*Environment and Planning B: Planning and Design* 2001, volume 28, pages 343 – 359

DOI:10.1068/b2758t

# "So go downtown": simulating pedestrian movement in town centres

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Received 15 July 2000; in revised form 2 November 2000

**Abstract. Pedestrian movement models have been developed since the 1970s. A review of the literature shows that such models have been developed to explain and predict macro, meso, and micro movement patterns. However, recent developments in modelling techniques, and especially advances in agent-based simulation, open up the possibility of developing integrative and complex models which use existing models as 'building blocks'. In this paper we describe such integrative, modular approach to simulating pedestrian movement behaviour. The STREETS model, developed by using Swarm and GIS, is an agent-based model that focuses on the simulation of the behavioural aspects of pedestrian movement. The modular structure of the simulation is described in detail. This is followed by a discussion of the lessons learned from the development of STREETS, especially the advantages of adopting a modular approach and other aspects of using the agent-based paradigm for modelling.**

## 1 Introduction

In urban space, the central area is often associated with vibrant movement, intensive commercial use, and a wide variety of leisure activity. Even in highly developed economies which have seen a move of business activity to the periphery in recent years, the town centre (or downtown) remains significant to the health of the wider urban system. More often than not the town centre is the social, economic, and cultural heart of the town. Furthermore, it has been argued that understanding the movement of people in town centres is an important factor in understanding how they function (Londonomics, 1998; Department of the Environment, Transport and the Regions, 1998). Interest in pedestrian behaviour spans the retail industry, emergency services, urban planners, and other agencies that operate within the urban environment.

There are a number of possible approaches to simulating and modelling pedestrian movement (Helbing et al, 2001). Most models focus on a specific aspect of pedestrian movement, which can often be distinguished on the basis of geographical scale—from the microscale movement to obstacle avoidance, through the mesoscale of individuals planning multistop shopping trips, up to the macroscale of the overall flows of masses of people between places. In the STREETS model, presented here, we adopt a holistic, agent-based approach to pedestrian simulation. STREETS has been built to enable the integration of various scales of movement in a modular way. This approach potentially enables the relatively straightforward incorporation of lessons learned from the development of any previous pedestrian models or theory into the STREETS model. It also differentiates STREETS from other models—the approach developed here synthesises existing models and by doing so, offers a test bed for

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synergetic and cumulative influences between those models. Each agent in the model represents a single pedestrian and operates at multiple scales simultaneously using five behavioural modules, which are distinguished principally by their scale of operation. The operation of each module can therefore be modified to reflect different theories about the way people move in urban space at the scale on which that module operates, without affecting the operation of modules operating on other scales.

In the next section, we outline some other approaches to understanding and predicting pedestrian movement. Our brief survey focuses on approaches that have had a direct influence on STREETS. For a more complete review see Helbing et al (2001). Reviewing the current state of the art suggests that, in spite of its importance, this field is underresearched. This may be owing to the absence of sufficiently powerful computers and suitably rich data sets in the past. In section 3 we provide a brief outline of an agent-based model which retains some of the strengths of earlier models by using rich data sets stored in a geographical information system (GIS). In section 4, we focus on the fundamental development in STREETS—the multilevel, modular, behavioural model of agents. We discuss the lessons learned from our work on STREETS in section 5 and conclude, in section 6, with some ideas for further development of agent-based models for the simulation of pedestrian environments.

## 2 Explaining pedestrian movement patterns

Pedestrian activity can be considered to be an outcome of two distinct components—the configuration of the street network or urban space and the location of particular attractions (shops, offices, public buildings, and so on) 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 (Helbing et al, 2001). Physical counts involve recording the number of people passing set points, or *gates*, over a set period of time to given 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 deriving 'trail' diagrams to plot their actual movement. 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 fewer 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 made by means of shuffling.

Although 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. Arguably, LOS measures only 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 focused 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 and urban spaces Research in this field is still active (see Hillier et al, 1993; Krafta, 1994; 1996). However, 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. 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 (a small town in the southeast of England), 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 (The Urban and Economic Development Group, 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, our emphasis). These comments apply with equal force to pedestrian traffic.

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

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

where $A_i$ is the population at location $i$, $B_j$ 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 f is usually described by a number of parameters, and survey data is used to calibrate models based on these techniques. Where $C$ is a distance, it usually represents Euclidean distances on an isotropic plain, or distances between points over road and other transport networks. These models enable prediction of the intensity of interaction between where people start their journeys (the origins) and where they are going (their destinations), and form the basis of many transport planning models. It is possible to distribute such overall flow results across the transport network to predict the intensity of use of different routes, but, in general, this is rarely done at the level of detail required for the prediction of pedestrian numbers.

The approaches introduced so far have rarely been successfully applied to modelling pedestrian movement at the scale of buildings and streets (see Kurose et al, 2001). Although this can be partly explained by the absence of adequate data at this level of detail, ultimately the underlying assumptions (such as by using Euclidean distance or shortest paths through the network in gravity models) are less applicable at small spatial scales. Moreover, they are only suited to modelling general patterns of movement and can never be used to model the movement of individuals.

