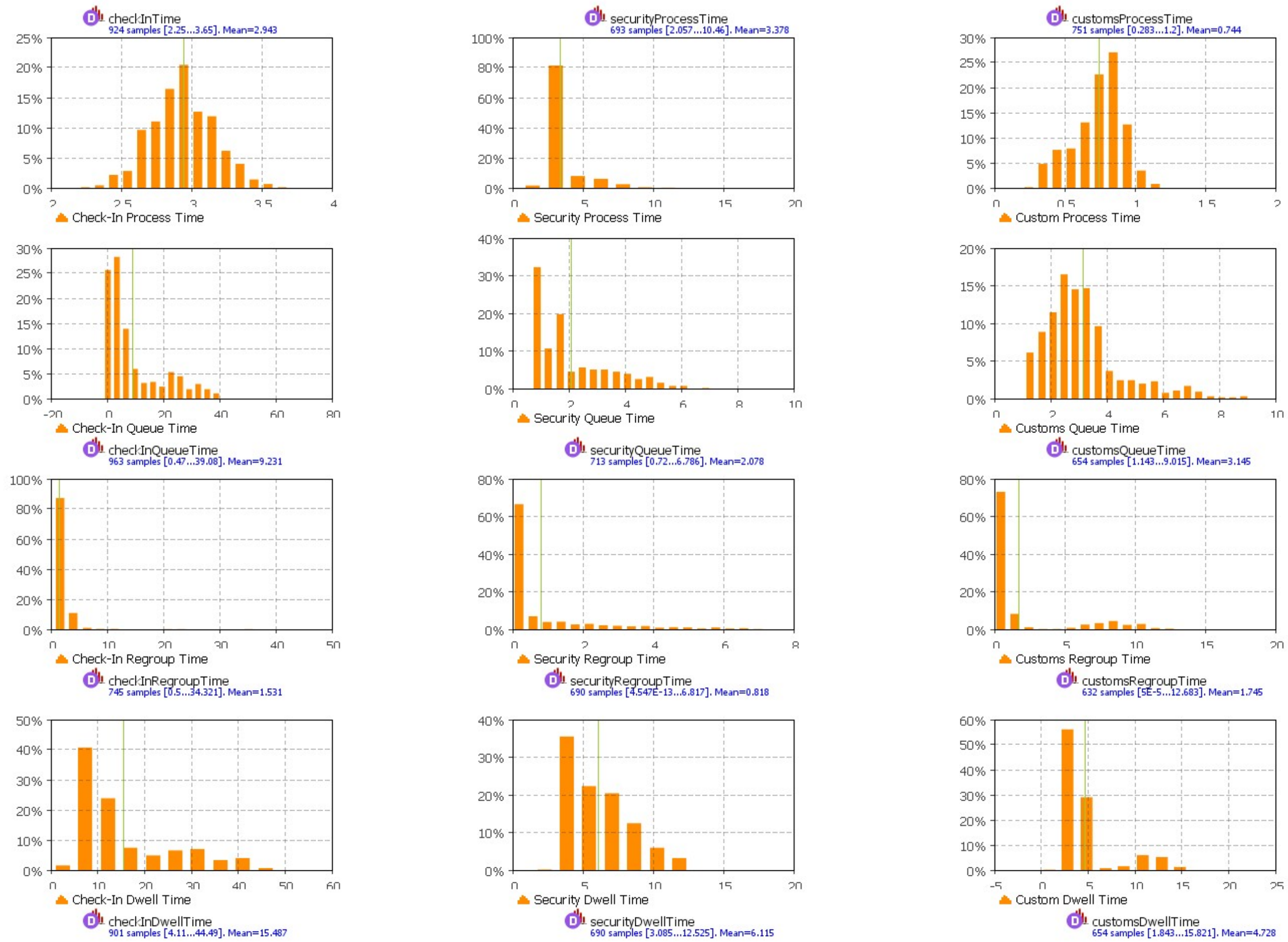


Figure 3-19 Simulation data of passenger dwell time at airport processing activities.

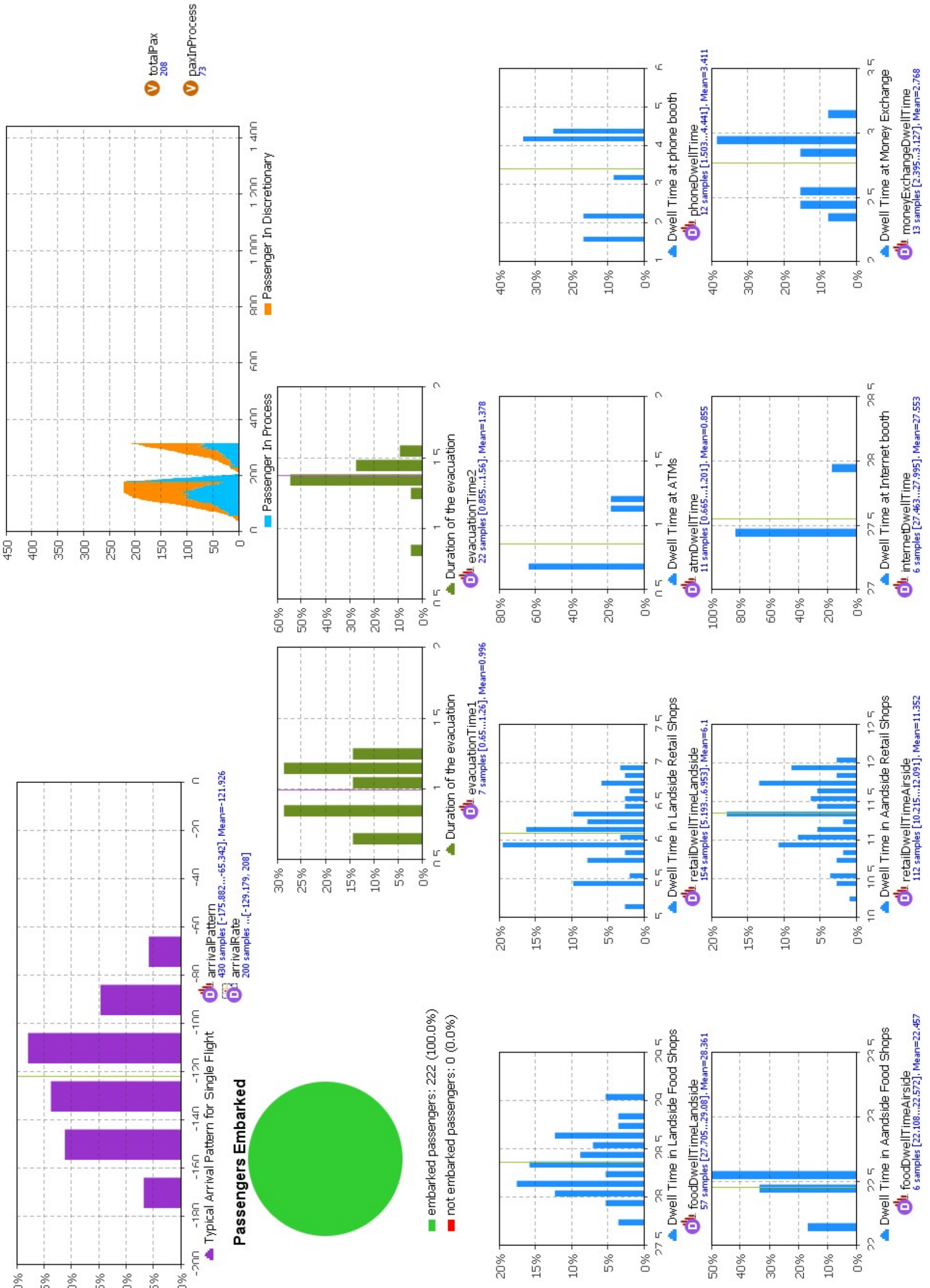


Figure 3-20 Simulation data of airport discretionary activities and auxiliary airport operation status.

3.6 CHAPTER SUMMARY

This chapter has introduced a novel pedestrian flow simulation model of an international departure terminal. This simulation model had for the first time, explicitly introduced pedestrian group dynamics into the model which has allowed the model to be more realistic and reflect the real-world scenarios in the airport terminals.

The development of the model is introduced according to the three key elements of an agent-based model: (1) a set of agents; (2) agents' relationship and interactions; (3) simulation environment and agents' interaction with the environment. The agents in the model are airport pedestrians who can be characterised into passengers and wavers. Passengers are further divided according to their travel purposes (business or leisure).

Agents arrive in the simulation environment according to the information in the flight timetable. The flight departure time and passenger number on board define the arrival pattern of a flight. Upon agent arrival, pedestrian groups are assembled according to Poisson distribution. Based on previous research and survey in airport passengers, the model defines four basic pedestrian characteristics: age, gender, country of residence and travel purpose. These four basic characteristics are the foundation of defining advanced pedestrian attributes such as mobility and airport activity preference. Pedestrian movement and activity choice are governed by pre-defined rules. The interaction within pedestrian groups can be reflected on individual pedestrians waiting for other pedestrians in the same group at processing activities and group members making discretionary activity choices together. The airport environment and detailed airport departure processes are demonstrated. Passenger dynamics at each processing activity (check-in, security control, customs) and discretionary activities were also introduced.

The model is validated by face validation and statistical validation. The face validation shows that the behaviour of pedestrians in the airport is normal and the airport departure procedure is correct. The statistical validation ensures the time agents spend in the simulation environment is comparable to the actual time collected from the airport field observation. The validation process shows that the model reflects the real-world situation and thus can be used to analyse passenger dynamics.

The next chapter demonstrates how the model can be used to analyse pedestrian group dynamics in the airport. To achieve this, the results under different pedestrian settings will be compared. The model will be run under the settings that pedestrians arrive individually, in groups, with wavers and without wavers in order to investigate the group effect and the influence of wavers.

Chapter 4: **The Impact of Group Dynamics on Airport Passenger Activities**

4.1 INTRODUCTION

In this chapter, the simulation model proposed in Chapter 3 will be used to investigate the impact of group dynamics on pedestrian airport activities. To understand the influence of pedestrian groups, the model compares the simulation results under different settings. Through comparing the results obtained from the setting that passengers travelling alone and passengers travelling in groups under the same condition that no waver exists, the influence of group dynamics can be shown. The impact of the existence of wavers can be obtained by comparing passenger groups' activities between wavers existing and when wavers are absent. The analysis of group dynamics is based on processing activities: check-in, security control, customs process and discretionary activities in the airport.

This chapter starts by introducing the model configuration in Section 4.2. Section 4.3 and 4.4 analyses the influence of pedestrian group dynamics on pedestrian behaviour at check-in, security control and customs. This is followed by Section 4.5 which investigates the group dynamics at airport discretionary activities. Finally, experimental results, analysis and discussions are presented in Section 4.6.

4.2 MODEL CONFIGURATION

The input parameters of the model are shown in Table 4-1. To evaluate the effect of group dynamics on facilitation and overall congestion at each airport processing unit, simulations were run under three different scenarios and results were compared. The scenarios are passengers travelling: (a) alone; (b) in groups of varying size; (c) in groups of varying size with wavers. The configuration of pedestrian group structure and the existence of wavers can be defined on pedestrian arrival in the model.

The impact of group dynamics on passenger behaviour can be seen by comparing the results from scenarios (a) and (b). By comparing scenarios (b) and (c), we can understand whether wavers have influence on passengers' behaviour in airport terminals. Since wavers are not permitted to enter the airside, the activities undertaken at airside are only compared between scenarios (a) and (b).

