A conceptual framework for specifying and developing pedestrian models

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ABSTRACT

Pedestrian modelling is frequently used for making decisions regarding the planning, design, and management of pedestrian areas. For example, the designer of a new shopping mall would be interested in what locations people are likely to be attracted to, or the operators of a large-scale event might like to know where congested areas are likely to occur so they can develop management plans. The outputs of these models can include flows on certain routes, entry and exit counts, and level-of-service graphs.

Computational modelling of pedestrians is sometimes difficult due to the complex and random nature of pedestrian movement. Pedestrians often make unconscious decisions that are difficult to explain or measure. They move at a much smaller scale and in a less constrained manner than other vehicles, meaning techniques developed for modelling other modes of transport cannot be translated to pedestrians easily.

Pedestrians interact with many different kinds of environments. Enclosed spaces can consist of rooms connected by corridors leading to and from exits (eg. office buildings, shopping centres) or can be more open-plan (eg. sports arenas, train stations). Mixed mode environments consist of areas, possibly shared with cars or public transport, which connect the pedestrian to building entrances and other streets. Open areas consist of open areas and/or designated pathways where pedestrians wander and sightsee. Some environments are a hybrid of the above, for example sports precincts or universities, and generally include pedestrian areas or low vehicle traffic areas containing several attractions.

There are also several different types of behaviour exhibited by pedestrians in these environments. Some pedestrians know where they are going, how to get there, and has a very low probability of being distracted on the way (purposeful and familiar). Some know where they want to go, but is not sure how to get there and as a result may get distracted or lost on the way (purposeful and unfamiliar). Sometimes pedestrians have no purpose and are just wandering. On rare occasions, pedestrians may be in panic mode and will behave differently to normal. Two other behaviours are forced waiting, where pedestrians need to wait for an environmental action before continuing (eg. waiting in a queue or waiting for traffic lights to change), and also the incorporation of temporal constraints into their planning (eg. being on time for a train).

A range of techniques have been used for pedestrian modelling. Mathematical approaches typically use differential equations to model the speed and location of pedestrians. Alternatively, cellular automata models employing simple update rules have also proven to be useful. However, the discrete nature of automata based-models reduce their functionality for some applications. Agent-based modelling and simulation has also been explored with some success. Finally, simulations based on aggregate traffic modelling techniques have been used in industry.

Many stakeholders are involved in the development of a pedestrian model, including the client, the practitioner, and the developer. The client requires results that they can incorporate into their decision-making process and communicate to others. The practitioner requires a model that is easily adapted and models the environment closely. The developer must create a model that meets their requirements.

The main factor in selecting an approach is the location and intended use of the area to be modelled. Other factors include the behaviours required and the scale of the model.

We discuss the strengths and weaknesses of each approach for each environment and proceed towards a framework for selecting an approach for the intended application. This framework will be of use to clients, practitioners, and developers. It will play a strong role in the usefulness and reliability of pedestrian modelling in the decision-making process for planning and design of pedestrian-frequented areas.

1 INTRODUCTION

Pedestrian modelling is frequently used for making decisions regarding the planning, design, and management of pedestrian areas. The outputs of these models can include flows on certain routes, entry and exit counts, and level-of-service graphs. Other factors, such as costs and environmental effects, are combined with the model outputs to help management make decisions.

For example, the designer of a new shopping mall would be interested in what locations people are likely to be attracted to. This information could be used to place artwork or amenities such as rubbish bins or seats in appropriate positions. Designated footpaths and garden features may be redesigned in a way that people have to pass less attractive shops or alternatively as many shops as possible.

In another example, the operators of a large-scale event might like to know where congested areas are likely to occur. This information could be used to develop a management plan. Fences may be used to redirect people. The number of security checkpoints at key entrances may be increased to allow faster flow into the event.

