Pedestrian Flow Simulation Using PedFlo

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Abstract

Pedestrian flows appear chaotic and unstructured but there is a need to analyse and predict these flows when designing pedestrian facilities. The complexities of pedestrian behaviour arise from ranges in walking speeds, clustering, changing crowd density and interaction with obstacles. PedFlo is a micro level pedestrian simulation tool that models each individual pedestrian and can be used for capacity analysis, comparison of design options and assessment of performance under different scenarios for pedestrian facilities. Published research on pedestrian behaviour and international standards have been applied to model the pedestrian flows. PedFlo uses a commercial simulation engine and distributes walking speeds over a range appropriate to the population being studied, pedestrian travel times increase dynamically with increasing crowd density and arrivals are statistically generated depending on transport types. PedFlo provides quantitative results including level of service indicators and expected through times for scenario comparisons. It also produces 3-D animated movies of the simulated crowd behaviour. PedFlo has been successfully used to model a train station in Hong Kong, a theatre in Singapore and an airport, sports event and train station in New Zealand. This paper discusses the PedFlo methodology and examines a case study for a ferry terminal upgrade.

1 Introduction

Pedestrian movements appear chaotic and unstructured with people moving as individuals or in groups, at different speeds, overtaking, diverting and travelling in opposing directions. The study of pedestrian flows is becoming increasingly important as the demands on transportation and transport facilities around the world rises and space becomes increasingly expensive. Designers and architects can use simulation of pedestrian flows to verify that facility designs will conform to their design standards and to compare the performance of proposed layouts. It can also be used to model future facility performance under projected pedestrian volumes. The study of evacuation scenarios is also important - can a building be evacuated in sufficient time in an emergency situation? People behave differently in varying situations and these different behaviours can be included in the modelling. One off events such as large sporting events can be studied using simulation to predict the likely crowd density, comfort, expected delays and the numbers of ticket gates required. PedFlo is an applied simulation tool developed by Beca Applied Technologies Ltd for use in pedestrian simulation and analysis.
2 Previous Research

Early pedestrian flow modelling theory originated from traffic design and simulation. However there are few rules for pedestrian flows like those that govern vehicular traffic movement. Some classical and new techniques are listed below and are covered in detail by Harney (2002).

- Regression models
- Steady state assigning of routes
- Particle flow models
- Simulation models
- Cellular Automata
- Visibility Graph Analysis
- Agent Based Models

PedFlo is a simulation model that attempts to simulate pedestrian flow on a micro level and apply the technique to real life situations and problems. Each pedestrian is modelled individually and moves through the model using a set of logical rules. The PedFlo technique has been used to model a train station in Hong Kong, a theatre in Singapore and an airport, wharf, sports event and train station in New Zealand.

3 Standards

PedFlo applies a range of published standards and research to model pedestrian flows. It has the flexibility to accommodate alternative standards to suit different situations.

3.1 Level Of Service

The Level Of Service (LOS) concept originated from traffic modelling and has been applied to pedestrians by Fruin (1987) and in other research. LOS ratings are based on the level of pedestrian congestion acceptable in different facilities and cultures.

<table>
<thead>
<tr>
<th>Level of Service A</th>
<th>&lt;0.31 pedestrian/m²</th>
<th>Unconstrained flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of Service B</td>
<td>0.31 – 0.43 pedestrian /m²</td>
<td>Minor cross flow conflict</td>
</tr>
<tr>
<td>Level of Service C</td>
<td>0.43 – 0.72 pedestrian /m²</td>
<td>Restricted flow</td>
</tr>
<tr>
<td>Level of Service D</td>
<td>0.72 – 1.08 pedestrian /m²</td>
<td>Most people have their speed reduced/restricted</td>
</tr>
<tr>
<td>Level of Service E</td>
<td>1.08 – 2.15 pedestrian /m²</td>
<td>All people have their speed restricted</td>
</tr>
<tr>
<td>Level of Service F</td>
<td>&gt; 2.15 pedestrian /m²</td>
<td>Speed severely reduced. No cross flow possible</td>
</tr>
</tbody>
</table>
3.2 Distribution of Walking Speeds
The distribution of walking speeds among human beings is generally normally distributed. The mean walking speed has been observed to vary by city as shown in Table 1.

<table>
<thead>
<tr>
<th>City</th>
<th>Mean walking speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hong Kong</td>
<td>1.20</td>
</tr>
<tr>
<td>Singapore</td>
<td>1.23</td>
</tr>
<tr>
<td>New York</td>
<td>1.35</td>
</tr>
<tr>
<td>Calgary</td>
<td>1.40</td>
</tr>
<tr>
<td>London</td>
<td>1.47</td>
</tr>
<tr>
<td>Sydney</td>
<td>1.48</td>
</tr>
</tbody>
</table>

3.3 Degradation of Speed with Increasing Passenger Density
As pedestrian density increases the speed of individual pedestrians decreases as shown in figure 1. This is due to the difficulty in overtaking in denser crowds and the effects of cross-flow movements where pedestrians must continuously adjust their speed to avoid conflicts. When pedestrian density increases above 2 pedestrians/m² everyone is forced to move at the same speed, as there is no room for overtaking. This is observed as a shuffling effect in dense queues. The rate of speed degradation also varies by city.

