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Building 3D Agent-Based Models for Urban Systems

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Abstract: There is a growing interest in relating agent-based models to real-world locations by combining them with geographical information systems (GIS) which can be seen with the proliferation of geosimulation models in recent years. This coincides with the proliferation of digital data both in the two and three dimensions allowing one to construct detailed and extensive feature rich and highly visual 3D city models. This paper explores some of these developments in relation to our own initial work on building 3D geospatial agent-based models of urban systems and the technologies that allow for such models to be created. Furthermore, we highlight some techniques for the creation of 3D agent-based models and stress that such models are not a substitute to good models.

1: INTRODUCTION

Agent-based modelling (ABM) is increasingly being used as a tool for the spatial simulation of a wide variety of urban phenomena including: housing dynamics (e.g. Benenson *et al*., 2002); urban growth and residential location (e.g. Torrens, 2006); gentrification (e.g. Jackson *et al*., 2008) and traffic simulation (e.g. Barrett *et al*., 2002). At a more microscopic level there are agent-based models that simulate pedestrians in the urban centres (e.g. Haklay *et al*., 2001), and crowd congestion (e.g. Batty *et al*., 2003). These applications demonstrate a growing interest in linking agents to actual places and with geographic data (see Castle and Crooks, 2006 for a review) through the linking or coupling with geographical information systems (GIS) and agent-based models. The advantage of linking the two allows agent-based modellers to simulate agents related to actual geographic locations, thus allowing us to think about how objects or agents and their aggregations interact and change in space and time. This focus of linking agents to real-world locations are often referred to as geosimulation models (Benenson and Torrens, 2004).

As agent-based models move evermore into the spatial domain, we believe there is a need for new ways to explore, visualize and communicate such models especially to those who we seek to influence or where such models might inform decision makers' activities. This has already been identified as one of the key challenges facing ABM (Crooks *et al*., 2008). Not only does this relate to the notion that good models, which generate spatial or physical predictions that can be mapped or visualized must 'look right' (Mandelbrot, 1983), but it also relates to one of the major purposes of agent-based models, which is to visually convey the behaviour of the model clearly and quickly (Kornhauser *et al*., 2009). This is supported by North and Macal (2007) who write that "…visualization is one of the most effective ways to present key model information to decision-makers (p 280)." 2D visualization of agent-based and cellular automata models is common place such a as the animation of model results of land use change (e.g. Tobler, 1970; Clarke *et al*., 2007) which allows users to see the dynamic behaviour of recognizable characteristics of model results rather than just exploring models through data and statistics. However, just as in GIS, often the visualization of agent-based models is ineffective (Kornhauser *et al*., 2009), which hinders their communication to those we seek to influence.

One potential way to visualize and communicate agent-based models is to utilize the third dimension using advances in computer hardware, software and networked communication which has made powerful visualization tools once the domain of high-performance and expensive workstations and/or software available to all. This third dimension is rarely ventured into in academic models (see Dibble and Feldman, 2004; Thorp *et al*., 2006[1] for sample applications). We would argue that this is due for several reasons, first is to do with the nature of the discipline where the focus is on theory rather than outreach and end user visualization, unlike that of computer games and movies. Secondly until recently there has been a lack of 3D data to construct such models that is easily accessible to the modeller, however, this is changing (which we discuss below). Thirdly, most agent-based model builders outside of computer science are not taking advantage in improvements in computer graphics and processes, networked communication and associated technology.

The intention of this paper is to explore the recent advances in computer technology, software and associated techniques that allow for the creation of 3D agent-based models which can be used to simulate various aspects of city life focusing on our own initial research of creating 3D cityscapes and 3D agent-based models. The remainder of this paper will therefore explore our attempts to use digital data to create feature rich 3D cityscapes (Section 2), discuss why such cityscapes are important for ABM (Section 3), before moving into how advances in computer hardware allow for the creation of 3D agent-based models (Section 4); we then briefly explore a potential application domain, that of pedestrian modelling (Section 5). Section 6 presents techniques which we are currently utilizing to create 3D agent-based models through various linking and coupling approaches along with advantage and disadvantages of each approach before a discussion is presented (Section 7). However, a caveat is first needed, that is the communication of agent-based models is not only through visualization; there are numerous other ways. For example, through the provision of modelling source code or by providing executables of models (as advocated by Parker *et al*., 2003 and Grimm, 2002, but which is rarely done). Models can also be communicated through their logical and consistent descriptions (e.g. Grimm *et al*., 2006). Nevertheless the focus of this paper is the communication of agent-based models through 3D visualization.

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[1] Further information about this work can be seen at http://www.redfish.com/wildfire/ and http://www.redfish.com/stadium/

2: RISE IN DIGITAL DATA

ABM generally focuses on how micro-scale interaction of many individuals result in more aggregate patterns emerging. However, to create a real-world environment for these agents to inhabit, one needs fine scale and potentially extensive digital geometric data sources to represent the world in which the agents inhabit. Many of the applications highlighted in Section 1 utilize such data as a foundation for the environment in which the agents inhabit (albeit in a 2D world). Such data might include a terrain for agents to walk over, buildings for the agents to live in, locations of business for them to work at, footpaths and roads for their travel, etc. The last decade has seen a proliferation of fine scale data sources becoming increasingly available at finer and larger extents and being coupled with height data as can be seen with the growing number of 3D digital city models (see Smith and Crooks, 2010 for further information). Such 3D models are a result of the integration of computer-aided design (CAD) software, GIS, computer graphics, web and aerial sensing technologies. Notwithstanding their application for a basis for ABM (i.e. acting as an environment for the agents to inhabit), such digital data sources have other applications ranging from urban planning, telecommunications, architecture, facilities and utilities management, property analysis, marketing, tourism and entertainment (see Batty *et al*., 2001 for a review). The development of web and virtual globe technologies has given a massive boost to digital urban models, enabling widespread access and interaction by the public through geo-browsers such as the popular Google Earth.

Whilst the visualization capabilities of 3D city models are clear as we highlight in Fig. 1, their analytical functionality is often underdeveloped (Batty and Hudson-Smith, 2002). Significant advances have been made in increasing the geometrical sophistication of 3D city models, yet many models remain ‘empty shells’ without any socio-economic data associated with the buildings, or the capability to analyze the role of the built environment in urban processes which we consider a major hindrance for the creation of 3D ABM. However, we believe that future advances will explore how such models can be populated with socio-economic data and linked to transportation networks, thus moving from visualization to focus on policy applications and analysis, and acting as a foundation of 3D worlds for agents to inhabit. For example, Smith and Crooks (2010) link the empty shells of the buildings with residential and commercial property information for all the buildings within the Greater London Authority which is similar to the work of Orford (2010). There is much synergy in these aims with those of planning support systems (PSS), which provide tools to aid and enhance planning tasks (Brail and Klosterman, 2001). However, incorporating multiple datasets into 3D city models also has its challenges in relation to visualizing such data (see MacEachren and Kraak, 2001 for a discussion) but also computationally in terms of the shear amount of data.