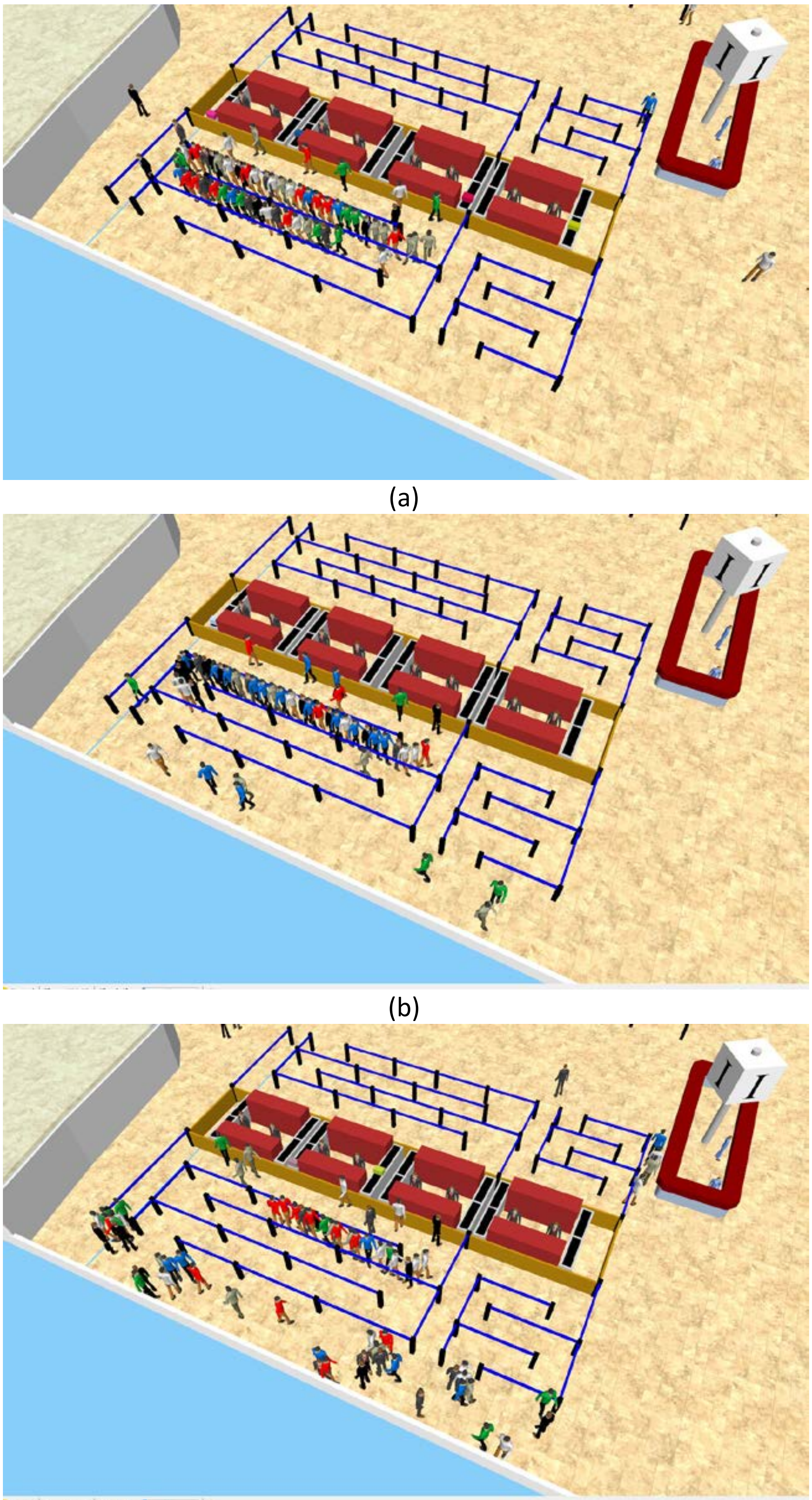
Parameters	*Value*
Basic time parameters	
Time from check-in open to flight departure	150 minutes
Time from check-in closure to flight departure	25 minutes
Time from boarding start to flight departure	30 minutes
Processing parameter	
Add one (Check-in) staff when passenger number in queue increases by	1
Add one (Security) staff when passenger number in queue increases by	15
Add one (Customs) staff when passenger number in queue increases by	5
Passenger failure rate at metal detector	10%
Bag need extra security check	15%
Passenger complete OPC before customs	85%
Import resource	
Flight timetable	Appendix A

Table 4-1 Input parameters of the model.

4.3 PEDESTRIAN BEHAVIOUR AT CHECK-IN PROCESS

Figure 4-1 illustrates the screenshots taken for the same flight (EK433 in the flight timetable) and timeline (02:30 a.m.) of the simulation. From the model observation, it can be seen that passengers who travel in groups will wait for group members in the pathway after finishing the check-in process, as was defined in the model setting (refer to Section 3.4.1). This waiting behaviour of passenger groups can cause congestion in the pathway behind the check-in area and slow down the passenger flow. More severe congestion can be seen in the scenario where passenger groups are accompanied by wavers (Figure 4-1.c).

For a clearer visual comparison, a pedestrian density map at the check-in area is calculated and shown in Figure 4-2. The density maps presented below recorded the maximum observed pedestrian density at each point of the check-in area during the check-in period of the specific flight (EK433). At the model runtime, areas with the pedestrian density values equal or greater than the critical density threshold are painted with red colour. Areas with the lowest density will be painted with blue colour. In this case, the critical density is 2 pedestrians/m^2. The waiting areas for pedestrians to reassemble their groups are highlighted in black round rectangle in Figure 4-2. From the density map, we can see that in scenario 2 (passengers travelling alone), the maximum pedestrian density in the waiting area is higher than that of scenario 1 (passengers travelling in groups). While scenario 3 (passenger travelling in groups with wavers) shows the highest pedestrian density in the waiting area during check-in period.



(a)

(b)

(c)

Figure 4-1 Facilitation and overall congestion at check-in for three different scenarios. Passenger travelling: (a) alone; (b) in groups; (c) in groups with wavers.

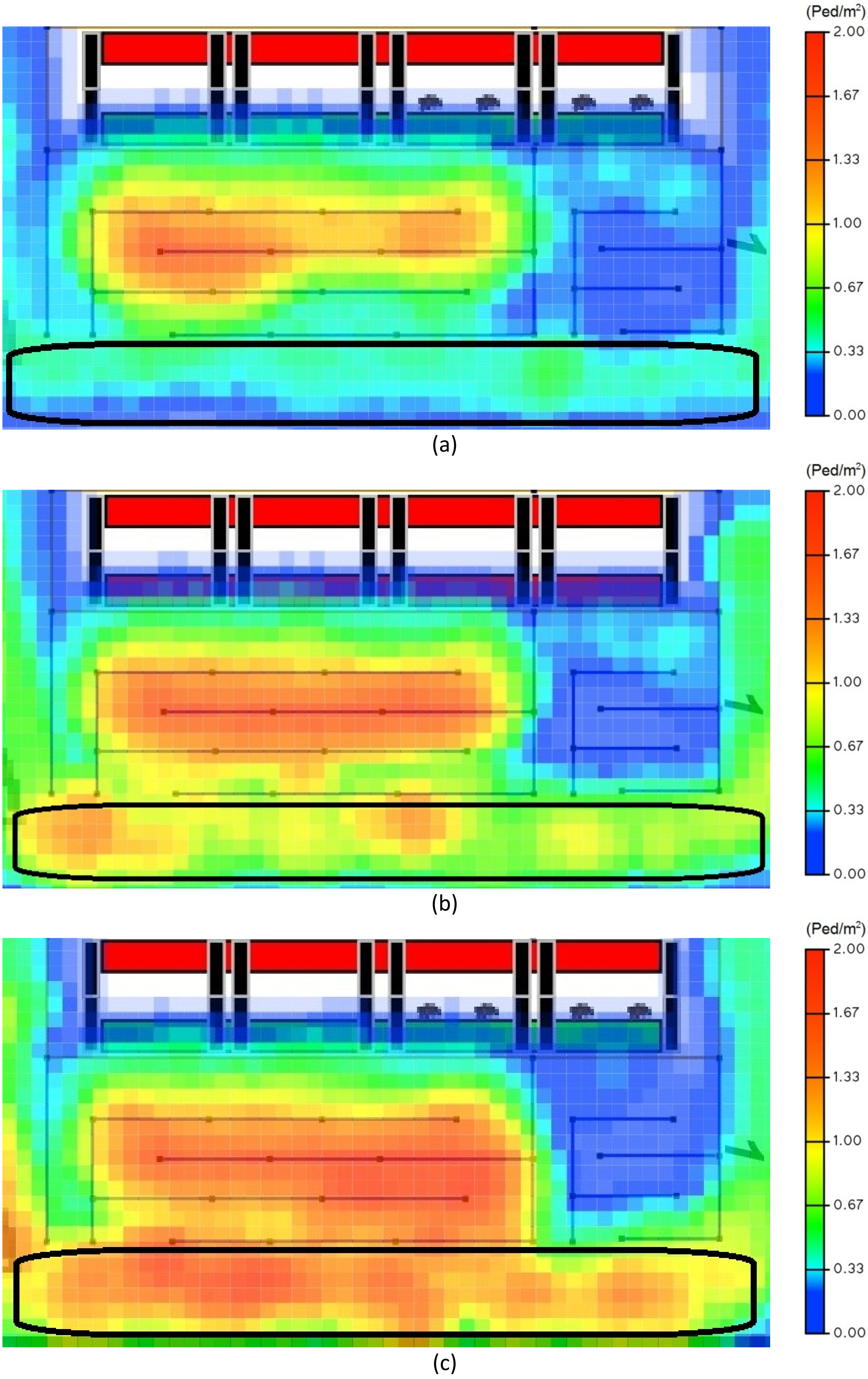


Figure 4-2 Pedestrian density map of check-in area for three different scenarios. Passenger travelling: (a) alone; (b) in groups; (c) in groups with wavers.

Figure 4-3 shows the change of pedestrian density in the waiting area during the check-in period. The density data in the model is collected at 1 minute intervals, from the start of flight check-in to the close of check-in counters. It can be seen in Figure 4-3 that pedestrian density in the waiting area has the lowest values over the check-in period in scenario 1 (passenger travel alone). The average density in the waiting area for scenario 1 is 0.05 Ped/ m^2. The density values in scenario 2 (passenger travel in groups) has a higher average density of 0.18 Ped/ m^2 over this period. The highest values over the check-in period can be seen in scenario 3 (groups & wavers). The average density of scenario 3 is 0.8 Ped/ m^2. At the most crowded time, the pedestrian density can reach about 1.5 Ped/ m^2 in this scenario.

The density data obtained in the model can be transferred to IATA Level of Service (LOS) standard (refer to Appendix B) (IATA, 2004). The average density in scenario 1 and 2 reach the level A (excellent) in the LOS standard, while the LOS in scenario 3 is only equivalent to level D (Adequate) according to the standard. However, it should be noted that because of the existence of the waver, the total number of pedestrians in scenario 3 is different from that of scenario 1 and 2. Therefore, the influence of group dynamics on pedestrian density in the waiting area can only be seen from the comparison between scenario 1 and scenario 2.

