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STREETS: AN AGENT-BASED PEDESTRIAN MODEL

Thorsten Schelhorn
David O'Sullivan
Mordechay Haklay
Mark Thurstain-Goodwin

UCL

Centre for Advanced Spatial Analysis
University College London
1-19 Torrington Place
Gower Street
London WC1E 6BT

Tel: +44 (0) 171 391 1782
Fax: +44 (0) 171 813 2843
Email: casa@ucl.ac.uk
http://www.casa.ucl.ac.uk

http://www.casa.ucl.ac.uk/streets.pdf

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ABSTRACT

In this paper we present a two stage model for investigating pedestrian behaviour in urban centres. Pedestrian movement is influenced by both configuration and the location of attractions. An examination of agent-based models shows that this new approach is well suited to integrating these aspects. An overview of the two stages of the STREETS model is presented, focusing on the division between the two stages: the first using GIS-based socio-economic data to populate the second stage which is an agent-based dynamic model of pedestrian activity. Some suggestions for development of this work are made.

Introduction

People are important in towns. They are the foundation of the social and economic processes that drive the urban system and sustain the urban fabric. While people spend much of their time inside buildings — at home, at work, and at play — it is the movement of people, whether in vehicles or on foot, that is indicative of the vibrancy of the town.

This vibrancy is usually most evident in the central area of the town. The town centre is still the engine that drives the wider urban system. More often than not it is the social, economic and cultural heart of the town and it has been argued that understanding the movement of people in town centres is an important factor in understanding the way in which town centres work (Londonomics, 1998; Thurstain-Goodwin and Batty, 1998). In the UK, planners have been particularly interested in pedestrian movement for assessing the vitality and viability of town centres. "[T]he numbers and movement of people on the streets, in different parts of the centre at different times of the day and evening, who are available for businesses to attract in to shops, restaurants or other facilities" (DoE 1996) are central to this assessment.

It is not just the planner who is interested in pedestrian movements in town centres. The retail industry has a particular interest since retailers aim to locate their shops in areas which can attract a lot of passing trade. While planners and retailers are the most obvious groups, it is clear that others (such as the emergency services) have an interest in understanding the way which people move in an urban setting.

The need to understand the way in which people move through towns leads to the desire to predict pedestrian movement - either to assist in identifying the likely impacts of pedestrianising a city street, identifying the optimum location for a new shop, or assigning and allocating staff to manage a street festival.

This paper describes an agent-based model (the STREETS model) which is intended as the beginning of such predictive models. In section 2 we outline some previous approaches to understanding and predicting pedestrian movement. Our brief survey suggests that in spite of its importance, this field is under-researched. It seems clear that this has been largely due to the absence of sufficiently powerful computers and suitably rich data sets. In section 3, we move on to show how recently developed agent-based modelling techniques have been applied to various problem domains, and suggest their suitability for pedestrian modelling. The remainder of the paper describes in outline an agent-based model which retains some of the strengths of earlier models by using rich data sets stored in a geo-information system (GIS). We conclude with some ideas for further development of the current model.

Explaining pedestrian movement patterns

Pedestrian activity can be considered to be the product of two distinct components — the configuration of the street network and the location of particular attractions (shops, offices, public buildings etc.) on that network. In order to explore the influence of each of these, it is first necessary to observe and record the movement of pedestrians in city streets.

Traditionally, records of pedestrian movement in the street network have been based on physical counts or time lapse photography work. Physical counts involve recording the number of people passing set points, or *gates*, on the network over a set period of time to give an initial sense of flow through the network. Time lapse photography takes this forward by recording the movement of all pedestrians in a defined area and drawing 'trail' diagrams to plot their actual movement.