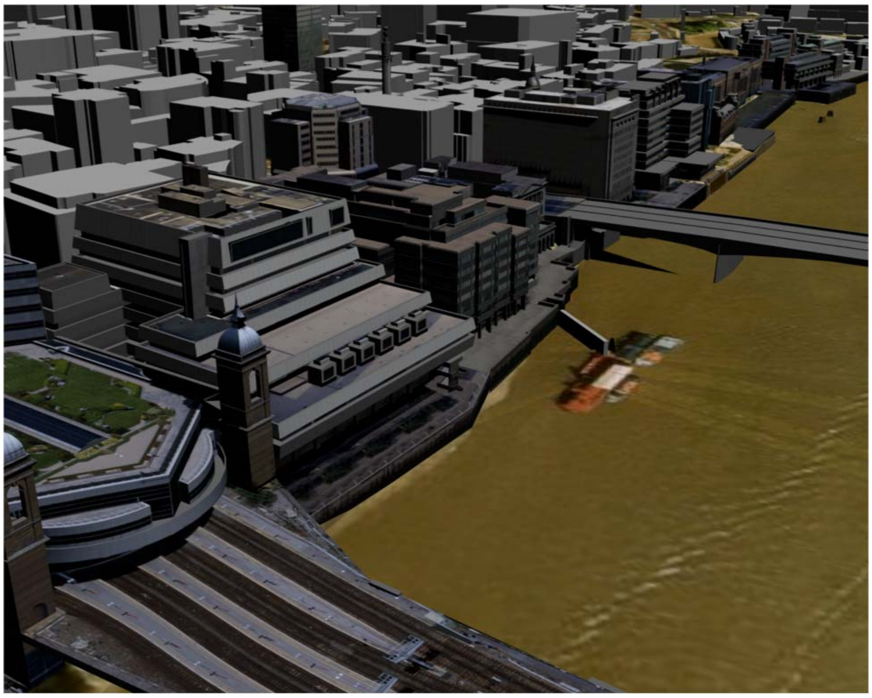


Fig. (1). Blackfriars railway station and the river Thames, central London

Such detailed data is important for the creation of agent-based models but also for the visualization of model results. Fine scale social and built environment data has already been used for the creation of agent-based models (e.g. Benenson *et al*., 2002). However, this is often in 2D but with the proliferation of 3D data and environments to visualize such data it is possible to use them as a backdrop for 3D agent-based models (this is discussed further in Section 6). This relates in a sense to urban modelling more generally. Lowry (1965) defined urban models on a continuum between the iconic and the symbolic. Iconic models are physical versions of the 'real' thing but normally scaled down. Typical traditional examples include the architects' block model as we show in Fig. 2 and 2D cartographic maps. Symbolic models represent the system in terms of the way they function, often through time and over space. Such models replace the physical or material system by some logical and/or mathematical formula, often in the form of algebraic equations within a digital form (e.g. a computer) such as in the case of land use transport models (e.g. Batty, 1976). However, the distinction between the two is increasingly being blurred as technology advances. For example, the iconic representation of the city within a 3D GIS such as the Virtual London Model (Batty and Hudson-Smith, 2005) is a digital manifestation of the architects block model which we showed in Fig. 1 and can potentially act as a container in which symbolic models are run, which we demonstrate in Section 6.

Combining the iconic with the symbolic models in a digital media gives us unprecedented power to understand, simulate, explore and visualize cities especially when combined with agent-based models (Batty, 2001). This was not possible hitherto and it coincides with the way we currently conceptualize and model cities. This has changed from the aggregate to disaggregate and from the static to the dynamic, taking ideas from complexity science. ABM provides us with tools to explore this change in approach. Specifically it allows us to explore the reasoning on which individual decisions are made and how such decisions lead to more emergence structures evolving. This has potentially great benefits for urban design. Take for instance, planners and architects who are increasingly being challenged to develop innovative uses for spaces but who do not know how people will use such spaces. Combining both the architect model with agent-based model on how people might use the space can potentially improve the design of such a building. For example, how might pedestrians in the form of agents use such a space or exit a building in an emergency. Combining the symbolic and iconic models therefore could potentially improve the design process through embedding pedestrian dynamics in the related architectural structures (Vizzari *et al*., 2006) given that human movement behaviour has deep implications on the design of effective pedestrian facilities (Willis *et al*., 2004).

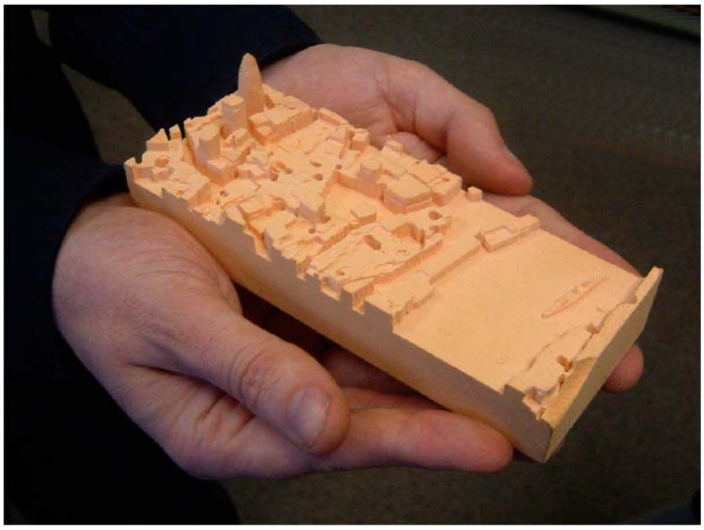


Fig. (2). 3D architects block model portraying part of central London.