In recent years, a new modelling approach has been adopted by researchers in social sciences—*agent-based modelling*.(1) Although the origins of this technique can be traced back to the 1970s, only recently has it become sufficiently mature to have potential as a tool for practical applications. 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, perhaps 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. Broadly speaking, an agent is an identifiable

(1) Arguably, agent-based models are more akin to simulations than to strict models. However, differentiation between the two is problematic, and beyond the scope of the current discussion.

unit of computer program code which is *autonomous* and *goal-directed* (Hayes, 1999). Agents are autonomous in that they are capable of effective independent action, and their activity is directed towards the achievement of defined tasks or goals. Although any review of recent computer science literature will reveal other uses of the term 'agent', for the purpose of the current discussion this loose definition will suffice. It is important to realise that agents are not necessarily either spatially located or aware, as they are in the STREETS model. In many models, spatial mobility is not considered at all, although sometimes the term 'space' appears as a metaphor for 'social distance'. The implications of such models' outcomes for actual, physical spatial outcomes are not generally considered, because in most agent-based models the researchers' main concern is understanding how individual behaviour leads to global outcomes in a generic sense, rather than in the modelling of the real world per se. For a critical discussion of agent-based models and their socioeconomic applications see O'Sullivan and Haklay (2000).

In the urban and regional planning context—the primary domain of the STREETS model—there is considerable interest in applications of agent-based techniques for spatial analysis, geocomputation, and spatial decision support systems (SDSS). For example, Rodrigues and Raper (1999) provide an overview of agent-based systems and consider examples of multiagent approaches to spatial decision support, GIS user interface development, and information retrieval in large spatial databases. MacGill and Openshaw (1998) present an intriguing multiagent approach to spatial data analysis. Of more direct relevance to the current context, Helbing and Molnar's (1997) work on small-scale pedestrian models, which simulate human behaviour in crowds and small spaces, is noteworthy, as well as the agent-based simulation of pedestrian movement in Kerridge et al (2001). Cellular automata models have been developed and proved useful for the simulation of urban traffic (see, for example, Chopard et al, 1995; 1996; Esser and Schreckenburg, 1997). However, these do not really fit the agent paradigm and are not considered here.

The most substantial application of agent-based models in the socioeconomic domain is the monumental TRANSIMS (Beckman, 1997). TRANSIMS is a hybrid, lying somewhere between more traditional transport gravitation–interaction models and a full-blown real-time agent-based simulation. It currently models the activities of up to 200 000 individual travellers, which is where the model departs from previous transport planning models. Individual travellers, having been 'loaded' into the model, act as autonomous agents, navigating the network with plans derived according to their socioeconomic profile. They are able to change their route from that planned in response to changing road conditions, such as congestion or accidents. Initially developed to model the road traffic of Albuquerque it is now being applied to other cities in the United States.

## 3 The STREETS simulation system

In this section, we provide a brief overview of the structure of the STREETS model (see also Schelhorn et al, 1999).

The STREETS model is close in approach to TRANSIMS but takes as its subject the activities of pedestrians in subregional, urban districts. Modelling proceeds in two phases: (1) a 'premodel' which uses socioeconomic and other data about the wider metropolitan area to populate the urban centre with a statistically reasonable population of pedestrians; and (2) an agent-based model to simulate the movement of this pedestrian population around the urban district as under the influence of spatial configuration, predetermined activity schedules, and the distribution of land uses. Figure 1 shows the division of data and processing steps between the two phases.

