Iterative Design of a Sensor Network for the Evaluation of Pedestrian Facility Design Using Agent-Based Simulations

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Abstract. This paper presents the iterative approach taken in the design of a sensor network for the purpose of evaluating pedestrian facility design. Specifically, sensors are to be used to measure pedestrian flows in a network of pedestrian walkways. Data collected by the sensors will be employed in agent-based pedestrian simulations for the visualisation and analysis of pedestrian flows. Using Fruin's (1971) Level-of-Service criteria, pedestrian flows will be evaluated to determine if they meet the requirements set out by the regulatory authorities for adequate pedestrian facility design.

Keywords: Iterative design approach · Agent-based simulations · Human-sensing · Sensor network · Pedestrian flows · pedestrian facility design · Pedestrian level-of-service criteria

1 Introduction

Singapore's public transportation network comprises the following modes: Mass Rapid Transit (MRT), Light Rapid Transit (LRT), bus and taxi. A seamlessly integrated network involves the design of adequate pedestrian infrastructure to connect the different transportation modes [3]. Pedestrian flow data is used to understand pedestrian movement patterns and peak periods/areas of usage, and to evaluate pedestrian facility design. Traditional data collection methods include the use of observations [5,6], interviews [7] and experiments [1]. We propose the alternative use of sensors, which are less labour-intensive and obtrusive than direct observational methods, and also allows information to be collected continuously over time.

In this paper, an iterative approach is adopted in sensor network design by employing pedestrian scenario simulations both before and after sensor installation. When employed before sensor installation, these simulations (1) clarify the

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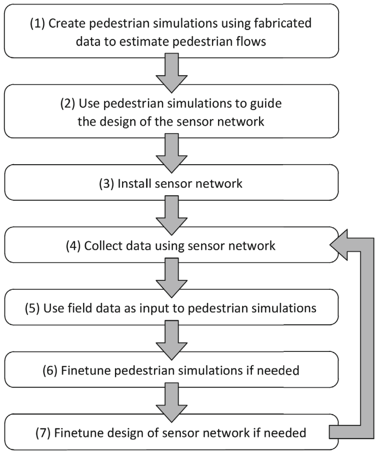


Fig. 1. Iterative approach to designing a sensor network

data required to create pedestrian simulations and to be collected by the sensors, and (2) identify potentially congested areas in the network, so that research resources can be directed to those areas. These findings can then be used to optimise the sensor network's efficiency in data collection. Simulations created after sensor installation will incorporate data collected by the sensors to refine the previously-created simulations. This allows initial assumptions made about pedestrian flows to be validated or refuted, estimates of pedestrian arrivals to be adjusted and pedestrian origin-destination matrices to be fine-tuned. Additionally, locations for the installation of more sensors (if needed) can be identified, or additional parameters to be measured determined.

2 Methodology

2.1 Iterative Design Approach

Figure 1 contains a visual representation of the iterative approach adopted in sensor network design. A test site in Singapore is adopted as a case study for the framework proposed in this paper.

2.2 Parameters of Study

To create the pedestrian simulations prior to sensor installation, the following parameters were assumed. Data collected by the sensors will subsequently be used to fine-tune these assumed parameters, as per Step 5 of the iterative design approach.

1. Pedestrian Speeds:
All pedestrians were assumed to walk at speeds following a normal distribution with a mean of 1.27 m/s and standard deviation of 0.14 m/s. These values were based on a study of pedestrian speeds in Singapore's MRT stations [8].

2. Pedestrian Arrivals (ped/hr):
A total of 10,000 pedestrians circulating in the network per hour was used, which is about 22 % of maximum expected pedestrian volumes at peak hours given train capacities and average train arrival times.

3. Pedestrian Origin-Destination (OD) Matrix:
OD matrices were used to describe the proportions of routes taken by pedestrians within the network.