3: 3D ENVIRONMENTS AS A BACKGROUND FOR SIMULATION

The previous section presented how there is an increasing amount of rich digital data to build 3D city models but only tentatively addressed why this might be of use for the creation of agent-based models. In this section, we will briefly sketch out why the use of the third dimension is a useful tool for ABM. Just as agent-based models can model real-world environments through the use of GIS (e.g. Benenson and Torrens, 2004) thus allowing us to map their outcomes spatially, digital 3D environments hold the ability to create a sense of place, and thus they are able to mimic the real-world for the purpose of digital planning (see Hudson-Smith, 2003). This relates to the concept of 'legibility' in urban planning. Legibility is used to refer to the ease with which inhabitants of a city can develop a cognitive map over a period of time and so orientate themselves within it and navigate through it (see Lynch, 1960). For example, Lynch (1960) writes "nothing is experienced by itself, but always in relation to its surroundings (p 1)." This is the reality of the city, the built environment. Therefore, if for the purpose of digital planning and for ABM, we are to replicate the built environment in digital space, the space itself must convey to the user a sense of location, orientation and identification; in short, it must convey a sense of place (Hudson-Smith, 2003). To gain an essential foothold, man has to be able to orientate himself; he has to know where he is. But he also has to identify with himself within the environment, that is he has to know he is in a certain place (Groat, 1995). Through the rise of digital data, GIS and CAD technologies it is now possible to create such environments within computers (however, internal structures of buildings is problematic). We believe that there is therefore a clear outreach and knowledge creation mechanism to applications here. Moving into the 3D realm has the potential to provide 'windows' into the complexity of phenomena and environments under investigation (Hudson-Smith, 2003). This is particularly important as agent-based models occur in space; they are inherently structured in two (latitude and longitude), three (position above or below the Earth's surface) or four (time) dimensions.

Not only do 3D city models provide this sense of place but by animating the agents who inhabit such models, we can give them realistic appearances. This is particularity appealing when modelling the individual in such applications of pedestrian modelling (see Pelechano *et al*., 2007 for an example). The visualization of people moving allow us to better convey situations such as pedestrian movement and allow urban planners to improve the structure of the street network and communicate the idea of space to the public (Burkhard *et al*., 2008). Additionally allowing for the third dimension to be incorporated into models allows us to augment such models within the real world. For example, Nakanishi *et al*. (2009) explore the use of virtual cities as a test bed for examining the design of urban public spaces. Specifically the authors combine an agent-based model with a virtual city model (in this case a platform at the Kyoto subway station) and used augmented reality to allow humans to interact with the agents (as if the agents and the humans were in the same crowd) through the use of positioning sensors around the station and then simulated an emergency. Combining agent-based models with 3D graphics not only allows us to carry out experiments which are not easy to do in reality, such as setting a building on fire, but also provides us with a sense of place which people can relate to. It can therefore potentially help communicate such models to people not familiar to ABM.

While there are clear benefits for linking agent-based models to 3D environments, many may consider 3D agent-based models as 'glorified' computer games or just 'eye-candy'. Perhaps this relates to the issue that many spatial problems can be treated in 2D such as finding the highest point on a terrain. Whilst essentially this is a 3D problem for each location has a height, a 2D surface is sufficient to find the highest point. However, there are problems such as line of sight or the spread of smoke which would benefit from the third dimension, not to mention giving agents more realistic appearances and giving them a sense of place (as discussed above). Even if we relate such models to computer games, 3D visualizations in computer gaming has a lot of potential for agent-based models. Take for example, SimCity (2009)[2], a city-building simulation game whose objective as the name suggests is to build and design a city, the player can own land (e.g. commercial, industrial, or residential), add buildings, change taxes along with building transportation systems and respond to disasters such as flooding or earthquakes. Scenarios within the simulation can be based on real cities and problems associated with them. For example, in the original model the Swiss capital, Bern in 1965 was one such scenario where at the time the roads were clogged with traffic; the mayor (i.e. a player) needed to reduce traffic and improve the city by installing mass transit systems. In a sense, such a game provides a valuable teaching tool for urban geography, planners, designers and policy makers (Adams, 1998) because while

[2] SimCity is not really a true 3D model, but a 2.5D as it uses an isometric viewpoint. The player navigates the environment by scrolling left, right, up or down. It gives a sense of 3D without having a z axis (see Krikke, 2000 and Hudson-Smith, 2003 for more details).

it is a game it has business rules, ecosystem modelling, and social dependencies. The graphical user interface (GUI) of the game facilitates the learning about the complex, dynamic, and interrelated nature of urban problems.

However, there is a difference between agent-based models and such games. That is agent-based models have relatively simple visualizations but deep behavioural content while within games, agents tend to have superficial behaviour but very enriching graphics. Within this paper we are not advocating 3D agent-based models for just the sake of it but as a means for explaining the model to non modellers. For example, one solution to this is the release of SimCity under the name of Micropolis (2009) an open source project therefore allowing developers to add more complex behaviours and rules to such a model by editing and expanding the code base.

The true advantage of 3D in these models is however difficult to gain; user testing is obviously required and this will be part of our future research in a similar vain to that of those who test 2D and 3D user interfaces (see Cockburn and McKenzie, 2002). Nevertheless, some of the main simulation toolkits are starting to explore the third dimension for visualizing model outcomes. For example, some 2D toolkits are starting to integrate 3D authoring environments into the system, most notably StarLogo TNG (2008). However, there are limitations to such software in relation to geospatial research especially when the source code of the models is not available (see Castle and Crooks, 2006 for a discussion). Others while having a 3D component such as NetLogo (2009) are essentially 3D visualization of objects on a 2D plain, therefore being still 2D models. Repast Simphony (2008) allows for the integration of 3D objects and terrains such as National Aeronautics and Space Administration (NASA) virtual globe Whirl Wind (NASA, 2009). This move into 3D has been facilitated by developments in computing as associated software, specifically Java 3D and computer processing units which we now briefly turn to.

4: MOVING TOWARDS 3D: ADVANCES IN PROCESSING UNITS

The ability to visualize and model entire cities on a computer not only relates to availability of data but also to developments in computing in general, specifically how computer processors have developed at exponential rates doubling approximately every two years (i.e. Moore's Law, 1965). This is especially the case for the central processing unit (CPU) which is at heart of the computer, and whose job is to execute a collection of machine instructions that in turn tell it what to do in terms of computation[3]. Generally speaking, 2D visualizations and simulations have been traditionally carried out on the CPU; however, moving to the third dimension requires moving the rendering of graphics onto the graphics processing unit (GPU). The GPU is a specialized processor optimized for accelerating graphics, and it offloads all the 3D graphics rendering from the CPU. The processor specifically uses most of its transistors to perform floating-point calculations which are fundamental to 3D graphics rendering. The development of the GPU and more generally graphic cards has been motivated by advances in games. It has become a fairly complex and specialized device that has allowed for the exploration of applications in different areas, which will be briefly explored below. While the graphics card plays an important role for graphic designers, and 3D animators, more recently the GPU has been utilized by scientists to perform computations that are beyond computer graphics. This technique is often referred to as general-purpose computing on graphics processing units or GPGPU for short (see Owens *et al.*, 2005). In relation to ABM, not only does the GPU allow for the creation of 3D visualization and rendering of agent-based models but through the GPGPU there is a potential to run agent-based models containing millions of agents much faster than general purpose CPU programs such as those employed in ABM toolkits such as Repast (2008) and NetLogo (2009). For more information pertaining to the use of the GPGPU for ABM the reader is referred to Lysenko and D'Souza (2008).