3.4 Edge Clearances
Physical objects such as walls and doorways affect the flow of pedestrians. A side clearance distance is applied for each type of physical constraint effectively reducing the available width for pedestrians to walk in. For example Fruin (1987) states that the effective width of corridors should be reduced by 0.45m on each side to account for the tendency of humans to maintain separation from stationary objects and walls.

3.5 Escalator Throughput
The maximum throughput for escalators varies by manufacturer so it is necessary to obtain detailed information on the escalators being modelled. The typical capacity for escalators in modern train stations is around 120 pedestrians/min (Lam and Lee, 1999).
It is important to note that the manufacturers rated capacity of escalators is never reached in practise over a sustained period of time because people generally only stand on every other step. The actual capacity is approximately half the rated capacity depending on the width of the escalator (Fruin, 1987).

4 Methodology

The PedFlo pedestrian flow simulation is based on published research, simulation techniques and engineering judgment.

4.1 Objective

Before any simulation project begins a clear objective must be defined. For example:

- Find the best option for a facility design
- Determine how many ticket gates will be required if 20,000 people are expected at an event
- Will a building/station/wharf cope with expected pedestrian flows in 20 years time?

4.2 Simulation Engine

PedFlo runs on a commercial simulation engine platform. This simulation engine, like most others, is usually associated with the manufacturing industry and provides built-in modules for simulating the transportation and processing of objects. A machine type module that can process several objects at the same time was customised to simulate an area of a facility processing several people as they walk through. The engine is responsible for timing, event handling, creating objects such as people, trains, and buses, moving objects through the matrix of connected cells and providing the visual output for analysing flows.

Discrete event simulation is used because people are discrete objects and the events associated with pedestrian flows are all discrete - trains arrive and people depart at discrete times.

4.3 Micro Level

PedFlo is a micro level simulation, modelling each individual pedestrian as they move through the facility.

Each pedestrian is assigned the following static attributes:

- Origin
- Ultimate destination
- Unconstrained walking speed

These attributes are used to move people through the facility using logic with each individual making separate routing decisions. Pedestrians can be grouped to act as a cluster of people by giving them identical attributes so that they move together.

4.4 Cell Structure

The facility to be modelled is divided into a matrix of interconnected cells as shown in Figure 2. Cells can have different functions such as door, escalator, lift, service counter and walking space. Each cell has a different distribution of process times for pedestrians based on their speed, origin, destination and other attributes. Queues are usually First In First Out (FIFO) however any queuing mechanism can be modelled.
Figure 2. Simple depiction of PedFlo cell structure

Walking cells are the basis for modelling pedestrian movements through the facility. They work by 'processing' each pedestrian that enters for a duration calculated from the pedestrian's speed and the current density of people in the cell.

Walking cells have the following attributes:
- Physical area
- Walking length (distance pedestrian travels through the cell)
- Maximum capacity
- Destination logic for where an exiting pedestrian will travel to next

Dynamic rerouting of pedestrians occurs where the perceived density in the cell the pedestrian intended to travel into is high. Pedestrians can choose the path with lowest density or stay on a pre-defined path even if the density is high. This decision is made using the logic built into each specific cell based on observations and engineering judgment.

4.5 Arrivals

The distribution of arrivals is specific to each type of pedestrian transport. Pedestrians on foot arrive as individuals or in small groups. Passengers on buses and trains arrive in larger groups. The interarrival time of pedestrians is generally modelled using a negative exponential distribution as shown in Figure 3. This causes many pedestrians to have a small interarrival time and occasionally a large interval occurs between arrivals.

Figure 3. Example of a negative exponential distribution for interarrival times
4.6 Calibration

Calibration of each PedFlo model is required before it is used to analyse future or design scenarios. In some cases the facility being modelled has not yet been constructed so calibration against other similar facilities is used.

Calibration usually involves comparing the output of several simulation runs with observed statistics. If the difference is sufficiently low for the study, the model is accepted as sufficient for modelling other scenarios that cannot be calibrated against.

4.7 Running the Model

Usually a series of simulation runs are performed to compare results. Each run is called a scenario and typically scenarios are chosen for worst-case situations. For example when studying options for a train station layout, each layout can be simulated using the peak expected pedestrian volumes. This is usually the morning rush hour period. The biggest pressure on the transport facility will highlight performance differences between the options. Also if a facility can cope with peak volumes it can be assumed to cope with the off-peak volumes.

4.8 Model Outputs

PedFlo provides quantitative results for the comparison of different scenarios. Results include graphs of pedestrian through times that indicate the average through time and the likely distribution of through times. Excessively long through times for a few pedestrians may be acceptable in some situations but not in others.

The occupancy of particular areas is recorded over the simulation. This can indicate areas where there is continuously high occupancy or long queuing.

Each travel cell changes colour dynamically to indicate the different levels of service. This provides visual feedback of where the areas of concern may be. Pedestrians from each origin are colour coded for identification and to visually trace the flow through the model.

2D and 3D movies can be used for visual analysis of pedestrian flow and density as shown in Figure 3.