Pedestrians often make unconscious decisions that are difficult to explain or measure. They move at a much smaller scale and in a less constrained manner than other vehicles, meaning techniques developed for modelling other modes of transport cannot be translated to pedestrians easily. Computational modelling of pedestrians is therefore difficult due to the complex and random nature of their movement.

This paper is intended to be an discussion of the issues involved in specifying pedestrian models, given the wide choice of approaches and applications. We begin by providing an analysis of the requirements for pedestrian models from both the end-user's and developer's viewpoints by reviewing models developed in research and in industry. We identify the key factors in designing pedestrian models and develop a scheme for selecting a particular modelling technique based on the type of model desired.

2 SYSTEM BACKGROUND

The Australian Pedestrian Council defines a pedestrian as "any person wishing to travel by foot, wheelchair or electric scooter, throughout the community" (Australian Pedestrian Council 2004). There are many reasons for walking, and the manner in which we walk changes depending on the purpose.

> "Commuters scurry; shoppers meander; bushwalkers trek; power-walkers stride; lovers stroll; tourists promenade; protesters march ... But we all walk." (Australian Pedestrian Council 2004)

Transport systems are constrained, sometimes weakly. For instance, people cannot cross the road whenever they feel like it - they should find a suitable place (such as an intersection) and wait until it is safe. They also should travel on the pedestrian network (eg. designated paths) at all times, however if it becomes too congested, pedestrians may overflow onto the road or surrounding parkland. A stricter constraint is that pedestrians cannot walk through solid objects or on water.

Pedestrian behaviour is usually individual-based and autonomous. In most cases, we decide where we want to go and how to get there without being told explicitly. Individually, in the system, there are cooperative elements (letting someone go through a door first, moving out of the way for a faster person) and competitive elements (pushing to get out of a stadium quickly).

There are many types of environments that pedestrians walk in. We propose that they can be categorised by examining the environmental features, walking behaviours, map representation, and the expected volume of pedestrians.

- **small-scale enclosed spaces:** these consist of small rooms connected by corridors and exits. For example, buildings often have many enclosed spaces (eg. offices, meeting rooms). Multistorey buildings will have lifts, stairs, or escalators to facilitate movement between floors. The type of walking trips in this environment are short and purposeful, with little chance of distraction. The number of pedestrians is variable depending on the location and the map representation would be at a small scale.

- **large-scale enclosed spaces:** these are generally larger buildings that are open-plan. For example, sports arenas consist of an area filled with seats, aisles, and exits. Cafes and souvenir stands could also be found within the arena, so queues are likely to occur outside these shops and also at exits at the end of the event. The trips in this environment are likely to be short and purposeful (eg. from entrance to seat, from seat to cafe), but some will be familiar with the environment, others not. Another example is an airport or a train station, where the main purpose of walking is to change between pedestrian and public transport mode. Another issue with these environments is that temporal constraints are present, in that one needs to catch a train/plane at a particular time (hard constraint) or one should aim to arrive for the start of a sports match (soft constraint). These environments would contain a large number of pedestrians in a small area.

- **mixed mode:** this environment consists of a area, possibly shared with cars or public transport, which connects the pedestrian to building entrances and other streets. The pedestrian has static objects (eg. public seating, rubbish bins, garden areas) to navigate around. Another element of this environment is a queue, which can be either an ordered queue of people waiting to get into a busy shop or an unordered queue of people waiting to cross the street or waiting for a bus. The trips in this environment are likely to be a mix of familiar trips with a purpose (eg. those who are walking to work), purposeful but unfamiliar trips (eg. I need a pharmacy but I don't know where one is), and purposeless trips (eg. a shopping trip to the city).

- **open space:** this consists of open areas, possibly with some designated pathways. The purpose is most likely to be leisurely, so the behaviour will consist of meandering, frequent stopping, and possibly longer stops for picnics or sightseeing.