2.3 Evaluation Criteria

Fruin's Level-of-Service (LOS) criteria describes pedestrian flows using coupled relationships between speed, flow rate and space, as well as qualitative factors, such as the ability to overtake slower pedestrians [2]. LOS A is the threshold of unhindered movement while LOS F reflects critical densities where movement is disrupted [2]. Singapore's Land Transport Authority (LTA) specifies that pedestrian flows/densities along corridors without commercial/transit facilities or information signages should not exceed LOS D [2], provided there are no cross-flows [4]. Additionally, LOS D should be an intermittent condition during peak hours [4]. The following set of evaluation criteria (Table 1) was thus formulated to determine the likelihood that pedestrian flows would satisfy LTA's requirements for adequate pedestrian facility design. These evaluation criteria were chosen arbitrarily, giving researchers the flexibility to alter them depending on their interpretation of the results or other requirements.

Due to the stochastic nature of the simulations, 100 iterations of each simulation were performed and results processed. For each iteration, pedestrian densities at three locations were obtained from the simulation every minute, and compared against pedestrian LOS criteria [2]. These locations (indicated in Fig. 2 as Points A, B and C) reflect critical congestion level zones in the pedestrian network.

3 Experimental Set-Up, Simulations and Results

3.1 Simulated Network Geometry

The simulated network (Fig. 2) contains eight entry/exit points, two of which are MRT station gantries. Another two entry/exit points are exits leading to/from the MRT station, while the remaining four lead to two shopping malls (labelled Malls A and B) adjacent to the MRT station.

3.2 Experimental Set-Up

AnyLogic 7 (trial version) was used to create pedestrian simulation models for this project. Due to functionality limitations of the trial version, some pedestrian routes were excluded from the simulations and are highlighted in blue/green in the following OD matrices.

Table 1. Summary of evaluation criteria

Evaluation Criteria				Satisfies LTA's requirements
Not exceed LOS D	LOS D <5%	LOS E <1%	LOS F = 0%	
✓	✓	✓	✓	Highly likely
✗	✓	✓	✓	Likely
✗	✗	✓	✓	Somewhat likely
✗	✗	✗	✓	Somewhat unlikely
✗	✗	✗	✗	Unlikely

Three experiments (Control (C), Experiment 1 (E1) and Experiment 2 (E2) were conducted. C was used both to estimate expected usage of the pedestrian network, as well as to establish a point of reference for comparison with E1 and E2.

Control Experiment (C). Pedestrian arrivals of 10,000 ped/hour were assumed, with a 70:20:10 ratio, representing the ratio of pedestrians entering the network via MRT, leaving the network via MRT, and remaining in the network (Fig. 3).

Pedestrian arrivals by MRT are likely to result in periodic discharge of a large number of pedestrians in a relatively short amount of time. This was modelled using the following arrival schedule for MRT Gantries 1 and 2 (Fig. 4), scaled to the magnitude of pedestrian arrivals. Pedestrian arrival rates at the remaining six entry/exit points were defined using Poisson distributions in ped/hour.

Experiment 1 (E1). Pedestrian flows were increased by 50 % from 10,000 ped/hour to 15,000 ped/hour. Arrivals per hour at each origin were increased proportionately. All other simulation parameters were kept constant compared to C (Fig. 5).

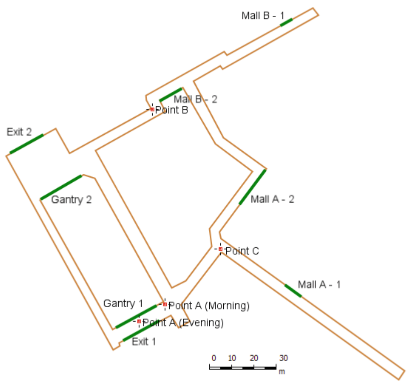


Fig. 2. Geometry of simulated pedestrian network

O/D	No of pp	Gantry 1	Gantry 2	Exit 1	Exit 2	Mall A 1	Mall A 2	Mall B 1	Mall B 2
Gantry 1	3425			0.86		0.05	0.05	0.02	0.02
Gantry 2	3550				0.85	0.02	0.02	0.055	0.055
Exit 1	425	1.00							
Exit 2	450		0.67			0.11	0.11	0.055	0.055
Mall A - 1	600	0.58		0.29	0.09			0.02	0.02
Mall A - 2	500	0.50		0.35	0.10			0.025	0.025
Mall B - 1	575		0.61	0.15	0.21		0.02		0.01
Mall B - 2	475		0.53	0.18	0.26		0.02	0.01	