Figure 3. Screen shot of 3D Pedflo movie
5 Case Study

Auckland City Council (ACC) had proposed two different layouts for a new ferry terminal building at Matiatia wharf on Waiheke Island. Interested parties including sponsors, ferry operators and local residents groups were concerned about the adequacy of the proposals. Because of the divergent views of these parties ACC looked for an objective means of assessing the likely performance of the new terminal.

5.1 Problem Description

Pedflo was used to simulate ferry passenger arrivals and movements through and around the terminal layouts during the weekday morning and evening peak and summer weekend flows to determine how the options would cope with predicted volumes until 2017. Scenarios for wet and dry weather were analysed for current (2002) and predicted future (2017) passenger volumes.

In dry weather most passengers bypass the terminal building while in wet weather most passengers will walk through the building to keep dry.

5.2 Methodology

A simulation model was built using the cell layout methodology superimposed on architectural plans of the wharf and the two terminal layouts. The area and walking length for each cell was calculated and the logical flow from each cell to the next was set up.

Bus, taxi and car arrivals were generated to distributions determined from studying the existing situation at the wharf. Ferry arrivals were generated to a timetable with the actual arrival being within a triangular distribution of the expected arrival time (See Figure 4). This is because ferries are sometimes early but rarely late (in contrast to other transport services).

5.3 Ferry Arrivals

Arriving ferries were populated with incoming passengers who travel up a ramp onto the wharf. They then proceed across the wharf and do any of the following actions based on the input probabilities:

- Bypass the terminal building

![Triangular Distribution for Ferry Arrivals](image)

Figure 4. Triangular distribution for Ferry arrivals

All passengers generated were assigned a non constrained walking speed from a normal distribution with a mean of 1.1 m/s (HCM 2000).
• Walk through the terminal building
• Wait for luggage at the collection point
• Visit a service counter in the terminal
• Leave the wharf by bus, taxi, car or on foot

Outgoing passengers arriving at the wharf wait inside the terminal if it is wet, otherwise most wait outside. When the ferry arrives and has discharged its incoming passengers, the outgoing passengers board. The ferry leaves at its scheduled departure time or after the last passenger has boarded.

5.4 Calibration

The output from the simulation was compared to data gathered from the existing wharf at Matiatia, the Downtown ferry terminal and the Devonport terminal. The calibration process verified that the model realistically represented the real world.

The distribution of arrivals in the 15 minutes before a ferry departs showed a good correlation to the observed data. See Figure 5 for a comparison between observed and simulated arrivals.

5.5 Simulation Runs

Simulation runs were completed using the calibrated model for several different scenarios, as described in section 5.1, to compare the performance of the two different layouts under different conditions.

5.6 Results

Figure 6 shows the occupancy of different areas on the wharf for the 2017 evening peak commuter scenario in wet weather. Both layouts show very similar occupancy levels.

Figure 6. Occupancy of different areas on the wharf for a 2017 wet evening simulation
Figure 7 shows the through-times for passengers from the ferry to departing the wharf area. Both layouts performed well with most passengers taking less than 2 minutes to depart the wharf. There are a few passengers taking longer to travel across the wharf as they stop to visit service counters.

Figure 7. Through times for a 2017 wet evening simulation

5.7 Sensitivity Analysis
Several simulations were performed to determine how sensitive the model was to small changes. One of these was the effect of a ferry arriving late. The results showed more people waiting in the building and under the covered areas up to the maximum capacity for future scenarios.

The effect of using dual disembarking ramps was also simulated. This reduced the required turnaround time for ferries and increased the short term demand on the terminal building.

5.8 Case Study Conclusion
The simulations showed that both layout options could cope with the projected passenger numbers considered. Overall layout 1 performed slightly better than layout 2 but only minor changes would be required to layout 2 to improve the through flow.

The good performance of the ferry terminal is assisted by the current behaviour of commuting passengers who arrive shortly before the ferry departs and board soon after it arrives. For weekend departures there is higher demand on the terminal building as passengers arrive earlier and wait on the wharf for the ferry to arrive.

The simulations showed that the approach footpath to the wharf would need to be widened to cope with the future demands as it could be a bottleneck in some situations.

The simulations were instrumental in getting agreement from all interested parties to allow the project to proceed.

6 Improvements
Since the case study discussed in this paper further improvements to the PedFlo methodology have been investigated. These include:

- Improving the performance under high density opposing flows.
- Improving the animation of pedestrian movements.
- Degrading the speed of pedestrians on crowded stairs (this is currently done for flat areas but stairs are assumed to operate at the speed that produces maximum throughput).
7 Conclusions

The study and simulation of pedestrian flows is becoming more important as urban environments develop and facilities come under increasing pressure. The PedFlo methodology incorporates published research, simulation theory and engineering judgment to successfully simulate pedestrian flows. Studies using Pedflo have enabled design decisions accommodating predicted pedestrian flows into the future to be made with confidence.

8 References

5. Lam, W.H.K., J.Y.S. Lee, “Pedestrian Travel Time Functions for the Hong Kong – Kanton Railway Stations – Calibration and Validation.”