- **hybrid:** this category includes generally pedestrian areas or low-traffic areas containing several attractions, such as sports precincts or universities. It will consist of a combination of behaviours from the open space environment (eg. meandering, afternoons on the lawn), the mixed-mode environment (eg. avoiding vehicles, queueing for public transport), and the enclosed spaces environments (eg. moving around lecture theatres).

In these descriptions, several behaviours were mentioned. We consider these behaviours to be the key behaviours that occur in a model and would influence the type of model required.

- **purposeful and familiar:** the pedestrian knows where they are going, how to get there, and has a low probability of being distracted on the way.

- **purposeful and unfamiliar:** the pedestrian knows where they want to go, but is not sure how to get there and as a result may get distracted or lost on the way.

- **purposeless:** the pedestrian is in wandering mode.

- **evacuation/panic:** the pedestrian is in panic mode and will behave differently to normal. If this behaviour is required, it will be the main focus of the model and other behaviours will probably not be included.

- **forced waiting:** this behaviour occurs in environments where pedestrians have to wait for an action to happen before they can continue. For example, they may wait in a queue to buy a train ticket, but they have no control over this queue. Another example is a unordered queue at a traffic light where pedestrians must wait for the green light.

- **temporal constraints:** these occur in train stations and airports (so-called hard constraints: the train leaves at a certain time and if you miss it, you miss it completely) and also at sporting events (soft constraints: you can arrive slightly late for the game, but you can still be admitted and see most of it). Temporal constraints have not always been considered in pedestrian models, but from our experience are a requirement for accurate outputs for some environments.

3 TRANSPORT MODELLING AND PLANNING

Transport planning is a decision-making process in which the problem is identified, strategies are developed, modelled and evaluated, and the most preferable solution is recommended for implementation (Ortúzar & Willumsen 1994). The evaluation of strategies involves examining the effects on stakeholders and the environment and can be undertaken in many ways. Several strategies could be selected for a trial run, however physical tests are not always feasible. For example, it is impractical (not to mention expensive) to build several versions of a pedestrian bridge in order to evaluate the option with the most benefit. In these cases, computers are used to set up an "artificial reality" - a computer model or simulation - which is used to test different strategies.

The inputs to transport models usually include demographic data (age, sex, place of residence, type of work), land use data (assists in determining attractability of certain locations), and demand drivers (what locations are popular, what times are people travelling). This data is sourced from public data, such as census and land-use data, and data collected specifically for the model, such as the results of an observation or a questionnaire survey. The results of transport models can include economic, environmental and social data.

A common use for pedestrian models is in the organisation of large, usually once-off events. These events include Olympic and Commonwealth Games, other international sporting events such as tennis, grand prix and world championship events, and street festivals. Planning for these events is a difficult task, as there is little historical information about pedestrian behaviour and the only opportunity to

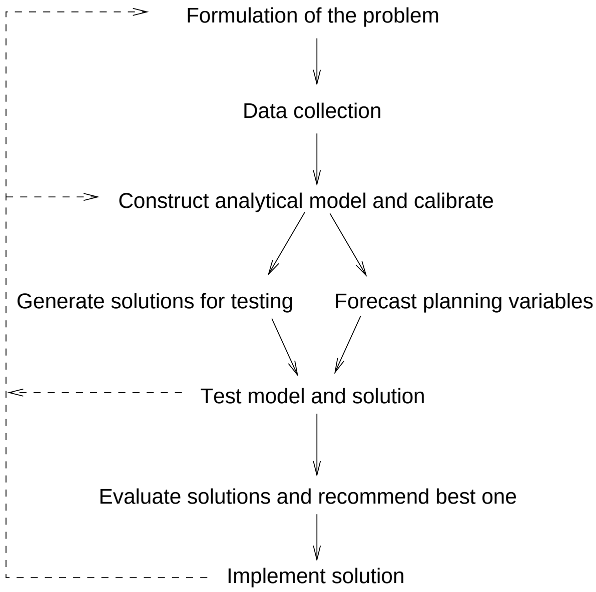

Figure 1. Key steps when using models in the decision making process for transport systems (Ortúzar & Willumsen 1994).

collect data is at the event itself. The organisers often have several planning issues, such as the location of security barriers and food stands and whether to build or upgrade infrastructure. Modelling can assist in developing mitigation plans or decide between two infrastructure scenarios.