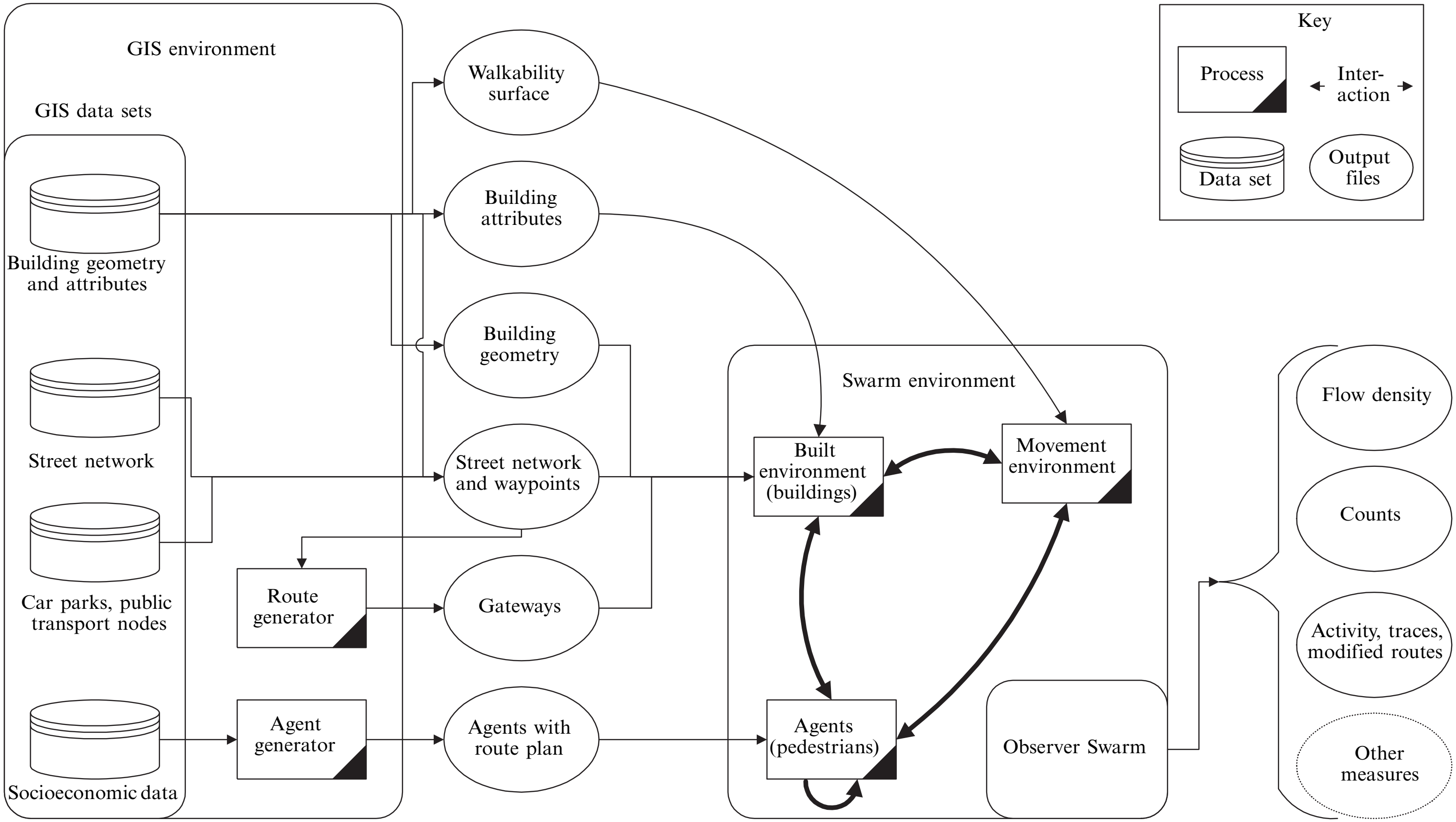

**Figure 1.** The overall structure of the STREETS model.

It should be noted that this overall structure means that we effectively treat the town centre as a *fixed* and *closed* system with a limited number of fixed (nonpedestrian) entry points. At the spatiotemporal scale of STREETS, a fixed town centre configuration is not entirely unreasonable, since the overall configuration and land uses in the town centre will not change in the course of a single simulated day. However, the model assumes that the town centre is spatially closed and this assumption is hardly realistic. In fact, the model structure we describe may be better suited to the simulation of building complexes, such as shopping malls or transport termini. Some such environments would also have the advantage that individual behaviours are more clearly goal-directed (think of an airport, for example).

In any case, the model is initially loaded with pedestrians who have prescribed activity schedules or *plans*, defined by the analysis and manipulation of rich socioeconomic 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 statistical distributions of agents are generated. Each agent has characteristics under two broad categories: *socioeconomic* and *behavioural*.

Pedestrian agents are taken as arriving in the modelled area at pedestrian *gateways*: points where people change transportation mode and start their visit to the town centre on foot. Typical gateways are car parks, on-street parking areas, railway stations, and bus stops. Currently, pedestrian gateways are treated as static elements during the simulation phase (the frequency of bus services is not considered, for example). The simplest way to model gateways is to have them 'release' pedestrians at a predetermined rate, according to a Poisson distribution. It is anticipated that, as the model is developed, gateways might 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 both the frequency of service, and the tendency of people coming into the town centre by train to arrive in large groups. At the current configuration, our insistence that all pedestrians arrive from a few gates is unrealistic.

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

(1) **Vector data** of building outlines, classified by general land-use categories—retail and commercial in the first instance.

(2) **Raster data** representing the *walkability* of all nonbuilding space. 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 rather than in the middle of streets) in a fairly simple and robust way.

(3) **Network data** representing the street network and building entrances. The street network is used in the generation of agents' planned routes. Nodes in the street network (including building entrances and gateway locations) are collectively referred to as *waypoints*.

The second (dynamic) phase of STREETS was developed completely within the Santa Fe Institute's 'Swarm' simulation environment. Processes in the premodel 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).

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

During a model run, agents are despatched from the pedestrian gateways. Each agent enters the simulated town centre environment with a planned or intended sequence of waypoints along the route up to, and including, their intended destinations. They do not have an explicit encoding of the precise route geometry. The whole simulation can be monitored by an observing Swarm, which collects information about the interaction in the model. Swarm offers a rich set of tools to develop and extract information from a model run, and those tools may be used to collect statistics about agent movement, the popularity of different buildings under different spatial configurations, and so on. Figure 2 shows the user interface of the STREETS model during a run. In the graphics window, buildings are represented by polygons, waypoints by circles, and pedestrians by dots. The walkability surface is visible as a grey area between the buildings. Information on certain objects can be obtained by a 'point-and-click' interface. The window on the top lefthand side controls which layers and objects are drawn, the small window below controls the model run. Monitoring functions are accessed via the 'PedestrianSwarm' window at the righthand side of the screen.