However, utilizing the GPU for ABM is not a trivial task. Users have two main options: the first is to write their own software code, the second is to use an existing piece of software. For the first option, programming languages such as C#, C++ or Java can be used to write software which can use graphic libraries such as DirectX (2009) and OpenGL (2009), which are two of the main types of graphics libraries that can be used to write programs that provide instructions to the GPU to perform complex tasks. While the second lower entry option is to use existing software such as 3ds Max (2009), a modelling, animation and rendering package developed by Autodesk which provides the capability to utilize the GPU for rendering outputs (which we discuss briefly in Sections 5 and 6).

[3] For further information about the CPU the reader is referred to its entry in Wikipedia, 2009.

5: 3D ABM APPLICATION DOMAINS

2D agent-based models have been developed to study a wide range of phenomena; however, here we will only focus on one application domain that of pedestrian modelling and trace how moving to the third dimension can aid such models. Pedestrian modelling itself is a wide domain. For example, there are models exploring the evacuation of buildings (e.g. Castle, 2007a), to that of movement in shopping areas or art galleries, and crowds (e.g. Batty *et al*., 1998). These models generate valuable insights into such events, and demonstrate how the action of many individuals results in more aggregate structures emerging. For example, in crowds, the agents themselves are often represented as dots or squares. We are able to validate such models through datasets of the real-world equivalent of the agents to be modelled, or by using human observers to collect data.

Compare such models with those from first person video games such as Crysis (2009) or fight scenes in Lord of the Rings between Orcs and Humans using purpose-built software called Massive (2009) with which thousands of agents can be programmed to make decisions such as to defend, to retreat if out numbered, etc. While such models are highly visual representations in 3D and look semi-realistic, they do not focus on behaviour per se. Within such models, be it from computer games or movies, behaviours are often homogeneous or have limited heterogeneity, while 2D social science applications tend to focus more on the latter. The reason for this, within movies, is that the realism of behaviour is not a great priority, as compared to realism of the agents, such as characters in crowds. This kind of modelling is focused on agents in movies, computer game productions, or virtual worlds / environments. Here, the rendering of the agents is the point of focus, and animating in a believable manner is sufficient.

There are a host of tools available to create such crowd simulations, not only Massive but also Autodesk's 3ds Max, Maya (2009), and Legion (2009). These tools have been used in the movie and games industry for years, and are high-end computer animation and artificial intelligent software packages. However, a recent trend has been the convergence of this high quality visualization along with realism of behaviour, where systems that are visualization oriented are trying to incorporate better behaviour, and vice versa. While agent-based models need to incorporate behaviour, adding high quality 3D visualization has its advantages over simple 2D in terms of representation. Specifically (adapted from Thalmann and Musse, 2007):

- the model is easier to understand, and gives a visual reference of the location;
- it gives a general feel for the environment, and shows how the environment will look, in addition to the ABM simulation;
- it enhances communication of ideas; a good example is the redesign of the Oxford Circus interchange in central London (Designhive, 2008);
- it helps spot obvious errors in the model;
- it makes ideas more accessible to others, that otherwise may not understand them; for example, planning proposals to councils; and
- it helps the user use his / her intuition in understanding a system.

More specific pedestrian applications that might benefit from the third dimension include the movement of pedestrians in complex structures, such as multi-floor buildings that are often spread over several floors with interconnecting stairways (as briefly discussed in Section 2), like office blocks and shopping malls, which are not 2D flat planes. The ability to move from the two to the third dimension allows us to simulate more realistic movement within such buildings but also to explore different land uses (mixes of land use) within the same model (in this example a building). For example, retail on the ground floor and residential on the upper floors cannot be easily visualized or modelled in 2D. This is not to say that 2D models of complex buildings are of no use, but that moving to the third dimension allows for more realism and flexibility within models especially when combined with advances in geometric and non geometric digital datasets (e.g. Akiyama and Shibaski, 2009). In relation to complex buildings, there is also the need to model evacuation scenarios in order to model overall evacuation performance. By taking into consideration the design of a building, in many cases, with several floors, a 3D simulation can highlight the impact the design of a building will have on individuals exiting it (e.g. Gwynne *et al.*, 2001). These types of models are seen with many of the commercial pedestrian modelling software packages such as Legion (2009) and STEPS (2009).

6: TECHNIQUES AND TOOLS FOR CREATING 3D AGENT-BASED MODELS

Thus far we have discussed how the rise in digital data can help create 3D models along with how advances in computer hardware are allowing us to create agent-based models within the third dimension. This section explores methods on how one goes about creating

3D agent-based models using existing software packages, or through linking/coupling agent-based models with 3D visualization software. These include creating an agent-based model within a specific software environment such as utilizing commercial game engines, which allow for the development of ones own models. Examples are provided by Unreal (2009) and Crysis (2009) that allow for the importation of 3D buildings and associated spatial data. For example, in Fig. 3 we show how the Virtual London 3D city model can be imported into the Crysis game engine. Alternatives to commercial game engines are their open source equivalents such as OGRE (2009) or Panda3D (2009), where models can be created using programming languages such as Python or C++. As with open source ABM toolkits such as Repast, the key advantage of open source games engines relates to the transparency of their inner workings. The user can explore the source code, permitting the modification, extension and correction of the system if necessary. This is particularly useful for verifying a model (see Castle and Crooks, 2006). A further advantage of using this approach is the ability to focus on modelling rather than spending time developing parts of the model that are not content specific such as user interfaces.

Fig. (3). The Swiss Re building and the City of London imported into the Crysis game engine.

Rather than directly embedding the agent-based model into a software environment, the coupling of an agent-based model to 3D visualization software might be the preferred option, especially if the model has already been built. Such coupling can therefore be broadly defined as the linkage of two stand-alone systems by data transfer. This coupling can be seen on a continuum between loose and tight coupling as seen within GIS (see Castle and Crooks, 2006 for further information). Loose coupling can be seen as the transferring of files, as we demonstrate in the NetLogo example in Section 6.2. Here, NetLogo is used to execute the model and store outputs of agent locations, which are then transferred to the 3D software for visualization. Tight or close coupling is characterized by the simultaneous operation of systems allowing direct inter-system communication during the program execution. For example, Merrick and Maher (2007) have created agent-based models in Java, communicating with Second Life via remote procedures XML-RPC requests to the Second Life server. Second Life is only used to collect and display model information.