Option not applicable

Omitted; assume pedestrian will choose exit closest to their destination

Omitted: limited options available in simulator

Fig. 3. Origin-destination matrix - control experiment

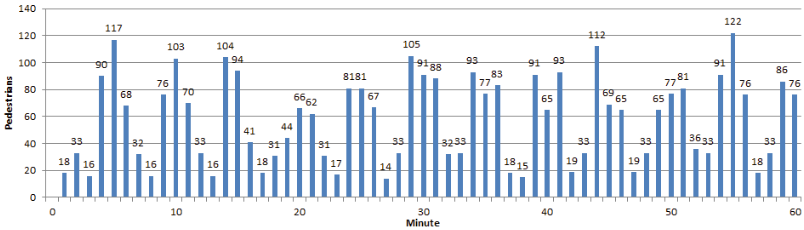


Fig. 4. Pedestrian arrival schedule (3500/hr)

O/D	No of pp	Gantry 1	Gantry 2	Exit 1	Exit 2	Mall A 1	Mall A 2	Mall B 1	Mall B 2
Gantry 1	5138			0.86		0.05	0.05	0.02	0.02
Gantry 2	5325				0.85	0.02	0.02	0.055	0.055
Exit 1	638	1.00							
Exit 2	675		0.67			0.11	0.11	0.055	0.055
Mall A - 1	900	0.58		0.29	0.09			0.02	0.02
Mall A - 2	750	0.50		0.35	0.10			0.025	0.025
Mall B - 1	863		0.61	0.15	0.21		0.02		0.01
Mall B - 2	713		0.53	0.18	0.26		0.02	0.01	

Option not applicable

Omitted; assume pedestrian will choose exit closest to their destination

Omitted: limited options available in simulator

Fig. 5. Origin-destination matrix - experiment 1

Experiment 2 (E2). The proportion of pedestrians heading to Malls A and B from Gantries 1 and 2 was increased (from 14–15 number of pedestrians heading to MRT Exits 1 and 2 (from 85–86 62–67 entering via MRT and remaining in the network constant (Fig. 6).

3.3 Results

Point A. Non-zero LOS F pedestrian densities were obtained in all experiments, with the highest observed in E1 (2.97 %). High LOS E pedestrian densities were also obtained (8.15 %, 16.60 % and 8.37 % for C, E1 and E2 respectively) (Table 2).

O/D	No of pp	Gantry 1	Gantry 2	Exit 1	Exit 2	Mall A 1	Mall A 2	Mall B 1	Mall B 2
Gantry 1	3475			0.67		0.17	0.12	0.02	0.02
Gantry 2	3450				0.62	0.02	0.02	0.17	0.17
Exit 1	475	1.00							
Exit 2	550		0.55			0.18	0.18	0.045	0.045
Mall A - 1	587.5	0.60		0.21	0.06			0.065	0.065
Mall A - 2	472.5	0.53		0.26	0.08			0.065	0.065
Mall B - 1	545		0.64	0.11 5	0.16		0.055		0.03
Mall B - 2	445		0.56	0.14	0.20		0.07	0.03	

Option not applicable

Omitted; assume pedestrian will choose exit closest to their destination

Omitted: limited options available in simulator

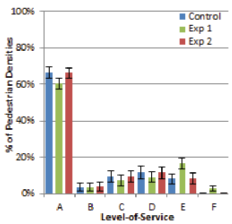
Fig. 6. Origin-destination matrix - experiment 2

Point B. Lower percentages of LOS A pedestrian densities were obtained in E1 and E2 (27.68 % and 28.55 % respectively) compared to C (56.98 %). Higher percentages of LOS E pedestrian densities were obtained for E2 (4.45 %) compared to E1 (1.02 %), while LOS F (0.02 %) pedestrian densities were obtained only for E2 and not for E1.