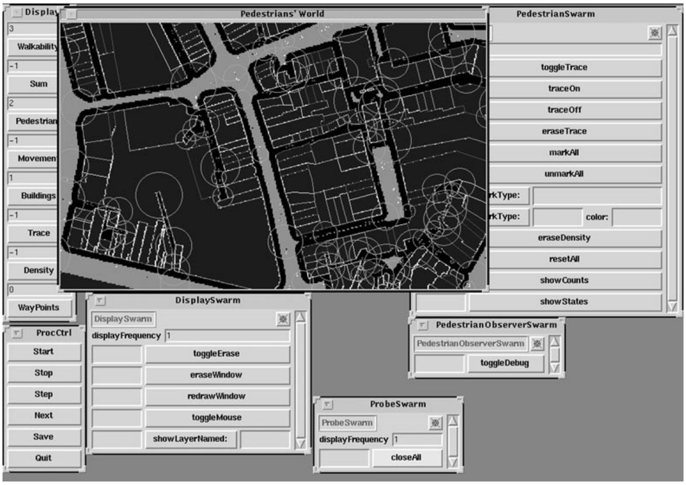

**Figure 2.** A screen-shot of the STREETS model in operation showing various user accessible controls and displays.

## 4 The pedestrian agent behavioural model

The first stage of STREETS builds agents and their attributes. In the rest of this section, we focus on the way that these characteristics come into play in the second stage of operation of the model during a dynamic run. Agent attributes can be divided into socioeconomic and behavioural characteristics.

*Socioeconomic characteristics* relate to income and gender, and are used to create a planned 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, at present, by using shortest-path determination on a detailed representation of the street network based on waypoints, so that the agent has a predetermined plan, which defines a route that it intends to take in the model. This route planning technique could be replaced with any other heuristic method (for example, the one suggested in Kurose et al, 2001) as it is not intrinsic to the model structure. As a result, much of the cognitive work done by agents occurs outside the dynamic run-time part of the model, and cognitive maps or similar concepts would be most readily incorporated into the model at this point. The effect of socioeconomic data is to populate the model with a variety of agents whose behaviour is likely to be different from each other. For example, more affluent agents are more likely to arrive at gateways in particular parts of the town centre, and are also more likely to include particular types of shops in their plans. In this way, STREETS integrates the effects of configuration and attractors on various socioeconomic groups.

*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 preset activity schedule. Variations in this element allow different, unpredictable behaviours to occur in the dynamic setting. 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. Behavioural characteristics are not directly related to socioeconomic factors, but may vary according to the purpose of a visit to the town centre.

In the dynamic operation of the model, agents have five levels of behaviour, programmed as modules, to navigate and find their way in the town centre. These different levels enable the agents to compute separately local movement (the process of moving to the next grid square on the walkability surface—the 'mover' module), medium-range movement (maintaining a proper direction—the 'helmsman' module), and longer range movement (trying to move to the next waypoint while avoiding dead-ends—the 'navigator' module). The combination of these modules allows each agent to find its own way from waypoint to waypoint. The modules mentioned so far implement deterministic way-finding—movement in space according to a predefined plan. To enable interaction between the agents and the surrounding environment, another level of behaviour was introduced to emulate agent 'recognition' of the built environment. This module, called the 'chooser', enables an agent to search the nearby area 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 predefined plan is calculated. Any resulting changes to an agent's plan are managed by the 'planner' module.

Before moving on to explain the functions of the controlling modules in more detail, we first consider how these behavioural modules interact to affect the behaviour of a pedestrian agent. Some of these relationships are depicted in figure 3. Agent A is moving towards target waypoint T. The agent itself represents an additional obstacle to movement on the walkability surface in its current grid square, and also a lesser obstacle on its likely next grid-square, which is determined by its current heading. This is controlled by the mover (the arrow marked M). The helmsman and navigator take care of the general heading towards the target (arrows marked H, N). The agent carries information about its heading, route, and other details relating to its movement. The chooser and planner operate in this space and control the agent's future movements. The visual field is controlled by the chooser and is marked on the walkability surface as a cone marked C.

Each behavioural module is a control system, working within a hierarchy of variables at different levels of abstraction. If deviations from a target value of a module's control variables are too large, the module adjusts target variables of lower level modules. Events (which occur external to the agent when some combination of uncontrolled variables matches given conditions) may trigger further actions by the various modules, so that control variables adapt to the new conditions. Thus, the more abstract goals of the upper levels are decomposed into simple actions by the lowest module.

Control and target variables are part of the state of the agent, noted on a blackboard public to all modules. All modules can access all agent states they need to know and change all states which their task requires them to change. In principle, this architecture allows the existence of more than one module on any level, either competing or complementary. Moreover, modules can be 'left blank' and substituted with a default operation, which just translates output from the layer above into input for the layer below, without change or action.

Together, the modules manage the complex state of the agent as shown in figure 4 (see over). This state comprises the following elements:

(1) Route—This includes the whole route, an agent's position on that route (in other words, relative to the next target waypoint), its current location in the world, its fixation on its route, its thresholds for evaluating possible new destinations (derived from its socioeconomic and behavioural profile), and a threshold for deciding that a target waypoint has been reached.

(2) Speed—includes the current, maximum, and preferred speeds.