Most transport modelling techniques have focused on the modelling of cars and vehicles on the road network (Batty 2001), due to the detail required for a realistic pedestrian model. The recent interest in environmentally sustainable transport modes however, has led to an interest in providing better infrastructure and facilities for cyclists and pedestrians and therefore a need for improved methods of modelling their behaviour.

4 REVIEW OF MODELLING APPROACHES

Many approaches have been used for modelling of pedestrian behaviour (Harney 2002). In terms of classification, there are four main approaches to modelling pedestrians: mathematical models, cellular automata/swarm models, traditional time-based simulation/microsimulation, and agent-based simulation.

Mathematical models are based on mathematical and physical equations. One form of the mathematical model is based on physical formula of motion. The modelled pedestrians have properties, including current position and speed. These models use the notion of force to move pedestrians around. Some of the force parameters include acceleration force, repulsive effects of boundaries and objects, repulsive effects of other people, and attraction to groups and objects. These models would use a metric representation of the environment and require plenty of interaction between the pedestrians to produce interesting results, hence they are commonly use for crowding models. Helbing used the notion of attraction and repulsion to model microscopic behaviour and has developed complex equations to model a range of pedestrian behaviours, commonly referred to as the “social force” model. (Helbing, Molnár, Farkas & Bolay 2001). He observed that streams formed in the crowds and resembled fluid flow. Hoogendoorn & Bovy (2004) used the same starting point of basic mechanics formula and developed a three-layered model encompassing activity choice, wayfinding, and walking. This model attempts to minimise the cost of walking and was applied to a multi-modal transfer station. Another mathematical model is the the use of statistical methods to estimate the flows on particular links. This method has been used with success by Intelligent Space (2005) and SpaceSyntax (2004), mainly for larger models of pedestrian movement in cities.

A similar approach is the use of cellular automata (CA), where pedestrians occupy cells on a grid and move according to some simple rules. This is a variant of the traditional CA models (eg. Conway’s Game of Life) where cells have a state which changes depending on the state of the surrounding cells and there is no explicit movement involved. These models generally use a grid-based model where one person can occupy a cell at once, hence the representation of large areas requires a large number of cells. Most of the models based on this approach used the Schreckenberg-Nagel approach to modelling vehicle traffic using CA as a starting point (Nagel & Schreckenberg 1992). Recently CA were used to model pushing behaviour in crowds leaving a sporting event (Henein & White 2004). The environment representation included two layers of information: a static layer pointing to the nearest exit and a dynamic layer containing the general direction of the crowd. Each pedestrian uses the information at their particular cell to decide where to move to next. An issue with CA models is what to do when a collision occurs, as this behaviour is not present in the traditional CA model. This has been explored for basic movement in a corridor but with the pedestrians learning what to do when a collision occurs (Narimatsu, Shiraishi & Morishita 2004). Cellular automata have been shown to be useful for disaggregate models with minimal activity choice. AlpSim (Gloor, Stucki & Nagel 2004) combines a cellular automata approach with aggregate representations of the environment to take advantage of the benefits of multiple map representations, specifically higher-level planning which is very complex using only a grid.

Traditional time- and event-based simulation has also been used in industry. In this approach, all pedestrians are controlled by an object who tells them where and when to move. It is useful for aggregate models as all the information can be easily combined. These models generally use a graph-based representation of the environment, where possible paths are represented as edges and decision points as nodes. PAXPORT, a microsimulation tool developed by the consulting firm Halcrow, has been used to model pedestrian movements in airports, train stations, and sporting venues. It provides aggregate measures of flow and level-of-service in a graph-based environment. It was recently used to model behaviour in the Sports and Entertainment Precinct, Melbourne in order to select a design for a new bridge to be built for the 2006 Commonwealth Games (Ronald 2004).