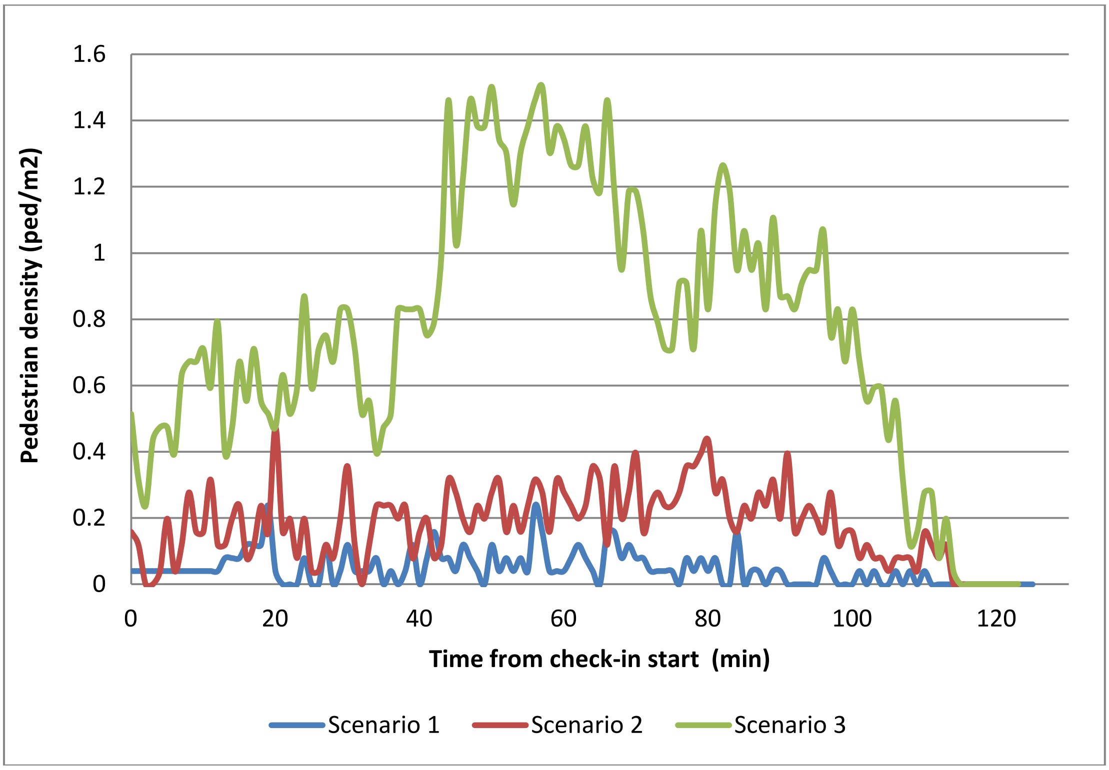
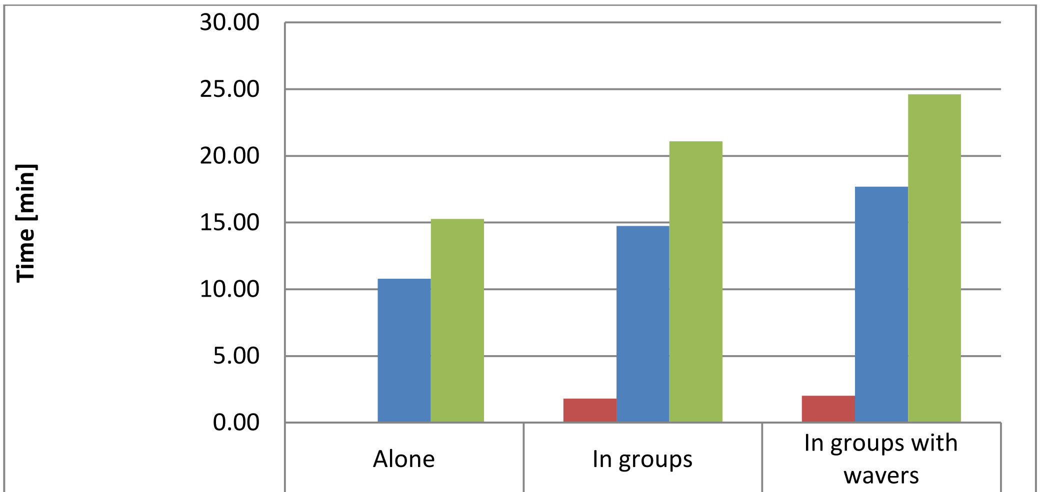


Figure 4-3 Pedestrian density at check-in area during check-in opening hours.

Data collected from above three different simulation scenarios at the check-in process show that passenger group dynamics influence the check-in queue time and dwell time (Figure 4-4). The check-in dwell time is the average time elapsed between passengers entering the check-in area and leaving it with their companions (if there are any), while check-in queue time is the average time elapsed between passengers entering the queuing area and getting served by the check-in staff. From the table in Figure 4-4, it can be noted that passengers travelling in groups or with wavers spend approximately 2 minutes to regroup after the process. This leads to a longer dwell time at the check-in process.



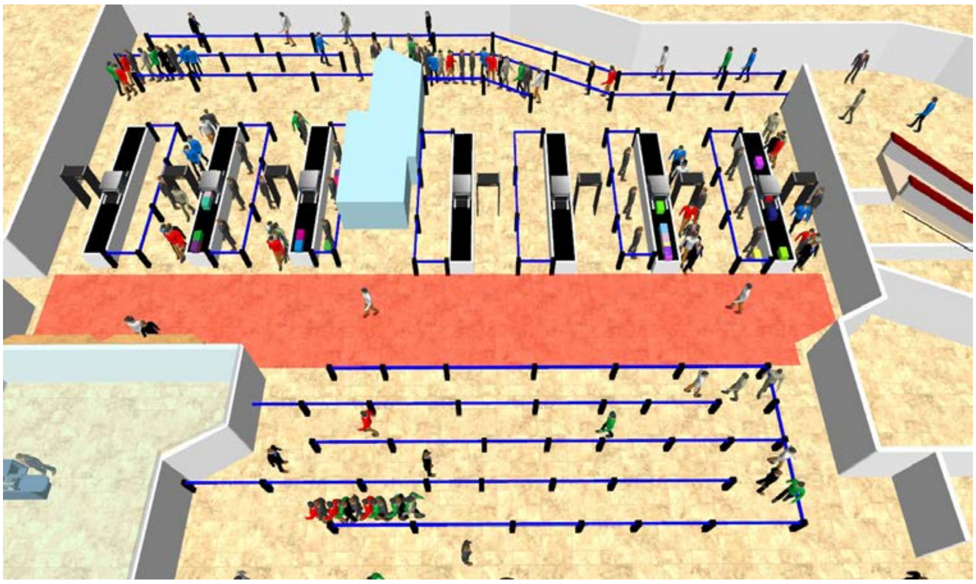
	Alone	In groups	In groups with wavers
Regroup time [min]	0.00	1.79	2.01
Queue time [min]	10.79	14.75	17.69
Dwell time [min]	15.28	21.10	24.63

Figure 4-4 Regroup, queue and dwell times at the check-in process for the three different scenarios.

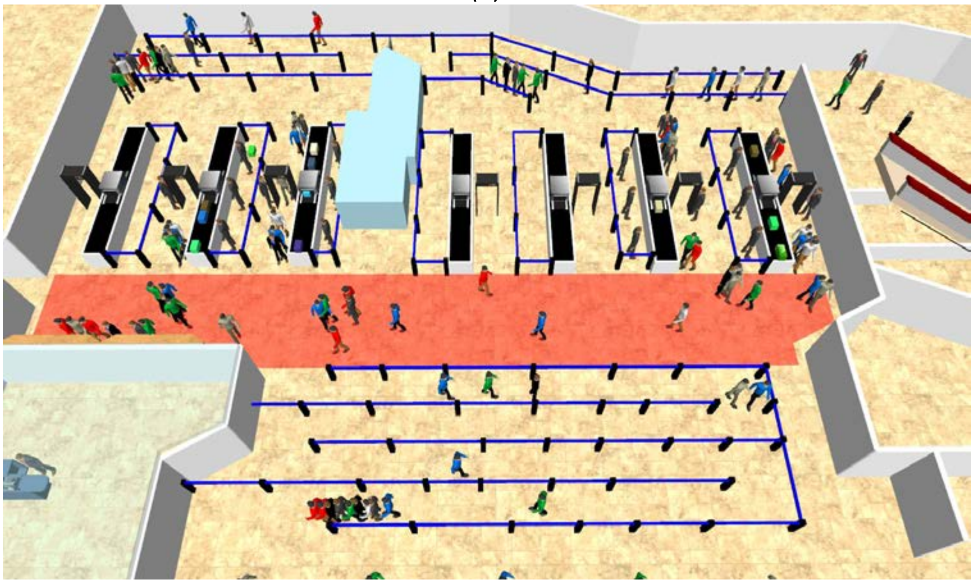
The model results also suggest that the time passengers spend in queuing can be influenced by group structure. It can be seen that passengers travelling alone spend approximately 5 minutes less in the queue when compared with passengers travelling in groups. A possible explanation for witnessing such a trend could be the congestion caused by people waiting to regroup with their fellow travellers around the queuing area. In essence, ignoring group dynamics in agent based modelling may yield results that may not accurately represent the real-world observations.

4.4 PASSENGER BEHAVIOUR AT SECURITY AND CUSTOMS

Figure 4-5 compares two passenger flow conditions at the same time point in the simulation. Since wavers are not allowed to enter the airside, the comparison is only between passengers travelling: (a) alone and (b) in groups. In the model, passengers who travel in groups wait for stalled group members until all members complete the security check. Those who finish the check earlier will wait in the narrow area (marked in red) between security check and customs queue.



(a)

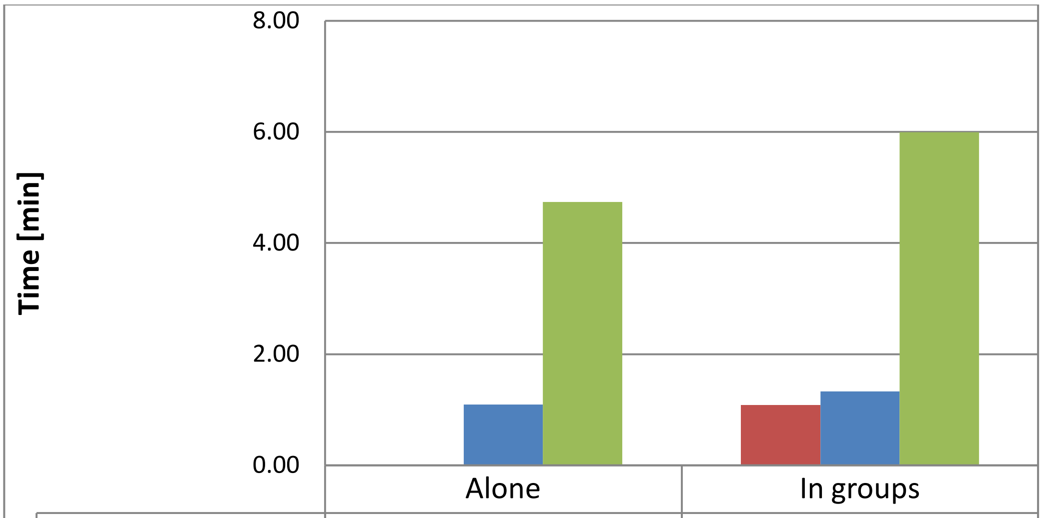


(b)

Figure 4-5 Passenger's behaviour at security process. Passenger travelling: (a) alone; (b) in groups.

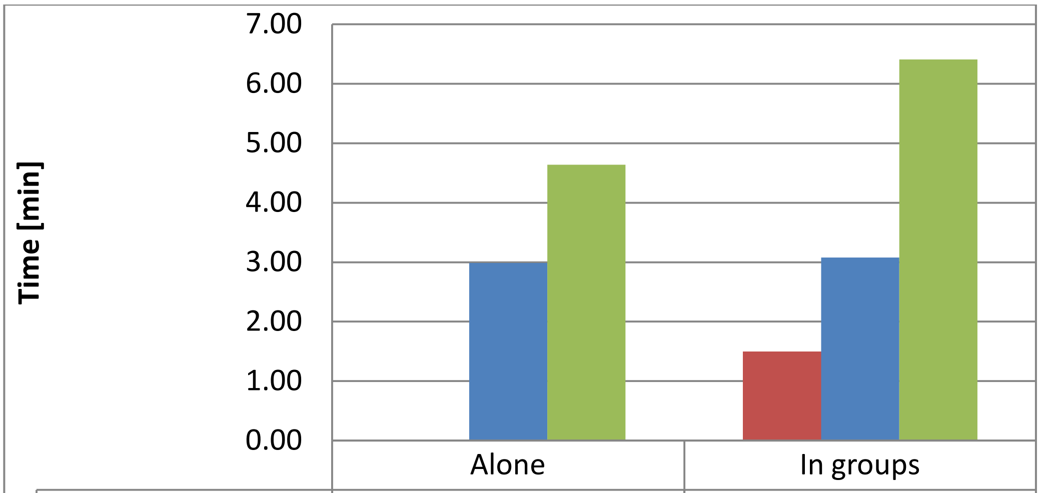
The security checking time depends not only on passengers, but also on their luggage. If their luggage fails at the X-ray scanner, passengers may be required to open their luggage for further inspection. Therefore, security checking time for group members can vary significantly. As a result, time can be long between the first member and the last member of the group passing through the security check. Moreover, the waiting members can lead to congestion in the area between security and customs, since there is no room specially designed for waiting in this area.

Consequently, longer dwell time and queuing time can be found at security and customs for group travellers (Figure 4-6).