6.1: TIGHT-COUPLING: CREATING 3D AGENT-BASED MODELS IN 3DS MAX

While not being a specialist agent-based visualization package *per se*, 3ds Max does have a built in simulation system. Known as ‘Crowd and Delegate’, it allows groups of 3D objects and characters to be animated using a system of delegates and behaviours. Using a series of simple rules, either those built in such as ‘avoid,’ ‘follow,’ ‘seek’ or custom written in the form of scripts, one can create crowds with highly complex behaviours. Fig. 4 illustrates the most basic level of agent based model in 3ds Max using the ‘follow surface’ and ‘wander behaviour’. Each delegate, represented as the blue triangles, forms part of a team assigned rule to wander for a set period of time in a random manner while following a 3D surface, in this case created to simulate a terrain. Once set in the scene, a time element is added for the simulation with the delegates location solved for each key frame (akin to a time step) of movement. Using the crowd and delegate method, it can also be extended to the simulation of schools of fish or people which can be quickly and easily achieved to a high level of visual realism (e.g. Stephens *et al*., 2003).

Models created in such software not only utilize advances in graphic card technology, but also advances in physics based engines (such as Havok, 2009) which allow us to easily add additional elements such as mass and gravity to influence the agents’ behaviour. For example, in Fig. 5 we extend a basic flocking algorithm to model pedestrian movement that also includes avoidance of vehicles, in this case a bus, and frame the model in a 3D cityscape. Other simple agent-based models within 3ds Max include simple ant like behaviours to simulate shockwaves within traffic akin to Nagel and Schreckenberg (1992) traffic example. The various built-in components of 3ds Max enables high quality graphic outputs as well as real time previews and outputs to game engines such as Crysis. This allows researchers to achieve ‘semi movie like’ results. However, as with all movie clips and demonstrations out of standard 3D packages they need to be taken with a pinch of salt. The science is there and the simulations are realistic but the science is hidden and not produced by the agent-based modeller but by the package itself as it is essentially a 'black box.' Since the inner workings are often hidden, it potentially makes these packages of limited value on their own, which makes us turn our attention to loose coupling approaches.

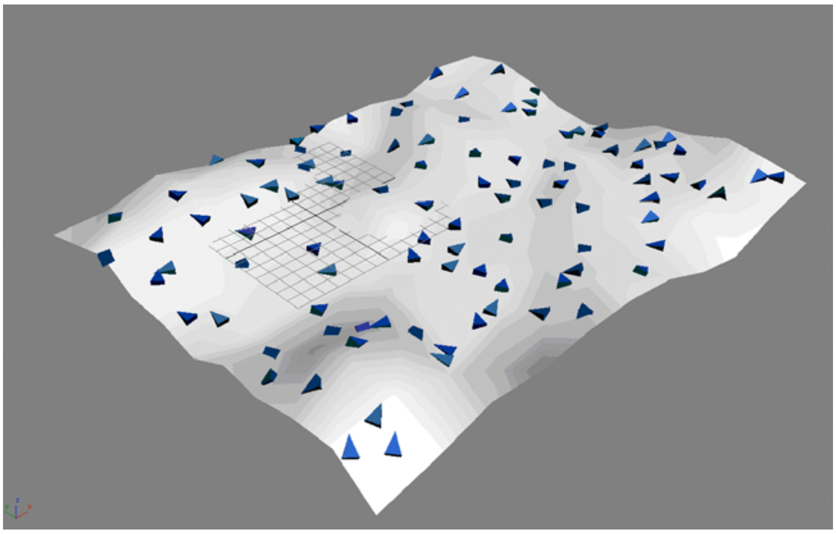


Fig. (4). 3ds Max crowd and delegate system: follow surface and wander behaviour.

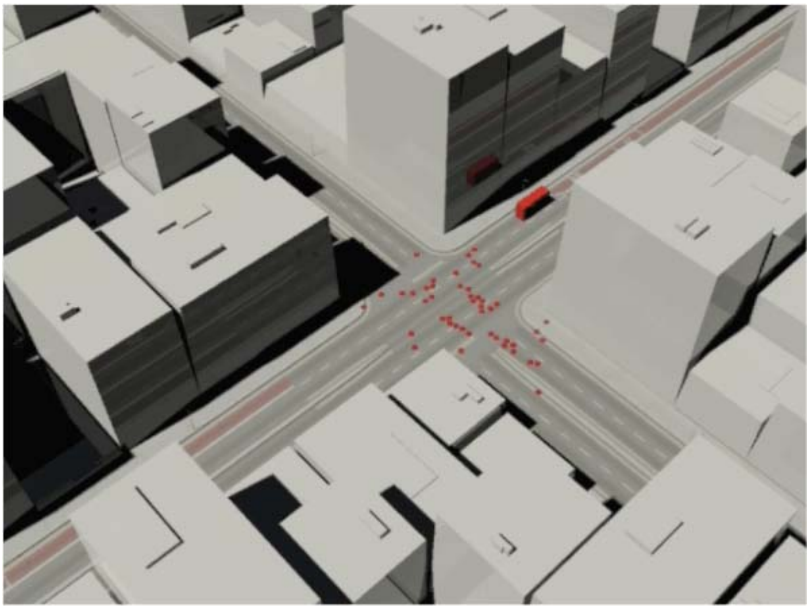


Fig. (5). Pedestrian agents and a vehicle agent within a cityscape created in 3ds Max.

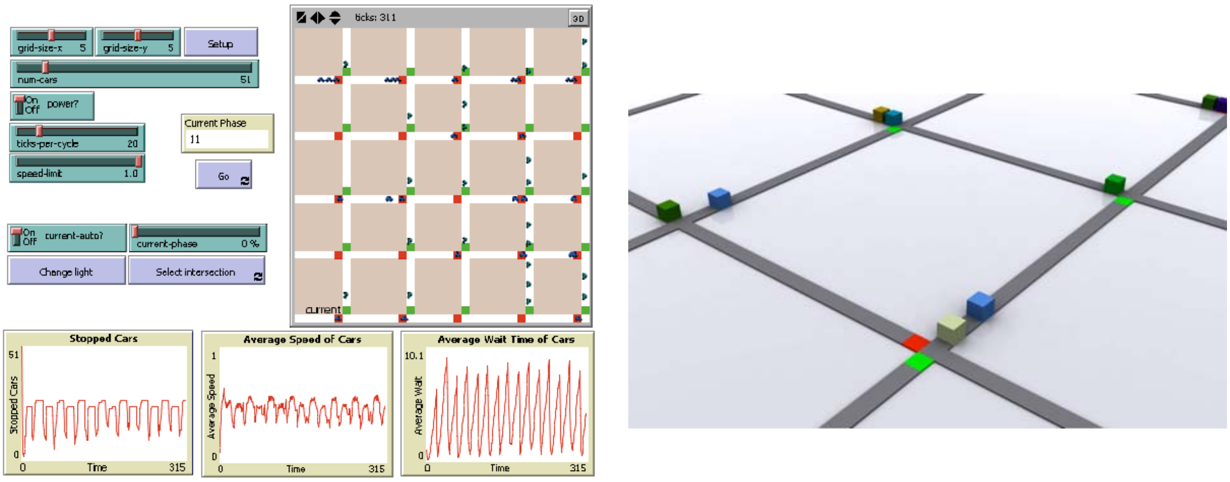
6.2: LOOSE COUPLING NETLOGO WITH 3DS MAX