Agent-based simulation is frequently used for models where there are distinct entities who are interacting with each other in a environment. The entities in the model are software agents, who have the ability to perceive, make decisions, act, and learn from their environment. The approach has been used for economic, social, business and logistics modelling, where there is a lot of interaction with the environment and other agents and also complex decision making involved. These models generally use a graph-based representation of the environment, however a metric representation is also possible. Legion (2004) is proprietary software specialising in modelling crowd behaviour and was first developed as a model of ingress and egress from events (Still 2000). It treats each person as a "virtual person" who senses their environment and makes decisions about where to move accordingly. Applications of Legion include train stations, sporting events, and evacuation scenarios. It was successfully used for decision making for the Sydney Olympic Games. We have also been exploring the use of of the BDI architecture for modelling pedestrian behaviour (Ronald & Sterling 2005).

5 REQUIREMENTS ANALYSIS

There are several stakeholders in the development of a pedestrian model. The roles of people involved in the development of the model have not been researched in depth, but are of interest to agent-based modelling (Drougoul, Vanbergue & Meurisse 2003).

The client has a need for forecasts and is likely to be a planner or event organiser. They are likely to have or have access to the most information about the domain, including the problem and the environment. They will have observed the environment and would provide information about the current situation in the form of current usage or environment layout. They can sometimes provide their opinion on the cause of particular behaviours. They will also usually provide a set of scenarios, which will assist them in making their final decision. However, clients have their own notion of what will happen for certain scenarios and are sometimes sceptical if the model reports differently.

The practitioner is likely to be an engineer or planner and needs to provide a service to the client, including provision of forecasts and analysis of scenarios. They interface between the client and the developer and therefore require some knowledge of both those roles.

The developer creates a model that is representative of the reality. They may develop a model from scratch (eg. in Microsoft Access or .NET) or use an existing package (eg. PAXPORT). They need to have good understanding of the features of the package/language, so that they can suggest modelling methods to the practitioner. The model needs to meet the requirements of the practitioner and the client.

A person may perform one or more roles, eg. the practitioner and developer may be the same person. Each role has different requirements for the model.

The client's needs are:

- an understanding of the model scope: they need to understand (at a high-level) the behaviours the model can create, in order to make a judgement about the validity of the model. They also need an understanding of the environment constraints. If they are interested and/or experienced in modelling, they would also like an understanding of the model parameters.
- results in a variety of formats: these include charts and maps for reports. 2D and 3D animations are also useful for presentations to senior stakeholders or the community, as it provides a more realistic feel for the effects of the scenario.

The practitioner's requirements are:

- ease of use: the package should follow current software engineering principles and should be straightforward to use. Graphical user interfaces should be intuitive and input and output data should be read and written to appropriate locations and in an easy-to-manipulate format.
- a clear understanding of parameters: the parameter should have some resemblance to the real world. It should also be clear what the intended effects of each parameter are, if changed in isolation. With emergent models this may not always be possible.
- the ability to modify parameters quickly and easily: again, the GUI should enable parameters to be changed easily. It should not take long to make changes to several parameters to set up a new scenario.

- the ability to read in environment data from various sources, including temporal constraints: environment data is extensive and there are various representations that can be used.

- flexibility with output: the practitioner should be able to select different outputs to suit the project and the client's needs. This involves selecting different calculations and at different environmental scales (eg. block, street, area, model) and at different times (peak/offpeak).

- a reasonable running time: often a large number of scenarios need to be developed and analysed, so model running time is a key factor. Often practitioners will not have access to a dedicated model-running machine.