	Alone	In groups
Regroup time[min]	0.00	1.08
Queue time [min]	1.09	1.33
Dwell time [min]	4.74	5.99

(a)

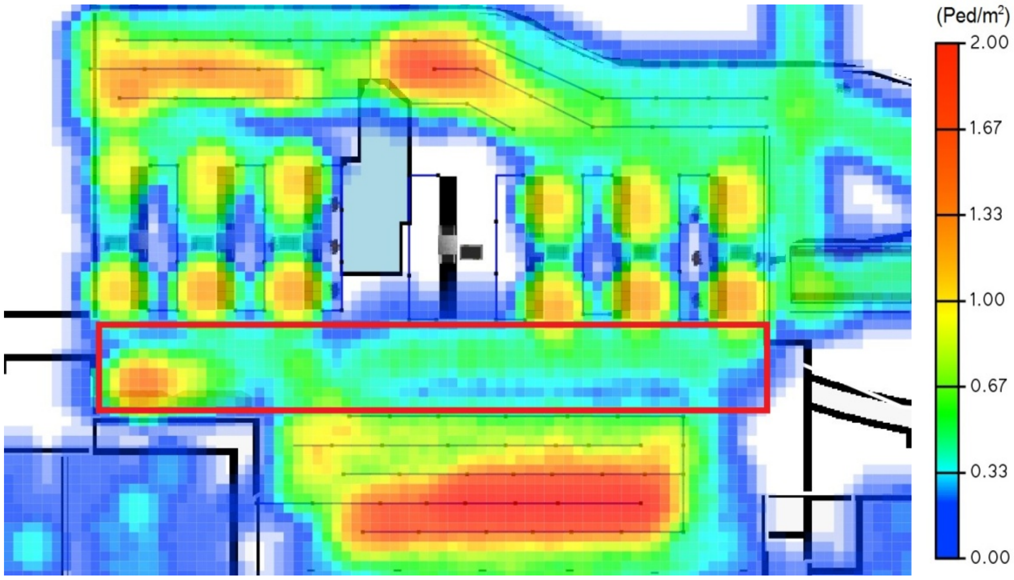


	Alone	In groups
Regroup time [min]	0.00	1.50
Queue time [min]	2.99	3.08
Dwell time [min]	4.64	6.41

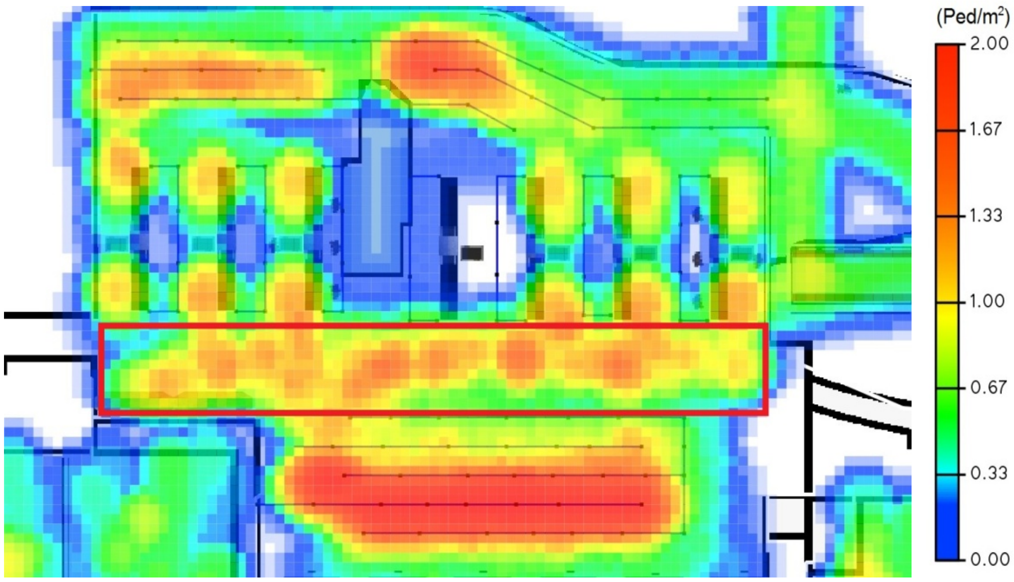
(b)

Figure 4-6 Regroup, queue and dwell times at (a) security and (b) customs for the two different scenarios.

Figure 4-7 illustrates the density maps at security and customs area. The density maps recorded the highest pedestrian density values during the day (24 hours) in this area. The waiting area between security and customs is highlighted in the red rectangle. Compared to the scenario that passengers are travelling alone, more serious blockage can be found in the waiting area when passengers are travelling in groups. Figure 4-8 demonstrates the comparison of pedestrian density in the waiting area during the full simulation run (24 hours in the simulation). Because of the waiting behaviour in pedestrian groups, the density values when passengers are travelling in groups (average 0.14 Ped/ m^2) are higher than the scenario that passengers are travelling alone (average 0.03 Ped/ m^2).



(a)



(b)

Figure 4-7 Density maps at security and customs area for the two different scenarios. Passenger travelling (a) alone; (b) in groups.

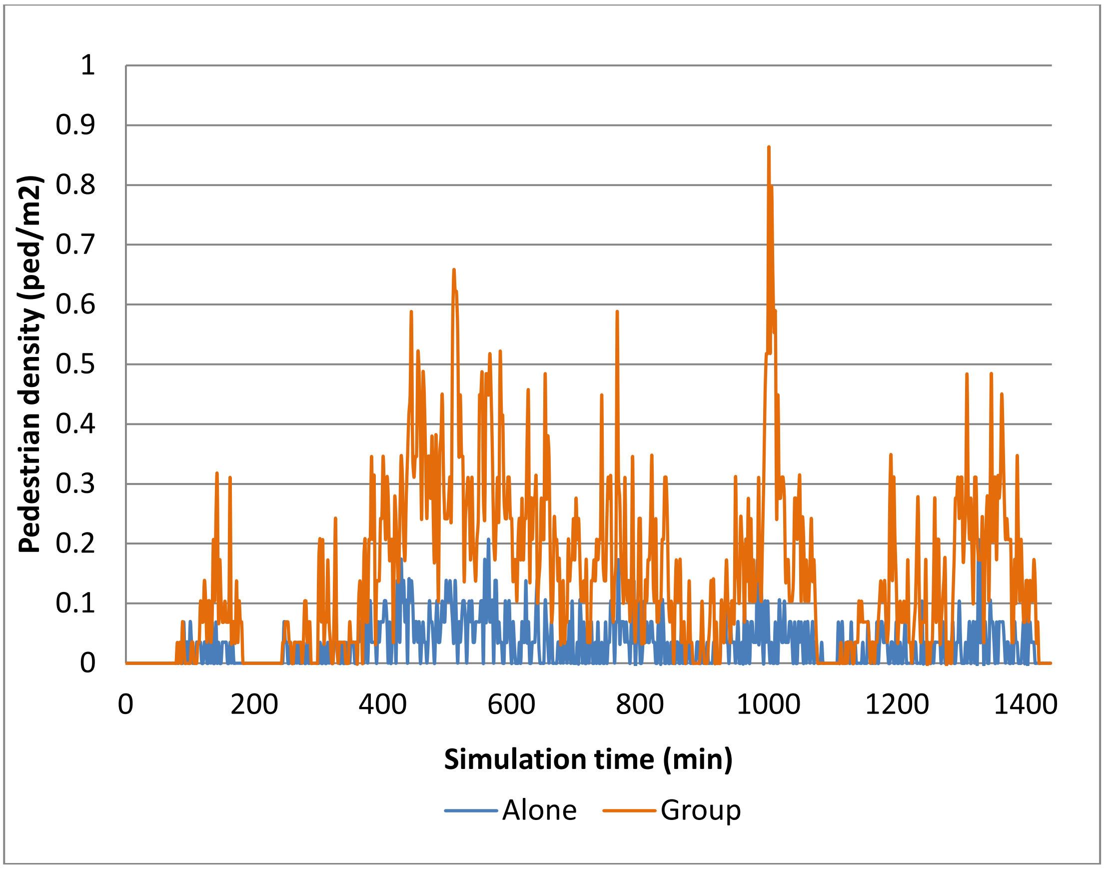


Figure 4-8 Pedestrian density in the waiting area between security and customs.

4.5 DISCRETIONARY ACTIVITIES AND RETAIL CHOICES

To investigate the influence of group behaviour on passengers' discretionary activities, the average time passengers spend on discretionary activities are recorded in Figure 4-9. The simulation result is obtained by averaging the data of 5 experiments for a single flight with 222 passengers on board. As can be seen from Figure 4-9, passengers travelling alone have the most amount of time for discretionary activities. The reason for this is that passengers who travel alone spend less time in mandatory processes compared with passengers travelling in groups and with wavers. Thus, they are left with more time to spend in discretionary activities. Figure 4-9 also shows that as the group structure becomes more complex (i.e. from passengers travel alone to passengers in groups and in groups with wavers), passengers spend more discretionary time at the landside than that at the airside. This finding, while preliminary, suggested that the form of passenger groups has influence on passengers' discretionary choices. This result is also intuitive. Since wavers are unable to progress to the airside, passengers which accompanied by wavers are more inclined to stay on the landside.

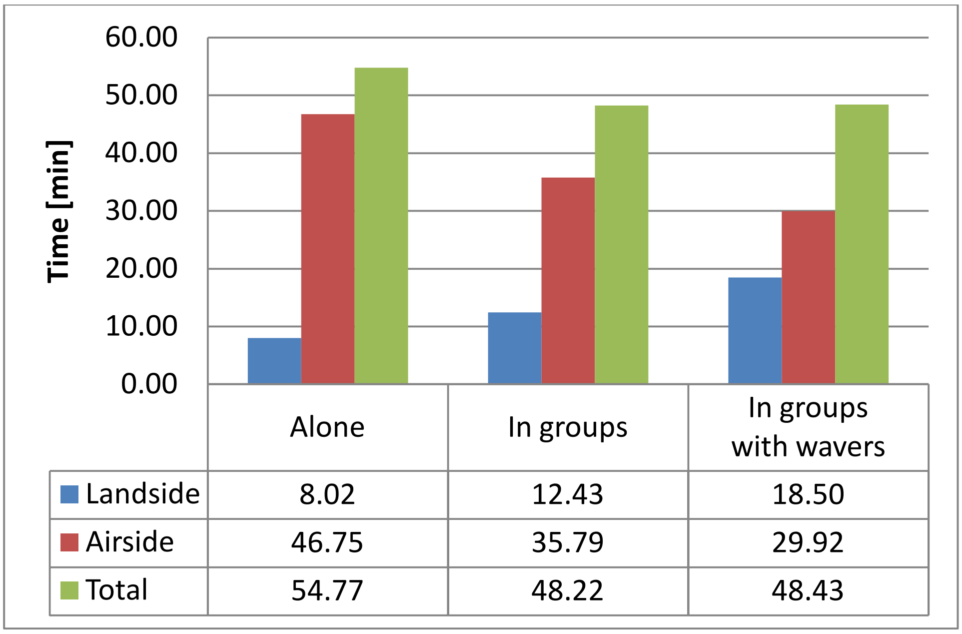


Figure 4-9 Passenger discretionary time in airport for three different scenarios. Passenger travelling: (a) alone; (b) in groups; (c) in groups with wavers.

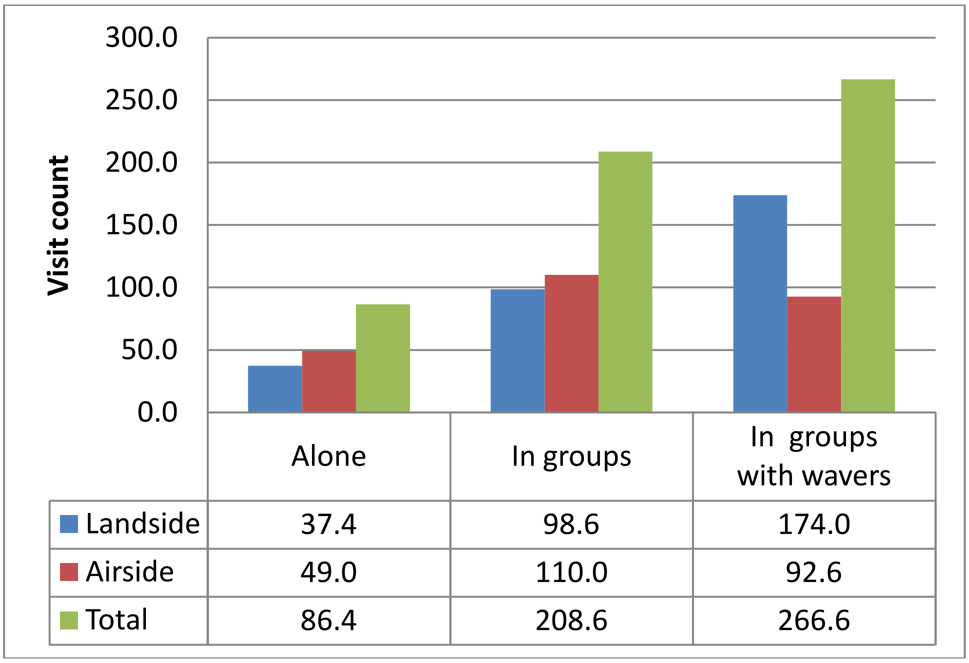


Figure 4-10 Retail visits in the airport for three different scenarios. Passenger travelling: (a) alone; (b) in groups; (c) in groups with wavers.