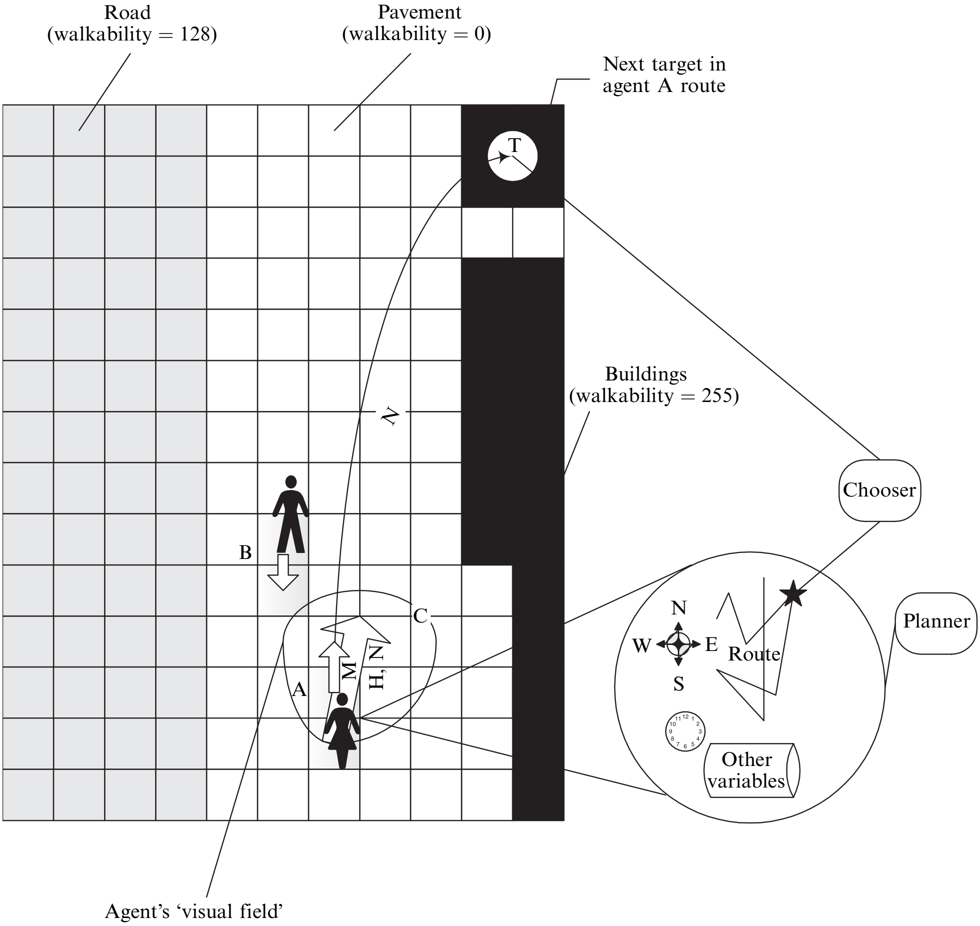

**Figure 3.** Schematic showing the effects of the different agent control modules. The grid shown is the walkability surface where darker grid squares are less accessible to pedestrians. Agent movement is controlled by five interacting modules (also see figure 4): the mover (M, the short arrow) controls immediate movement to the next grid square; the helmsman and navigator (H and N, the long arrow) control medium range movement in the direction of the next target on the agent's route (T); and the chooser (C) determines the next target on the route as the visual field changes. The planner module holds the agent's overall planned route through the space.

(3) Progress—the progress made towards the next target waypoint and the minimum acceptable progress per unit time.
(4) Direction—encompasses the agent's current directional heading and the direction to the next waypoint.
(5) Location—the coordinates of the agent's centre point and the agent's size expressed in terms of the effect on the walkability surface of the agent's presence in a grid square.