6 SELECTING AN APPROACH

In software engineering, the language or package to be used for building a system is dependent on the requirements of the system. However, in practice, the development environment is usually chosen before the requirements are set out. This could be because the developers have extensive experience in a particular package, or the client prefers a particular package.

With modelling, the same sometimes occurs: the approach chosen is the approach one of the stakeholders is the most familiar with. The client may want a model they can reuse or adapt in the future and this puts a constraint on the selected approach. The practitioner may also be more familiar with one approach over another. This is not necessarily the best tool for the job and ideally the approach should be chosen based on the requirements of the model.

For pedestrian models, there are several key factors that can point to an approach being more suitable than another.

In section 2, we identified five areas and six behaviours that may be modelled. Not all behaviours are present in the chosen environment or are of significant interest to clients. Some approaches suit the environment or behaviour better than others. For example, an agent approach is more suitable when there are complex decisions to be made about activities and moving through the environment.

Scale is also a key factor in choosing an approach. This includes both the number of pedestrians to appear in the model as well as the size of the environment and the detail required. The choice of the scale of the model is also related to the outputs. If approximate volume counts are required, then an approach that models the exact steps of each pedestrian is unnecessary.

As the first item to be decided usually is the location (or type of location) to be simulated, this should dictate the approach chosen. From our experience, it is common for clients to decide later the exact outputs required.

Small-scale enclosed spaces
Behaviours: direct, some wandering, possibly evacuation
Office buildings consist of mostly direct trips, whereas shops and other "leisure" buildings would have a combination of direct and distractable trips. A CA approach would suit the former, as there would not be enough traffic to require a mathematical approach and the microsimulation and agent approaches would be too complicated. For "leisure" buildings, an agent approach would be preferred, in order to see the individual choices that people make when moving through the area.

Large-scale enclosed spaces
Behaviours: direct, some congestion and queueing, hard and soft temporal constraints, possibly evacuation
A microsimulation approach would be good as this could model the queues and level of service at exits easily. For more detail of the crowding, a mathematical or CA model could be used. As there is minimal decision making involved in the environment and the pedestrian count may be high, an agent approach may not be appropriate, however Legion has also been used for arenas and train stations (Legion 2004). PAXPORT was designed for the airport and train station environments.

Mixed mode
Behaviours: direct, wandering, queues, congestion
All approaches are suitable for a mixed mode environment, however if the model is too large in area a CA model would probably be unsuitable, due to the detail of the environment. The models developed by Intelligent Space and Space Syntax would suit this environment. Agent-based simulation and microsimulation could also model the vehicles in the environment, especially public transport vehicles that are effectively an exit from the pedestrian model.

Open space
Behaviours: wandering, bushwalking (leisure), picnicking
Depending on the level of choice involved in the model, the best approaches are a microsimulation approach or an agent approach. There is not enough interaction or congestion to warrant a mathematical approach or a CA approach. Ideally the model should scale between a large block representation and smaller units. Itami & Gimblett (2001) have successfully used agents to model the decision-making behaviour of people in recreational settings.

Hybrid environments are complex and it is difficult to generally recommend an approach. It may be necessary to create more than one model to retrieve the required outputs.

7 CONCLUSION AND FUTURE WORK

This paper presented an analysis of the requirements for pedestrian models from both the end-user's and developer's viewpoints by reviewing models developed in research and in industry. We explored the key factors in designing pedestrian models and began developing a framework for selecting a particular modelling technique based on the type of model desired.

This framework will be of use to clients, practitioners, and developers. It will play a strong role in the usefulness and reliability of pedestrian modelling in the decision-making process for planning and design of pedestrian-frequented areas. The practitioner and client can use it to select the best approach to solving the client's problem. The client, depending on their knowledge and interest, can also verify that a defined process has been followed for the specification of the model.

The next step is to develop the framework further by investigating the inputs and assumptions required for each approach, developing recommendations for hybrid environments, and creating case studies. Experimentation with some of the approaches will also be undertaken to test their suitability for different applications.

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