Figure 4-10 compares passenger retail choices for three different scenarios by counting the shop visits. The visit count in Figure 4-10 calculates the sum of total number of pedestrians (include 222 passengers and their companions if there are any) who entered retail shops (includes (1) food and beverage; (2) specialty retails; (3) duty-free shops; and (4) airline services) on the landside, the airside and the entire departure terminal respectively. The visit of a passenger group to a shop is counted as the total number of people in the group. It is obvious that compared with passengers travelling individually, more visits to the retail shops can be seen on both landside and airside when passengers travel in groups. On average, when passengers are travelling alone, there are 37.4 and 49.0 visits for retail shops at landside and airside, respectively. The figures grow to 98.6 and 110.0 when passengers are travelling in groups. For those travelling in groups with varying number of wavers, the numbers are 174.0 and 92.6. It can also be seen in Figure 4-10 that the existence of wavers contributes to higher probabilities of shopping at the landside. Without wavers, in either passenger travel alone or with other travel companions, they are more likely to choose retails at the airside. This can be explained by the fact that passengers tend to complete their mandatory activities before their discretionary activities (Popovic, et al., 2010). Therefore, they prefer to pass all necessary processes such as security and customs and ensure that they have flexible time for discretionary activities at the airside before boarding an aircraft.

4.6 RESULT ANALYSIS AND DISCUSSION

Through the simulation of the international airport, it is shown that agent-based simulation can be used to analyse group dynamics of pedestrians in a complex environment. The results in this study suggest that the group dynamics have significant influence on passenger activities in the airport terminal in terms of dwell time and activity preferences and therefore influence the airport operation.

Although the group behaviour in the simulation is defined by simple rules (refer to Section 3.3 and 3.4), some general conclusions can be made. In airport processing activities such as check-in, security and customs, the group dynamics can potentially lead to congestion and longer dwell times. Such scenarios can lead to congestions and potential flight delays which can contribute to a lower level of service (LOS) and poor passenger experience. Furthermore, they may also leave the passengers with less time for discretionary activities which may not be favourable for airport retail operators. Group dynamics can also be a major factor, if not the only one, which affects passenger discretionary activities and retail choices. It shows that passengers with groups are more likely to choose retail activities than those who are travelling alone; and the presence of wavers can contribute to higher landside retail opportunities.

4.7 CHPATER SUMMARY

This chapter has analysed the influence of group dynamics on passenger processing activities (check-in, security, and customs) and discretionary activities using an agent-based model. Results from both visual and statistical aspects show that when group dynamics exist, pedestrians behave differently from the situations where group dynamics are absent in an airport departure terminal. It is a common phenomenon that many of the pedestrians are walking in groups in the airports. Therefore, in a complete and realistic pedestrian flow model, the group dynamics should be considered.

The agent-based model not only assists in understanding pedestrian behaviour in an airport, but also provides an essential tool to assess the performance of airport design and the quality of the pedestrian facilities in the terminal. The next chapter provides an example to illustrate how this agent-based pedestrian flow model can be used for investigating the effectiveness of an evacuation process in the airport. The evacuation case study presented in the next chapter considers the group dynamics as well and analyses the influence of group dynamics on pedestrian evacuation.

Chapter 5: **Case Study – Impact of Passenger Group Dynamics on Airport Evacuation Process**

5.1 INTRODUCTION

The safety of passengers is a major concern to airports. In the event of crises, having an effective and efficient evacuation process in place can significantly aid in enhancing passenger safety. Hence, it is necessary for airport operators to have an in-depth understanding of the evacuation process of their airport terminal. Although evacuation models have been used in studying pedestrian behaviour for decades, little research has been done in considering the evacuees' group dynamics and the complexity of the environment.

In this chapter, the agent-based model is used to simulate a passenger evacuation process in an international airport departure terminal. Due to limited access to detailed evacuation strategy in the airport, part of the evacuation procedure is based on assumptions. For example, different evacuation exits were allocated to passengers based on their location and the security level to ensure a more effective evacuation process. In order to simplify the model, the simulation scenario is an evacuation drill instead of a real evacuation event where panic behaviour should be considered. It is assumed that participants of the evacuation practice are only passengers and their fellow companions, airport staff are not included in the experiment.

The remainder of this section is organised as follows. Section 5.2 demonstrates the configuration of the model and the procedure of the evacuation process in the model. Section 5.3 describes the behaviour response of airport passengers to the evacuation. Section 5.4 provides the simulation results and analysis, while Section 5.5 concludes the findings using the agent-based simulation and points out the limitations.

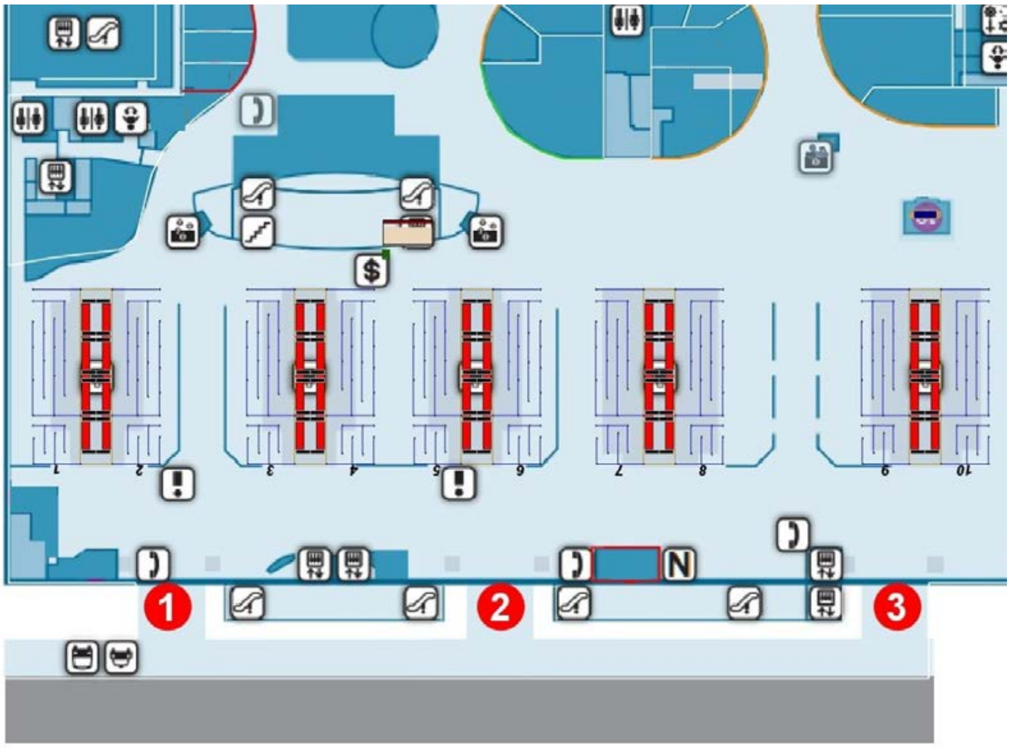
5.2 CONFIGURATION AND PROCEDURE DURING EVACUATION

Different from other building environments, an airport is considered as a complex system that comprises multiple stakeholders and social interactions (Wu & Mengersen, 2013). For example, before boarding the flight, passengers are required to pass mandatory processes which include check-in, security process and customs. Therefore, the security level varies in the airport, which needs special consideration during the evacuation.

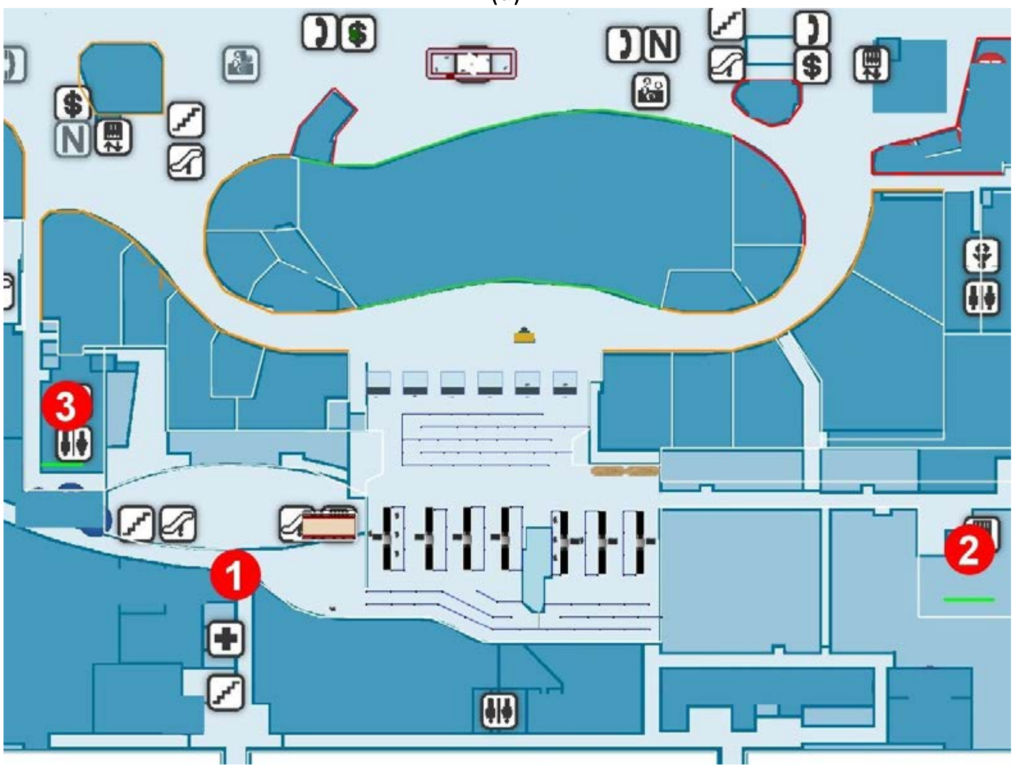
The layout of the airport departure terminal used in the simulation is shown in Figure 5-1. As can be seen from the terminal layout, three emergency exits (marked as red circles) are available on both landside (level 4) and airside (level 3) of the terminal. In the event of an evacuation, passengers will be notified by an emergency alarm, and then they will make their way to the nearest exit under the guidance of building wardens and airport staff. Passengers will remain at designated assembly points until it is safe for them to re-enter the terminal.

In our simulations, we presume there are three security levels (these could be adapted based on the operating conditions of the airport). Passengers who have not been examined by the security personnel are categorised as having security level 1 status; passengers that passed security but not the customs have security status level 2; passengers that pass both security and customs possess security status level 3. In our model, it is assumed that only certain exits are accessible to people depending on their security level status as described below.

The landside of the terminal is the public area. The crowd on the landside is treated to be on security level 1, along with all outgoing passengers who have not cleared the security check. They will choose one exit among the three located on level 4 that has the minimum walking distance while evacuating the airport. Situations are more complex on the airside of the terminal. On the airside, there are two mandatory processes: security and customs and different security levels are imposed on them. Passengers belonging to security level 2 will evacuate through exit 2 on level 3, and passengers with security level 3 will evacuate through exit 3 on level 3.



(a)



(b)

Figure 5-1 Airport environment defined in our simulation. The exits are marked as red circles. (a) check in area and retail (landside); (b) Security, Customs, Boarding and retail (airside).