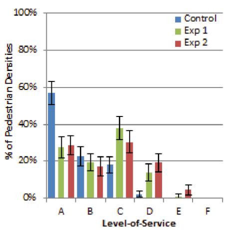
Point C. Lower percentages of LOS A pedestrian densities were obtained in E1 and E2 (51.08 % and 43.57 % respectively) compared to C (79.97 %). Higher percentages of LOS E pedestrian densities were obtained for E2 (1.07 %) compared to E1 (0.32 %). No LOS F pedestrian densities were obtained for all experiments (Table 3).

Summary. Most critical congestion levels were experienced in E2, followed by E1, then C. For Point A, pedestrian densities were unlikely to meet LTA's requirements for all experiments. This indicates that large numbers of pedestrians disembarking from the MRT, combined with the relatively small space between MRT Gantry 1 and Exit 1, are likely to result in high pedestrian densities at Point A. As for E2, more pedestrians were arriving from Malls A and B, instead of from the MRT Exits 1 and 2. This resulted in longer walking distances for pedestrians, and subsequently, longer durations spent in the pedestrian network, which caused increased congestion levels.

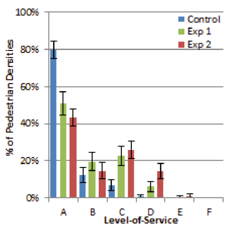
Table 2. Results - proportion of LOS at different points



Point A



Point B



Point C

Table 3. Summary of results

Experiment	Point A	Point B	Point C
Control	Unlikely	Highly likely	Likely
Experiment 1	Unlikely	Somewhat unlikely	Somewhat likely
Experiment 2	Unlikely	Unlikely	Somewhat unlikely

4 Discussion and Conclusion

4.1 Design of Sensor Network

Based on the simulations' results, the following layout of sensors is proposed (Fig. 7). This includes a cluster of sensors at each entry/exit point to measure flows of pedestrians entering, exiting and heading towards and away from the entry/exit points. Additionally, sensors installed along the walkways can be used to measure pedestrian flows, which not only facilitates calibration of the pedestrian simulations, but also provides an immediate estimate of pedestrian LOS experienced along the walkways. From here, subsequent fine-tuning of the model and redesigning of sensor locations will allow relevant stakeholders to better evaluate the design of this pedestrian facility.

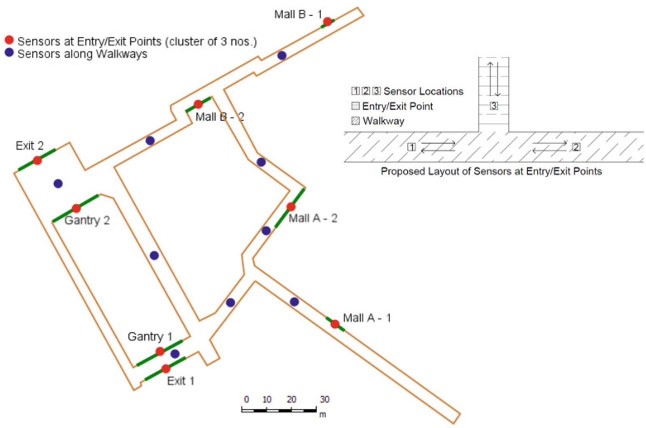


Fig. 7. Proposed Locations of Sensors

4.2 Conclusion

This paper describes an iterative approach to sensor network design by employing the use of pedestrian simulations before and after sensor installation. Prior to sensor installation, researchers can familiarise themselves with the creation and use of pedestrian simulations, and estimate the order of magnitude of expected pedestrian flows. The latter facilitates sensor network design as it informs sensor choice, and identifies critical locations for the placement of sensors to optimise data collection. Upon sensor installation, data obtained from the sensors can be used to refine and calibrate the pedestrian simulations. For example, assumptions made when creating the simulations can be validated/refuted, and estimates of pedestrian arrivals and their routes taken can be adjusted. The simulations also facilitate fine-tuning of sensor network design by identifying locations for the installation of more sensors, or determining additional parameters to be measured by the sensors.

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