While these techniques are able to give an indication of the relative intensity of movement in an urban setting, they cannot explain the processes which cause them, and certainly cannot be used to predict future patterns. An early attempt to extend these techniques was made by Fruin (1971) who devised the Levels of Service (LOS) indicator. LOS attempts to measure the level of comfort of pedestrians in an urban setting. It quantifies congestion by measuring the flow of pedestrian per unit width of walkway. Six levels of Service are identified from A (free flow with typically less than 23 people per minute per metre of walkway) to F (extreme congestion, more than 82 people per minute per metre of pavement) where progress would be by means of shuffling.

Arguably, LOS only measures the outcome produced by the current combination of street configuration and attractor locations. It certainly does not make it any easier to disentangle the effects of the two, or to predict the impact of changes in either. The first attempts to investigate the impact of spatial configuration at this scale were in the work of the Centre for Land Use and Built Form Studies at Cambridge University (March and Steadman, 1971; Martin and March, 1972; Steadman, 1983), which focuses particularly on some of the problems of applying geometry and other mathematical tools to the description and analysis of the complex layouts typical of large buildings urban systems. Research in this field is still active (see Krafta, 1994; 1996).

Configuration is sometimes assigned an almost mystical importance. Some researchers argue that the main generator of pedestrian movement is the configuration of the street network itself, and that patterns of movement are largely determined by this configuration, rather than by the distribution of attractors within the network (Hillier et al., 1993). This is an extreme view which is difficult to sustain without recourse to *ceteris paribus* arguments. In particular it ignores the evidence of changing land use patterns on movement rates. The original high street of Gravesend, for example, is no longer the main shopping location in the town because the port area has been in decline for some years. The actual street configuration has not changed, but the location of shops has, ultimately in response to changing activity patterns of the town's inhabitants (URBED, 1997).

This is not an isolated example and the importance of attractors in determining patterns of movement in urban systems has long been recognised. "Vehicles do not move about the roads for mysterious reasons of their own. They move only because people want them to move in connection with activities which they (the people) are engaged in. *Traffic is therefore a function of activities. This is fundamental.*" (Ministry of Transport, 1961).

Usually associated with traffic and retail impact modelling, the use of gravity or spatial interaction techniques has a long and distinguished history in modelling the relationship between attractions and movement (Foot, 1981; Batty, 1976). These models use a general formula for the interaction between two locations *i* and *j* of the form

$$A_i \, B_j \, / \, f(C_{ij}),$$

where A_i is the population at *i*, B_j is some measure of the attraction of facilities at location *j* (for example retail floor space), and C_{ij} is some measure of the cost or distance from *i* to *j*. The form of function *f* is usually described by a number of parameters, and survey data is used to calibrate models based on these techniques. Where *C* is distance, it usually represents Euclidean distances on an isotropic plain, or distances between points over the road and transport networks. These models enable prediction of the intensity of interaction between where people start their journeys (the origins) and where the are going (their destinations), and form the basis of many transport planning models.

The approaches introduced in this section have rarely been successfully applied to modelling pedestrian movement at the scale of buildings and streets. While this can be partly explained by the absence of adequate data at this level of detail, ultimately the underlying assumptions (such as using Euclidean distance or shortest paths through the network in gravity models) are less applicable at small spatial scales. Furthermore, they are only suited to modelling general patterns of movement and can never be used to model the movement of individuals.

In the next section a new modelling approach is considered which may resolve this difficulty.

Agent-based models

Definitions

An agent-based model is one in which the basic unit of activity is the agent. Usually a model will contain many agents (at least tens, occasionally many thousands) and its outcomes are determined by the interactions of the agents. Usually agents explicitly represent actors in the situation being modelled - often at the individual level. We will not define agent explicitly, but instead focus on the properties most often possessed by agents.

Broadly speaking an agent is an identifiable unit of computer program code which is *autonomous* and *goal-directed*. Autonomous in that an agent is capable of effective independent action and goal-directed in that its autonomous actions are directed towards the achievement of defined tasks. Agents may possess other capabilities in addition to these two (for example, intelligence and adaptability) but these are essential to a definition which distinguishes agents from ordinary software objects. However, agents *are* a kind of software object, and agent-based modelling is greatly eased by use of object-oriented programming techniques.