Loose coupling provides an attractive alternative, in the sense that we can create an agent-based model using a specific programming library or use a dedicated simulation/modelling toolkit designed specifically for ABM and then visualize the outputs from the model in a 3D environment (thus the 3D scene is purely for visualization purposes unless there are x, y and z coordinates directly incorporated in the modelling process). In this instance we use NetLogo, a simulation/modelling system for the modelling and 3ds Max for the visualization. As a proof of concept we take a simple traffic model (Wilensky, 2003) from NetLogo as shown in Fig. 6 (A), which models the movement of cars over a street network. Movement is restricted by traffic lights; agents stop at red lights and move on green. In order to achieve a physical three dimensional representation of the environment, the movement of the cars in NetLogo is translated into text files by recording their movement at each iteration (tick) of the model. Along with recording the coordinates of the cars, the coordinates of the road patches, and the green and red turtles (traffic lights) are stored for each tick for a total of 500 ticks. These data are then read into 3ds Max through a script. The script takes all the coordinate information from the cars movement, the traffic light states and the road patches. Key frames are first created, steps are then taken to animate and render the scene as we show in Fig. 6 (B). The process of linking NetLogo to 3ds Max is shown in Fig. 7. Further information including a tutorial can be found in Patel (2009).

This approach has the potential of creating high end visualizations of geographically explicit agent-based models especially as NetLogo supports the integration of geographic datasets. Another example of this loosely coupled approach is by Narahara (2007) who combined a pedestrian model from NetLogo, which explored human behaviour to room configurations, where the outputs were visualized with 3ds Max. The ability to import coordinates into these systems means that 3D cityscapes created in CAD and GIS packages can be populated with agents from other models. For example, outputs from large scale traffic models such as MATSim (2009) could be visualized in 3ds Max providing a sense of location and place, which non modellers could relate to.

6.3: AGENT-BASED MODELS IN VIRTUAL ENVIRONMENTS

With respect to visualizations, the models presented above can be broken down into two categories. The first is fly-through, where the creator has set up a prescribed flight path (viewing angle) that the viewer cannot deviate from. For example, those in 3ds Max (Sections 6.1 and 6.2). The second is interactive visualizations, where the viewer has control on how and where to view the simulation from (such as shown in Fig. 3). It is to these we now turn to as this represents immersing the user into the modelling environment.



A B

Fig. (6). 3D Visualization of NetLogo traffic simulation: (A) NetLogo Traffic Simulation; (B) Cars on top of roads, with red and green traffic light within 3ds Max.

With improved graphics and processes, networked communication and associated technology has led to the rise of interactive content through Web 2.0 technologies. These technologies have lead to users expecting a more interactive experience over the internet (Baird and Fisher, 2005) and we would argue that this is the case for modelling as well especially when embedding such models in virtual worlds. Virtual worlds offer such an experience as they allow users to explore areas and interact with the content that interest them. However, finding ones way through such worlds can be a difficult task (see Ingram and Benford, 1996), these problems can be overcome if one considers legibility (as discussed in Section 3), which refers to the ease at which inhabitants can develop a cognitive map over a period of time and thus can orientate themselves and navigate through the space. The use of actual buildings and 3D cityscapes could greatly facilitate such navigation and understanding of agent-based models directly related to spatial locations. For example, the Unity (2009) multi-platform game development tool platform allows us to embed models into rooms as highlighted in Fig. 8. The room itself is created in SketchUp (2009) and the models in 3ds Max. In essence these are just table-top models but one can extend such models into virtual environments, for example, in the virtual world of Second Life to which we now turn.

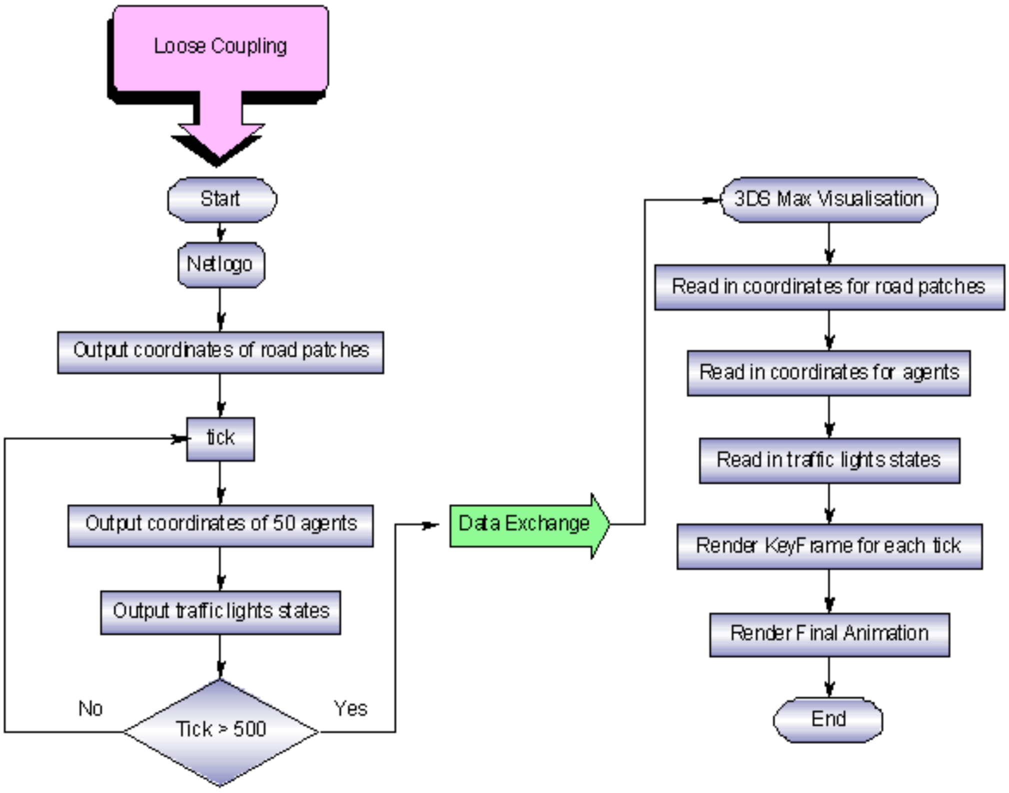


Fig. (7). Loose coupling between the two standalone systems.

Fig. (8). Agent-based models displayed in Unity.