In the simulation, once the emergency ceases passengers returning into the terminal will keep their security level status intact, so that they can continue to finish their remaining processes rather than doing them from the beginning. However, the simulation is flexible and different policies can easily be implemented and tested (e.g. the policy that all passengers must be re-scanned on entry, regardless of their security levels when they are evacuated). Table 5-1 summarises the corresponding exits for pedestrians with different security levels.

Security Level	Domain	Emergency exits
1	Security unchecked	Exit 1,2 and 3 on Level 4
		Exit 1 on Level 3
2	Security checked; Customs unchecked	Exit 2 on Level 3
3	Customs checked	Exit 3 on Level 3

Table 5-1 Exits assigned for passengers of different security levels.

5.3 BEHAVIOUR RESPONSES TO EMERGENCY EVACUATION

The likely behavioural response of the evacuees is essential to the model. There are two levels of behavioural responses: global and local (Filippidis, Galea, Gwynne, & Lawrence, 2006). The global behaviour level outlined the general escape strategy. At the start of the evacuation alarm, passengers and airport staff will spend some time to respond to the signal. After recognising the situation, passengers need to decide the evacuation option, for example, the available exits and the closest distance to the exit. Passenger groups with different opinions may spend more time on discussion. This period of time is described as response time. After making the decision, passengers will move towards the chosen exit, during this period, the movement time is recorded. Due to potential congestion in front of the exits, it is possible that passengers need to wait before they make their way out. Another reason that could lead to longer waiting times is that passengers travelling in groups will wait for fellow passengers to regroup around the exit area. They generally ensure that all group members are safe and would like to evacuate together. The evacuation time for a pedestrian (passenger) is defined as the time when the evacuation alarm set off to the time that the pedestrian leaves the exit. Typical steps passengers take during an evacuation can be seen from Figure 5-2.

On the local behaviour level, based on individual's personal attributes such as age and travel purpose, pedestrians have different degrees of knowledge about what to do when evacuating. Therefore, people in the model have varying response times to the evacuation alarm. Based on assumptions, the response time of passengers with different attributes in the model is defined in Table 5-2. During the movement, passengers in the same group will compromise their speed to the slowest group member in order to travel at the same speed.

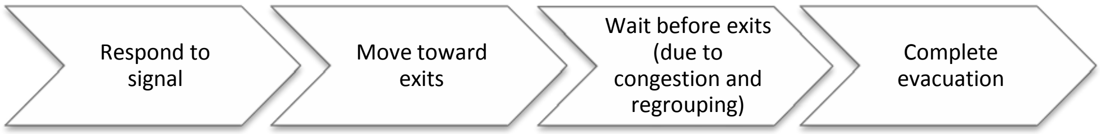


Figure 5-2 Typical response followed by passengers during evacuation.

Influence factor	**Category**	**Response time (sec)**
Age	Age < 15	20
	15 < age < 30	8
	30 < age < 55	12
	Age > 55	15
Gender	Male	8
	Female	11
Travel purpose	Business	12
	Leisure	15
Group size	Group size = 1	10
	Group size = 2	20
	Group size >= 3	40

Table 5-2 Pedestrian response time to terminal evacuation signal.

5.4 RESULTS AND ANALYSIS

5.4.1 **Distribution of Passengers in the Airport Terminal**

In order to demonstrate the general behaviour of passengers and ensure the reliability of the experimental results, the evacuation event is set at 7:30 AM, one of the peak times of the day to collect more sample data. An overview of the terminal during the evacuation process is illustrated in Figure 5-3 and Figure 5-4. Table 5-3 summarised the distribution of passengers in the airport departure terminal. The results are collected from five experiments in two scenarios: passengers travelling (1) alone; and (2) in groups of varying sizes. There are no wavers in this simulation because pedestrian numbers in the two simulation scenarios need to be comparable in order to investigate the impact of pedestrian group dynamics.

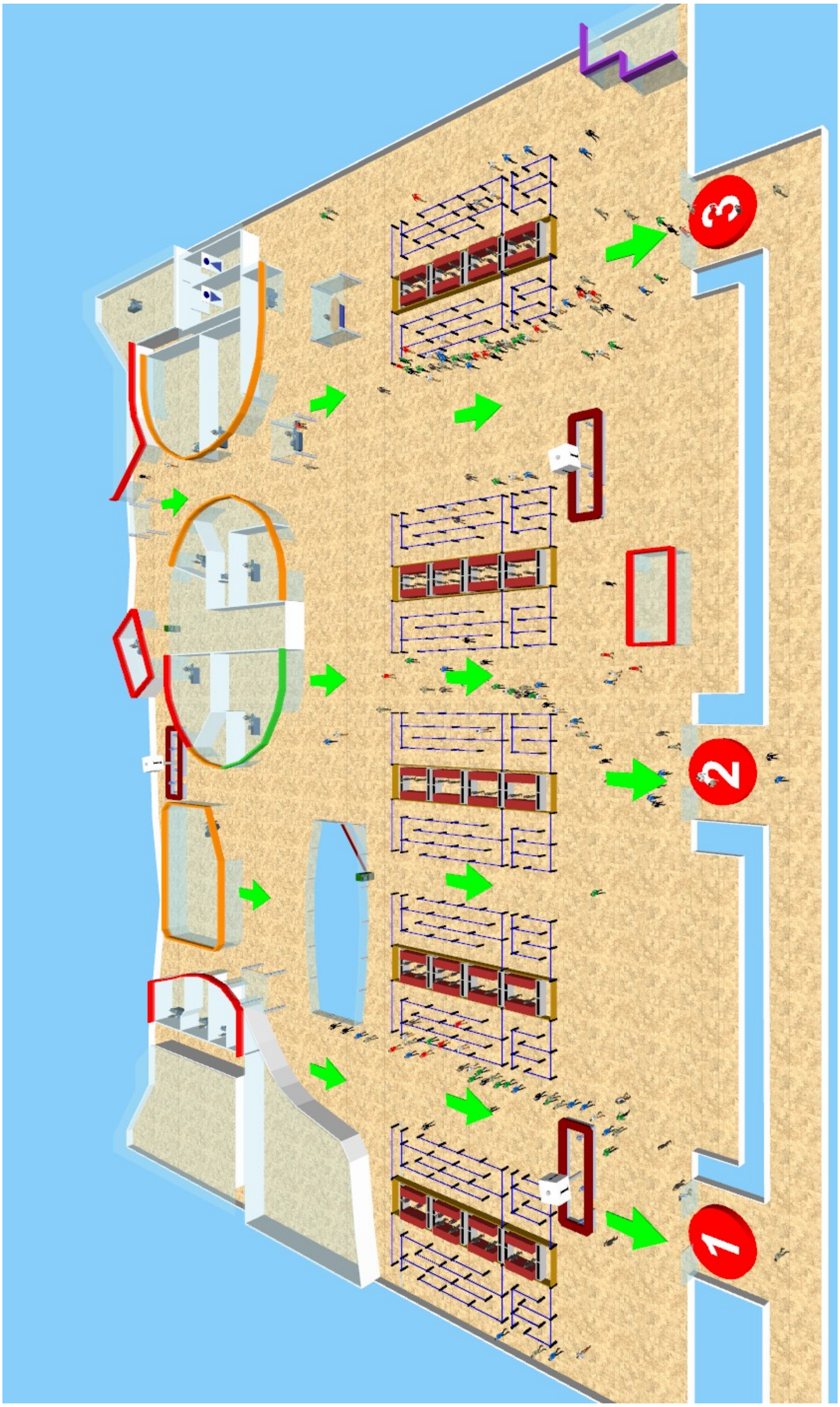


Figure 5-3 Overview of the landside of the terminal during evacuation.

Figure 5-4 Overview of the airside of the terminal during evacuation.

On average, there are approximately 1000 passengers in the simulation system at 7:30 AM (Table 5-3). In the condition of passengers travelling alone, on average 218 passengers (22% of total passengers) are found on level 4, while 782.2 passengers (78%) are on level 3. These figures changed to 361.2 (36%) and 644.6 (64%) under the condition that passengers are travelling in groups.

One of the most distinctive characteristics of an agent-based model is that agents are able to act autonomously in the simulation environment. This advanced feature strongly reflects the real-world human behaviour. As a result, even at the exact time-point of several experiments, the agent number in the system, agents' positions and their undertaking activities can be different.

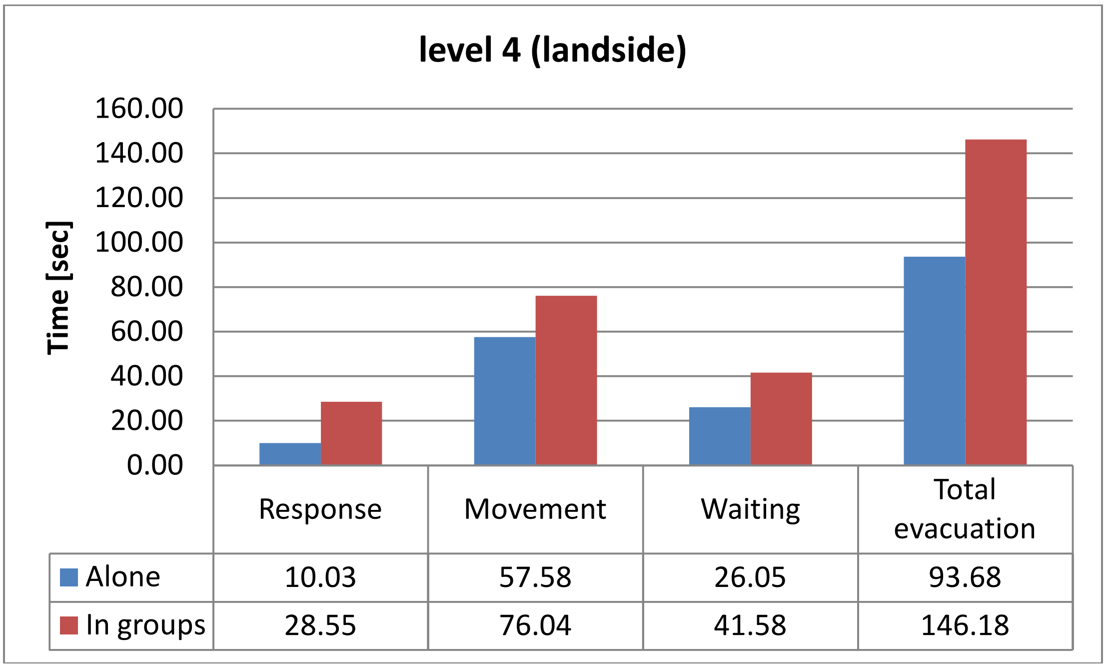
Number of agents in the experiment						
	Passenger travelling alone			Passenger travelling in groups		
Exp No.	**level4**	**level 3**	**Total**	**level4**	**level 3**	**Total**
1	219	771	990	343	654	997
2	222	768	990	378	626	1004
3	212	789	1001	328	678	1006
4	217	786	1003	381	629	1010
5	220	797	1017	376	636	1012
Avg.	218	782.2	1000.2	361.2	644.6	1005.8

Table 5-3 The distribution of agents in the airport terminal under the setting of passengers travelling: (1) alone; and (2) in groups.