Examples

Reynolds' (1987) Boids model of the flocking behaviour of birds, is a straight-forward application of the agent modelling approach to a previously difficult problem: how do birds (or other 'flocking' animals) synchronise their movements so that the whole flock seems to have a common purpose. The Boids model is based on a set of simple rules governing the behaviour of individual 'boids' in relation to their near-neighbours in the flock, which nevertheless successfully emulates the complexity of flocking behaviour. A similar sort of model is Helbing's (1992; Helbing and Molnar, 1997) modelling of pedestrian group behaviour at the micro-scale, which successfully accounts for queuing effects at doorways, and the formation of ‘lanes’ on pavements.

Other readily understood examples where simple agent behaviour in response to their local environment can lead to emergent group behaviours are provided by Epstein and Axtell’s (1996) *Sugarscape*, Portugali et al. (1997), Arthur (1994), and Hegselmann and Flache (1998). The latter points out that this sort of approach is not new, citing work by Schelling (1971), and Sakoda (1971).

Commentary

It is important to realise that agents are not necessarily spatially located or aware. In many of the models mentioned in the previous paragraph ‘space’ functions more as a metaphor for ‘social distance’. The implications of these models’ outcomes for actual spatial outcomes are not really considered, because the interest is in understanding how individual behaviours lead to global outcomes, not in modelling per se. The agents in the STREETS model are mobile and spatially aware, since one of their primary tasks is navigation in a representation of a real spatial environment. This is the main mechanism by which spatial configuration affects behaviour in the STREETS model.

An important distinction between agent-based models is the extent to which agent behaviour is determined by limited local information, or by overall knowledge of global outcomes. This distinction is closely related to that between reactive and cognitive agents, which is explained by Ferber (1994). All the models in the foregoing incorporate reactive agents whose behaviour is a of a ‘stimulus-response’ kind, occasionally with the addition of adaptive mechanisms. Cognitive agents, in contrast, incorporate some model of their world into their decision making framework. Examples of cognitive agents are found in models of societal development in archaeology (Doran et al., 1994; Lake and Mithen, 1998; Mithen, 1994).

In STREETS most of the cognitive work done by agents occurs outside the dynamic part of the model. Socio-economic data is used to populate the model with a variety of agents whose behaviour is likely to be different (see section 4 below). This means that STREETS integrates the effects of configuration and attractors, in an obvious way through their effects on agent behaviour.

Agents in urban and regional planning

Agents have been considered in the urban and regional planning context in a number of different ways. Our main concern here, is in the field of spatial simulation. Before considering examples of this, it is worth mentioning other applications of agents in GIS and decision support; Rodrigues et al. (1997) provide an overview, and consider examples of multi-agent approaches to spatial decision support, GIS user interface development, and information retrieval in large spatial datbases. MacGill and Openshaw (1998) present an intriguing multi-agent approach to spatial data analysis.

Returning to spatial simulation in urban and regional planning, it is difficult to find examples of agent-based models. Of course, Boids and its relatives are spatial simulations, and Helbing and Molnar’s (1997) work has implications for the design of human spaces at some scales. Cellular automata models for simulation of road traffic are relatively common (see for example, Esser and Schreckenburg, 1997; Chopard et al., 1995; 1996), but do not really fit the agent modelling paradigm.

However, the only substantive application is the monumental TRANSIMS (Beckman, 1997), initially developed to model the road-traffic of Albuquerque and now being extended to other examples. TRANSIMS is a hybrid - somewhere between more traditional transport gravitation-interaction models based on transport analysis zones and their socio-economic characteristics and a full-blown real-time agent-based simulation of the activities of (currently) up to about 200,000 individual travellers. This is where the model departs from previous transport planning models. Individual travellers, having been 'loaded' into the model, with plans based on their socio-economic characteristics then act as agents as the model runs, changing their route from that planned in response to changing road conditions, such as congestion or accidents.