Agent-based models are usually considered as forming a miniature laboratory where the attributes and behaviour of agents, and the environment in which they are housed, can be altered, and experimented with, where their repercussions are observed over the course of multiple simulation runs. Virtual worlds such as Second Life act in a similar way to agent-based models i.e., they are artificial worlds populated by agents. The idea behind such systems is to engage a community of users where people represented as avatars can be active users contributing to sites and participating in site content in real time through the world wide web which opens their use to whoever is connected. Such worlds can potentially be used as online laboratories – collaboratories (see Science of Collaboratories, 2009 for a further discussion), for example, where model building and users engage in mutual and shared development activities, although their infancy are very much on the horizon.

Virtual worlds such as Second Life have great potential for research in the social and behavioural sciences along with offering an environment for education and outreach (see Bainbridge, 2007). These systems allow people to discuss and visualize models in real time; they provide an effective medium to clearly communicate models and results between the developer and the decision maker which in the past was the sole province of powerful scientific workstations. For agent-based modellers it offers a unique way for the exploration and understanding of social processes by means of computer simulation. Researchers have used agents within virtual worlds to study a variety of phenomena from human-to-agent interaction (e.g. Berger *et al*., 2007), the study of norms between agents and avatars (e.g. Bogdanovych *et al*., 2007), healthcare issues (Dieterle and Clarke, in press), to herding behaviour (Merrick and Maher, 2007). We are using Second Life as a collaborative geographic space (see Hudson-Smith and Crooks, 2008) for the dissemination of geographic content and for the exploration of agent-based models in an interactive 3D media.

Within this world we have created a number of agent-based models using the Linden Scripting Language (see Rymaszewski *et al*., 2007) as we show in Fig. 9. It is the purpose of these models to act as pedagogic demonstrators and as a 'proof-of-concept', thus we have chosen Conway's Game of Life and Schelling's (1971) segregation model. These models were selected to highlight how classical automata styles of models that have inspired a generation of modellers can be created and explored in Second Life (see Crooks *et al*., 2009 for more details). The third model we have created is a prototype pedestrian evacuation model, which is not only more complex than the first two, but highlights how more complex models can be created and be linked to actual buildings as we show in Fig. 10.

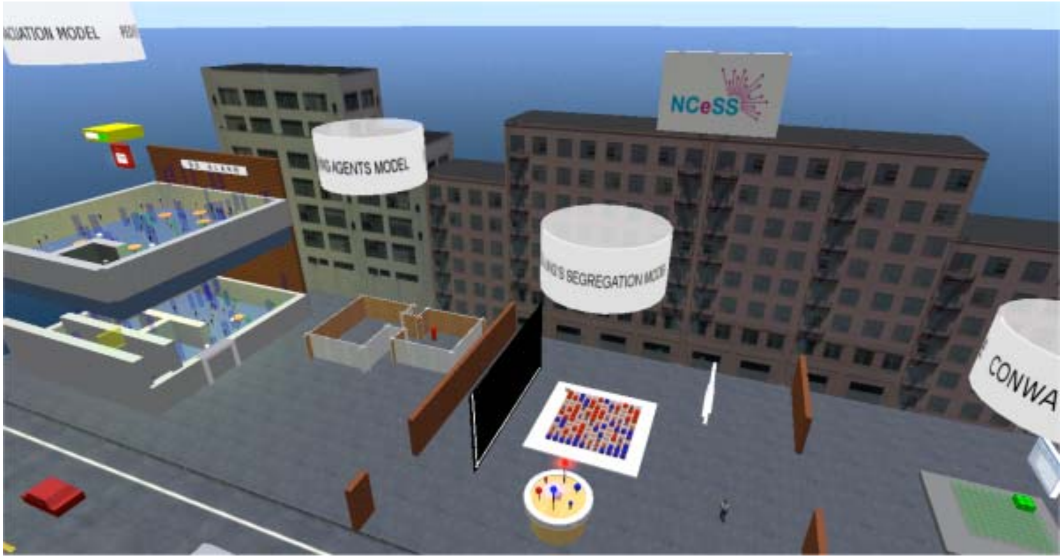


Fig. (9). Agent street: Agent-based models in Second Life.

Agents within the evacuation model have been designed to mimic ‘real’ people with realistic anthropomorphic dimensions that exit a building when an alarm is sounded. We represent the building (enclosure) as a continuous space opposed to the more common regular lattice (grid) or coarse network enclosure representations (Castle, 2007b) which are common in 2D pedestrian models. Therefore agents are not restricted to discrete cells nor represented as flows thus enabling us to simulate pedestrian movement more explicitly in the x, y and z dimensions. The agents within the model interact with each other and their environment (e.g. obstacle avoidance) both of which can have an effect on occupant movement. For example, agents adjust their walking speed when approaching congestion. Users can explore several room configurations that allows one to study exit route choice and way finding, and identify bottlenecks in building design. This model relates to the genius of such models of which the social forces model developed and popularized by Helbing and Molnár (1995) is typical. Additionally the agents within the model can also be influenced by the presence of avatars –digital representations of actual people (i.e. users of the model)[4].

[4] The website accompanying this work can be found at http://www.casa.ucl.ac.uk/abm/secondlife/.