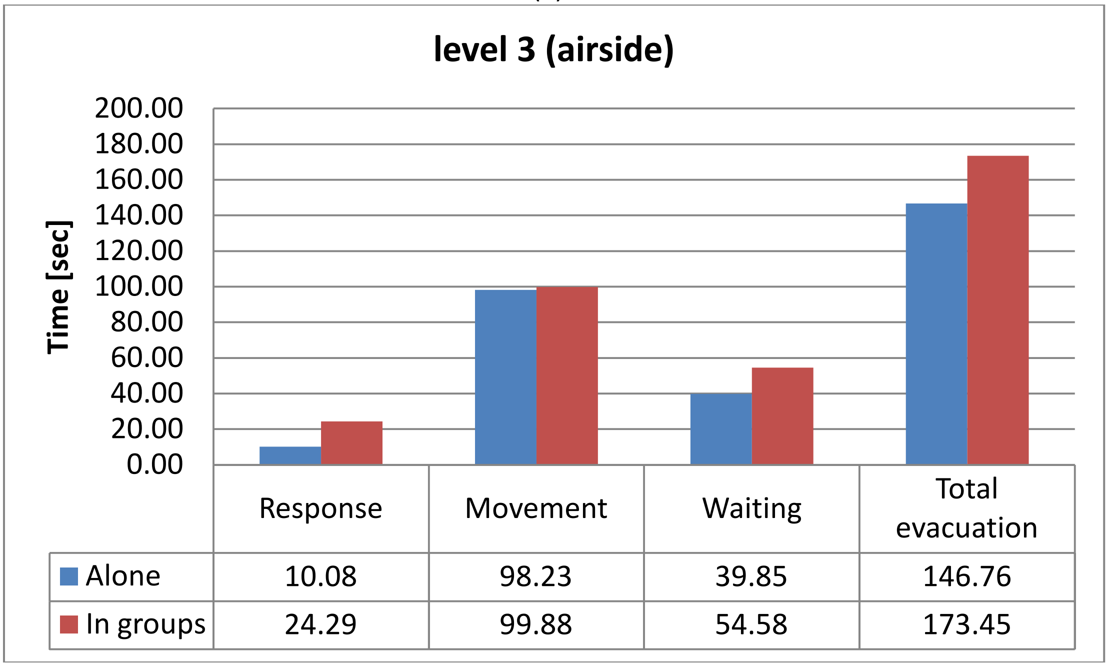
5.4.2 **Evacuation Time**

The differences in building layouts, passenger numbers and activities require the evacuation process to be analysed separately on level 4 (the landside) and level 3 (the airside). Figure 5-5 compares the time distribution of the evacuation event on both levels between the simulation setting of passengers travelling (1) alone; (2) in groups. It is shown that the total evacuation time of passengers travelling in groups is longer than that of passengers travelling alone. On level 4 and level 3, passengers in groups spend 146.18 and 173.45 seconds to finish the evacuation. The figures are 93.68 and 146.76 for passengers travelling alone, which are 36% and 15% shorter in comparison.

Distinct time differences can be found on all sub-events of the evacuation process on level 4 as well as the response time and waiting time on level 3. This result of response time indicates that the initial response of passengers who travelling in groups is slower than those travelling alone. It can take longer time for passengers in a group to communicate with each other and make decisions in response to the evacuation signal. The waiting time for passengers who are travelling alone is mainly caused by the congestion in front of the exit. While for group travellers, the waiting time is not only due to the congestion, but also the time associated with ‘regrouping’. Therefore, the waiting time for passengers travelling in groups is reasonably higher.

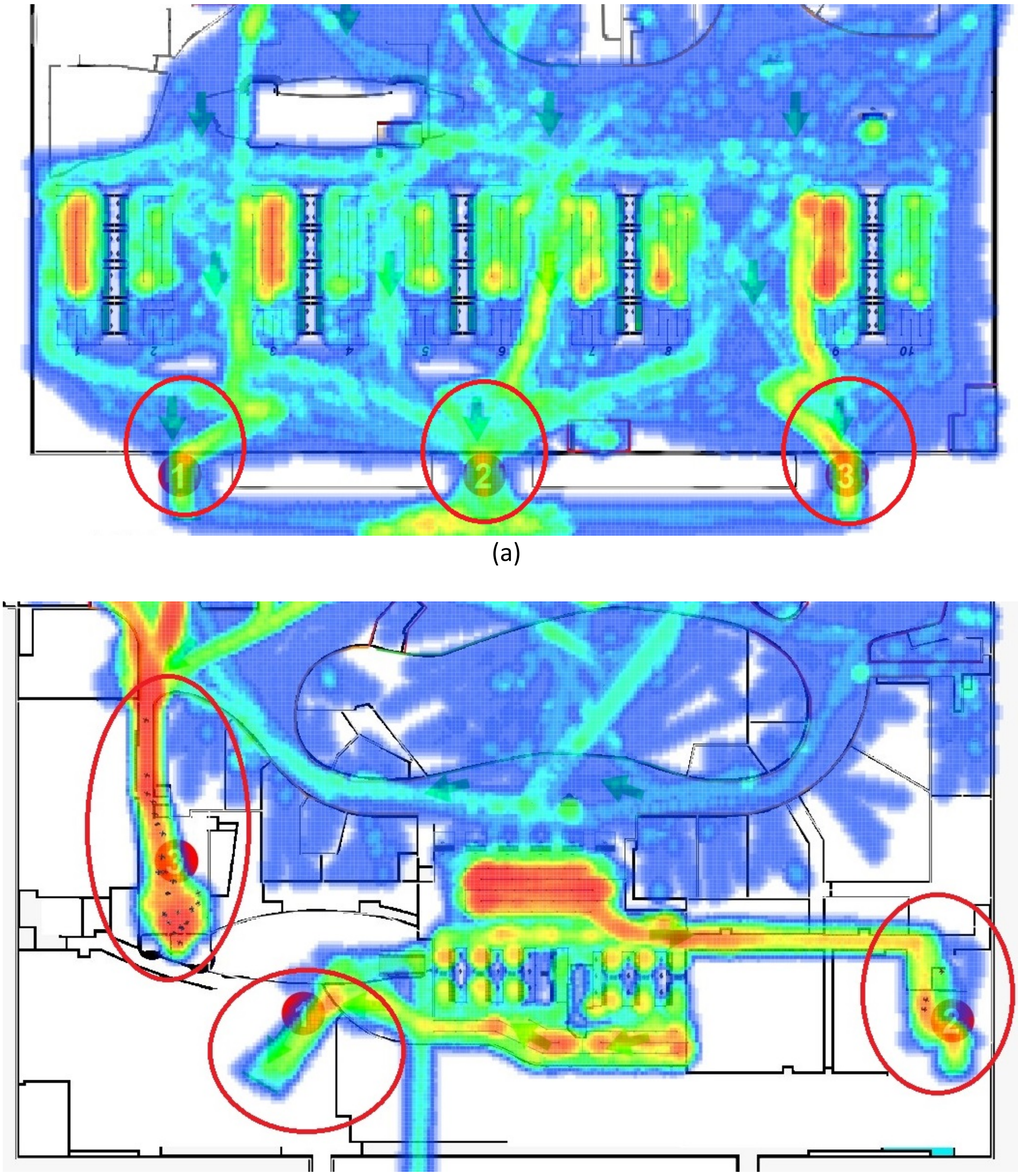


(a)



(b)

Figure 5-5 Average evacuation time of passengers on: (a) level 4, landside; and (b) level 3, airside for the two different settings.



(a)

(b)

Figure 5-6 Pedestrian density map during the evacuation process. (a) level 4; (b) level 3.

On both level 4 and level 3, passengers spent the majority of their evacuation time on the evacuation movement. Because of the group dynamic, larger groups are supposed to move slower than small groups or individual travellers (Santos & Aguirre, 2004; Schultz, et al., 2010). This behaviour is well illustrated on level 4. Passengers travelling in groups on level 4 spend approximately 20 seconds longer in moving during the evacuation. However, the movement times under the two different settings on level 3 are very close. A possible explanation for such a phenomenon is that the pathways to the exits on level 3 are narrower than those on level 4 (as can be seen from the highlighted areas in Figure 5-6). Severe congestion was observed all along passageways through to exit on level 3. Thus, passengers who are travelling alone had to slow down due to congested passageways and their speed was comparable to those travelling in groups. On the other hand, passengers on level 4 had more open space, which allowed those individual travellers to advance towards the exit quickly.

5.5 DISCUSSION

The simulation of the evacuation process in the airport terminal shows that the agent-based model can be applied in evaluating the performance of pedestrian facilities. Based on passenger's locations in the airport, three security levels are differentiated, which require passengers to evacuate through different exits. The simulation results suggested that passengers with group dynamics spend longer time in making decisions, moving to the exits and waiting for other group members during the evacuation.

This simulation technique prevents the potential risks in real practical trials and reduces research expense. Moreover, the simulation results provide valuable information such as how passengers react to an evacuation signal, which route to choose in the evacuation and the average time for passengers to finish the evacuation. The simulation is also to report congestions through the 3D visual demonstration during the evacuation. The evacuation model offers an expedient way for airport managers to propose and test evacuation plans. Given the information of flight schedule and passenger number, the evacuation simulation can be run at any time of day and the simulation results will provide valuable information for them to respond proactively to any potential congestion.

However, a few limitations of this case study need to be acknowledged. First, the proposed model is not designed for the extreme evacuation situation. Under extreme cases, there is no guarantee that the pre-defined escaping routes are safe for the evacuees. Second, the evacuation subjects in the model are all passengers. However, in the real-world, there are large numbers of airport staff that need to be considered as well. As part of future research, we would like to consider a phased evacuation approach i.e. only areas directly threatened will be evacuated first and areas at lesser risk will be evacuated later. Furthermore, different exit strategies employed at various airports could also be trialed using this framework. The dissemination of evacuation information among passengers and further addition of attributes to agents (such as age, gender, spatial cognition) will also be explored along with the inclusion of airport staff into the model.

5.6 CHAPTER SUMMARY

This chapter demonstrated a case study of simulating an airport evacuation process using an agent-based model. The evacuation strategy applied in this simulation divides passengers into three different security levels and evacuates passengers through different exits. The model is able to capture passenger behaviour during evacuation visually and collect passenger evacuation time statistically. This enables airport operators and building planners to design evacuation strategy and terminal layout according to the simulation results. By comparing evacuation time of individual passengers and passengers in groups, the impact of group dynamics during airport evacuation process can be seen. Experimental results demonstrated that group dynamics can significantly impact pedestrian behaviour during the evacuation and the total evacuation time in the airport.

Chapter 6: **Conclusions**

6.1 INTRODUCTION

This chapter summarises the main areas covered by this research, discusses the major findings and how they contribute to new knowledge of pedestrian modelling. In this chapter, the research questions raised at the beginning of this thesis will be answered. Limitations of this research will be considered and future research direction will be recommended.

6.2 THESIS SUMMARY

Nowadays, airports are becoming more and more passenger focused and passenger experience in airports is highly valued. Under this context, this research is motivated to investigate passenger behaviour in airport terminals using a passenger flow model. The literature review in Chapter 2 revealed that grouping is a common phenomenon among pedestrians, while most research failed to consider the group dynamics when developing pedestrian models. In order to reflect the actual passenger flow condition, the group dynamics must be included in the model.

Chapter 3 demonstrates the detailed procedure of building a passenger flow model using an agent-based method. The model defined pedestrian characteristics such as age, gender and travel purposes. Pedestrian group attributes were implemented in their characteristics as well.

In Chapter 4, the model was used to analyse the impact of group dynamics on airport passenger activities. Simulation results were compared under three different scenarios: passenger travelling (1) alone; (2) in groups; and (3) in groups with wavers. The results from both visual and statistical analysis showed that the group dynamics can significantly influence passenger behaviour in terms of dwell time at processing facilities and discretionary activity choices. Therefore, the group dynamics can influence the passenger experience and level of service in the airport. Publications arising from this work can be found in (Cheng, Reddy, Fookes, & Yarlagadda, 2014a), (Cheng, Reddy, Fookes, & Yarlagadda, in press) and (Cheng, Reddy, Fookes, & Yarlagadda, submitted).

In Chapter 5, a case study was conducted to demonstrate how the agent-based passenger flow model can be used by airport operators to examine the efficiency of an evacuation strategy. By comparing evacuation time of individual passengers and passengers in groups, the impact of group dynamics during an airport evacuation process was analysed. The simulation results shows that group dynamics can significantly impact passenger behaviour during airport evacuation process and the total evacuation time. A publication arising from this work can be found in (Cheng, Reddy, Fookes, & Yarlagadda, 2014b).

6.3 RESEARCH CONTRIBUTION

The primary objective of this research was to investigate the influence of group dynamics on passenger behaviour in airports. By simulating pedestrian flow in an international airport terminal using an agent-based model, the influence of group dynamics on pedestrian behaviour has been found and analysed. The main contributions of this thesis are embodied in the following four aspects:

1. **Improve the understanding of group dynamics among pedestrians.**

The literature review in this thesis had suggested that crowds consist of both individual pedestrians and people in groups. The percentage of people in groups within a crowd ranges from 40% to 70% at different occasions. Researchers also discovered that the size of a pedestrian group can influence pedestrian walking dynamics such as speed, group formation, and avoidance behaviour. As a result, one should pay attention to group dynamics when developing pedestrian flow models.