The STREETS model

The STREETS model is close in approach to TRANSIMS but takes as its subject the activities of pedestrians in sub-regional, urban districts. Modelling proceeds in two phases: (i) a 'pre-model' which uses socio-economic and other data about the wider metropolitan area to populate the urban centre with a statistically valid population of pedestrians; and (ii) an agent-based model to simulate the movement of this pedestrian population around the urban district under the influence of spatial configuration, pre-determined activity schedules, and the distribution of land-uses.

The pre-model phase is described in this section. The agent-based model based on the Santa Fe Institute's Swarm simulation system (Minar et al., 1996) is described in more detail in the next section. The figure below shows the division of data and processing steps between the two phases.

Creating pedestrians

Initial loading of the model with pedestrians with intended activity schedules is achieved using rich socio-economic data sets in a GIS setting. These pedestrians are then 'released' into the district being modelled as agents who may choose to change their plans in response to their surroundings and the behaviour of other agents.

Currently simple statistically determined distributions of agents are generated. Each agent has characteristics under two broad categories: *socio-economic*, and *behavioural*.

Socio-economic characteristics relate to income and gender, and are used to create an activity schedule for the agent, that is a sequence of locations which the agent intends to visit once in the town centre. This schedule is refined using shortest-path determination on the street network so that the agent has a pre-determined plan, which defines a route that it intends to take in the model. It is envisaged that this phase of the model will be enhanced considerably in later versions of STREETS, perhaps introducing the travelling salesman algorithm, for example. For example, provision will be made for agents with different levels of knowledge about the urban centre, and hence non-optimal paths from location to location.

Behavioural characteristics contribute to the detailed behaviour of agents. Factors include speed, visual range, and fixation. Speed is simply the maximum walking speed of which an agent is capable. Visual range relates to an agent's visual acuity and determines which buildings and other elements in the environment the agent will 'see' and potentially respond to. 'Fixation' describes how focused an agent is on following the pre-set activity schedule. Variations in this element allow different behaviours to occur. Some agents with high fixation are likely to follow their plan almost exactly, whereas those with low fixation will be easily distracted, visiting shops which they never 'intended' to visit, and even dropping whole sections of their original plan.