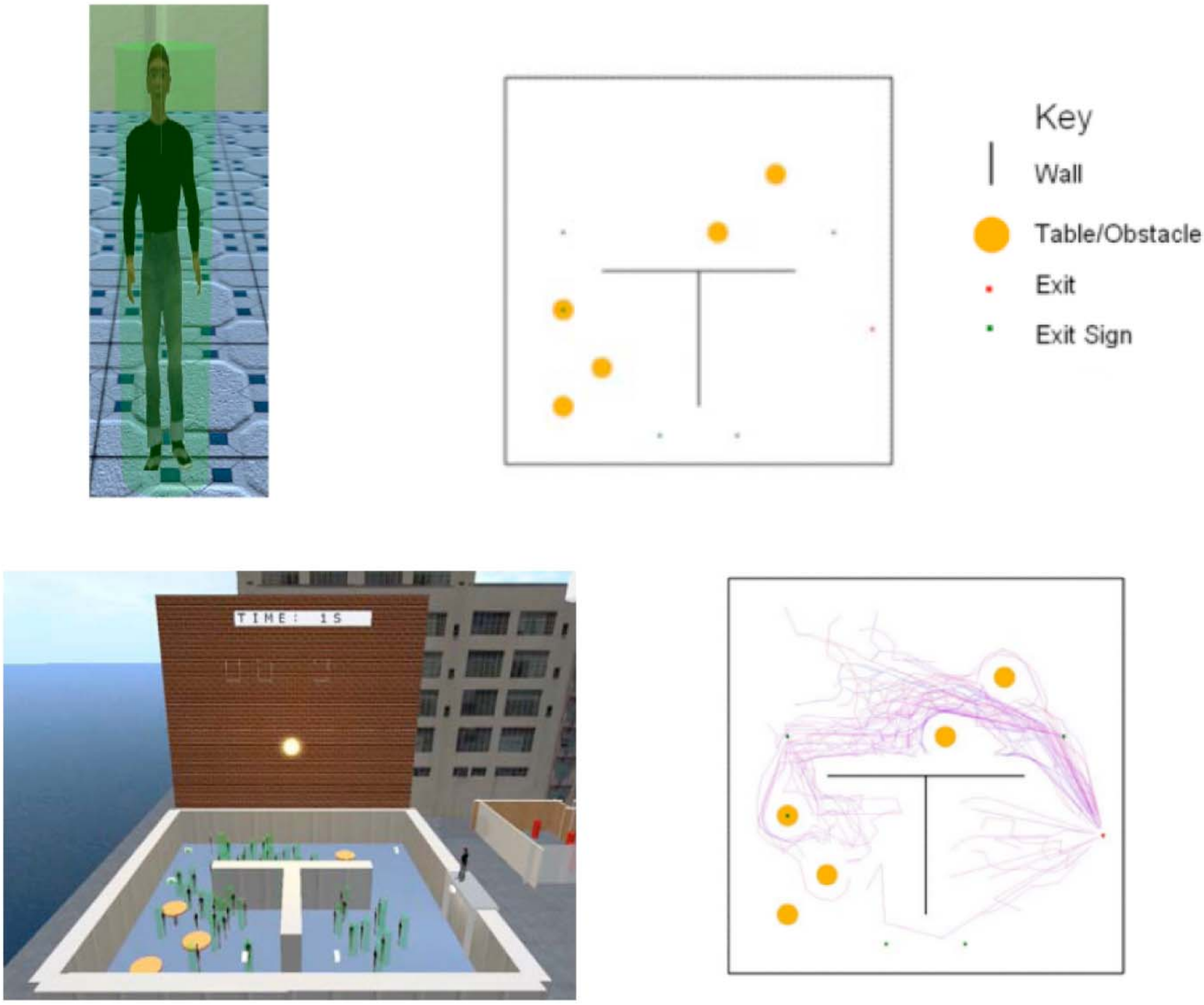


Fig. (10). Pedestrian modelling within Second Life: (top left) a pedestrian agent within the model in green; (top right) room configuration; (bottom left) pedestrians and their environment; (bottom right) tracing the pedestrians routes to the exit (red dot).

7: DISCUSSION

In the past, the communication of models was mainly done through discussion of model results. However, increasing amounts of digital data and advances in GIS and CAD software, enables us to not only create geographic explicit agent-based models, but also detailed 3D cityscapes in which to embed such model results. Advances in computer technology specifically the CPU and the GPU, and networked communications allow us to analyze and communicate such data and models to anyone who is connected to the internet. Nevertheless, combining ABM and 3D cityscapes is still much in its infancy and their combined potential is still unknown for scientific research. This paper has attempted to explore this potential outlining some of our initial research, why it might be important and how 3D agent-based models can be created utilizing advances in computer technology. While there are many software environments that support the development of 3D agent-based models, many are commercial applications originating from computer gaming and the entertainment industry, and are to some extent black boxes. However, programming 3D agent-based models from scratch using the GPU is a non trivial task but perhaps in the future, toolkits might be developed to do this, just as Repast and NetLogo have developed functionality to deal with geospatial data.

One question this paper attempts to address is why do we need the 3D component in agent-based models? In Section 3 we discussed how people make cognitive maps of their environment. By relating models to actual places we would argue that people can more easily relate to such models (i.e. gain a sense of location and place). This is perhaps one of the most important roles of 3D agent-based models. If the role of the model is to portray some complex behaviour or problem to those that we seek to influence by relating it to actual places, people may more easily understand what is occurring within the model. We believe such an approach allows us to share modelling processes and its outcomes with various non-expert participants and potentially allow non-experts to participate in actual model construction in the case of virtual worlds. However, to truly understand the utility of 3D agent-based models over their 2D counterparts we need to carry out user testing, which we see as a future avenue of research. We do not want to simply state that by moving agent-based models from the 2D to the 3D will further enhance their communication, usability and persuasive powers without just cause. The tools and techniques presented show the potential of virtual worlds, CAD packages and game engines to act as portals for allowing modellers, policy makers and citizens to communicate, share and visualize 3D spatial agent-based models which tentatively further our understanding of how these models work. By making these models available to whoever is connected to the internet allows them to go under greater scrutiny than was possible in the past, thus aiding the use of agent-based models as a tool for decision support.

However, a note of caution is also needed, that is 3D visualization of agent-based models does not replace the need for good models. Just as their 2D counterparts, 3D agent-based models that attempt to tackle the real-world problems need to be based on theory or insights gained from the phenomena under investigation. If this is not the case, 3D agent-based models are no better than ‘eye-candy’ and tell us little about the phenomena under investigation. We envisage 3D visualization as a tool for conveying the complexities of agent-based models to those we seek to influence. Both in relation to how people relate to space (as discussed in Section 3) but also how human spatial behaviour within the built environment may be related to some simple physical properties of the urban environment (see Yang *et al*., 2007). Without incorporating the complexities of the third dimension into these models this may be missed. For example, the use of 3D models allows one to evaluate potential visual impacts of the existing and proposed urban form before urban design decisions are made. Furthermore, in the introduction we discussed how agent-based models exploring spatial patterns must look right. Combining models to 3D digital environments might therefore be of benefit here. However, maybe the biggest benefit of the development of 3D city models and game engines is the development of GPUs that allow us to simulate millions of agents as discussed in Section 4.

Looking towards the future, it is clear that cities are composed of many individuals and objects. Such objects interact with each other over varying scales both spatially and temporally, from the movement of pedestrians, to the hourly flows of traffic, to urban growth and change over months, to that of migration over years, to the rise and fall of civilizations over eons. What these processes all have in common is that they are composed of individual actors and to some extent, progress in exploring these using agent-based models is being made. The potential of combining these different processes within a single 3D modelling environment is highly appealing in the sense of giving a picture of city life. With the growth in computational power in the not so distant future it may be possible to use virtual worlds such as Second Life or OpenSim (2009) to model whole cities, combining various types of models from iconic to symbolic in a single environment. Models exploring issues such as pedestrian movement, traffic, residential location, employment, gentrification could be merged in a single environment whose interactions feed back into each other and to the overall character of the city. A SimCity for real if you like, but where the focus is not just on end-user visualization but on understanding the behaviour and interactions of all the agents and processes that underpin a city. However, to do this we need to improve our understanding of these complex processes.

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