2. **Provide a more realistic agent-based passenger flow model by incorporating group dynamics.**

An agent-based modelling approach was applied in developing the pedestrian model in this thesis because of its advantages in modelling pedestrian behaviour in complex environments. As the simulation environment becomes more and more complex, research had suggested a trend to combine multiple modelling approaches into one simulation. This statement can be supported by the proposed model in which heterogeneous agents are created according to the agent-based mindset, while the pedestrian movement is governed by the customised social force algorithm.

The most significant feature of the proposed model is that it considered pedestrian group dynamics in a complex environment (an international airport departure terminal in this case). Pedestrians in the model have their own attributes which allow them to interact within groups, with pedestrians from other groups and the airport environment. The model is able to collect statistics and present real-time 3D visualisations during the simulation. This advanced feature enables the statistical validation and face validation of the model, and provides data for analysing pedestrian group dynamics.

3. **Demonstrate the influence of group dynamics on passenger flow in an airport departure terminal.**

By incorporating group dynamics into the agent-based model, simulation results of different scenario settings had shown that the group dynamics have significant influence on passenger activities in the airport terminal in terms of dwell times, waiting behaviour and choices of discretionary activities.

In airport mandatory processing activities such as check-in, security control and customs, passengers with group dynamics had a larger dwell time in the processes. The waiting behaviour of passengers travelling in groups can lead to higher pedestrian density in the waiting areas around the processing areas, which can cause congestions and a lower level of service (LOS). Moreover, longer dwell time in processing activities means less time for passengers to undertake discretionary activities, which is not favourable for airport retail operators. Passenger group dynamics can also influence the choices of retail activities. It was found that passengers travelling in groups are more likely to undertake retail activities than those who are travelling alone. The existence of wavers contributes a higher landside retail opportunity.

4. **Introduce the potential application of the agent-based pedestrian flow model in design and management of pedestrian facilities.**

From the airport design and management perspective, the model can be used to test the impact of design changes, allocate optimal queuing area based on passenger traffic, measure peak capacity and analyse the effectiveness of airport processing and discretionary facilities. Running such a simulation provides flexibility and insights into the design process at no extra cost. An application of the model in analysing potential effects of airport self-service technology can be found in Kirk, et al. (submitted).

Furthermore, if terminal operators could run the simulation beforehand by simply importing flight schedules and passenger quantity, then simulation results can provide valuable information for them to respond proactively to potential congestions. The density map in Appendix C shows the pedestrian density in the airport terminal after a whole day simulation. According to the density map, airport operators can easily predict critical congestion areas, and therefore take preventive measures.

Hence, we envisage that such a simulation tool can be critical to airport designers and operators. An airport with minimal congestion will in turn assist in providing a positive experience for passengers using the airport. However, the potential application of the model is not limited to the airport terminals only. It can be extended to simulate pedestrian behaviour in all public pedestrian environments such as railway stations, shopping centres, and theme parks.

6.4 RESEARCH LIMITATIONS

The limitation of this thesis lies in the lack of access to detailed airport data, which leads to difficulties in model development, validation and calibration. For agent-based models, the accuracy of decision making processes and human activities determine the reliability of the model. Passenger attributes such as gender, age and culture background all have influence on the passenger’s behaviour, retail choice and environment cognition. However, due to the lack of access to such empirical data, the model was considerably simplified by using data obtained from previous research papers or empirical assumptions while simulating the human behaviour.

6.5 RECOMMANDTIONS

As was mentioned in the previous section, a limitation of this research was the access to airport passenger characteristic data. Therefore, it is recommended that future research be undertaken in the following areas:

1. **Field data collection of pedestrian characteristics**

Since the environment can influence pedestrian behaviour and group dynamics such as the proportion of people in groups, the group size and group speed, it is necessary to collect further field data from the reference environment in order to build a realistic model. To build a pedestrian model for an international airport terminal, one needs to consider field data such as basic pedestrian status (e.g. arrival time distribution, passenger group size, waver status) and personal information (such as gender, age, nationality, destination, travel purposes, etc).

2. **Explore passenger discretionary activities and retail behaviour in airports**

A large proportion of airport revenue is generated in the airport retail segment. High-quality airport retail service can contribute to higher passenger satisfaction and enhanced airport experience, which in turn attracts more passengers and benefits the airport. Therefore, future study investigating airport passenger retail activity would be very interesting. The agent-based model can be used to simulate the retail and purchasing behaviour of passengers with different characteristics.

3. **Investigate the application of agent-based pedestrian flow model**

Future research should also concentrate on the application of agent-based pedestrian flow model. The model can be used as a tool for airport operators to propose regulations, test the level of service (LOS) in each processing unit and sub-system, and design new airports.

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Appendices

A. FLIGHT SCHEDULE

Flight schedule used in the model:

Flight	Departure Time	Passenger Quantity	Departure Gate	Entrance Number	Check-In Counter Number
EK433	3:30	222	81	1	1
QF123	6:20	134	82	2	2
EK434	7:25	222	83	3	3
DJ080/EY6117	8:20	134	80	4	4
DJ186/EY6189	8:20	134	77	5	5
DJ066/EY6194	8:30	134	79	6	6
DJ175/VA175	9:00	134	85	7	7
HT531	9:00	128	78	8	8
SQ256/VA5668	9:10	241	75	9	9
DJ4191	9:15	134	86	10	10
IE701	9:30	120	84	11	1
QQ371	9:30	51	79	12	2
CX146/AY5832	9:35	241	83	13	3
DJ4197	10:30	134	76	14	4
DJ181	10:30	134	86	15	5
PX004/QF349	10:40	180	82	16	6
VA007/DL6795	11:20	222	84	17	7
NZ136/CA5104	11:15	251	80	18	8
QF015/AA7380	12:30	258	75	19	9
QF051/9W4051	13:40	258	78	20	10
TG474/LH9759	14:20	251	85	21	1
SQ236/LH9773	14:40	265	77	22	2
NZ734/CA5139	16:45	134	82	23	3
PX026/QF379	17:40	99	80	24	4
QF125/AA7303	17:40	134	81	25	5
DJ068/EY6195	17:45	134	86	26	6
DJ082/EY6190	18:00	134	76	27	7
DJ188/EY6188	18:30	134	75	28	8
HA444	18:35	180	85	29	9
EK435	20:45	222	84	30	10
SB153	21:20	134	76	31	1
FJ922/QF347	22:40	134	83	32	2
BR316/QF329	22:45	243	85	33	3
SQ246/LH9783	23:45	265	86	34	4
MH134/KL4101	23:50	265	77	35	5

Table A-1 Flight timetable in the model.

B. IATA LEVEL OF SERVICE (LOS) FRAMEWORK

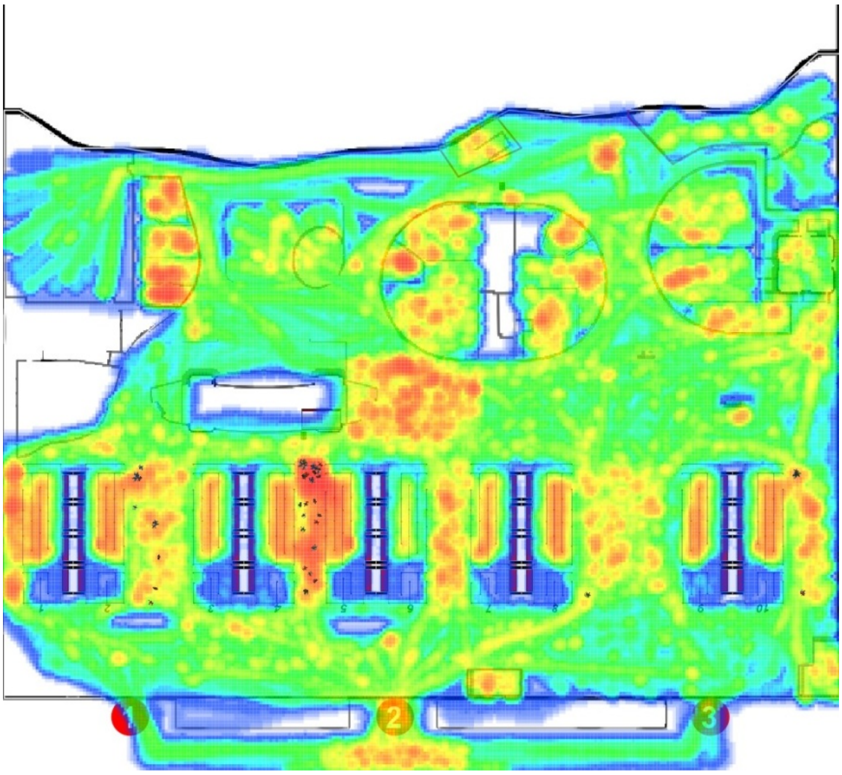
LOS	*Description* Flow	Delay	Comfort
A. Excellent	Free	None	Excellent
B. High	Stable	Very Few	High
C. Good	Stable	Acceptable	Good
D. Adequate	Unstable	Acceptable for short time	Adequate
E. Inadequate	Unstable	Unacceptable	Inadequate
F. Unacceptable	Total system breakdown	Unacceptable	

Table B-2 IATA LOS Framework (IATA, 2004).

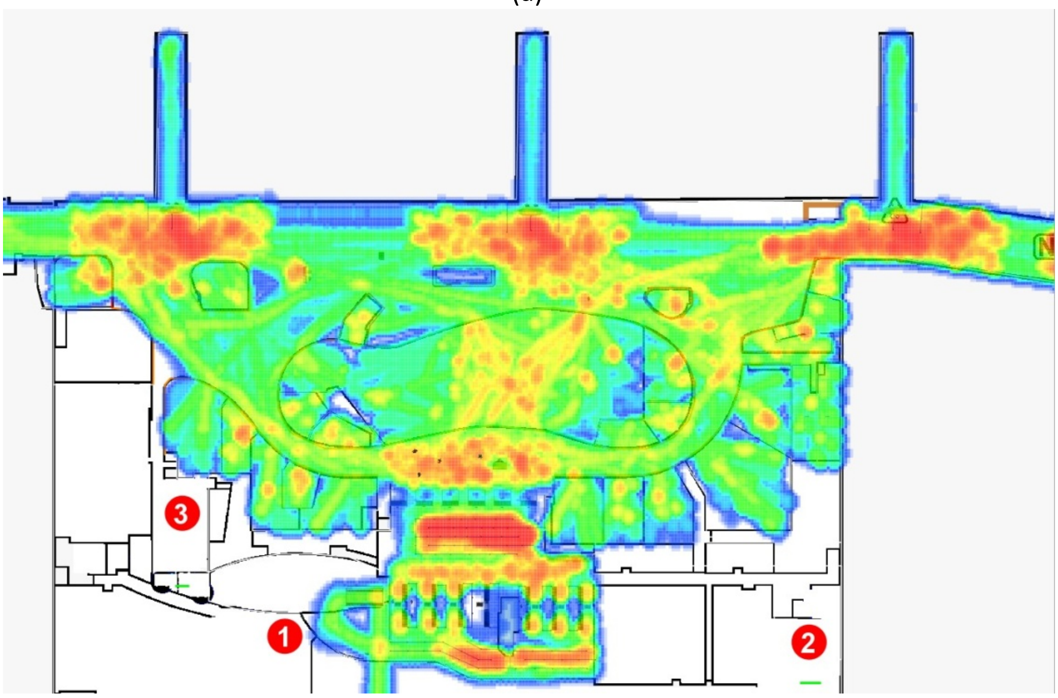
Sub-system	*LOS standards (square meters per occupants)* A	..B..	..C..	..D..	E..	..F..
Check-in queue area	1.8	1.6	1.4	1.2	1	Total System Breakdown
Wait/circulate	2.7	2.3	1.9	1.5	1	
Hold room	1.4	1.2	1	0.8	0.6	
Bag clain area	2	1.8	1.6	1.4	1.2	
Government inspection	1.4	1.2	1	0.8	0.6	

Table B-3 IATA LOS Congestion Standards (Ashford, Mumayiz, & Wright, 2011a).

C. PEDESTRIAN DENSITY MAP OF THE AIRPORT DEPARTURE TERMINAL



(a)



(b)

Figure C-1 Pedestrian density map of the airport departure terminal after whole day simulation. (a) level 4; (b) level 3.