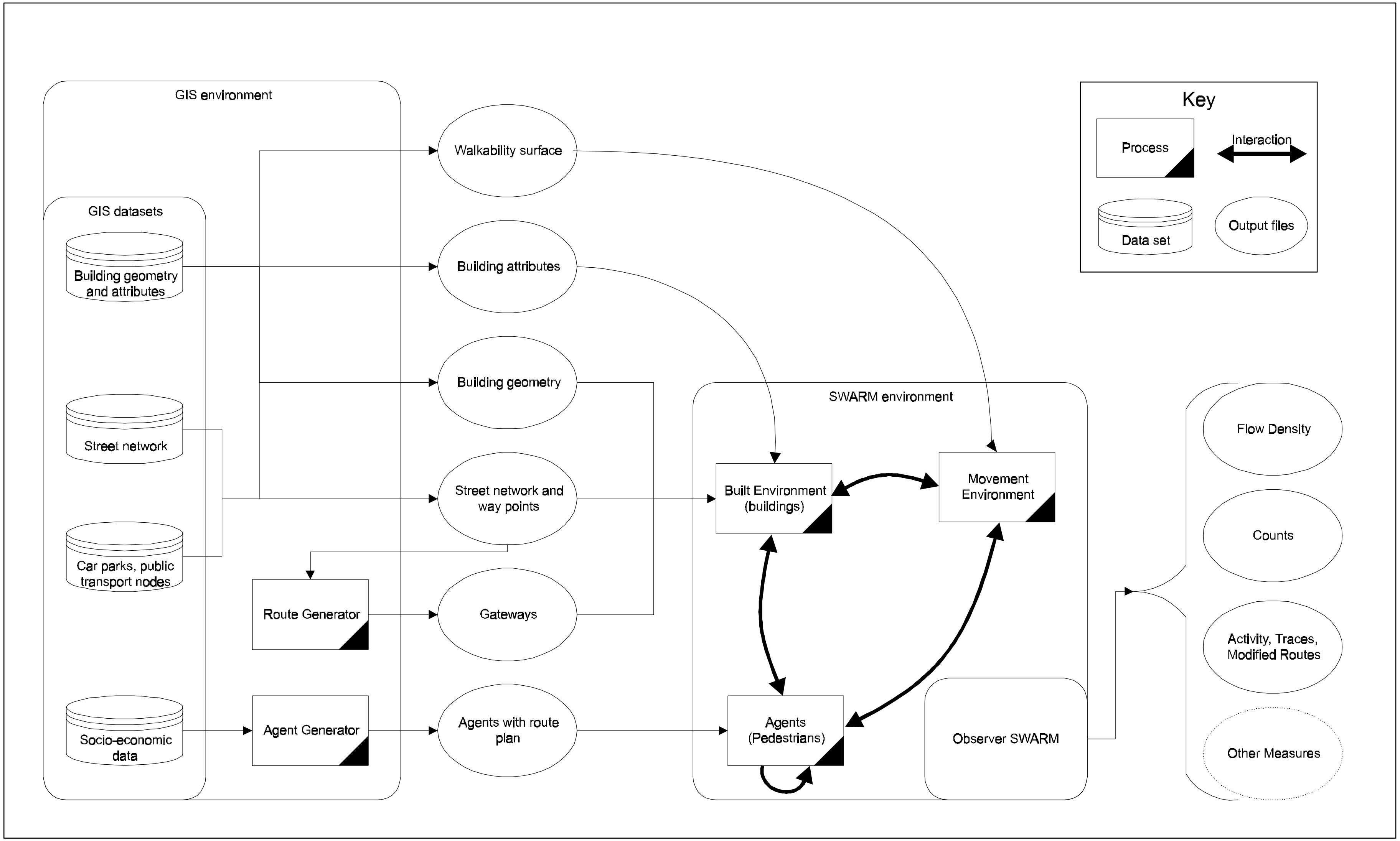

Figure 1: *Block diagram of data and processing flows in STREETS*

Arrival in the urban centre

Pedestrian agents are taken as arriving in the modelled area at ‘gateways’, representing car parks, on-street parking areas, bus and railway stations and bus stops. Currently, gateways are static elements during the simulation phase. They simply ‘release’ pedestrians at the predetermined rate, according to a Poisson distribution. It is anticipated that as the model is developed, gateways may be modelled more fully so that the full variety of observable events is included. For, example the arrival of trains at a station requires a more complex model than a Poisson distribution to capture the arrival of people in groups.

The urban district

The urban district being modelled is represented using detailed data from a GIS. A number of representations are used:

Vector data of building outlines, with the land-use categories. Currently land-uses are arbitrary (classes 0, 1, 2) but this can easily be extended to a detailed breakdown. Such a breakdown would probably be hierarchical with residential, commercial, administrative at the highest level, and a detailed breakdown of commercial and administrative functional land uses.

Raster data representing the ‘walkability’ of all the non-building spaces. Pavements are highly walkable, and roads are less so. This abstraction allows the model to handle some complex issues (such as ensuring that agents walk on pavements and rather than in the middle of streets) in a fairly simple and robust way. Since the raster resolution is about one square metre per pixel, the presence of an agent in a particular pixel make it less walkable, this avoids the requirement evident in models like Boids for computationally intensive geometry in the avoidance behaviour of agents, since buildings, roads, street furniture and other agents are all part of the walkability surface.

Network data representing the street network, and building entrances. The street network is used in the generation of agent routes.