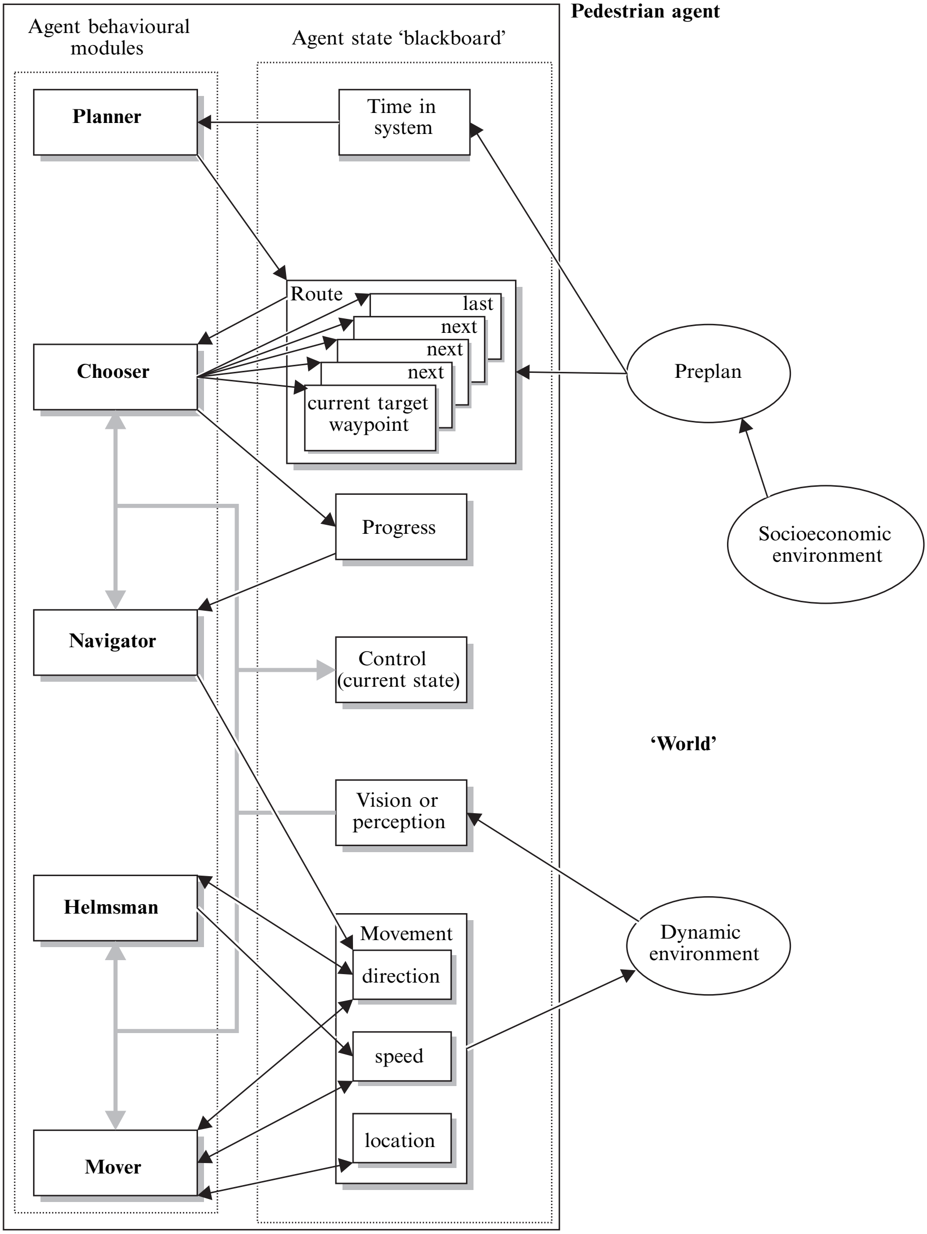

**Figure 4.** The interactions between the agent control modules and the agent state variables stored on its 'blackboard'. Note that the vision/perception and control variables effect operations at all of the four lower levels. Aside from these interactions there is a general 'zig-zag' of interaction whereby high level modules control the state variables to which lower level modules respond.

(6) Vision—describes an agent's visual capabilities expressed as a vision cone with breadth and range into the surroundings. Potential destinations inside the visual cone are considered as potential deviations from the current plan by the chooser module, or as obstacles by the way-finding modules mover, helmsman, and navigator.
(7) Time—tracks the agent's time spent in the system and the time available to spend in the system.
(8) Control—reflects the agent's movement state. For example, is the agent active or waiting, moving normally or stuck?

The modules as currently used are presented in figure 4. The following sections describe their operation in more detail, starting with the low-level operation of the mover and proceeding up to the highest level of the planner. As the model uses the object-oriented paradigm, it is important to note that each agent has its own instance of the modules. In each cycle, the agent executes the appropriate modules that are needed at that time.

### 4.1 The mover module

This module moves the agent 'physically' through the environment. It reserves space for the agent in the environment and checks for obstacles like other agents and buildings. Each grid square or 'cell' in the 'world' has a certain capacity, its walkability value, ranging from 0 to 255, where 255 refers to a nonpenetrable object, such as a building wall. Values indicate the proportional occupation of that grid square, so that low values are preferred by pedestrians and high values indicate that a cell is unsuitable for pedestrians—such as the centre of busy roads. Each agent is also assigned a value representing its own occupancy of a grid cell. Additionally, agents themselves take up space at their anticipated *future* position according to their actual heading and speed. This helps to prevent agent collisions. When the mover tries to place the agent on a new cell, it determines whether there is enough space in that cell (that is not occupied by too many other agents, or other obstacles). If there is enough space on a cell for an agent to move there, the agent is able to move. As this action is performed, the value in the cell from which the agent moved is also modified. If many agents are attempting to occupy the same or immediately adjacent cells, these cell values will increase, indicating that the area is crowded and less walkable, thus preventing entry. Streets with vehicular traffic and street furniture also take up walkability space.

The mover also places the agent 'physically' into the environment when it starts its route, or leaves a building, and removes it when it enters a building or disappears owing to its arrival at the end of its planned route (which usually happens at the pedestrian gateway from which the agent originally entered the system). In a normal run, the mover module looks in up to five directions, starting from the current heading direction, to determine where the most space is available. It sets the heading to this direction and tries to place the agent at the new location, according to its heading and speed. If a collision is detected, the agent's speed is set to 0 and it enters the 'stuck' state. If there is no collision, the agent continues in the 'moving' state and is placed in its new location. If its speed drops below 20 cm $s^{-1}$, its speed is set to 0, and the agent enters the 'standing' state.

There are some exceptions to this behaviour: when an agent is 'stuck' the mover module looks around all 360 degrees for the best possible heading in terms of available space in its immediate surroundings, setting the speed to a small value. This may result in erratic movement for some steps, or for as long as the navigator or helmsman modules do not intervene. Eventually though, the agent's progress will be adjudged by the navigator to be insufficient and the agent will be set on a new, hopefully more sensible, course.

### 4.2 The helmsman module

At the next level, the helmsman module mediates between the target direction—determined from the absolute location of the current target waypoint—and the current best heading on a medium scale, trying to adjust the heading in small steps in the direction of the target. If the agent is far from the target, the helmsman does nothing. As the agent approaches the current target, it evaluates the deviation from the target direction. Large deviations cause it to adjust the agent's current heading. The helmsman also resets the speed and heading of the agent when it is in the 'standing' condition, triggered by the mover module.