Implementation

As mentioned above, the second (dynamic) phase of the STREETS model was developed completely within the Santa Fe Institute’s SWARM simulation environment. The processes in the pre-model phase save computation time at runtime and enable the SWARM model to focus on the dynamic aspects of the model. A full description of SWARM is beyond the scope of this paper, and we refer the interested reader to Minar et al. (1996).

The STREETS model starts by creating the pedestrian swarm, and populating it with different elements — buildings, the walkability surface, agents (with their route plans). Agents are then ‘sent’ to the gateway from which they will enter the system. Once these parameters have been loaded, the model run can be started.

During the model run, agents are dispatched from the gateways. Each agent enters the model with a sequence of way-points along their intended route, not an explicit encoding of the precise route geometry. Agents use 5 levels of behaviour, programmed as modules, to navigate and find their way in the system. These levels enable the agents to compute separately local movement (the process of moving to the next grid square), and medium-range movement (trying to move in a straight line to the next way-point while avoiding dead-ends), while the longer range movement (keeping track of the whole route) is handled by another module. This combination of modules allows each agent to find its own way from way-point to way-point. A feature of way-points is that they are not dimensionless points but have areal extent. An agent uses this extent to decide when it has reached one way-point and can start looking for the next.

All the modules described so far, implement deterministic way-finding — movement in space according to a pre-defined plan. To enable interaction between the agents and the surrounding environment, another level of behaviour was introduced by implementing a 'vision' module. This module enables the agent to search the nearby visible environment and to recognise buildings near its route. Periodically, the possibility that a building which an agent has 'seen' in this way, will distract the agent from its pre-defined plan is calculated.

Various parameters are used in determining the likelihood of such distraction:

- the match between agent type and building type. Thus, we assume that an agent who is shopping might be attracted to enter another shop during her journey, but is less likely to enter an office building.
- the attractiveness of the building. This aspect of the model is under-developed, and determining suitable attraction factors still requires further work.
- the level of fixation of the agent, which is a general behavioural characteristic of individual agents (see section 4.1 above). This simulates the fact that some people are simply more easily distracted than others. Fixation is defined when the agent is created in the system, and interacts with the agent's internal clock, which measures the time that the agent has planned to stay in the system. As the amount of time remaining decreases, the agent is more focused in completing its tasks and in some cases some way-points will be dropped from the route plan, and the agent will head to its exit gateway.

Another factor in the system is the behaviour of buildings. Once an agent enters a particular building, she will be released back to the continue her journey according to parameters describing the building. The most important of these is the average time that needs to be spent in this building. If a building is becoming crowded, then the average time of agents in the building will increase.

The whole simulation can be monitored by an observing swarm, which collects information about the interaction in the model. Currently, we are developing a 'gate' which counts the number of agents passing its location on the street network. SWARM offers a rich set of tool to develop and extract information from a model run, and those tool will be used to collect statistics about agent movement, the popularity of different buildings under different configurations and so on.

Figure 2 shows the user interface of the STREETS model during a run.

Further development

It will be clear from the foregoing that there is scope for a great deal of further development of the STREETS model.

Currently some of the agent navigational behaviour is unreliable, and we hope to use ideas from