### 4.3 The navigator module

Supporting the helmsman at the next level is the navigator, which also maintains the agent's heading so that it does not deviate too far from the target direction. However, the agent must be allowed to deviate somewhat from the crow's flight heading towards a target so that it can negotiate corners and get out of dead ends. Therefore, the controlled variable is the agent's progress towards its current target. Progress is recorded as a moving average of the decrease in the distance to the target coordinates in the last few time-steps, normalised by the agent's speed. If progress becomes low, the agent may reorientate itself by looking all around (360 degrees) starting from the target direction, and by taking the first direction with sufficient unhindered visible range as a new heading. When this occurs the progress and speed of the agent are reset to their initial values and updated until the target is reached, or progress again becomes low. In normal operation, when progress is good, the navigator module checks if it is possible to walk in the target direction. If so, the navigator sets a new heading; if not, the heading remains unchanged.

These three modules together deal with 'tactical' movement—the business of getting to the next point in the route. The remaining two behavioural modules attend to more strategic movement and planning.

### 4.4 The chooser module

The chooser identifies the next target in the route of the agent. The target can be a waypoint like a junction in the street network, or a building or location the agent wants to enter. At every time-step the chooser evaluates the position of the agent, assessing if it has reached the current target, by comparing the extent of the target itself and the agent's threshold for deciding that a target has been reached. Street network waypoints have nonzero extents, and this ensures that agents do not need to proceed to the precise geolocation of a road junction (which may be at the centre of a busy road intersection) in order to decide that they have arrived. Since various agents may have different thresholds for this purpose, this mechanism produces plausible behaviour at street corners, with different agents 'cornering' more or less accurately. When the target is adjudged to have been reached, the agent chooser examines whether it is a location to enter. At a potential 'entry' location (such as a shopping destination) the agent state is set to an 'entering' mode and other possible destination objects are not assessed. The chooser also decides how long the agent will stay in this building and sets the agent's state to 'wait' accordingly. At a waypoint, the chooser sets the next object on the route as the new target, and resets the progress variable.

If an agent is not in 'entering' mode, it is also free to change its route, and the chooser uses the agent's visual field to detect candidate building objects in its immediate surroundings. The visual field's extent is defined by the agents speed and fixation on its task: the higher the speed and fixation, the narrower is the fan of rays which the vision module sends to the environment. Building objects in the field of view are considered by the chooser module as potential new destinations which may be added to the current planned route. Building attributes such as type and general attractiveness are compared with the agent's profile, and if a match is found then the location may be pushed onto the route as a new next destination.

### 4.5 The planner module

The planner module is not currently implemented. Its current default behaviour sets the agent onto its preplanned route and allows it to execute until it exits the system. The planner's role is to take care of overall time constraints and route planning. It is envisaged that this module will have an important role when agents deviate significantly from their preplanned route. The planner module will probably be required to implement a representation of an agent's cognitive map in order to perform this function. This cognitive map would be consulted by the agent in combination with its current location and visual field in order to plan sequences of waypoints making up routes to alternative locations to those originally planned.

## 5 STREETS in the wider context: modularity and emergence

The development of STREETS was sparked by our shared curiosity in agent-based models and their potential uses in spatial analysis and modelling. Beyond the development of the conceptual model which we have described, we have used a wide range of computerised tools and programming languages to connect the various parts of the system together to enable the development of STREETS over a very short period of time. The development process demonstrated the relative ease of combining the many available data sets required for the simulation task and suitable for manipulation and analysis in a modern GIS environment. Beyond these immediate and practical lessons, STREETS has raised two interesting aspects of agent-based models that will be expanded in this section. First, is our modular approach to agent behaviour, which is unique to STREETS. Second, is the issue of 'emergent' social behaviour which agent-based models are commonly hailed as demonstrating.

### 5.1 Modular behaviour

Our approach to agent movement is modular and loosely hierarchical. Although it bears some similarity to cognitive models of movement (especially in terms of the separation between strategic and tactical movement), STREETS does not claim to imitate such behaviour, still less to represent any particular psychological model of movement. The main purpose of adopting a modular approach is pragmatic, enabling us to cope with the complex, multivariate state of the agents in this environment, as well as supporting the implementation of the model in a relatively clear and robust way.

This approach differentiates STREETS from many other models of pedestrian movement which treat pedestrians in a less integrated way (Borgers and Timmermans, 1986; Helbing and Molnar, 1997; Hillier et al, 1993). The apparent reason is that these models focus on a specific aspect of pedestrian movement, often at a particular spatial scale. For example, gravity models developed in the 1970s (see Batty, 1976) tend to model the movement of masses of pedestrians at the macro level. Such models rarely consider the specific route taken by the pedestrian, or how they get from their origin to their destination, in detail. At a medium spatial scale, we find models like Hillier et al's (1993) 'Space Syntax' which attempts to explain pedestrian movement along streets. In this case, there is no consideration about where the pedestrians are coming from, or where they wish to go. Finally, other models offer a very detailed explanation of specific flow patterns at micro spatial scales, such as movement of crowds of pedestrians at a junction (Helbing, 1992).

By contrast, STREETS integrates agent behaviour across spatial scales in a more complete manner. As we described earlier, in the first stage of the model, agents' socioeconomic attributes are assigned, routes calculated, and agents are provided with 'history'. This 'history' encapsulates both long-term trends (such as lifestyle) and short-term trends (such as a planned route in the town centre). Once a model run ensues, an agent's behaviour develops as the result of interaction between the various levels of movement by the different modules. The integration of modules provides a 'programmatic locus' for long-term routing, medium-term guidance, microlevel movement and overall control. This approach provides the potential for replacing modules, as new ideas and techniques to deal with different scales of movement are developed. For example, the mover may be enhanced by the use of genetic algorithms, such as those currently providing good results in collision detection and avoidance in animal movement simulations (Reynolds, 1994). It is possible to envisage the addition of more modules to this schema. If, for example, a more realistic visualisation were needed (if, for example, STREETS was used to provide input to a virtual reality urban scene simulation) it would be possible to develop modules that interact with agent avatars to control the representation of physical movement in the urban space.

### 5.2 Aggregation, emergence, model closure, and spatiotemporal scale

Although it is difficult to demonstrate in the static context of a journal article, STREETS produces overall aggregate patterns of movement in the pilot study model which are at least 'plausible'. As soon as the first phases of development were complete, and even though some agent parameters were set arbitrarily (even randomly), the movement of agents on the computer screen seemed intuitively to 'make sense'. However, it is important to realise that such aggregate patterns of movement are not mysterious or surprising, since the model design has been squarely aimed at producing precisely such plausible behaviour. Can we label such aggregate behaviour and patterns as 'emergent' or even 'self-organising' in any meaningful sense?

This is a significant question because emergence 'from the bottom up' is frequently cited as an important attribute of agent-based models (see Epstein and Axtell, 1996). Emergence is generally seen as unidirectional, since agents are autonomous objects. The focus in the agent-based modelling community on emergence has been criticised by some (see, for example Gilbert, 1995). We are strongly inclined to agree when Castelfranchi (1998) comments, that

> "A notion of emergence which is simply relative to an observer...or a merely accidental cooperation, are not enough for social theory and for artificial social systems. We need an emerging structure *playing some causal role in the system* evolution/dynamics; not merely an epiphenomenon. ...Possibly we need even more than this: really *self-organizing emergent structures.* Emergent organisations should reproduce, maintain, stabilize themselves..." (page 179, original emphasis).

The one-way notion of emergence often found in agent-based models is most readily understood as an acceptance of the truism that society is nothing more than the aggregate of individuals, and this is precisely the subjective emergence which occurs in the STREETS model. A more subtle and meaningful possibility which might occur, given the structure of STREETS—although considerable further observational work would be required to confirm it—is that certain types of buildings and streets in the model might be systematically more popular as a result of their locational or configurational properties. An example would be if corner buildings proved to be more frequently visited than neighbouring buildings. However, for such an outcome to be significant in the sense which Castelfranchi demands, would require the model to somehow 'institutionalise' the locational preferences of the pedestrians. One way of doing this would be to introduce building tenants into the model, in the shape of retailers, commercial offices, entertainment businesses, and so forth. Presumably, given a sufficiently rich range of tenants, microscale land-use patterns might emerge in the model, with more successful retailers, in particular, able to pay the higher rents demanded for the popular corner sites with frontages on two streets.

The noticeable point here (apart from the significant extra effort which would be required in implementation and testing) is that the spatiotemporal scale of the model would be dramatically altered in such a development, from footsteps along individual routes to the location decisions of large organisations, and from minutes and seconds to months and years. It is also evident that, for such a model to be plausible, it would have to be opened up to the wider spatioeconomic context in which any particular town centre is set. Competing town centres, demographic factors, suburban business, and retail parks would all have to be considered for inclusion, together with developments in the regional economy and transport infrastructure. The difficulties of scaling up from aggregate behaviour at the spatiotemporal microscale to the macroscale of institutional and organisational responses are formidable. In fact they are a compelling argument for models with relatively limited ambitions which may be used to inform decisions at the macroscale rather than attempt to predict them.

This interdependence between spatiotemporal scale, model closure, and aggregate or emergent behaviour seems to us to be a general one (see O'Sullivan and Haklay, 2000). The range of entities which ought to be represented as autonomous agents in a model is strongly affected by the desired range of application in both time and space of the model under development. The entities represented, and whether there is any hierarchy inside which they act (for example, agents playing roles in institutions, households, firms, and so on), are modelling decisions intimately intertwined with issues of scale. This seems to be associated with the fact that the habitual, patterned, aggregate behaviours which may be observed in a model like STREETS are one of the key drivers of change at more aggregate levels, and it takes time for actors in any socioeconomic setting to recognise the patterns and adjust their individual and collective responses to those patterns. These observations are in keeping with Conte and Castelfranchi's (1995) remarks about the way in which emergence must be understood as occurring through social action via the cognitive processing of events by individuals over time.

## 6 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 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 is crucial in making any useful decision support tool from the model. Other work could extend the range of measures which can be extracted from the model runs. With such additions, 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 could be undertaken.

Another direction for future developments is a more complete and sophisticated approach to socioeconomic variables. This aspect is of special importance in view of the use of pedestrian models in retail planning. One possibility for such development is to adopt schema similar to the one proposed by Lake (2001) to enable easy alteration of agents' profiles and to experiment with different agent demographics.

What is clear from the work already done is that the agent-based modelling approach is highly applicable to this field. It is also clear that the application of socioeconomic 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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