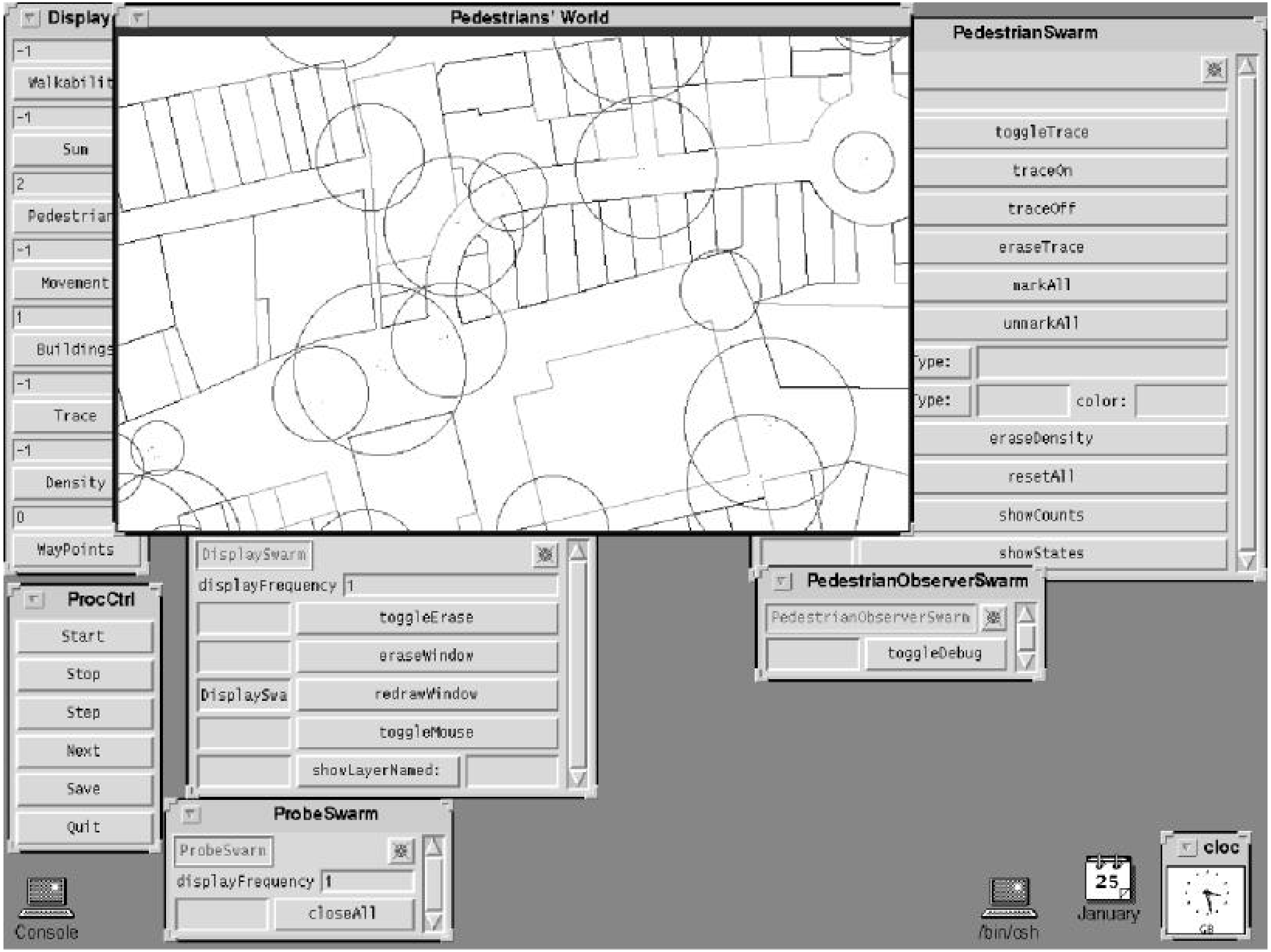

Figure 2: *Screen shot of the STREETS model running*

Helbing and Molnar's (1997) work to improve this aspect of the model. We also hope to incorporate some group behaviours into the model, so that agents might meet with friends, and subsequently move around in groups.

As has been noted the matching of buildings with agents and the problem of setting values of building attractiveness needs further development and will be crucial to making a useful decision support tool from the model.

Other work will be focused on extending the range of measures which can be extracted from the model runs.

Once this has been done, we intend to run a series of experiments to investigate the ways in which configuration and the location of particular popular attractions interact to produce patterns of observed movement. We will report on this work in due course.

Nevertheless, it is clear from the work already done that the agent-based modelling approach is highly applicable to this field. It is also clear that the application of socio-economic and other data to populate such models with representative populations is viable and promises to enhance the prospects for this modelling approach in urban planning more generally.

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